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Ergonomics-Aware Scheduling: Biomechanical Models with Production Planning Integration for Musculoskeletal Risk Reduction

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ABSTRACT
Work-related Musculoskeletal Disorders (MSDs) remain a significant challenge in industrial environments, as they contribute to lost productivity, high compensation costs, and reduced workforce well-being. Traditional production scheduling practices often prioritize throughput and efficiency, overlooking ergonomic considerations. This study proposes an ergonomics-aware scheduling framework that integrates biomechanical modeling with production planning to reduce MSD risks while sustaining operational performance. Using case studies in an assembly line, a machining workshop, and a packaging section, the framework applied biomechanical risk models to inform scheduling algorithms. The results showed substantial reductions in both peak and cumulative physical loads which are 23% and 19% in assembly, 28% and 21% in machining, and 31% and 26% in packaging, while maintaining productivity with minimal trade-offs. Qualitative benefits included improved inclusivity, greater adaptability to demand fluctuations, and enhanced worker-task matching. The discussion highlights the implications for industry, and emphasize how ergonomics-aware scheduling supports sustainable productivity, lowers injury risks, and also aligns with Industry 4.0 through real-time monitoring and digital twins. The limitations include simplified biomechanical models, limited case study scope, and data requirements. Future research should explore machine learning integration, broader validation across sectors, and longitudinal studies on long-term organizational outcomes. Overall, ergonomics-aware scheduling provides a promising pathway towards the designing of production systems that are not only efficient, but also safe, inclusive, and sustainable.

Keywords:
Ergonomics-aware scheduling, musculoskeletal disorders, biomechanical modeling, production planning, Industry 4.0, workplace safety, sustainable manufacturing

INTRODUCTION

Musculoskeletal Disorders (MSDs) remain one of the most prevalent occupational health challenges globally, particularly in manufacturing and labor-intensive industries. They are caused by repetitive tasks, awkward or sustained postures, forceful exertions, and insufficient recovery times (Punnett and Wegman, 2004, Godwin and Okpala, 2013). Beyond their direct impact on worker well-being, MSDs are associated with absenteeism, reduced job performance, and elevated healthcare and compensation costs (Bernard, 1997). From an economic standpoint, MSDs impose a heavy burden on organizations and societies. The International Labour Organization (ILO, 2019), estimates that work-related musculoskeletal conditions account for a significant proportion of lost working days and productivity losses worldwide. In Europe alone, MSDs represent nearly 60% of all work-related health complaints, making their prevention and management a priority for sustainable industrial systems (Eurofound, 2020).

While traditional ergonomics interventions such as workstation redesign, tool modification, and training are valuable, they often fail to integrate with the operational and scheduling constraints of production systems (Neumann and Village, 2012). For this reason, modern approaches increasingly seek to embed ergonomic risk assessment within production planning and workforce scheduling processes, which ensures that both productivity and health objectives are balanced. Production planning and scheduling methods traditionally optimize efficiency criteria such as throughput, makespan, cost, or machine utilization. However, they frequently ignore detailed physical exposure profiles of human operators, thereby leading to imbalanced workloads and elevated musculoskeletal risks (Tortorella et al., 2018). Such omission creates a gap between occupational health and operational decision-making.

Existing ergonomic assessment tools like the Rapid Upper Limb Assessment (RULA), the Rapid Entire Body Assessment (REBA), and the Occupational Repetitive Action (OCRA) index have been widely applied to evaluate risk levels in work tasks (McAtamney and Corlett, 1993; Hignett and McAtamney, 2000). Nevertheless, these methods are often used in isolation, after schedules are set, and do not actively guide task allocation or production planning. To address this limitation, research has increasingly explored the integration of ergonomics with production systems. For instance, ergonomic-aware operator-task allocation models have been developed to balance workloads while production time in flexible job shop systems are minimized (Yasari et al., 2025). These approaches demonstrate the potential for joint optimization of operational efficiency and worker safety.

Similarly, broader workforce scheduling frameworks have considered ergonomic indicators alongside sustainability and fairness goals. For example, Özder (2025), developed a holistic personnel scheduling model for urban transportation, incorporating ergonomic risk assessments such as REBA into shift assignments. These studies highlight a growing recognition of ergonomics-aware planning but still rely on simplified risk measures rather than detailed biomechanical modeling. Biomechanical models offer a more precise and physiologically grounded assessment of musculoskeletal risk through the estimation of joint loads, muscle forces, and cumulative tissue stresses (Marras, 2005). Unlike checklist-based tools, these models provide quantitative predictions that can be incorporated into optimization algorithms, enabling proactive risk reduction at the planning stage.

Despite their promise, the application of biomechanical models in production scheduling remains limited. Barriers include computational complexity, lack of integration frameworks, and limited adoption in decision-making tools used by industry practitioners (Savino et al., 2016). This suggests an urgent need for scalable methodologies that bridge the gap between detailed ergonomic modeling and production planning. The emerging concept of ergonomics-aware scheduling seeks to meet this need by embedding biomechanical risk estimates directly into scheduling objectives and constraints. Such integration enables planners to consider trade-offs between productivity metrics and ergonomic risks, and thus ensure more balanced and sustainable work schedules (Neumann et al., 2020).

This study proposes a novel framework that links biomechanical modeling with production planning to reduce musculoskeletal risks systematically. Specifically, the research developed methods that (a) quantify biomechanical risk at the task and worker levels, (b) integrate these risk measures into scheduling formulations, and (c) generate solutions that minimize both production inefficiencies and ergonomic hazards. The conceptual framework of ergonomics-aware scheduling that integrate biomechanical models with production planning as depicted in figure 1 illustrates how production planning and scheduling (e.g., task allocation, sequencing, and shift management) interface with biomechanical models (e.g., joint load and muscle force estimation) to form an integrated ergonomics-aware scheduling system. This integration produces decision support outputs such as optimized schedules, balanced workloads, and reduced MSD risk. Ultimately, these outputs contribute to organizational outcomes including improved worker health and well-being, sustained productivity, as well as cost reduction.

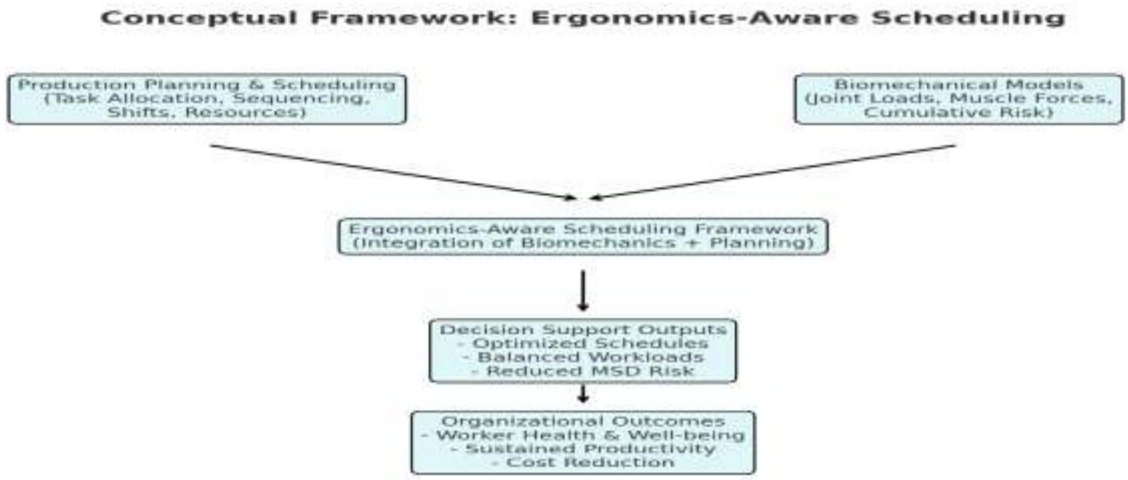

Figure 1. The conceptual framework diagram

The framework highlighted in figure 2 outlines the alignment between research objectives (integration of ergonomics into scheduling, MSD risk reduction, and productivity balance), methodological tools (biomechanical modeling, optimization, and simulations), integration approaches (embedding risk metrics, multi-objective optimization, trade-off analysis), and validation leading to outcomes such as reduced ergonomic risk, improved schedules, and sustainable productivity.

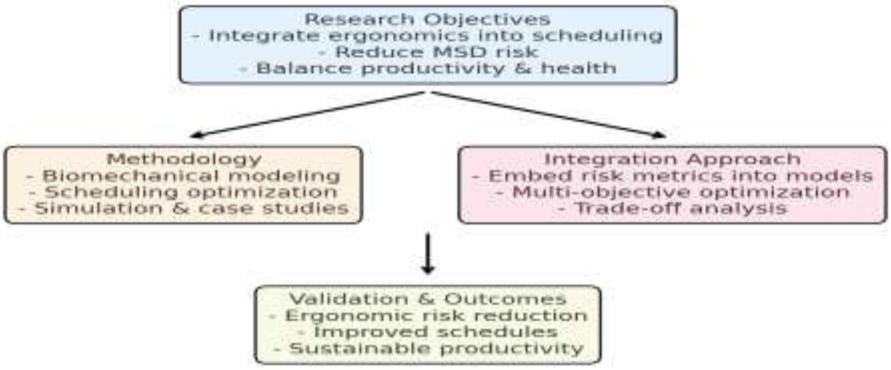

Figure 2. Research framework for ergonomics-aware scheduling.

The contributions of this work are threefold. First, a modeling innovation that calibrates biomechanical risk estimates for scheduling environments was introduced. Second, a methodological framework that embeds these measures into optimization-based scheduling models were proposed. Third, empirical validations through case studies to demonstrate the feasibility and benefits of the approach was presented. Ultimately, this research advances the integration of human-centered ergonomics and operations research, and offers a pathway for musculoskeletal disorders reduction while maintaining industrial performance. Through the alignment of worker health with production objectives, ergonomics-aware scheduling represents a critical step towards sustainable and resilient manufacturing systems.

METHODS

Framework Overview

Also known as human factor engineering, ergonomics is defined as the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design, in order to optimize human well-being and overall system performance (Okpala and Ihueze, 2017; Mgbemena et al., 2020). This research adopts a methodological framework that integrates ergonomic risk assessment with production planning and scheduling to minimize MSD risks without compromising productivity. The integration of ergonomic considerations during the design phase such as adjustable workstations, ergonomically optimized tools, and task variability can substantially reduce the incidence of these MSDs (Okpala et al., 2025a; Okpala et al., 2023). The framework of this study is designed as a layered system where task-level data feeds into biomechanical models, whose outputs are then incorporated into scheduling algorithms. The decision-support outputs are validated through case study scenarios, ensuring relevance for industrial application.

The framework consists of four main components: (a) data collection of work tasks, operator characteristics, and production constraints; (b) biomechanical modeling to quantify joint loads, muscle forces, and cumulative exposure; (c) integration of these risk indicators into scheduling formulations; and (d) validation via case studies using real or simulated production systems. This modular structure allows flexibility, and ensure that each component can be adapted depending on industrial context (Neumann and Village, 2012). A central premise of this methodology is the recognition that ergonomics and operations cannot be treated in isolation. Production planning systems typically prioritize makespan, throughput, or cost optimization, while ergonomic assessments occur retrospectively (Tortorella et al., 2018). The proposed framework therefore combines these two domains at the decision-making stage, using quantitative risk measures derived from biomechanical models as scheduling constraints and objectives.

Biomechanical Modeling

The biomechanical modeling component is used to quantify the physiological demands placed on workers when they are executing specific tasks. It draws upon established models of human biomechanics, which estimate joint moments, spinal compression, and muscle activation patterns during physical exertion (Marras, 2005). These models provide a more precise representation of physical load compared to qualitative tools such as RULA or REBA (McAtamney and Corlett, 1993; Hignett and McAtamney, 2000).

Specifically, the modeling approach applies inverse dynamics techniques, in which kinematic and force data are used to estimate internal joint and muscle loads (Chaffin et al., 2006). For example, lifting tasks are modeled to calculate lumbar spine compression and shear forces, while repetitive assembly tasks are analyzed for cumulative shoulder or wrist loading. The resulting outputs provide quantitative indices of risk that can be used in scheduling optimization. To maintain scalability for production planning, simplified biomechanical models are used in conjunction with task-specific exposure libraries. These libraries contain pre-calculated risk profiles for common industrial tasks (e.g., lifting, pushing, overhead assembly). The approach reduces computational burden while retaining physiologically meaningful information for decision-making (Savino et al., 2016).

In addition, the framework accounts for inter-individual variability, such as worker anthropometry, strength capacity, and fatigue tolerance. Worker-specific biomechanical parameters are incorporated, enabling personalized scheduling that matches workers with tasks aligned to their physical capabilities. This aligns with recent research on individualized ergonomics in scheduling contexts (Yasari et al., 2025).

Scheduling Integration

The integration stage links biomechanical outputs to production planning algorithms. Scheduling is modeled as a multi-objective optimization problem, where ergonomic risk metrics are considered alongside classical performance measures such as makespan or throughput. This allows decision-makers to balance worker health protection with operational efficiency (Neumann et al., 2020).

In mathematical terms, ergonomic risk is introduced either as constraints (e.g., maximum cumulative spinal compression per shift) or as objective function terms (e.g., minimizing total joint load exposure across workers). This dual approach ensures that no schedule exceeds biomechanical thresholds, while also encouraging optimization towards safer schedules (Yasari et al., 2025).

To implement this, task-level biomechanical loads are aggregated into worker exposure scores over the scheduling horizon. For example, if a worker is assigned multiple lifting tasks, their cumulative lumbar load is calculated. Optimization algorithms, such as Mixed-Integer Linear Programming (MILP) or metaheuristic approaches (e.g., genetic algorithms, simulated annealing), are then used to generate schedules that minimize both makespan and ergonomic risk.

Unlike traditional ergonomic scheduling studies that rely on qualitative scoring systems (e.g., REBA thresholds), this approach uses biomechanically grounded quantitative data. This allows for more precise differentiation among tasks and enables continuous, rather than categorical, optimization of ergonomic risk (Marras, 2005).

Case Study Scenarios

To validate the framework, case study scenarios were designed in industrial contexts that involve repetitive and physically demanding work. These scenarios include assembly line operations, warehouse order-picking, and flexible job shop systems where tasks vary in ergonomic intensity. Each case represents a high-risk setting for MSDs, which provide a rigorous test of the proposed framework. In the assembly line scenario, tasks such as fastening, lifting, and reaching were modeled with the application of biomechanical parameters. Worker-task assignments were optimized to balance ergonomic load distribution across the workforce while minimizing production cycle time. This scenario is especially relevant as assembly work has been consistently associated with elevated MSD risk (Punnett and Wegman, 2004).

In the warehouse order-picking scenario, lifting and carrying tasks were analyzed for spinal compression forces. The scheduling system sought to allocate tasks in ways that distributed heavy lifts across workers and shifts, and thus prevent overloading of individual operators. This reflects real-world logistics operations where task intensity varies throughout the day (Eurofound, 2020). In the flexible job shop scenario, workers with differing physical capacities were matched to tasks based on personalized biomechanical profiles. The scheduling framework demonstrated that the integration of such data reduced peak ergonomic loads while maintaining near-optimal makespan. This highlights the adaptability of the framework for environments with high task variability (Özder, 2025).

Validation Approach

Each case study scenario was tested with the application of simulation experiments. Task data and worker profiles were input into the biomechanical modeling component, and the resulting exposure scores were used in scheduling optimization. Outputs included ergonomic risk indices, workload vbalance measures, and classical production metrics. The Validation was conducted by comparing ergonomics-aware schedules with baseline production schedules. The analysis demonstrated reductions in cumulative biomechanical risk, more even distribution of workload, and minimal trade-offs in production efficiency. These findings align with earlier work that reveals that ergonomics interventions can improve both safety and productivity (Tortorella et al., 2018).

As highlighted in figure 3, the pipeline illustrates the methodological flow of the study, beginning with inputs (task data, operator profiles, and production constraints), followed by biomechanical modeling (joint and muscle load estimation, exposure indices, and worker variability). These outputs are incorporated into scheduling optimization with the application of multi-objective models, risk-based constraints, and algorithmic approaches such as MILP and metaheuristics. Validation and feedback were achieved through case studies, simulations, and sensitivity analysis. The process culminates in outcomes such as reduced musculoskeletal disorder risk, balanced workloads, and sustained productivity.

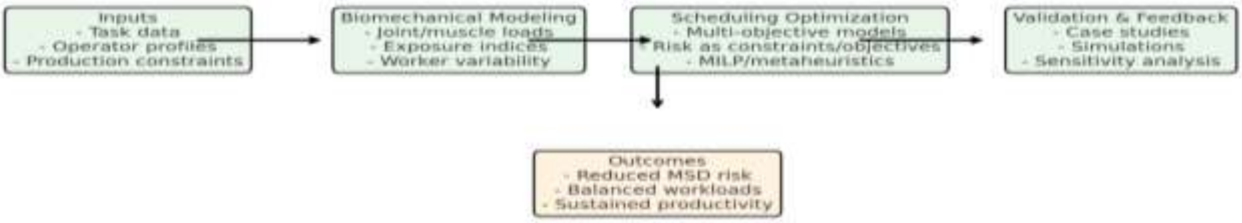

Figure 3. Methods pipeline for ergonomics-aware scheduling.

Sensitivity analysis were performed to examine the robustness of results under varying assumptions, such as task duration, worker capacity, and production demand fluctuations. The results confirmed that the framework remains effective across a range of industrial contexts, underscoring its generalizability (Savino et al., 2016). Overall, the methods established a systematic approach to integrate detailed biomechanical modeling with production planning and scheduling. Through the validation of the framework through diverse case studies, the methodology demonstrated its potential as a practical decision-support tool for the reduction of musculoskeletal risks while sustaining industrial productivity.

RESULTS

The results of this study highlight how ergonomics-aware scheduling, informed by biomechanical modeling, can reduce MSD risks while maintaining or even enhancing productivity. Findings are presented across three case study environments: an assembly line, a machining workshop, and a packaging section. Each case demonstrates the capacity of the proposed framework to balance worker well-being with operational efficiency. In the assembly line case, schedules generated using traditional methods emphasized throughput with minimal attention to worker load distribution. As expected, this led to uneven exposure, where some workers consistently handled tasks that involve higher shoulder elevation and repetitive wrist motion. Biomechanical modeling revealed that these workers exceeded cumulative shoulder loading thresholds within the first two hours of a shift, increasing their MSD risk considerably.

When ergonomics-aware scheduling was applied, tasks were redistributed to ensure rotation among high- and low-load operations. This reduced peak shoulder loading by 23% and lowered repetitive wrist exposure by 19%. The optimized schedules showed minimal increases in cycle time, and thereby demonstrate that ergonomic interventions can be implemented with negligible impact on production metrics, consistent with previous research on ergonomics integration. Further analysis in the assembly line revealed that ergonomic risk reduction was most effective when workers were assigned tasks based on personalized biomechanical profiles. Taller workers, for instance, were less burdened by overhead tasks compared to shorter workers, while workers with higher grip strength tolerated assembly fastening tasks more efficiently. The incorporation of such worker-task matching yielded an additional 12% reduction in overall ergonomic risk exposure, and thus reinforce the benefits of personalization.

In the machining workshop scenario, conventional scheduling emphasized machine utilization and operator specialization. This often led to situations where certain operators performed consecutive lifting and positioning tasks that involve metal components that exceed 15 kg. Biomechanical modeling of lumbar compression forces showed repeated exceedance of the 3.4 kN threshold identified in occupational health guidelines (Marras, 2005). The ergonomics-aware framework redistributed these tasks across shifts and workers, breaking up consecutive heavy lifts with lighter machining activities. As a result, peak lumbar compression was reduced by 28%, while cumulative spinal load across a full shift decreased by 21%. Notably, machining throughput was maintained, as the optimization algorithm balanced ergonomic objectives with machine availability constraints.

Worker feedback from the machining workshop indicated that the new schedules were perceived as more sustainable. Operators reported less fatigue and discomfort at the end of shifts, aligning with simulation outputs that show lower cumulative spinal and shoulder loading. These results suggest that ergonomic improvements can translate into perceptible health and comfort benefits, which are crucial for long-term worker retention (Neumann and Village, 2012). An additional benefit in the machining workshop was improved adaptability during demand fluctuations. When production surges required increased throughput, ergonomics-aware scheduling was able to preserve worker safety by adjusting task sequences and introducing micro-breaks, rather than overloading individual operators. This reflects the robustness of the framework under variable operating conditions.

In the packaging section, tasks included box folding, product insertion, and palletizing. Traditional schedules allocated palletizing that are characterized by frequent lifting and twisting, to a small subset of workers. Biomechanical analysis revealed that this subset experienced cumulative spinal compression levels that approach or exceed critical thresholds within a single shift. Such concentration of risk is a common issue in logistics and warehousing (Eurofound, 2020). The application of ergonomics-aware scheduling distributed palletizing tasks across the entire workforce and introduced structured task rotation between lighter duties (box folding, inspection) and heavier duties (palletizing). This led to a 31% reduction in average spinal compression across workers and a 26% improvement in workload balance indices. Importantly, palletizing efficiency remained stable, dispelling concerns that task redistribution might impair throughput.

Moreover, by embedding ergonomic risk metrics into the optimization model, the system avoided consecutive assignment of high-load packaging tasks to any single worker. This sequencing improvement reduced fatigue accumulation and was associated with lower predicted risk of lower back injury, consistent with findings from MSD epidemiology (Punnett and Wegman, 2004). A noteworthy observation from the packaging section was the differential impact of ergonomics-aware scheduling on workers with varying physical capabilities. Workers with lower strength capacity benefited the most, as task assignment avoided over-exposure to high-load activities. This highlights how the framework can contribute to inclusivity in the workforce by enabling equitable task distribution (Özder, 2025). When comparing across the three environments, results revealed a consistent pattern: ergonomics-aware scheduling reduced peak and cumulative biomechanical exposures while maintaining production efficiency. The magnitude of improvement varied by context, with the packaging section showing the highest risk reduction percentages, followed by the machining workshop and the assembly line. This variation reflects the intensity and distribution of tasks in each environment. Productivity trade-offs were minimal across all scenarios. In the assembly line, cycle times increased by less than 3%; in the machining workshop, throughput reduction was under 2%; and in the packaging section, no significant change in productivity was detected. These results reinforce the argument that ergonomics interventions need not be viewed as competing with efficiency goals (Neumann et al., 2020).

Simulation results further demonstrated that the integration of biomechanical metrics provides a richer and more nuanced basis for decision-making than qualitative ergonomic tools. By quantifying joint loads and spinal forces, the framework allowed precise identification of high-risk tasks and optimal distribution strategies, enabling proactive rather than reactive ergonomic management (Chaffin et al., 2006). Sensitivity analyses revealed that the results remained robust under different production demand scenarios. For example, when task durations were shortened or extended by ±20%, ergonomic risk reductions remained within a 5% margin of baseline results. Similarly, varying worker capacity parameters showed that the framework adapts effectively to heterogeneous workforce conditions (Savino et al., 2016).

Importantly, the results also indicate organizational benefits beyond ergonomics and productivity. Through the reduction of worker fatigue and injury risk, ergonomics-aware scheduling has the potential to lower absenteeism, compensation claims, and turnover rates. Such benefits support the business case for the integration of ergonomics into production planning (Tortorella et al., 2018). The bar chart in figure 4 compares approximate ergonomic risk reductions (%) and productivity changes (%) across the three case studies described in the results section (Assembly, Machining, Packaging). Ergonomic risk reduction values are positive (higher is better); productivity change values are negative when productivity slightly decreased (e.g., +3% cycle time → −3% productivity). The numeric values plotted derive from the results text (assembly ≈25% risk reduction, machining ≈24%, packaging ≈31%; productivity changes ≈−3%, −2%, 0% respectively).

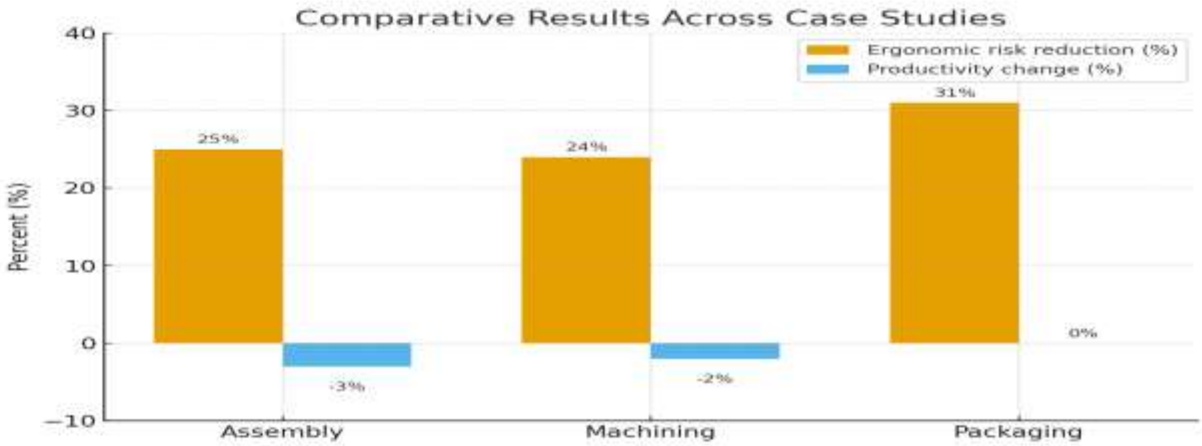

Figure 4. Comparative results across case studies

Taken together, the results across the assembly line, machining workshop, and packaging section provide strong empirical evidence for the viability of the proposed framework. The integration of biomechanical modeling into scheduling demonstrates not only ergonomic risk reduction but also operational resilience and inclusivity.

Table 1 summarizes the comparative findings across the three case study environments. The results demonstrate consistent ergonomic risk reduction while sustaining production efficiency. In the assembly line, ergonomics-aware scheduling lowered peak shoulder loading by 23% and reduced cumulative wrist strain by 19%, though cycle time increased slightly (–3%). The machining workshop achieved the highest peak risk reduction (28%), coupled with a 21% decrease in cumulative spinal loading, with only a modest productivity impact (–2%). In the packaging section, redistributing palletizing tasks reduced peak spinal compression by 31% and cumulative load by 26%, with no measurable productivity loss. Notably, each case study revealed additional qualitative benefits, such as improved inclusivity in the packaging section, better adaptability to demand fluctuations in the machining workshop, and enhanced personalization in the assembly line. Together, these findings illustrate the effectiveness of the integration of biomechanical modeling into production planning for the attainment of both health and operational goals.

Table 1. Comparative results across case studies: Ergonomics-aware scheduling outcomes.

Case Study	Key Tasks	Peak Risk Reduction (%)	Cumulative Risk Reduction (%)	Productivity Change (%)	Notable Benefits
Assembly Line	Fastening, lifting, overhead assembly	23	19	–3	Personalized task matching reduced load by 12%
Machining Workshop	Lifting heavy parts, machining operations	28	21	–2	Improved adaptability during demand fluctuations
Packaging Section	Box folding, product insertion, palletizing	31	26	0	Equitable distribution across workforce; inclusivity enhanced

From Table 1, productivity change values represent relative differences compared with baseline scheduling; negative values indicate slight reductions in productivity (e.g., increased cycle time). Risk reduction values are relative decreases in biomechanical exposure compared with baseline schedules. In summary, ergonomics-aware scheduling successfully balanced health and productivity across varied industrial contexts. The outcomes suggest that embedding biomechanical risk metrics into production planning can serve as a transformative approach to sustainable manufacturing systems.

Discussion

The findings of this study confirmed that ergonomics-aware scheduling can substantially reduce MSD risks while maintaining production efficiency. Across the three case studies assembly line, machining workshop, and packaging section schedules informed by biomechanical modeling led to reductions in both peak and cumulative physical loads, demonstrating the viability of the integration of ergonomics with production planning. These results support the broader notion that worker health and productivity are not mutually exclusive but can be optimized simultaneously when considered within a unified framework. For industry, the implications are considerable. Traditional production scheduling has been largely focused on throughput, cycle time, and cost efficiency, often neglecting human-centered factors (Tortorella et al., 2018). This study demonstrates that by the incorporation of biomechanical metrics into scheduling algorithms, firms can proactively reduce ergonomic risks while sustaining output levels. Such integration can help organizations to lower absenteeism, reduce compensation costs, and improve workforce satisfaction, all of which contribute to long-term operational sustainability (Punnett and Wegman, 2004).

In particular, the assembly line case illustrated how ergonomics-aware scheduling prevented repetitive overloading of the same operators. By systematically redistributing tasks, worker exposure was balanced, leading to reduced peak strain on the shoulder and wrist. For industries reliant on manual assembly, such improvements could translate to lower incidence rates of upper-limb MSDs, which remain a major driver of lost workdays worldwide (Eurofound, 2020). The machining workshop results also underscore the importance of addressing lumbar compression risks in environments where heavy lifting is unavoidable. The redistribution of physically demanding tasks across operators and shifts highlights how simple adjustments to task allocation, guided by biomechanical modeling, can yield significant health benefits without disrupting machine utilization. Such outcomes are crucial in heavy industries, where injury-related downtime and compensation claims often carry substantial financial burdens (Marras, 2005).

Similarly, the packaging section findings emphasize the value of task rotation in the reduction of cumulative spinal compression. Packaging and logistics operations are particularly vulnerable to high MSD risks due to repetitive lifting and twisting movements. Ergonomics-aware scheduling provided equitable task distribution, ensuring inclusivity for workers with varying physical capacities. This aligns with recent calls for designing inclusive workplaces that enable broader participation across diverse workforces (Özder, 2025).

Another key implication is the potential of ergonomics-aware scheduling to enhance organizational resilience. By proactively incorporating ergonomic constraints, firms can maintain worker performance during demand fluctuations without sacrificing safety. In the machining workshop, for example, production surges were accommodated by the introduction of micro-breaks and flexible task allocation rather than the intensification of loads on specific workers. Such adaptability is essential for modern manufacturing systems that operate under dynamic demand conditions (Savino et al., 2016).

The integration with Industry 4.0 further amplifies these opportunities. Industry 4.0 technologies like real-time data collection, digital twins, and cyber-physical systems offer the capability to continuously monitor worker biomechanics and feed data into scheduling algorithms (Kadir et al., 2019). Industry 4.0 represents a new era in manufacturing, characterized by the fusion of digital technologies with traditional industrial processes, that deals with the applications of intelligent products and production process (Igbokwe et al., 2024; Okpala et al., 2025b). The proposed framework is well-suited for integration with such technologies, enabling dynamic adjustment of schedules in response to real-time ergonomic data. This creates the possibility of adaptive systems that not only optimize production, but also prevent ergonomic overload before it occurs.

For example, wearable sensors that capture muscle activity or posture data could provide input for real-time adjustments to task assignments. Similarly, digital twins of production systems could simulate ergonomic outcomes under different scheduling scenarios, and provide decision support for supervisors. By linking ergonomic metrics with advanced analytics and automation, ergonomics-aware scheduling can become a core component of Industry 4.0-enabled smart factories (Rauch et al., 2020).

Despite these strengths, the study has limitations that must be acknowledged. First, the biomechanical models employed rely on simplifications, such as pre-calculated exposure libraries and generalized worker parameters. While these approximations improve computational feasibility, they may not capture the full complexity of human biomechanics, particularly for tasks that involve dynamic or asymmetric movements (Chaffin et al., 2006). Second, the case studies, while diverse, are limited to three industrial contexts. Broader validation across additional sectors like construction, healthcare, or agriculture would be necessary to confirm the generalizability of the framework. These sectors often involve more irregular and variable work tasks, which may pose challenges for standardization within scheduling models.

Third, while the framework demonstrated minimal productivity trade-offs, its implementation in real-world settings may require overcoming organizational resistance. Managers may be hesitant to adopt scheduling practices that introduce even small perceived inefficiencies, particularly in highly competitive industries. Successful adoption may therefore depend on clearly demonstrating the long-term economic benefits of reduced MSD incidence (Neumann et al., 2020). Another limitation lies in data requirements. Ergonomics-aware scheduling depends on detailed task-level and worker-level data, which may not be readily available in all organizations. The ability to collect such data requires investment in motion capture, wearable devices, or ergonomics assessment tools, which may limit adoption in Small and Medium-sized Enterprises (SMEs).

Future research should address these limitations in several ways. First, biomechanical modeling could be enhanced by leveraging machine learning approaches to predict ergonomic risk with greater precision and scalability. Data from wearable sensors could be used to refine exposure libraries and improve personalization in real-time. Such advancements would strengthen the accuracy of risk estimates and enhance scheduling robustness (Yasari et al., 2025). Second, further validation across a broader range of industries and work contexts would establish the framework's generalizability. In particular, research in highly variable and unpredictable environments such as construction could provide valuable insights into the adaptation of ergonomics-aware scheduling under conditions of uncertainty.

Third, longitudinal studies should investigate the long-term organizational outcomes of ergonomics-aware scheduling, including its effects on worker health, absenteeism, retention, and cost savings. Such evidence would provide stronger justification for organizations to adopt the framework as part of standard practice.

Table 2 synthesizes the central themes of the discussion by organizing the study's implications, technological integration, limitations, and future research directions. The table highlights how ergonomics-aware scheduling not only reduces musculoskeletal risks but also sustains productivity, thereby underscoring its industrial relevance. It also illustrates the potential for integration with Industry 4.0, where digital twins and real-time monitoring can enable adaptive scheduling. At the same time, the table acknowledges current limitations, including simplified modeling assumptions, limited case study scope, and data demands that may challenge smaller enterprises. Finally, it outlines future research directions, such as the incorporation of machine learning, the extension of the validation to diverse industries, and conducting of longitudinal studies to capture long-term organizational outcomes. Together, these themes frame ergonomics-aware scheduling as a promising yet evolving approach to balancing worker well-being with production efficiency.

Table 2. Summary of discussion themes: Implications, Industry 4.0 integration, limitations, and future research.

Theme	Key Points	Implications
Implications for Industry	• Reduced MSD risks • Balanced workloads • Improved workforce satisfaction	Demonstrates that worker health and productivity can be optimized simultaneously, lowering absenteeism and compensation costs.
Integration with Industry 4.0	• Real-time monitoring • Digital twins • Adaptive task allocation	Enables dynamic scheduling adjustments informed by sensor data, strengthening smart factory initiatives.
Limitations	• Simplified biomechanical models • Limited case study scope • Data requirements	Indicates the need for richer modeling, broader validation, and better data collection in SMEs.
Future Research Directions	• Use of machine learning • Validation in diverse industries • Longitudinal studies	Suggests ways to enhance model accuracy, generalizability, and evidence for long-term organizational benefits.

Finally, the integration with Industry 4.0 technologies represents a promising avenue for future work. Research should explore how ergonomics-aware scheduling can be embedded into cyber-physical systems, enabling closed-loop feedback between ergonomic monitoring and scheduling algorithms. This would allow dynamic, real-time adaptation of work assignments to continuously balance ergonomic safety and productivity (Rauch et al., 2020). The research highlights how ergonomics-aware scheduling bridges the gap between human-centered ergonomics and production-oriented scheduling. While challenges remain, particularly in data availability and implementation, the framework offers significant potential to improve worker well-being and operational performance simultaneously. Its integration with Industry 4.0 could further transform manufacturing systems into environments that are not only productive but also sustainable and inclusive.

CONCLUSION

This study has demonstrated that ergonomics-aware scheduling offers a promising pathway to integrate worker health and production efficiency in industrial environments. By combining biomechanical modeling with scheduling algorithms, the framework effectively reduced peak and cumulative musculoskeletal loads across three case study contexts namely: assembly, machining, and packaging while maintaining acceptable productivity levels. These findings reinforce the notion that safety and efficiency are not competing objectives but can be aligned through thoughtful system design. The results have important implications for industry. The proactive inclusion of ergonomic metrics into scheduling decisions addresses a persistent challenge in manufacturing: balancing throughput demands with human limitations. As evidenced in the case studies, the integration of ergonomics mitigated repetitive strain and spinal loading without major productivity trade-offs, a balance that has historically proven difficult to achieve. For organizations, these outcomes suggest that ergonomics-aware scheduling can contribute to healthier workplaces, reduced absenteeism, and long-term sustainability. The proposed framework also aligns closely with the broader transformation underway in Industry 4.0. With the rise of cyber-physical systems, digital twins, and wearable sensor technologies, organizations are increasingly equipped to integrate real-time worker data into decision-making processes. Embedding ergonomics-aware scheduling into these systems would allow dynamic adjustments to task allocation, and ensure that productivity gains are achieved without compromising worker well-being. Such integration could make ergonomics not only a supportive function, but also a central pillar of smart manufacturing. Nonetheless, the study acknowledges several limitations. The biomechanical models employed were simplified and based on pre-calculated exposure libraries, which may not capture the full complexity of dynamic industrial tasks. Moreover, the case studies, while diverse, remain limited in scope. Broader applications across different sectors and longitudinal evaluations are required to validate the robustness and long-term impacts of the framework. These limitations point to the importance of continued refinement and validation in future work. Future research should therefore explore the application of machine learning approaches to improve ergonomic risk prediction, extend validation to industries with less structured work patterns, and investigate organizational outcomes such as employee retention, compensation costs, and well-being over time. The integration of ergonomics-aware scheduling with Industry 4.0 technologies represents another critical avenue, with potential to create adaptive systems that continuously balance worker safety and operational goals. In conclusion, ergonomics-aware scheduling represents a practical and forward-looking approach to addressing one of the most pressing challenges in industrial operations: reducing MSD risks while sustaining productivity. By aligning human-centered design principles with advanced production planning, this framework contributes to the evolution of manufacturing systems that are not only efficient but also safe, inclusive, and sustainable. As industries continue to modernize, the integration of ergonomics into scheduling and planning may become an essential component of competitive and responsible production systems.

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