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ORIGINAL ARTICLE

Applying Anthropometric and Biomechanical Data in Product and Workstation Design

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ABSTRACT

This review synthesizes recent advances in the application of anthropometric and biomechanical data for ergonomic product and workstation design. Emphasizing the importance of human centered approaches, the paper explores how precise anthropometric measurements and biomechanical analyses enhance customization and musculoskeletal safety. It highlights technological innovations such as digital human modeling, simulation platforms, and real time adaptive systems including posture detection and human digital twins, which facilitate dynamic ergonomic risk mitigation. Case studies from industries like healthcare, manufacturing, and agriculture demonstrate diverse applications of these methods, while evaluation methods combining quantitative metrics and user feedback validate their effectiveness. The review underscores challenges in integrating real time data and the need for continued development of adaptive ergonomic solutions to improve comfort, safety, and productivity in various work environments.

Keywords: Anthropometry, Biomechanics, Ergonomic Design, Digital Human Modeling, Real Time Monitoring, Workstation Design, Musculoskeletal Risk

THE ROLE OF ANTHROPOMETRY AND BIOMECHANICS IN ERGONOMIC DESIGN

Anthropometric measurements play a critical role in tailoring products and workstations to individual users, thereby enhancing comfort, safety, and performance. For instance, Yao et al. (2024) developed digital modeling methods that incorporate human intention prediction in human robot collaboration, leveraging detailed musculoskeletal and anthropometric data to generate virtual collaboration scenarios responsive to user needs. Similarly, Kikumoto et al. (2021) investigated lever position design in vehicle seats, highlighting the necessity to consider anthropometric variability, such as height and gender, to optimize operability under stringent spatial and safety constraints. These examples underscore how anthropometric data serves as a foundation for customization and functional integration in diverse contexts.

Biomechanical analysis is essential for safeguarding musculoskeletal health by quantifying physical load and optimizing task design. Harari et al. (2021) compared 3D dynamic and quasistatic models to examine spinal loading during manual material handling tasks, showing that neglecting dynamics can underestimate spinal moments by nearly 20%, with potential safety implications. Concurrently, Bispo et al. (2022) assessed ergonomic risk factors related to lower limb musculoskeletal disorders, revealing the complex interplay of biomechanical, mechanical, and individual factors affecting work-related pain and disorder development. These biomechanical insights are pivotal for designing interventions that mitigate injury risks in occupational settings.

The emergence of Industry 4.0 and its evolution towards Industry 5.0 emphasize flexible, data driven ergonomic solutions that continuously adapt to human factors. Ling et al. (2024) introduced RHYTHMS, a real time human machine synchronization framework facilitating proactive ergonomic risk mitigation by combining machine precision with human cognitive ability in smart manufacturing settings. Complementarily, Berti et al. (2023) developed human digital twin architectures for real-time monitoring of postural behavior and workload, illustrating a paradigm shift towards dynamic worker centric scheduling and ergonomic risk management.

Integration of digital twins and smart systems has become central in advancing ergonomic designs. Baratta et al. (2024) reviewed digital twin applications in human robot collaboration, emphasizing how realistic simulations enable optimization of collaboration strategies for improved safety and productivity. Nicola et al. (2023) demonstrated the feasibility of real time monitoring platforms coupled with human digital twins capable of detecting awkward postures and workload imbalances, enabling adaptive job rescheduling to reduce ergonomic risks. Furthermore, Ciccarelli et al. (2022) showcased tools combining posture analysis and stress detection using inertial sensors and machine learning, demonstrating the convergence of biomechanical data collection and artificial intelligence in ergonomic assessments.

This review aims to synthesize recent advancements in applying anthropometric and biomechanical data to the design of ergonomic products and workstations. It highlights technological innovations such as digital human modeling, simulation based optimization, and integration of real time smart systems that facilitate adaptive, human centered design. Additionally, it addresses current challenges in data integration and real time adaptation within evolving industrial contexts, while presenting application cases across multiple sectors demonstrating efficacy and usability improvements. By providing this comprehensive synthesis, the review supports the ongoing shift toward ergonomically optimized, productive, and safe workplaces in the Industry 4.0 and 5.0 paradigms.

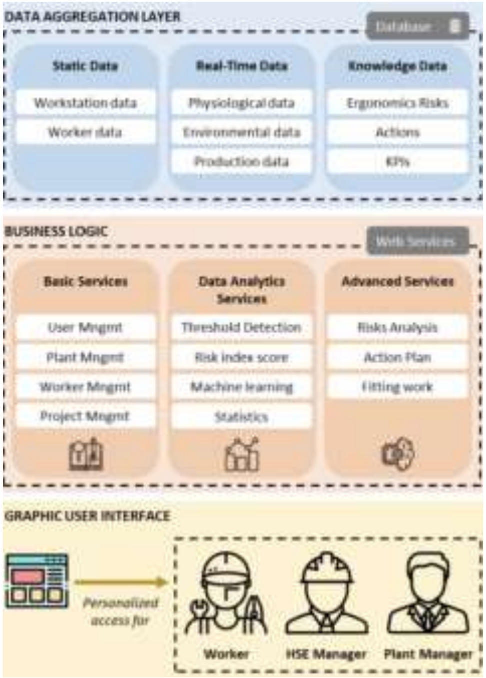

Figure 1: The architecture three main layers of the working environment and operator's needs within a factory evolving toward the industry 4.0 (Ciccarelli et al. , 2022) .

ANTHROPOMETRIC DATA IN PRODUCT AND FURNITURE DESIGN

The application of anthropometric data in product and furniture design faces considerable challenges due to the limitations of existing standards in adequately matching diverse populations. Castellucci et al. (2021) emphasized that most dimensions present in common office furniture standards do not conform to the anthropometric measurements of a large sample population, particularly regarding seat width and depth. Their analysis revealed that these mismatches can reduce comfort and compromise safety, especially when adjustability does not fully compensate for the discrepancies. Similarly, Kikumoto et al. (2021) investigated ergonomic constraints on car seat lever positioning and highlighted the difficulty in optimizing lever placement within confined vehicle interiors, compounded by anthropometric variability among occupants. These issues illustrate that one size fits all standard furniture solutions often fail to address the variability in body sizes and shapes, which can contribute to the risk of musculoskeletal discomfort and injury.

To address the shortcomings of current standards, researchers have proposed biomechanical and ergonomic models that integrate anthropometric data more precisely. Silva et al. (2025) developed and validated a novel maximum desk height equation for educational furniture. Their study demonstrated that this new equation not only preserves biomechanical safety but substantially improves anthropometric fit, notably increasing the percentage of matched users from 63% to 94% in students and significantly reducing mismatch cases in workers. This validates the potential of using biomechanical safety principles combined with anthropometric data to enhance furniture design.

Dynamic and personalized models further advance fit customization. Wang et al. (2023) introduced a 3D standard motion time based ergonomic risk analysis method that systematically determines motion times and quantifies ergonomic risks, enabling workspace designs that consider dynamic motions and body postures. Yao et al. (2024) proposed a digital modeling approach for human robot collaboration that generates virtual data reflecting realistic metabolic energy consumption aligned with human biomechanics. These methodologies allow for personalized adjustments in furniture and workstation design, enhancing comfort and reducing injury risk by accommodating dynamic human factors rather than static measurements alone.

Applied studies showcase the use of anthropometric and biomechanical data to tailor furniture and interiors to user-specific profiles. Silva et al.'s (2025) work on educational furniture utilized their biomechanically informed desk height equation in designing desks that meet both safety and anthropometric criteria, illustrating direct application in mitigating classroom musculoskeletal disorders. Kikumoto et al. (2021) provided an example in automotive ergonomics by mapping lever position variations based on gender and height, offering optimized lever positioning rules for diverse anthropometric profiles within vehicle constraints.

In vehicle interiors, Lee and Lee (2022) developed an AI-based posture recognition system (SEE) to assess ergonomic risks in automotive settings. This system enables real time ergonomic risk analysis and could inform the customization of seating and control interfaces to users' anthropometric characteristics, supporting adaptive vehicle interior designs that enhance comfort and safety. Figure 2 shows the human skeleton model and joint point numbers.

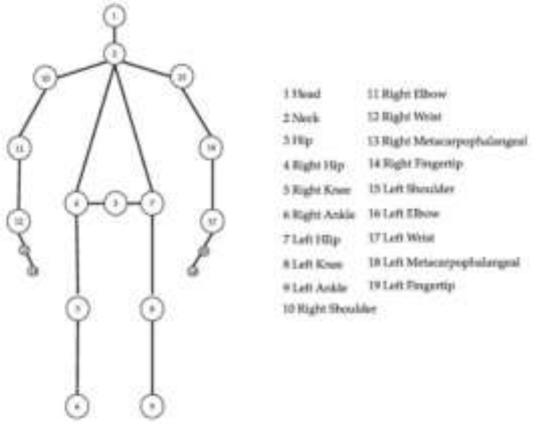

Figure 2: Human skeleton model and joint point numbers (Lee & Lee, 2022)

These studies collectively underline the importance of integrating detailed anthropometric data with biomechanical safety models to drive customized, user centric product and furniture design solutions that address mismatches in standards and enhance overall ergonomic performance.

BIOMECHANICAL CONSIDERATIONS IN WORKSTATION DESIGN

a) Impact of Work Design on Musculoskeletal Loading

Ergonomic risk factors inherent in manual tasks are critical determinants of musculoskeletal loading and the long term health outcomes of workers. Singh et al. (2022) demonstrated that postural stress, repetitive motions, and handling loads contribute significantly to musculoskeletal disorder risks, with their integrated mathematical model considering postural fatigue and risk levels to design ergonomic human robot collaborative workstations. Similarly, Qureshi et al. (2024) employed a macroergonomic simulation approach, combining digital human modeling (DHM) with discrete event simulation, to quantify biomechanical and mental workload impacts on nurses caring for COVID-19 positive patients. Their study indicated that attempts to reduce physical biomechanical load sometimes led to increased mental workload and task waiting times, illustrating the complexity of ergonomic trade-offs.

Moreover, Mazaheri et al. (2022) explored reaction forces during tool use in assembly, revealing nuances in muscle activation patterns tied to different tightening strategies, which further emphasize the importance of considering biomechanical loading in tool and task design to minimize musculoskeletal stress. Choi and Park (2025) evaluated arm support exoskeletons during simulated orchard pruning and harvesting tasks, finding that while these devices reduce upper limb muscle activity, they may transfer strain to other body regions like the lower back, demonstrating the biomechanical complexity of ergonomic interventions.

b) Quasistatic vs Dynamic Modeling

Accurate biomechanical modeling is essential for proper ergonomic risk assessment. Yaar Harari et al. (2021) compared quasistatic and dynamic 3D models to assess spinal loading during combined manual material handling. They found that neglecting dynamic body movements by relying solely on quasistatic models results in underestimation of peak spinal moments by approximately 19.7%, which in some cases may exceed safety thresholds. Therefore, dynamic modeling provides a more realistic representation of biomechanical loads and better informs workstation design.

Applications of these models extend to healthcare and manual labor. For instance, Munawar et al. (2024) demonstrated in a nursing context how biomechanical load reduction through workstation reconfiguration must be balanced against increases in mental workload and task delays. Similarly, Taifa (2022) applied ergonomics combined with Six Sigma methods in educational settings to reduce musculoskeletal disorders, indirectly highlighting the utility of biomechanical modeling to identify risk and optimize design show in Figure 3.

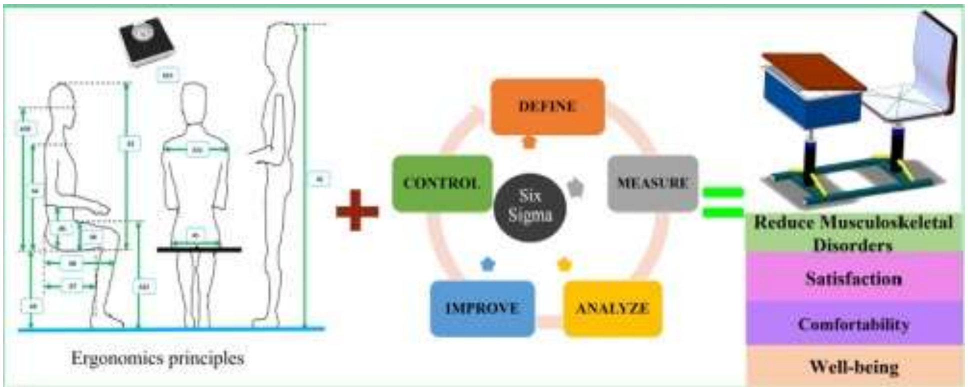

Figure 3 : Example from Taifa (2022) to reduce musculoskeletal disorders

c) Case Studies

Assembly line environments benefit from ergonomic interventions informed by biomechanical insights. Beuss et al. (2023) presented an automated simulation based methodology incorporating robotic process automation and human in the loop decision making to design ergonomic workstations dynamically. This strategy allowed real time ergonomic checks integrated into product development, enabling early identification and mitigation of musculoskeletal risks during assembly.

Healthcare presents a complex scenario where biomechanical and psychosocial demands intersect. Qureshi et al. (2024) used simulation to analyze nurse workload and biomechanics related to COVID-19 patient care, revealing how infection control protocols can inadvertently increase mental and physical workloads, highlighting the need for integrated ergonomic design solutions that consider multiple dimensions of worker health.

ERGONOMIC SIMULATION AND DIGITAL HUMAN MODELING (DHM)

a) Digital Tools and Platforms

Digital Human Modeling (DHM) and ergonomic simulation platforms have become pivotal in advancing ergonomic design by enabling virtual assessment and optimization of workstations and tasks before physical deployment. Systems like SEE (Smart Ergonomic Explorer), HMWS (Human-Machine Work System), and methodologies such as SAGE integrate detailed posture analysis, risk assessment algorithms, and user interfaces that facilitate ergonomic evaluations tailored to operator characteristics (Ling et al., 2024; Iriondo Pascual et al., 2024).

Ling et al. (2024) developed the RHYTHMS system, which employs real time data driven human machine synchronization to proactively mitigate ergonomic risks in smart manufacturing environments. This system integrates adaptive fuzzy control with continuous ergonomic assessments to facilitate seamless human cyber physical workstation (HCPW) interactions, demonstrating the power of digital tools in real time ergonomic risk identification and mitigation.

Similarly, the SAGE methodology leverages axiomatic design principles combined with functional requirements satisfaction to enable early ergonomic evaluations and redesign of manufacturing tasks. This method supports human factors integration from the initial design phase, significantly improving operator well being and decreasing ergonomic risks (Arkouli et al., 2024). Complementing these approaches, Baratta et al. (2025) introduced a multi simulation based Digital Twin system for Human Robot Collaboration (HRC) scenarios. It incorporates both ergonomic and productivity key performance indicators, offering a user friendly interface that permits dynamic task allocation driven by real time ergonomic data.

Surrogate models, which approximate the outputs of complex ergonomic simulations, also play a critical role in reducing computational cost and time in the early phases of workstation design. They allow for rapid scenario assessment and have been successfully applied in assembly operation case studies to tailor workplace adjustments based on worker-specific parameters (Bittencourt, Saakes, & Thiede, 2025).

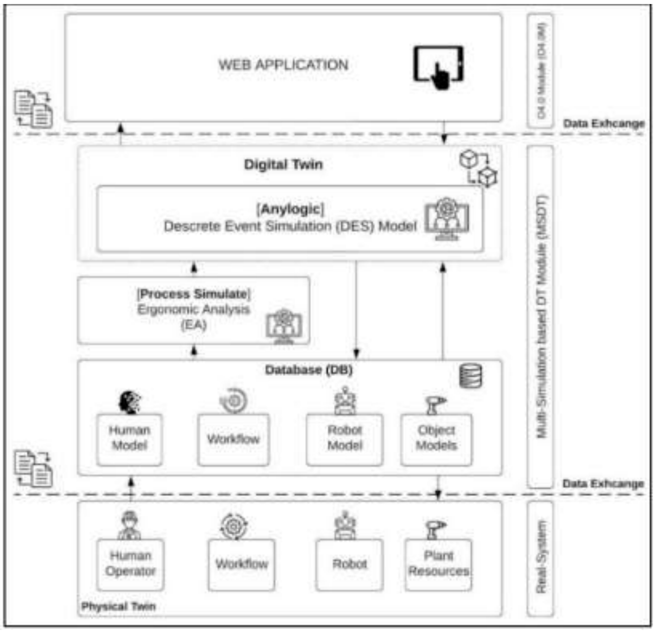

Figure 4 : System architecture (Baratta et al. , 2025)

b) Benefits for Design and Risk Mitigation

The adoption of ergonomic simulation and DHM platforms significantly enhances workplace safety and supports preventive measures for musculoskeletal disorders. Automated simulation approaches, such as those combining Robotic Process Automation (RPA) with human in the loop decision making, have been shown to facilitate the generation of ergonomic workplace designs that continuously incorporate ergonomic criteria during development (Beuss, Sender, & Fluegge, 2023).

Additionally, these tools support rapid scenario iteration, enabling designers and engineers to explore various workstation configurations efficiently. For example, the UX assessment strategy employing wearable sensors and virtual reality simulations allows for identification of operator stressful conditions, encompassing both physical and mental aspects, thus broadening the scope of ergonomic intervention beyond physical postures (Khamaisi et al., 2022).

Further expanding the scope of ergonomic simulation, virtual data generation methods for human intention prediction in human robot collaborative assembly scenarios have demonstrated success in training prediction models effectively, reducing the cost and complexity of experimental data collection (Yao et al., 2024). Such approaches directly contribute to safer and more intuitive human robot interaction environments.

Moreover, integration of digital twins with ergonomic monitoring platforms stands as a promising advance to enhance real time detection of awkward postures and unbalanced workloads. These systems can dynamically propose adaptations to job scheduling, balancing workload distribution, and proactively reducing the risk of musculoskeletal disorders (Berti, Finco, Guidolin, & Battini, 2023). Collectively, the growing ecosystem of digital tools and simulation based ergonomic assessment paves the way for proactive, adaptive, and human centered workplace design, meeting both productivity and well being objectives in the Industry 4.0 and 5.0 contexts.

REAL TIME MONITORING AND ADAPTIVE SYSTEMS

a) Posture Detection and Feedback

The advancement of real time ergonomic monitoring has been substantially enhanced by the integration of computer vision and wearable sensor technologies, enabling continuous assessment of worker postures and associated risks. Systems such as the Smart Ergonomic Explorer (SEE) employ deep learning based pose estimation methods, combining Convolutional Pose Machines with rapid ergonomic risk assessments to provide accurate and continuous evaluation of body postures (Lee & Lee, 2022). This approach facilitates timely detection of risky postures, allowing for immediate ergonomic alerts which can mitigate musculoskeletal disorder (MSD) risks.

Complementing vision based systems, inertial measurement units (IMUs) embedded in wearable sensors have been utilized to monitor postural risks in industrial settings, as shown in footwear industry job rotation studies where both physical and psychological workloads are continuously assessed (Leite et al., 2024). These sensor systems enable dynamic adjustments through ergonomic alerts, prompting workstation or task modifications to optimize operator well being while maintaining productivity.

Further, smart workplace models have been developed that dynamically optimize operator posture by integrating characteristics of the individual, product, and task parameters. Papetti et al. (2022) demonstrated how workplace design solutions based on real time feedback can naturally and dynamically reduce ergonomic risks by positioning products optimally in relation to the operator, thus preventing musculoskeletal strain.

b) Human Digital Twins and Task Adaptation

Human Digital Twins (HDT) have emerged as transformative tools that integrate real time monitoring data for proactive ergonomic risk management and adaptive task allocation. Real time monitoring systems continuously track awkward postural behaviors and workload imbalances unique to each worker, feeding data into the HDT to enable dynamic job rescheduling that balances ergonomic safety with production goals (Nicola et al., 2023). The HDT concept empowers a human centered approach to manufacturing by facilitating workload redistribution to minimize physical strain while maintaining operational efficiency.

Virtual modeling methods further enhance HDT capabilities by generating realistic human robot collaboration (HRC) data, validated using metabolic energy consumption indicators. Yao et al. (2024) demonstrated how virtual data driven models improve the accuracy of human intention predictions, reducing costs and time associated with experimental data collection for ergonomic task sequencing.

Multi simulation based digital twin systems enable operator driven task management interfaces, integrating ergonomic and productivity indicators for refined control in collaborative environments. Baratta et al. (2024) developed such a system to enhance Human Robot Collaboration with real time task allocation that adapts to ergonomic risk levels, improving cycle times and operator safety.

Moreover, adaptive control systems combining real time computer vision data with model reference adaptive fuzzy control algorithms have been implemented to achieve synchronized human machine workflows. Ling et al. (2024) illustrated this through their RHYTHMS system, showing how proactive ergonomic risk mitigation can be attained within Industry 4.0 and Industry 5.0 frameworks, contributing to value oriented, human centric manufacturing.

Similarly, Silva et al. (2025) validated new ergonomic equations integrated within HDTs for task reallocation, demonstrating improved biomechanical safety and anthropometric fit in workstation configurations, further emphasizing HDTs' potential to dynamically adapt work environments to individual worker needs.

APPLICATIONS ACROSS INDUSTRIAL CONTEXTS

a) Sector Specific Interventions

Ergonomic interventions have been increasingly tailored to specific industrial sectors to address unique physical demands and improve worker well being. In agriculture, Choi and Park (2025) evaluated the efficacy of arm support exoskeletons (ASEs) during simulated orchard pruning and harvesting tasks. Their findings indicated that while ASEs significantly reduced muscle activity in the upper limbs, they introduced compensatory strain in other body regions such as the lower back and lower limbs, alongside longer task completion times. This highlights that sector specific ergonomic solutions must consider holistic biomechanical impacts rather than isolated limb benefits.

In healthcare, Qureshi et al. (2024) utilized a combination of digital human modeling and discrete event simulations to understand the biomechanical and mental workload of nurses caring for COVID-19 positive patients. They found that reducing biomechanical workload resulted in an increase in mental workload and missed care incidents, emphasizing the complexity of ergonomic risks in healthcare environments where physical and cognitive demands coexist.

Manufacturing applications demonstrate diverse approaches to ergonomic risk mitigation. For instance, Segura et al. (2022) stress the importance of safety assurance in human robot collaborative systems, advocating human centered approaches over techno centric methods to protect operator well being in dynamically interactive settings. Similarly, Choi and Park (2025) exemplify the necessity of adaptability in ergonomic design, especially when integrating wearable assistive devices in labor intensive tasks.

b) Ergonomic Strategies for Work Design

Biomechanical and psychosocial risk factors in repetitive and physically demanding jobs can be mitigated through strategic work design. Leite et al. (2024) proposed a job rotation model in the footwear manufacturing industry that considers both physical and psychological workloads. Their multi objective mathematical model integrates assessments of repetitive actions and job stress, aiming to minimize musculoskeletal disorder risk by promoting variability and reducing workload peaks. The study demonstrated reduced variation in both physical and psychological load indices across rotation scenarios, illustrating the effectiveness of a multifaceted approach in work scheduling.

Task allocation methods also show promise in preventing musculoskeletal risks. Khamaisi et al. (2022) advanced a multi simulation based digital twin system to optimize task allocation in human robot collaboration within automotive assembly. By integrating ergonomic and productivity indicators, the system dynamically manages human workloads and demonstrated improvements in cycle times and ergonomic safety. Such technology enabled task assignment approaches facilitate proactive workload balancing and ergonomic risk reduction.

c) Psychosocial and Mechanical Factors

The interplay between psychosocial and mechanical factors is critical in understanding musculoskeletal disorder (MSD) risks in industrial contexts. Studies emphasize that physical exposures alone do not account for the full spectrum of MSD risk. For example, Miranda Bispo et al. (2022) identified mechanical factors such as uncomfortable lower limb positions as significant contributors to musculoskeletal symptoms in workers from under resourced regions, while psychosocial elements like perceived meaning of work and control over tasks influenced symptom prevalence but to a lesser extent.

Complementing this, Macdonald and Oakman (2022) argued for a more holistic risk management framework that incorporates both biomechanical and psychosocial hazards rather than focusing solely on physical risk factors. They suggest that ergonomists should advocate improved regulatory guidance and engage in multidisciplinary research to more effectively manage workplace MSD risks.

Furthermore, Karim Khamaisi et al. (2022) and Olivas Padilla et al. (2024) demonstrated the utility of monitoring physiological and psychological stress indicators via wearable sensors and virtual simulations, enabling identification of stress conditions that may compromise industrial worker performance and health.

EVALUATION METHODS AND USABILITY STUDIES

a) Quantitative Metrics

Quantitative assessment of ergonomic risk and workstation design efficacy often relies on tools such as the Rapid Entire Body Assessment (REBA), electromyography (EMG), maximum voluntary contraction (MVC), and torque measurements to ensure objective evaluation of musculoskeletal risk factors. Kikumoto et al. (2021) employed EMG alongside kinematic evaluations to identify optimal lever positions in automotive seat adjustments, providing data on muscle activation and confirming ergonomic suitability across gender and anthropometric variability.

Similarly, Singh et al. (2022) investigated reaction force exposure during tool use, employing psychophysical methods integrated with EMG and torque measurements, revealing nuanced muscular loading patterns that inform sustainable reactive force thresholds in industrial tasks. These quantitative metrics not only measure the biomechanical load but also enhance understanding of user comfort and fatigue.

Studies such as Silva et al. (2025) compared a novel maximum desk height equation incorporating biomechanical safety and anthropometric fit against traditional models through EMG, motion capture, and performance measures. Results demonstrated maintained biomechanical safety alongside significantly improved anthropometric fit, suggesting that integrating advanced biomechanical models can refine ergonomic design assessments.

Beyond individual experiments, simulation validation is crucial. Forero Velasco et al. (2022) and Qureshi et al. (2024) demonstrated that digital human modeling (DHM) combined with discrete event simulation could provide realistic assessments of workload and musculoskeletal risks, aligning simulation outputs with real world ergonomic outcomes, thus emphasizing the utility of simulation in ergonomic risk prediction and intervention planning.

b) Usability and Effectiveness

The usability and effectiveness of ergonomic digital tools and automated systems have gained prominence with the integration of Industry 4.0 and 5.0 technologies. Iriondo Pascual et al. (2024) developed a digital tool for simulation based multi objective optimization balancing productivity and worker well being. Their usability evaluations confirmed that industrial engineers found these systems accessible and supportive in streamlining ergonomic workstation design, reducing the need for specialized optimization knowledge.

Baratta et al. (2024) presented a multi simulation digital twin system facilitating task allocation in human robot collaborative environments. User friendly interfaces permitted operators to intuitively manage task assignments, which led to measurable improvements in cycle times and ergonomic safety, illustrating the synergy between digital tools and operator engagement.

From an ergonomic intervention perspective, Stefannia et al. (2022) reported statistically significant reductions in ergonomic risk for industrial operators using a human centered workstation design without productivity losses, highlighting practical benefits of ergonomics in manufacturing contexts. Silva et al. (2025), likewise, showed no significant compromise in performance or comfort when implementing new furniture designs with improved anthropometric fits, reflecting the balance between safety and user satisfaction.

Advanced posture detection systems such as the SEE (Smart Ergonomic Explorer) developed by Lee and Lee (2022) integrate deep learning for risky posture recognition, achieving high agreement with traditional REBA scores. This demonstrates the evolving role of AI in ergonomic evaluation, where automated, real time posture assessment can substantially reduce human evaluator bias and enhance workplace safety protocols.

Additionally, Mazaheri et al. (2022) leveraged psychophysics and EMG to refine torque tightening strategies, illustrating how quantitative muscular response measurements can inform ergonomic tool use practices. Together, these studies emphasize the integration of robust quantitative metrics with practical usability testing to optimize ergonomic interventions effectively.

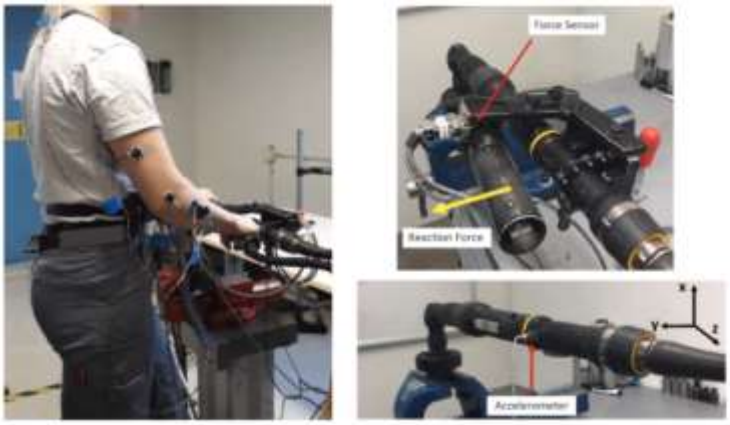

Figure 5 : Experimental setup. Study participants working position(left), instrumented measurement handle used for measuring reaction load from QS (upper right), and accelerometer used for calculation of reaction load from TT(lower right). (Mazaheri et al. , 2022)

CONCLUSION

The review demonstrates that integrating anthropometric and biomechanical data is essential for achieving tailored, safe, and effective ergonomic designs in products and workstations. Emerging technologies like digital human modeling and real time adaptive systems significantly advance the capacity to predict and mitigate musculoskeletal risks dynamically, fostering improved worker comfort and productivity. Applications across diverse industrial sectors confirm the value of these approaches, yet challenges remain, particularly in seamless data integration and personalized model development. Addressing these gaps through interdisciplinary research and enhanced adaptive solutions will be critical to fully realizing the potential of ergonomic design in Industry 4.0 and beyond.

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