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Occupational Biomechanics in Practice: A Review of Musculoskeletal Load Quantification Using EMG, IMU/Motion Tracking, and Ergonomic Interventions

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ABSTRACT

Occupational biomechanics plays a crucial role in understanding and mitigating musculoskeletal disorders in work environments by quantifying physical load using surface electromyography (EMG), inertial measurement units (IMU), and motion tracking technologies. This review synthesizes current research on biomechanical loading during manual material handling, emphasizing lumbar spinal load assessment and muscle fatigue quantification through EMG. It evaluates the capabilities and limitations of IMU and optical systems for joint kinematics and moment estimation, highlighting the applicability of portable, markerless technologies in field ergonomics. The review also addresses the influence of human variability, including demographic and expertise factors, on posture and ergonomic risk. Equipment biomechanics, such as helmet, footwear, and tool design, are examined for their impact on muscle demand and injury risk. Additionally, workstation configurations and user interfaces, including emerging AR/VR systems, are analyzed for their biomechanical implications. Finally, the review discusses interventions like exoskeletons, VR-based training, and AI-driven ergonomic optimization frameworks that show promise in reducing musculoskeletal load. Identified research gaps and technological advancements set directions for future developments in occupational biomechanics to enhance worker safety and performance.

Keywords: Occupational Biomechanics, Electromyography (EMG), Inertial Measurement Units (IMU), Ergonomic Interventions, Musculoskeletal Load, Manual Material Handling, Equipment Design, Exoskeletons

1. INTRODUCTION

Occupational biomechanics plays a crucial role in understanding and mitigating the physical risks that workers face in various industries. Biomechanical loading—the physical stress experienced by muscles, joints, and the skeletal system during work activities—can lead to musculoskeletal disorders (MSDs), which are among the leading causes of workplace injury and disability. Quantifying this load accurately is essential for developing ergonomic interventions, improving workplace safety, and enhancing worker productivity. In response to growing concerns about biomechanical risks in occupations that require manual material handling, prolonged postures, or repetitive movements, researchers have increasingly turned to technologies such as electromyography (EMG), inertial measurement units (IMUs), and motion tracking systems to objectively assess physical demands and the efficacy of ergonomic measures.

The overarching objective of this review is to synthesize current research that utilizes these advanced biomechanical quantification methods to assess musculoskeletal load across diverse occupational settings. This includes manual lifting tasks, biomechanical analysis of personal protective equipment, workstation setups, and emerging digital interfaces such as augmented

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reality (AR) and virtual reality (VR). By reviewing the measurement techniques and their applications, the review aims to provide a comprehensive understanding of how EMG, IMU, and motion capture technologies contribute to identifying risk factors, guiding ergonomic design, and preventing injury.

Manual material handling remains a fundamental activity in many workplaces, often associated with high biomechanical loads and consequent risk of MSDs. Vijaywargiya, Bhiwapurkar, and Thirugnanam (2022) quantitatively evaluated the effects of different weight and height combinations during symmetrical lifting tasks on biomechanical stress and subjective discomfort. Their findings indicated that lifting weights heavier than 15 kg between floor and ear levels significantly increased musculoskeletal loading, recommending safe limits to prevent injury. Such insights emphasize the importance of precise biomechanical assessments to inform safety guidelines.

Electromyography has emerged as a critical tool for quantifying muscle activation levels and fatigue patterns during occupational tasks. Iyer and Jeong (2025) developed an integrative framework combining EMG and IMU data to assess ergonomic risks, demonstrating that muscle activation intensity corresponded with perceived discomfort and varied by task complexity and individual expertise. This multimodal approach elucidates the relationship between neuromuscular demands and biomechanical efficiency, highlighting potential intervention points.

Motion tracking technologies, including marker-based and markerless systems, further complement biomechanical analyses by capturing joint kinematics and estimating joint moments, such as lumbar spine loads during lifting or prolonged postures. Wang et al. (2021) demonstrated that computer vision-based methods can estimate L5/S1 (lumbar) joint moments with an error margin minimal enough to be usable outside laboratory environments. Meanwhile, Chen et al. (2025) benchmarked flexible sensor-based and phone video-based systems against marker-based motion capture, confirming their suitability for simpler field tasks but cautioning interpretation during complex movements involving axial rotations. Advances like the fusion of optical and inertial motion capture techniques provide enhanced robustness and continuous monitoring capabilities essential for real-world ergonomics studies (Hicks, Chen, & Harper, 2025).

Ergonomic interventions, from equipment design to workstation configurations, have been informed by biomechanical assessments. Investigations into firefighter helmets revealed that helmet mass and center-of-mass location influence neck muscle fatigue, with implications for redesigning protective gear to reduce musculoskeletal strain (Wei, Paulon, & Chowdhury, 2025). Similarly, footwear studies by Farjad Pezeshk et al. (2025) indicated that hybrid shaft materials in military boots can improve gait efficiency and reduce muscle activity, emphasizing product biomechanics' role in occupational health.

Moreover, the expanding use of AR and VR in workplace training and operations has introduced new biomechanical considerations. Kia, Hwang, and Kim (2023) found that interaction errors during AR tasks increase biomechanical loads on the neck and shoulders, suggesting that interface ergonomics are critical for preventing injury. Concurrently, VR-based training can enhance workers' perception and appropriate use of supportive devices like back exoskeletons, which show promise for reducing trunk extensor muscle activity and perceived exertion during patient handling (Ransing et al., 2023; Wang et al., 2025).

2. BIOMECHANICAL LOADING IN MANUAL MATERIAL HANDLING

Manual material handling tasks impose significant biomechanical stress on the musculoskeletal system, primarily affecting the lumbar spine and associated musculature. The types of

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biomechanical loading experienced during such tasks include mechanical stress, loading rate, and moment forces acting on the joints and intervertebral discs, each contributing to the cumulative risk of musculoskeletal injury (Vijaywargiya et al., 2022).

Biomechanical stress during lifting tasks can be characterized by the magnitude of the load and the rate at which force is applied. Vijaywargiya et al. (2022) investigated the impact of weight and height in symmetric lifting tasks performed in the sagittal plane, revealing that heavier weights naturally produce higher stress levels, and the loading rate increases linearly once the lifting height exceeds the waist level. This emphasizes that not only the external load but the vertical position of the lift considerably influences biomechanical risk.

Acceptable limits for manual lifting activities have been proposed based on these biomechanical analyses. Specifically, Vijaywargiya et al. (2022) suggested that the maximum acceptable lifting weight from the floor up to ear level should be capped at 15 kg to mitigate the possibilities of musculoskeletal or chronic injuries. This limit intends to balance work demand while limiting biomechanical strain that leads to long-term injury.

In terms of lumbar and spinal loads, a critical focus is often placed on moments at the lumbosacral junction, especially the L5/S1 segment, due to its vulnerability and central role in load transmission. Wang et al. (2021) utilized a computer vision-based pose reconstruction method (VideoPose3D) to estimate L5/S1 joint moments during lifting tasks in comparison to traditional laboratory motion tracking systems. Their findings demonstrated a strong positive correlation between the estimated and reference joint moments, with a low percentage error of 7.7%, validating that portable video-based methods can reliably estimate biomechanical loads in practical settings.

Similarly, Li et al. (2024) used AnyBody biomechanical software to model skeletal muscle mechanics and analyze muscle activation under different driving postures but provided broader insights relevant to spine loading principles during physical tasks. Their results highlight that body posture significantly influences muscle activation patterns and forces around lumbar joints, which translate directly to joint moments during manual material handling tasks. Their model, validated against rig test results, supports ergonomic design considerations aimed at reducing excessive lumbar stress.

Anthropometric variability also underpins biomechanical load estimations. Mahajan et al. (2021) simulated effects of anthropometry on joint stresses in transtibial amputees, emphasizing that body size and mass distribution alter the biomechanical loading patterns—not only in lower limbs but affecting overall posture and compensatory loading in the lumbar region. While focused on amputees, the principles highlight the importance of considering individual differences in manual handling task assessments.

In addition to the biomechanical quantification of load, properly integrating these data into ergonomic standards is critical for injury prevention. Ergonomic risk assessments increasingly rely on metrics such as the loading rate and joint moment thresholds to set safe work limits and recommend interventions. For example, optimizing lift heights within known biomechanical load limits reduces lumbar moments and overall physical strain (Vijaywargiya et al., 2022; Wang et al., 2021).

Moreover, advances in motion capture and sensor technologies facilitate more accurate, field-applicable biomechanical analysis during manual handling. Chen et al. (2025) benchmarked various motion capture technologies for ergonomics evaluations in industrial tasks, underscoring the value of flexible sensor-based systems to capture joint kinematics without restrictive lab environments. Such approaches provide critical real-time data on biomechanical loading during material handling, enabling more responsive and precise ergonomic recommendations.

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3. EMG-BASED QUANTIFICATION OF MUSCLE DEMAND AND FATIGUE

Electromyography (EMG) serves as a fundamental method for quantifying muscle activation and assessing biomechanical loading during occupational tasks. EMG captures the electrical activity generated by muscles, providing objective data on muscle demand and fatigue. Common metrics include root mean square (RMS) amplitude, which relates to muscle activation intensity, and median or mean frequency, which reflects muscle fatigue through shifts in the power spectral density of the EMG signal. By integrating EMG with inertial measurement unit (IMU) data, researchers achieve a comprehensive biomechanical assessment that couples neuromuscular strain with joint kinematics, enhancing the understanding of task-specific physical demands (Iyer & Jeong, 2025).

Task demands are closely linked to muscle activation patterns. Physically demanding occupational activities consistently show elevated EMG activation correlating with perceived discomfort and effort ratings. For instance, Iyer and Jeong (2025) demonstrated that tasks such as assembly work, culinary operations, and ladder climbing induced differing levels of activation across muscle groups, with higher perceived ergonomic risk corresponding to increased RMS values in primary muscles responsible for task execution. Their approach utilized a large cohort (n=94), enhancing ecological validity, and employed Bayesian hierarchical modeling, which uncovered the influence of expertise and demographic factors on ergonomic risk perception and muscle activation relationships.

Muscle-specific responses under varying work conditions are also critical for ergonomic evaluations. Wang et al. (2024) employed AnyBody biomechanics software combined with experimental EMG data to study muscle activation in Chinese drivers under straight-line and steering conditions. Steering significantly increased activation levels in muscles such as the wrist extensors, serratus anterior, deltoid, and triceps brachii, indicating higher biomechanical loading during dynamic driving compared to steady-state driving. This muscle-specific activation information aids in designing vehicle ergonomics and interventions tailored to reduce excessive muscular demand and subsequent injury risk.

Fatigue, a crucial factor in occupational biomechanics, can be effectively assessed through EMG analysis. Wei et al. (2025) investigated neck muscle fatigue induced by firefighter helmet properties, finding that helmets with a less optimal center of mass increased muscle activation and fatigue indicators, such as normalized mean absolute value and decreased median frequency of EMG signals, especially during sustained neck flexion and extension tasks. This finding underscores the importance of equipment design not just in mass reduction but in biomechanical balance to minimize occupational musculoskeletal injury risks.

Similarly, Albin and Molenbroek (2023) explored cervical muscle activity in different computer display configurations, observing that ultrawide and dual display setups altered neck kinematics and potentially muscle workload. Though EMG specifics were not detailed, the biomechanical implications suggest varied neck muscle demands dependent on task setups.

Interaction errors in emerging technologies also impact biomechanical load. Kia et al. (2023) evaluated neck and shoulder muscle responses during augmented reality (AR) tasks with and without interaction errors, revealing that errors elevated neck extension and shoulder flexion angles alongside increased peak muscle activity in the anterior and medial deltoids. These findings highlight the need to optimize AR interfaces to prevent unnecessary increases in muscular loads and discomfort that could lead to injury.

Footwear design also influences muscle activation during locomotion, as demonstrated by Pezeshk et al. (2025), who measured ground reaction forces and EMG during walking with military boots versus formal shoes. The hybrid boot design incorporating synthetic materials

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decreased tibialis anterior muscle activity and modulated impulse forces, suggesting that material and structural adjustments in footwear can reduce muscle demand and improve biomechanical efficiency.

The subjective correlation of muscle demand with perceived exertion is well elucidated in manual material handling contexts. Vijaywargiya et al. (2022) found that heavier lifting weights and higher lifting heights proportionally increased biomechanical stress and perceived workload ratings, as measured by body discomfort charts, supporting the use of EMG and biomechanical loading as reliable indicators of task strain.

This body of research validates EMG as a robust and nuanced tool for quantifying occupational muscle demand and fatigue. By combining EMG with kinematic data and subjective evaluations, ergonomic practitioners can better identify risk factors, optimize equipment, and develop interventions to mitigate musculoskeletal disorders in diverse work environments.

4. KINEMATICS AND JOINT MOMENT ESTIMATION USING IMU AND MOTION TRACKING

The quantification of human kinematics and joint moments in occupational biomechanics is primarily achieved through technologies such as inertial measurement units (IMUs), optical motion capture systems, and increasingly, video-based markerless methods. These technologies facilitate the assessment of biomechanical demands in work settings by tracking body segment movements and estimating joint loads, critical for injury prevention and ergonomic intervention design.

IMUs are wearable sensors that integrate accelerometers, gyroscopes, and sometimes magnetometers to capture orientation and motion data dynamically. Their portability and ease of use make IMUs suitable for field assessments where traditional lab-based equipment is impractical. Optical motion capture (OMC) systems, on the other hand, rely on reflective markers tracked by multiple cameras to reconstruct 3D movement with high spatial and temporal resolution, often considered the gold standard for precision but limited by constraints such as controlled lighting conditions and marker occlusions.

Video-based markerless systems utilize advances in computer vision and machine learning to estimate body segment positions without physical markers. For instance, Wang et al. (2021) introduced an approach combining VideoPose3D, an open-source pose estimation library, with biomechanical modeling to estimate L5/S1 joint moments during manual material handling tasks. This system provided estimated peak moments that correlated positively with a laboratory-based motion tracking system, with a reported percentage error of 7.7%, establishing its potential for practical biomechanical analysis outside controlled environments.

Chen et al. (2025) benchmarked three motion capture technologies—including marker-based, flexible sensor-based, and phone video-based systems—in simulated offshore wind turbine maintenance tasks. Their findings revealed that sensor- and video-based systems closely approximate marker-based measurements in simpler movements, reporting root mean square error (RMSE) values below 7° and strong correlation coefficients. However, for more complex or multi-plane motions, particularly involving axial rotations, sensor- and video-based systems showed reduced accuracy, highlighting the need for cautious application when evaluating dynamic or asymmetric occupational tasks.

Inertial measurement-based approaches have been effectively leveraged to acquire precise joint kinematics. Iyer and Jeong (2025) integrated EMG with IMU data, employing accelerometer and gyroscope readings to compute joint angles while simultaneously assessing muscle activation patterns. Their study across various standardized occupational tasks demonstrated reliable joint

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motion estimation and muscle demand characterization, showcasing the comprehensive biomechanical insights achievable through such multimodal sensor integration.

Despite the advantages of individual systems, each technology suffers limitations. Optical systems require restrictive laboratory conditions and are vulnerable to marker occlusions, while IMUs can suffer from drift and magnetic interference. Recognizing these challenges, Hicks et al. (2025) developed a custom sensor fusion algorithm combining optical motion capture (OMC) and inertial motion capture (IMC) data. Utilizing the initial and terminal frames from OMC to anchor data, their fusion approach successfully filled gaps in OMC data with continuous IMC measurements, achieving an average error of only 2.5° over 10-minute durations of data absence. This fusion method demonstrates the feasibility of maintaining high-quality kinematic data in extended field-based measurements, overcoming the individual system weaknesses.

Comparisons between markerless and marker-based systems reveal a trade-off between system portability and measurement accuracy. While marker-based systems remain the benchmark for detailed biomechanical analysis, markerless and flexible sensor-based methods offer compelling alternatives for field ergonomics due to their reduced setup time and improved user comfort. However, users must carefully interpret data, especially for complex movements where these systems can lose fidelity. This balance informs the choice of technology depending on the specific occupational scenario's complexity and resource availability.

5. PERCEPTION, HUMAN VARIABILITY, AND DEMOGRAPHIC INFLUENCES

Understanding perception and the considerable variability introduced by human anthropometry, expertise, and demographic factors is essential in occupational biomechanics and ergonomics. Individual differences profoundly affect not only postural choices and biomechanical load but also how ergonomic risk is perceived and managed in workplace environments.

Recent research highlights that expertise influences ergonomic perception significantly. For example, Iyer and Jeong (2025) applied Bayesian hierarchical modeling alongside electromyography (EMG) and inertial measurement unit (IMU) data to reveal how workers' expertise levels and demographic variables modulate their interpretations of physical discomfort and biomechanical risk. Their findings show that task-specific physical demands are evaluated differently depending on one's experience, underlining the importance of considering user experience when designing workplace interventions.

Anthropometry and body size are critical dimensions of human variability impacting biomechanical stress and reach capabilities. Loddeke, Jones, and Garcia (2025) examined how people judge others' maximum horizontal reach and found that observers rely predominantly on static upper body characteristics rather than movement cues. This insight points to the relevance of visible anthropometric features in assessing action capabilities, which is crucial for robotic caregiver system design and personalized ergonomic adjustment.

Supporting these perceptual findings, Mahajan, Saravanan, and Menold (2021) used musculoskeletal modeling to examine how anthropometric differences in transtibial amputees influence joint stresses, particularly in the contralateral limb. This work demonstrates that heavier and taller individuals face different biomechanical challenges, emphasizing the need to customize ergonomic solutions according to body morphology to prevent secondary injuries.

Similarly, Horina et al. (2025) conducted ergonomic risk evaluations with digital human models that accounted for variations in European morphotypes. They found consistent moderate to high ergonomic risk levels across different anthropometric profiles in tram drivers due to poorly adaptable cabin design. This systemic mismatch illustrates how lack of ergonomic accommodation to user variability contributes to musculoskeletal disorder (MSD) risk.

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To parse such inter-individual differences, statistical techniques like Bayesian hierarchical modeling have become invaluable. Iyer and Jeong's (2025) integrated approach of combining subjective assessments with objective EMG and IMU metrics allows deeper understanding of how biomechanical strain correlates with personal factors. Their model enables prediction of ergonomic risk perceptions and muscle fatigue while accounting for expertise and demographic diversity, which informs targeted ergonomic interventions.

Environmental ergonomics also interacts with human variability. Yaroshenko, Zhuravleva, and Zapirov (2023) stressed that physiological responses during motor tasks in university students differ according to environmental conditions and physical culture practices, reflecting acclimatization and ergonomic adaptation processes influenced by individual and contextual factors.

Digital human modeling (DHM) techniques, like those reported by Koç et al. (2021), aid in redesigning fixtures and workspaces by simulating biomechanical load across diverse anthropometric spectra. DHM enables evaluation of lumbar compression and moment loading to optimize ergonomic compliance for different body sizes and postural behaviors.

Moreover, Albin and Molenbroek (2023) highlighted challenges in designing wearable products and furniture to fit a spectrum of anthropometric and demographic variations, noting the importance of advanced technologies such as 4D scanning to capture dynamic body dimensions relevant for ergonomic customization.

6. PRODUCT AND EQUIPMENT BIOMECHANICS

The biomechanical properties of equipment significantly influence muscle demand, fatigue, and injury risk, making ergonomic design essential for occupational safety and performance. Research on firefighter helmets has notably underscored the effect of helmet mass and center of mass (COM) placement on neck muscle fatigue. Wei, Paulon, and Chowdhury (2025) conducted a study involving 36 firefighters performing sustained neck flexion and extension tasks under three helmet conditions: no helmet, a U.S. helmet, and a European-style helmet. Electromyography (EMG) data from eight neck muscles revealed that the U.S. helmet, characterized by a more forward-shifted COM, induced higher muscle activation and fatigue than the European design. This finding emphasizes that optimizing helmet COM location is as critical, if not more, than overall weight in mitigating neck strain and potential injury risks for firefighters.

Footwear design also plays a vital role in shaping biomechanics during locomotion. Pezeshk, Vafaie, and IlBeigi (2025) compared muscle activity and gait characteristics across formal shoes and three types of military boots differing in shaft material. Their findings indicated lower muscle activity in shoes compared to boots. Notably, a hybrid leather-synthetic boot reduced tibialis anterior muscle activation and minimized negative ground reaction force impulse, enhancing gait efficiency and mobility. The results highlight that incorporating synthetic materials to decrease shaft stiffness can create biomechanical advantages, reducing muscle loading and potentially lowering injury risk in challenging military environments.

Ergonomics of tool handles is another critical aspect influencing biomechanical load during task performance. Mantilla, Maradei, and Castellanos (2025) evaluated an innovative agricultural hoe using a quasi-experimental participatory co-design approach. Their prototype demonstrated a 96.2% satisfaction rate among small-scale farmers and significantly reduced physical strain associated with hoe use. Importantly, an inverse correlation between discomfort and satisfaction was statistically confirmed, validating the ergonomic improvements. Such co-design with end users incorporating biomechanical metrics ensures tools not only enhance comfort but also improve productivity and reduce musculoskeletal disorder risks.

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In the context of musical instrument ergonomics, Orme, Sommerich, and Lavender (2023) examined the effects of a Neotech Trombone Grip on muscle activity in the left upper extremity. A two-week period of grip use among trombone players showed consistent reductions in finger flexor muscle activity and smaller, less consistent changes in other shoulder and arm muscles. The most pronounced benefits were observed in players with smaller hands, suggesting handle adaptations tailored to individual anthropometry can decrease muscle strain and improve comfort during prolonged use.

Regarding hand-operated devices, Stone et al. (2022) investigated the biomechanical effects of augmented slide pull devices on law enforcement officers during pistol racking. While no significant difference in racking time was found between standard and augmented slides, the augmented slide produced a slightly lower error rate and was preferred by most participants. This preference suggests that minor ergonomic enhancements can facilitate more precise and possibly less strenuous firearm operation, underscoring the value of biomechanical considerations in equipment design for improved performance and reduced physical strain.

Emerging technologies also contribute to biomechanical evaluation of equipment designs. Chen, Zheng, Yin, and Zhang (2024) explored the use of flexible, wireless, skin-mounted sensors (BioStamp nPoint) to assess joint kinematics during patient handling with back exoskeletons. Offering an alternative to traditional optical motion capture, these sensors facilitate portable and unobtrusive biomechanical assessment, providing valuable data to optimize exoskeleton design by monitoring joint motion in real-world tasks.

7. WORKSTATION AND INTERFACE DESIGN EFFECTS ON BIOMECHANICAL RISK

Workstation and interface design significantly influence biomechanical risks, particularly concerning neck, shoulder, and upper limb musculoskeletal loads. Burruss et al. (2021) investigated the effects of different computer display configurations—single, dual, and ultrawide (UW) monitors—on neck biomechanics and task performance. Their study with seventeen participants performing five distinct tasks revealed that centered configurations produced significantly different median neck rotation angles compared to secondary configurations, with these effects dependent on task type. Interestingly, the use of a 34-inch curved UW display at a longer viewing distance yielded neck kinematics comparable to a single 24-inch display and appeared to reduce the need for frequent screen interactions. This suggests that properly configured UW displays may aid in minimizing neck strain during prolonged computer use. Participants also expressed preferences for UW, centered dual, and secondary dual setups over single-monitor configurations, indicating potential ergonomic and subjective benefits for complex work tasks. Burruss et al. caution that while dual displays remain beneficial, the optimal use involves adjustable monitor arms to switch configurations according to the task demands, thereby better managing biomechanical risk across different workflows.

Complementing this, Lee et al. (2021) focused on the ergonomic design of standing workstations, specifically evaluating desk shape and height along with monitor positioning to reduce biomechanical costs. Their experiments with sixteen participants demonstrated that increasing desk height by 5 cm combined with a concave desk shape reduced wrist extension by 10.5° (42%) and decreased muscle activation in critical muscles such as the extensor carpi radialis (8.6%) and anterior deltoid (28.8%). However, there was an associated increase in wrist adduction angle by 2.2° (19%), which suggests some trade-off effects that need consideration. Moreover, the irregularity of the center of pressure increased, indicating more complex postural corrections during standing work. Based on these findings, providing a standing armrest with a higher and concave desk surface is recommended to alleviate upper extremity stress in standing computer work while using a split keyboard to minimize adverse wrist postures.

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In the realm of augmented reality (AR), Kia et al. (2023) examined how interaction errors during AR tasks impact neck and shoulder biomechanical loads. Their repeated-measures study with twenty participants performing omni-directional pointing and cube placing tasks observed that interaction errors significantly increased neck extension and shoulder flexion angles as well as peak muscle activity in shoulder muscles, especially the anterior and medial deltoids. Such biomechanical consequences are concerning because they can elevate the risk of musculoskeletal discomfort and injuries among users engaging in AR activities, which are increasingly common in occupational and training settings. This emphasizes the critical need for designing AR interfaces that minimize interaction errors to mitigate these unintended physical burdens.

Additional insights come from Wei et al. (2025), whose study on firefighter helmets underlines how equipment design affects neck muscle fatigue. They found that helmets with less optimized center of mass (COM) locations, such as US-style helmets compared to European designs, led to greater neck muscle activation and fatigue during sustained tasks. These results highlight the importance of ergonomic interface design—beyond just displays and desks—to include equipment carried or worn by workers, which can substantially influence biomechanical loading and injury risk.

Furthermore, Orme et al. (2023) explored grasping biomechanics by comparing the use of a specialized trombone grip versus standard methods. Their biomechanical analyses showed significant decreases in muscle activity in the left finger flexors when the grip was used, illustrating how interface modifications—even for handheld equipment—can dramatically alter muscle load patterns and potentially reduce repetitive strain injuries.

Tang et al. (2021) contributed relevant evidence on the ergonomic effects of wearable devices in work-associated postures. Their investigation of prism glasses designed to reduce awkward neck flexion during smartphone use found that these glasses lowered neck extensor muscle activity and neck flexion angles, especially in users experiencing neck discomfort. These findings support the concept that altering visual interface ergonomics, even subtler ones like lenses, can have tangible effects on biomechanical loads and associated discomfort.

8. INTERVENTIONS AND ERGONOMIC OPTIMIZATION FRAMEWORKS

Recent advances in occupational biomechanics emphasize interventions designed to reduce musculoskeletal load and improve ergonomic compliance across diverse work environments. Among these, the integration of exoskeleton technologies, virtual reality (VR) training, redesign of fixtures and tools, and artificial intelligence (AI)-driven optimizations represent significant strides in mitigating muscle demand, fatigue, and injury risk.

Back-support exoskeletons (BSEs) have gained attention for their capability to assist workers in physically demanding tasks, such as patient handling and load lifting. Wang et al. (2025) evaluated flexible sensor-based technologies integrated with back exoskeleton usage, highlighting measurable joint kinematics improvements during patient transfers. Complementing this, Srinivasan et al. (2023) conducted mixed-methods evaluations with Emergency Medical Services (EMS) clinicians, revealing that powered BSEs significantly reduced trunk extensor muscle activity and perceived exertion compared with passive variants. These assessments incorporated electromyography (EMG) measures of muscle activation alongside subjective exertion ratings, providing a holistic view of biomechanical benefits. Importantly, participants reported greater comfort and reduced fatigue when using powered devices, underscoring their potential for practical ergonomic enhancement.

The adoption of VR-based training techniques further enhances exoskeleton usability and perceived usefulness. Srinivasan et al. (2023) investigated novice users' perceptions following different exposure types to a back-support exoskeleton, including VR simulations. VR training

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effectively clarified specific task conditions where the exoskeleton was beneficial and moderated extreme preconceived biases about the technology. This immersive approach promotes informed adoption, bridging the gap between theoretical ergonomic benefits and actual user acceptance.

Redesigning fixtures and hand tools also contributes significantly to ergonomic interventions. Lee and Choi (2021) studied the impact of standing armrests and desk configurations on upper extremity biomechanics during typing tasks. Their findings demonstrated that a higher and concave desk surface, combined with an armrest elevated by 5 centimeters, substantially reduced wrist extension angles and muscle activation in key muscles such as the extensor carpi radialis and anterior deltoid. However, the adjustment increased wrist adduction, suggesting that interventions must be evaluated for trade-offs, with additional considerations such as keyboard type to mitigate secondary risks. Similarly, the co-design of agricultural hoes with ergonomic descriptors achieved reduced physical strain and higher user satisfaction, reflecting the importance of participatory design in ergonomic tool development (Mantilla et al., 2025).

Military footwear represents another domain where ergonomic design influences biomechanical efficiency. Pezeshk et al. (2025) examined the effects of shaft materials in boots on muscle activity and gait patterns, finding that hybrid leather-synthetic shafts lowered tibialis anterior muscle activation and optimized force impulses. Their biomechanical assessments employed EMG and force plate measurements, illustrating how material innovations can enhance occupational safety and mobility.

Augmented Reality (AR) and Virtual Reality (VR) interfaces also introduce new ergonomic challenges and opportunities. Kia, Hwang, and Kim (2023) analyzed the effects of interaction errors in AR tasks, noting increased muscle loads in the neck and shoulders associated with task inaccuracies. Their work underscores the necessity of error reduction methods in human–machine interfaces to prevent inadvertent biomechanical overload.

Artificial Intelligence-driven interventions represent an emerging frontier for ergonomic optimization. Das (2024) reviewed AI applications across manufacturing, IT, healthcare, and construction sectors, highlighting its role in automating physical tasks, predicting ergonomic risks, and customizing workstation layouts. AI improves ergonomic outcomes by analyzing human biomechanics data and task repetition patterns, enabling adaptive scheduling and equipment design modifications that minimize musculoskeletal disorders. Despite challenges such as high cost and cultural resistance, AI offers scalable solutions for proactive ergonomic management.

Finally, evaluation of ergonomic interventions increasingly leverages advanced biomechanical metrics. Employed methods include EMG for quantifying muscle demand, inertial measurement units (IMUs) for joint kinematics, video- and sensor-based motion capture for movement analysis, and subjective workload assessments (Iyer & Jeong, 2025; Chen et al., 2025). This integrated assessment framework facilitates comprehensive understanding of intervention effectiveness, evidencing benefits across both simulated and real-world settings.

9. SYNTHESIS OF CURRENT EVIDENCE AND FUTURE RESEARCH DIRECTIONS

Contemporary occupational biomechanics research has advanced considerably by integrating diverse quantitative methods such as electromyography (EMG), inertial measurement units (IMU), optical and markerless motion capture, and digital human modeling to assess musculoskeletal load across various work contexts. Methods like EMG provide direct quantification of muscle activation and fatigue levels, contextualizing neuromuscular demands in physically demanding tasks (Iyer & Jeong, 2025). Meanwhile, IMU and flexible sensor technologies enable kinematic analyses in field settings, addressing limitations of traditional optical systems that require controlled environments (Chen et al., 2024; Chen et al., 2025). Sensor

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fusion approaches combining optical and inertial data have shown promise in filling data gaps and enhancing motion capture fidelity during dynamic occupational tasks (Hicks et al., 2025).

Ergonomic interventions such as exoskeleton-assisted patient handling and the redesign of assembly fixtures demonstrate practical applications of biomechanical insights, offering measurable reductions in muscle workload and joint loading (Wang et al., 2025; Koç et al., 2021). Similarly, equipment design studies focusing on firefighter helmets reveal the critical influence of center of mass over mere weight in mitigating neck muscle fatigue and injury risk, emphasizing biomechanical optimization in personal protective gear (Wei, Paulon, & Chowdhury, 2025).

Research investigating manual material handling also identifies biomechanical stress factors and acceptable lifting limits, with targeted analyses on lumbar spine moments to guide injury prevention standards. For instance, Vijaywargiya and colleagues (2022) recommend a maximal safe lifting weight around 15 kg for symmetric lifts from floor to various heights to mitigate musculoskeletal injury risks.

There remain significant research gaps in understanding how human variability—demographic factors, expertise, and anthropometry—modulates ergonomic risk perception and biomechanical responses, as demonstrated through Bayesian statistical models correlating subjective task difficulty with objective muscle activation and movement efficiency (Loddeke, Jones, & Garcia, 2025; Iyer & Jeong, 2025). Moreover, perception studies reveal that static cues rather than dynamic movement inform judgments of an individual's physical reach capacities, suggesting the need for tailored ergonomic designs that account for perceptual biases (Loddeke et al., 2025).

Looking forward, several technological innovations stand to substantially advance occupational biomechanics research and practice. Artificial intelligence (AI) integration enables predictive analytics and real-time ergonomic optimization across industrial and healthcare settings, thereby reducing musculoskeletal strain and enhancing workstation design (Das, 2024). Virtual reality (VR) training can refine user perceptions and acceptance of assistive devices like back-support exoskeletons, fostering more effective ergonomic interventions (Ransing et al., 2023).

Sensor developments continue to improve with flexible, skin-mounted wireless devices that allow whole-body kinematic monitoring outside of traditional labs, facilitating more ecologically valid biomechanical studies (Chen et al., 2024). The advancement of markerless pose reconstruction algorithms coupled with biomechanical modeling software is similarly enhancing the feasibility and accuracy of joint moment estimations during manual tasks, with error margins acceptable for field-based ergonomic risk assessment (Wang et al., 2021).

Finally, ergonomic research continues to evolve towards participatory, co-design approaches that incorporate user feedback, such as in the design of agricultural tools or footwear shafts, which address discomfort and improve biomechanical efficiency (Mantilla, Maradei, & Castellanos, 2025; Pezeshk, Vafaie, & IlBeigi, 2025). As digital human modeling and rapidly updating body scanning technologies become more widely accessible, personalized ergonomic solutions aligned with user anthropometry and task demands become increasingly viable (Albin & Molenbroek, 2023; Koç et al., 2021).

10. CONCLUSION

This review underscores the pivotal role of biomechanical quantification methods, particularly EMG and IMU-based motion tracking, in advancing our understanding of musculoskeletal load and injury risk in occupational settings. Findings reveal consistent associations between muscle activation patterns, spinal loading, and task demands, while highlighting variability influenced by individual factors such as expertise and anthropometry. Equipment and workstation design significantly affect biomechanical stress, underscoring the necessity for ergonomic optimization

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tailored to user characteristics. Emerging interventions, including wearable exoskeletons and AI-driven task modifications, demonstrate potential to mitigate muscle fatigue and biomechanical overload. However, challenges remain in achieving accurate, real-world motion capture and integrating multifactorial data to inform personalized ergonomic strategies. Future research should prioritize refining portable biomechanical measurement technologies, expanding demographic inclusivity, and developing adaptive intervention frameworks to enhance occupational health and productivity.

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