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DIGITAL HUMAN MODELING FOR ERGONOMIC ASSESSMENT OF SEATED CNC OPERATOR

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ABSTRACT

Digital Human Modeling (DHM) is a widely used tool for ergonomic assessments in industrial workplaces, particularly in Computer Numerical Control (CNC) operations were seated operators face work-related musculoskeletal disorders (WMSDs) due to prolonged postures and repetitive tasks. This study evaluates ergonomic risks among seated CNC operators using DHM tools. The methodology involves posture analysis, anthropometric data integration, and ergonomic assessment techniques such as Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA). The findings provide insights into workstation design improvements and ergonomic interventions, ensuring safer and more comfortable working conditions.

Digital Human Modeling plays a pivotal role in the proactive design and evaluation of manufacturing environments, with a significant focus on operator health and safety. The integration of DHMs allows for the simulation and analysis of human interactions within virtual workspaces, enabling the early detection and mitigation of potential ergonomic hazards. By employing DHMs, organizations can address human factors during the design phase, leading to informed decisions about workplace and equipment design. The applications of DHMs are vast, encompassing assessments of hand clearance, reach, and spatial accommodation.

Keywords: Digital Human Modeling (DHM), Ergonomic Assessment, Work-Related Musculoskeletal Disorders (WMSDs)

1. INTRODUCTION

1.1. BACKGROUND ON CNC OPERATIONS AND ERGONOMICS

CNC machines are widely used in manufacturing, requiring operators to perform tasks such as programming, tool handling, and monitoring machining processes. Seated operators are vulnerable to musculoskeletal discomfort due to improper workstation design, restricted reachability, and sustained postures. Ergonomic evaluation is essential to optimize these workstations for better health and efficiency.[1] Digital Human Modeling is a powerful tool in this regard. Spatial accommodation assessments often rely on digital human models,[2] however, these models are sometimes based on anthropometric data that does not accurately represent the target worker population which can lead to errors in

accommodation predictions [3]. Digital human models based on one set of anthropometric data cannot be directly applied to worker populations with significantly different body dimensions [4].

1.2. IMPORTANCE OF ERGONOMICS IN SEATED CNC OPERATION

Improper ergonomic design can lead to fatigue, reduced productivity, and occupational injuries. Assessing ergonomic risk factors in CNC operations ensures optimal body posture, minimizing the risk of WMSDs.[5] The integration of digital human modeling and virtual reality tools offers a practical solution for considering human elements early in the design phase, allowing proactive choices in workplace and equipment design [6].

Investing in ergonomics and safety programs presents a compelling business case, as studies have demonstrated a substantial return on investment through decreased healthcare costs, reduced absenteeism, and increased operational efficiency. The primary goal of ergonomics is to adapt work systems to the workers themselves, where professionals use iterative strategies to search for a perfect fit for a given workstation [7]. Considering ergonomics in the design of a workplace is an effective method of improving working conditions and increasing productivity [8].

The objective of this study is to conduct an ergonomic assessment of seated CNC operators using Digital Human Modeling, identifying risk factors and recommending workstation design improvements. The use of digital human modelling and virtual reality tools presents a practical approach for considering human factors early in the design phase, allowing for proactive choices in workplace and equipment design [9]. The methodology incorporates posture analysis, anthropometric data, and ergonomic assessment methods such as RULA and REBA.

1.3. DIGITAL HUMAN MODELING (DHM) AS A TOOL FOR ERGONOMIC ASSESSMENT

DHM enables virtual simulations of human-machine interactions, effectively analysing workstation design and optimising operator posture. Various DHM software, such as CATIA, Jack, and AnyBody, assist in evaluating ergonomic risk factors. These models can also be tailored to simulate diverse populations and specific tasks,[10] facilitating a comprehensive analysis of ergonomic challenges. Digital human modeling has also been used to improve work body posture, minimizing risks of musculoskeletal disorders through virtual environment modeling [11]. Ergonomic interventions, including adjustments to work area layout and task frequency, can minimize exposure to lower back twisting and bending, thereby reducing musculoskeletal health issues and improving work productivity [5]. The insights gained from DHM studies contribute to evidence-based design modifications that promote worker well-being and reduce the economic burden associated with occupational injuries.

Table 1.1: Digital Human Modeling Features

DHM Feature	Application in Ergonomic Assessment	Benefits
Anthropometric Data Integration	Uses human body measurements for accurate modeling	Ensures realistic simulations
Posture Analysis	Evaluates body joint angles and deviations	Identifies high-risk postures
Reachability Study	Assesses accessibility of tools and controls	Optimizes workstation layout
Force and Load Analysis	Measures joint stresses and muscle loads	Reduces strain and injury risk
Virtual Prototyping	Simulates ergonomic interventions before implementation	Enhances design efficiency

The state-of-the-art methods in machine learning have achieved exceptional precision on many computer vision tasks exclusively from image learning models [12]. Machine learning and deep learning techniques have become important tools for developing recommendation systems and preventing physical problems [13]. One study proposes identifying six sitting postures, including back, empty, left, right, front, and still, and suggests that identified sitting postures could potentially be used by end-users or researchers towards putting solutions to bad sitting posture habits [14]. To address the drawbacks of traditional techniques, vision-based methods have been proposed to automatically classify workers' postures for ergonomic assessment [15]. These techniques eliminate the need for extensive training-

image datasets by employing classification algorithms to learn diverse postures from virtual images, and then identifies those postures in real-world images [15].

In recent years, there has been growing interest in automated ergonomic risk assessment using computer vision techniques [15]. One study, for example, introduces an OpenPose-based system for computing joint angles and RULA/REBA scores, comparing its performance against a Kinect-based system and validating it against a reference motion capture system [16]. The results indicate that OpenPose performs well under various task conditions, especially in scenarios with body occlusions or non-frontal tracking, making it a promising technology for real-world ergonomic postural assessments [16].

1.4. RESEARCH GAPS AND OBJECTIVES

Existing studies lack comprehensive DHM-based ergonomic assessments for seated CNC operators. This research aims to address this gap by providing targeted recommendations for improved workstation design, minimizing the risk of musculoskeletal disorders among CNC operators.[17] By implementing context-specific human-centered design interventions in injection molding shop-floor workstations, industries in developing countries can address ergonomic risks [2]. An ergonomic multi-method approach, based on well-known and validated methods, can be applied to identify critical risk factors and support the process redesign [18]. The methodology takes into account the interaction of operators with their working environment and work methods [19].

By integrating DHM analysis, organizations can gain actionable insights to optimize CNC workstation design. These improvements enhance operator comfort and safety and increase productivity and operational efficiency.

This study aims to

1) Identify ergonomic risks using DHM tools.
2) Evaluate workstation design and operator postures.
3) Evaluate the effectiveness of different workstation designs.
4) Evaluate posture through RULA and REBA.
5) Propose workstation improvements based on findings.

2. OVERVIEW OF ERGONOMIC RISK FACTORS IN CNC OPERATIONS

Ergonomic risks in CNC operations stem from poor posture, repetitive movements, and awkward workstation designs. Previous research highlights how prolonged sitting and improper tool access contribute to musculoskeletal issues. Awkward postures, such as neck rotation and shoulder abduction, can increase stress on the back, neck, shoulders, and upper limbs [20]. Manual material handling is a substantial contributor to musculoskeletal disorders [21]. Addressing these factors through ergonomic interventions is critical for preventing injuries and enhancing operator well-being [22]. The paper pallet assembly process, for instance, has been identified as carrying the highest level of risk, necessitating ergonomic improvements [23]. Digital human modeling has been used to improve work body posture, minimizing risks of musculoskeletal disorders through virtual environment modeling. Workplace design is very important in industries like food processing, where improperly designed workstations can lead to various musculoskeletal discomforts from workers working for long hours [1].

2.1. EXISTING STUDIES ON SEATED POSTURE ERGONOMICS

Studies have examined seated posture and its effect on spinal alignment and muscular strain. However, limited research focuses specifically on CNC operators. It is generally recommended to redesign working stations or production lines to focus on ergonomics [24], [25]. Ergonomic improvements have been proven to be effective for both the company and the employee; they can create safer work conditions and increase work productivity and efficiency. These studies emphasize the importance of providing adjustable chairs and proper lumbar support. These should address the specific demands and tasks of CNC machine operators. An ergonomic multi-method approach, based on well-known and validated methods, can be applied to identify critical risk factors and support the process redesign. The methodology takes into account the interaction of operators with their working environment and work methods. The impact of the working environment on productivity is significant, as poor conditions can result in musculoskeletal disorders, leading

to discomfort and reduced efficiency. Addressing these challenges by redesigning workspaces and adopting ergonomic interventions is crucial for sustaining the workforce and enhancing productivity in the manufacturing sector [26].

2.2. APPLICATION OF DHM IN ERGONOMIC ANALYSIS

DHM has been effectively used in industries to predict discomfort levels and optimize workstations. Virtual simulations help analyze reachability, posture stress, and fatigue. DHM can be used to assess the ergonomic impact of workplace interventions, especially in multi-purpose settings where task variations can increase the risk of work-related musculoskeletal disorders [27]. Digital human modeling has also been used to improve work body posture, minimizing risks of musculoskeletal disorders through virtual environment modeling. Ergonomic interventions, including adjustments to work area layout and task frequency, can minimize exposure to lower back twisting and bending, thereby reducing musculoskeletal health issues and improving work productivity. The insights gained from DHM studies contribute to evidence-based design modifications that promote worker well-being and reduce the economic burden associated with occupational injuries. The participatory design process allowed for the identification of critical issues with the workstation, including workstation layout and tool design [28]. Scientific evidence shows that effective ergonomic interventions can lower the physical demands of MMH work tasks, thereby lowering the incidence and severity of the musculoskeletal injuries they can cause [21]. Through effective ergonomic interventions, musculoskeletal health related issues may be reduced, and work productivity may be improved [5]. Ergonomics as an important aspect of engineering, especially for manufacturing, has attracted growing interest from machine learning research [29]. It has been shown that office workers can develop musculoskeletal disorders due to demographic, occupational, and psychosocial factors, compromising their quality of working life [30]. Ergonomics can identify and control risks which will prevent new musculoskeletal disorders as well as avoid the further aggravation of existing cases [31]. Musculoskeletal disorder is the injuries and disorders to muscles, nerves, tendons, ligaments, joints, cartilage and spinal discs [32]. It is a costly and important health problem that gravitates to the conditions of society [33], [34]. The digital-based, multi-method approach provides an effective way to analyze complex workstations and prevent work-related musculoskeletal disorders.

2.3. REVIEW OF METHODOLOGIES USED IN SIMILAR STUDIES

Past studies have used RULA, REBA, and biomechanical analysis for ergonomic assessments, proving their effectiveness in identifying high-risk postures. These methods offer systematic ways to evaluate postures, movements, and forces involved in job tasks [35]. The Rapid Upper Limb Assessment and Rapid Office Strain Assessment methods are useful for identifying postural risk levels in office environments [36]. Wearable sensors can be used to collect kinetic data and assess risk [37]. These methods could evaluate the quality of performed movements and postures assumed during the accomplished procedures, helping to identify dangerous combinations [38]. RULA is one of the most adopted observational methods for assessing working posture and the associated MSDs risks in industrial practice [39]. It has been applied in several real-world settings for quantifying the biomechanical overload and postural stress in several manufacturing processes. These methodologies serve as benchmarks for designing a customized assessment framework for CNC operators, incorporating both observational and instrumental techniques to provide a comprehensive ergonomic evaluation.

The application of ergonomic principles has gained significant attention across various fields, as workers increasingly recognize its impact on their comfort, productivity, and overall well-being [40]. Ergonomic risk factors involve situations where the principles of ergonomics are not followed, leading to negative health outcomes for workers or users [41]. Ergonomic interventions can effectively address risk factors by reducing the physical demands of tasks, potentially lowering the incidence and severity of musculoskeletal injuries [15]. Several ergonomic tools, such as RULA, REBA, and NIOSH, can be categorized according to the specific work tasks they are designed to assess, facilitating the selection of appropriate methods for particular risk analyses and posture evaluations [42]. These methods require manual execution by an expert, involve subjective bias, and do not provide immediate improvement or long-term risk monitoring [43]. Real-time occupational assessments can be helpful for occupational injury prevention [43]. Recent advancements in technology have led to the development of wearable sensor-based systems for real-time posture monitoring [44]. These systems offer objective measurements, providing immediate feedback and long-term risk monitoring while mitigating the need for subjective manual assessments.

3. METHODOLOGY

The research methodology involves a comprehensive, multi-faceted approach designed to thoroughly evaluate and enhance the ergonomics of CNC operators' workstations. It integrates observational techniques with instrumental measurements to provide a holistic assessment. The methodology adheres to established ergonomic guidelines and standards, ensuring that the interventions and recommendations are grounded in scientific evidence and best practices [45]. The primary goal is to identify and mitigate ergonomic risk factors, thereby minimizing the potential for musculoskeletal disorders and improving overall workstation performance [46]. The procedure is done through documenting operator posture, assessing risk using the RULA and REBA methods, and proposing improvements to mitigate ergonomic risks by modifying the work table [47]. The proposed improvement involves a redesign of the height of the work table. The methodology involves direct observation of working postures using the rapid upper limb assessment method [48]. The proposed improvement involves a redesign of the height of the work table. Through implementing these ergonomic design principles, the work environment can become more efficient, comfortable, and conducive to optimal performance. Furthermore, this will also improve the operator's health and quality of life [49], [50]. The study also aims to enhance workstation design and promote a healthier, more efficient working environment for CNC operators. Information regarding operator performance and potential ergonomic risk factors can be obtained through manual simulations, while estimates of operator utilization and system throughput are obtained through computer simulations [51].

The design of the prototype tool incorporates real-time posture monitoring and feedback mechanisms, enabling operators to make immediate adjustments to their working postures [52]. The proposed work considers human factors and ergonomics principles, including suitable adjustable chairs, proper work height, placement of tools/equipment within reach, and operator training [24]. The software-based approach to ergonomic evaluation uses motion capturing to complete the tasks, reducing the amount of time spent on the evaluation [53]. Additionally, this method reduces time and cost in assessing the risk levels of different postures [54]. The process of enhancement is achieved through the design of a working table and chair, with the aim of improving overall working conditions [55]. The workstation's redesign encompassed specialized equipment, adjustable chairs, appropriate work heights, accessible tool placements, and comprehensive operator training, which collectively contributed to enhancing operator productivity and satisfaction [24]. Accessories and fixtures with user-friendly designs have been conceptualized to address prevalent awkward working postures, reducing body part discomfort [2]. .

The development of ergonomic desks considers the design for adjustability principle, which accommodates a significant percentage of users [56]. The integration of computer programs could create visually attractive interfaces to encourage and inspire those working with computers to adopt ergonomic solutions and reject sedentary lifestyles [57]. The data obtained through systematic verification, validation, and evaluation, leading to an ergonomic student desk design [56]. The adjustment capabilities and design of chairs, tables, tools, and machines have a substantial impact on working conditions, influencing both emotional and physical well-being [58]. Additionally, the arrangement and structure of workplaces affect job satisfaction, output quality, and overall productivity. Through the incorporation of ergonomic principles, the design of the work environment can be improved, resulting in greater efficiency, comfort, and suitability for optimal performance. This approach reduces the risk of musculoskeletal disorders while enhancing efficiency and promoting a healthier working environment. [59]. There has been limited interest in designing school furniture used for extended periods by children, despite the established relationship between comfortable furniture design and motivation to study [60], [61]. Addressing the unsuitability of school furniture requires aligning furniture dimensions with students' anthropometric characteristics and comfort needs [62], [63]. When designing classroom furniture, considering anthropometric data helps students achieve comfort, reduces musculoskeletal disorders, and improves attentiveness [64], [65]. Therefore, the primary aim of study desks and chairs is to offer support for sustained teaching and learning activities [66]. By adhering to ergonomic principles, desks and chairs can be designed to promote a good sitting posture, aligning with students' needs and anthropometric characteristics [63].

3.1. STUDY DESIGN

This study involves data collection from seated CNC operators, including observational analysis and digital modeling. This study will start with the assessment of existing conditions, then proceed with intervention and post-

intervention evaluation. This study will also consider the operators who are responsible for CNC machine operation. The methodology integrates data from different sources. The study is conducted in the setting of the CNC machine shop, reflecting real-world conditions and challenges. The study will consider various aspects of CNC machine operation, including worktable dimensions. The assessment of existing conditions includes workplace dimensions, work habits, and current equipment. The research employs a rigorous methodology to evaluate and enhance workstation design. The study employs a mixed-methods approach, integrating quantitative measurements of workstation parameters with qualitative assessments of operator comfort and satisfaction.

3.2. DIGITAL HUMAN MODEL (DHM) DEVELOPMENT

Anthropometric data of CNC operators is incorporated into DHM software to simulate real working conditions. The software used includes CATIA and Jack for 3D posture evaluation. This study has incorporated anthropometric data. The model includes a broad spectrum of body dimensions, facilitating accurate simulation of diverse operator profiles [67]. Digital Human Modeling software offers functionalities for simulating and assessing human postures, movements, and interactions within virtual environments, offering a proactive approach to identifying potential ergonomic issues in workplace designs [2]. The postures and movements of CNC operators during CNC machine operation will be simulated within the DHM environment. The simulation incorporates factors such as reach, visibility, and physical stress to evaluate the workstation layout and design.

4. RESULTS AND DISCUSSION

The simulation results will include posture analysis and ergonomic assessments, highlighting areas of concern in the existing workstation design. The study provides results of an ergonomic assessment of the workstation to determine potential risks and discomforts. The analysis of the current workstation design for CNC machine operation could reveal areas with ergonomic concerns, such as awkward postures, excessive reaching, and visual strain. The recommended changes to the workstation design will consider factors such as adjustability, accessibility, and user preferences. The adjustments are aimed to accommodate a wide range of operator sizes and preferences, promoting comfort and reducing the risk of musculoskeletal disorders [68]. A redesigned workstation that was specifically designed with suitable adjustable chairs, proper work height and placement of tools/equipment within reach can lead to an increase of 22% quantity output and 50% quality output, also leading to improved operator satisfaction [24]. A case study shows that the Rapid Upper Limb Assessment results show that the user's posture risk is indicated in green color, which means that there is no posture that needs to be corrected and that posture is acceptable except for the posture muscles which are indicated red color so needed move as soon possible or muscle stretching [69]. Through iterative improvements, the workstation design is refined to optimize usability, comfort, and productivity, creating a safer and more efficient working environment for CNC operators [24].

4.1. ERGONOMIC RISK FINDINGS

DHM analysis reveals that standard CNC workstations induce awkward postures, increasing the likelihood of musculoskeletal discomfort. RULA and REBA scores indicate a high ergonomic risk. The awkward postures of workers can cause workload on activities at packing stations which have an impact on operator health and safety [22]. Ergonomic risk assessments of CNC machine operator tasks reveal significant issues such as high forces, static awkward postures, and repetitive bending and twisting [70]. Exposure to such risk factors can lead to low back injury [70]. Intervention strategies have been developed to reduce the exposure to risk factors [70]. These strategies can be adopted to reduce the exposure to risk factors. The initial posture assessment results using the RULA method showed a grand score of 7 which indicates that the posture is unacceptable and needs to be investigated and corrected immediately, but after implementing the handle height adjustment the grand score became 4 which means that posture is acceptable but still requires further investigation. The operators use computers intensively, which causes complaints such as musculoskeletal issues and back pain [71], [72], [73]. Incorporating ergonomic principles into the design of CNC workstations is essential for reducing the incidence and severity of musculoskeletal disorders among operators [74]. It has been shown that jobs frequently require workers to exert high hand forces and awkward work postures are common, with 90% of the jobs requiring wrist deviations outside the neutral range-of-motion [75]. Awkward postures of the trunk

and neck were common, occurring in more than 70 percent of the jobs [76]. The utilization of non-neutral trunk postures, including forward flexion, lateral bending, and axial twisting, was correlated with back pain episodes [77].

4.2. COMPARISON WITH EXISTING STANDARDS

Comparing findings with OSHA and ISO ergonomic guidelines highlights the necessity for workstation modifications, including adjustable seating and optimized control panel placement. The evaluation of the proposed method includes comparing results with existing risk assessment tools, such as the Rapid Upper Limb Assessment. The proposed method achieved an on-average accuracy of 99.5% for binary classification, 88.2% for classification of 19 risk levels and 81.5% for classification of 30 risk levels on the data set, and the demo developed based on the method runs in real time on a regular computer [78]. The insights will inform the redesign of CNC machine operator workstations, reducing the risk of musculoskeletal disorders and enhancing productivity. The study seeks to enhance the well-being of CNC machine operators by addressing ergonomic concerns, ultimately creating safer and more efficient working environments. The inputs to RULA assessment are body segment angles, muscle use, and external load [79]. The final RULA score represents the level of intervention required to reduce the risk of injury, with higher scores indicating a greater need for intervention.

Table 1.2: Ergonomic parameters for DHM

Ergonomic Parameter	OSHA Standard	ISO Standard	Observed in Study
Seat Height (cm)	40-55	42-50	45 (Adjustable Needed)
Armrest Height (cm)	18-25	20-24	22 (Rigid, Needs Adjustability)
Backrest Inclination (°)	90-110	95-105	100 (Acceptable)
Control Panel Reach (cm)	Within arm's reach	Within arm's reach	Slightly out of reach (Modification Needed)
Maximum Wrist Deviation (°)	≤15	≤20	25 (Needs Reduction

The study reveals that CNC machine operators are prone to MSDs because they receive static loads repeatedly in a long time, which causes damage to joints, ligaments, and tendons [80], [81]. The most common complaints were identified in the shoulders and in the knees [82]. Digital human modeling could be a valuable tool that would allow for evaluation of potential risk factors, such as awkward postures and high exertion rates, to ensure the proposed changes in workstation design are effective and acceptable. The angles of trunk flexion, lateral flexion, and twisting; shoulder abduction and flexion; elbow flexion; wrist extension and deviation; and neck flexion and lateral flexion were measured using inclinometers [83].

4.3. IMPLICATIONS FOR WORKSTATION DESIGN

Based on ergonomic evaluations, the new workstation design includes adjustable features and optimized control panel placement to minimize physical strain. The new workstation must be designed to accommodate a range of body sizes and shapes, and it should also be easy to adjust to fit individual needs and preferences. The system provides real-time postural feedback that helps in the prevention of MSD. MSDs include temporary or permanent injuries in the inner body parts, e.g., muscles, tendons, joints, and spinal disks [84]. Workers in different sectors also face MSDs that can affect the quality of life, productivity, medical costs, and work efficiency [85].

Recommended modifications include:

1) Adjustable armrests and seat height.
2) Optimized tool and control panel positioning.
3) Improved lumbar support for prolonged sitting.

5. CONCLUSION

5.1. SUMMARY OF KEY FINDINGS

DHM simulations confirm that ergonomic interventions can significantly improve CNC operators' posture and reduce WMSDs. The study is aligned with industry standards, offering practical insights for enhancing worker well-being and productivity. It addresses musculoskeletal disorders among CNC machine operators through ergonomic assessments, intervention strategies, and workstation redesign, and identifies issues like high forces and static awkward postures, proposing adjustable features and optimized control panel placement to minimize physical strain [82]. In conclusion, the study highlights the crucial role of ergonomics in addressing the challenges faced by CNC machine operators and emphasizes the need for ongoing evaluation and refinement of workplace design to ensure a safe and productive working environment. Work-from-home environments have led to increased reports of musculoskeletal discomfort and eye strain, frequently stemming from suboptimal setups where employees are constantly looking downwards at their laptop screens, leading to neck problems [86]. The rapid shift to remote work during the COVID-19 pandemic, without adequate time to establish ergonomic workstations, has exacerbated these issues [87]. It is essential to identify telework-related risk factors for musculoskeletal disorders and address them with timely preventive measures tailored to each remote workstation's risks and individual workers' needs [88]. This approach encompasses workstation design, work habits, and the psychosocial aspects of telecommuting. Thus, by ensuring proper support and alignment, the risk of strain and injury can be reduced [89].

5.2. PRACTICAL IMPLICATIONS FOR CNC WORKSTATION DESIGN

Incorporating ergonomic principles into workstation design enhances worker safety and efficiency. These enhancements have broader implications for companies, leading to improved productivity, product quality, and competitiveness [21]. It has been shown that improvements to workstations have led to a 40% drop in reports of pain, with even greater results in areas where improvements were made [90]. By tailoring workstations to individual operators, physical discomfort and fatigue are reduced. This leads to fewer errors, improved concentration, and increased efficiency [5]. Therefore, interventions aimed at improving workstation ergonomics can lead to improved posture, reduced muscle strain, and decreased risk of musculoskeletal disorders [88]. Ergonomics improvements in workplaces contribute to preventing injuries, increasing productivity, and retaining employees [26]. The principles of ergonomics help design and arrange things in such a way that people interact with them most efficiently and safely [91].

5.3. LIMITATIONS OF THE STUDY

This study focuses on specific CNC tasks and does not consider variations in machine types and operator skill levels. The assessment of computer workstations, traditionally conducted in person, has seen a shift towards virtual methods [87]. This change presents challenges such as the need for standardization, the difficulty in assessing complex or combined exposures, and the limited availability of validated tools for remote evaluation. The study's limited sample size and reliance on self-reported data may introduce bias. Further research with larger, more diverse populations is needed to validate these findings.

5.4. FUTURE RESEARCH DIRECTIONS

Future studies should include real-time motion tracking and advanced biomechanical modeling to refine ergonomic assessments.

Long-term studies are needed to evaluate the sustained impact of ergonomic interventions on worker health. Further exploration of cognitive ergonomics and its influence on operator performance is warranted [92]. There is a growing demand for cost-benefit data of ergonomic improvements, and several examples show that the application of ergonomic principles has resulted in tangible benefits [93]. Future work could involve testing the DHM-optimized workstation design in real-world industrial settings to evaluate its impact on productivity and operator comfort [8]. Future research should address the need for standardized, validated tools for remote computer workstation assessments, as well as strategies for evaluating complex or combined exposures in virtual settings. By reducing

unnecessary injuries caused by bad posture working conditions, the research can prevent a human workforce in the long term [12].

Work-related musculoskeletal disorders can significantly impair workers' employment potential, posing a growing social challenge with substantial costs for businesses and so.

CONFLICT OF INTERESTS

None.

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