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Exploring the Impact of Factors on Upper Limb Functional Space and Operational Efficiency: A Theoretical Analysis

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ABSTRACT

Operators in transportation environments, such as aircraft cockpits and vehicle cabins, must perform high-precision tasks within constrained spaces. Understanding the factors impacting upper limb functional space and operational efficiency is essential for optimizing human-machine collaboration. This study follows PRISMA guidelines and systematically reviews literature from Scopus, Web of Science, and SpringerLink to examine the impact of posture, environmental conditions, and task demands. Results show that posture impacts functional space by affecting muscle load distribution, force transmission, and fatigue. Environmental conditions restrict visual input, joint mobility, and dexterity while influencing efficiency through vestibular perception, grip friction, and muscle activity. Task demands regulate interaction distance, movement strategies, and muscle load, optimizing efficiency via task complexity and coordination. Task demands determine optimal posture under specific conditions, while environmental factors modulate muscle load and strategies. Proper posture adjustments mitigate environmental constraints, whereas improper posture increases strain and task difficulty. These findings provide insights for optimizing cockpit and cabin ergonomics. Future research should explore individual differences and biomechanical factors to enhance ergonomic design and human-machine collaboration.

Keywords: Upper limb, Functional space, Operational ergonomics, Human-machine collaboration, Transportation human factors

INTRODUCTION

With the rapid advancement of industrial automation, aerospace, and human-machine interaction technologies, the accuracy and efficiency of control tasks have become increasingly important. In human-machine interaction processes, the functional space of the upper limb is a critical factor affecting operational efficiency. The upper limb functional space, defined as the task-effective movement area under specific operational constraints, is biomechanically bounded by the anatomical reachable workspace that describes maximum joint mobility ranges. The boundary of the reachable workspace is typically referred to as the reachable envelope or reachable surface. Since the reachable envelope provides a geometric visualization of the human body's reachability, it has been widely applied in system design involving reaching tasks (Selvan et al., 2020). A well-designed upper limb functional space and appropriate operating posture can effectively enhance operational efficiency, reduce error rates, improve comfort, and ultimately enhance overall task performance.

In practical applications, especially in environments such as aviation cockpits, operators frequently perform high-precision tasks where the range of upper limb movement and operational efficiency directly affect task completion speed, accuracy, and comfort. However, existing studies often analyse the impact of single factors on upper limb functional space and operational efficiency in isolation, neglecting how these factors interact. In highly dynamic and complex work environments, understanding these multi-factor interactions is crucial. For instance, during high-precision tasks in a confined cockpit, it is unclear whether operators adopt different posture adjustment strategies under varying task loads.

Therefore, this study aims to explore the influence of key factors—including posture, task characteristics, and environmental conditions—on upper limb functional space and operational efficiency. It further examines how these factors shape operational performance by affecting joint kinematics, movement trajectories, and task execution strategies, providing both theoretical and practical insights for optimizing human-machine interaction. These findings will serve as a theoretical foundation and design reference for increasingly complex and technologically integrated work environments in transportation and aerospace systems, ensuring that operators can perform tasks efficiently and comfortably.

METHODOLOGY

This study strictly follows the PRISMA guidelines and conducts a systematic literature search in three major databases: Scopus, Web of Science, and SpringerLink, focusing on research related to upper limb functional space and operational efficiency in the past decade. The search strategy includes predefined exclusion criteria, filtering out medical research, robotics kinematics studies, lower limb movement research, and review articles. The specific search terms include "Upper Limb Functional Space", "Reachable Workspace", "Reachability" "Manipulation Efficiency", "Performance" and "Ergonomics".

In the literature screening phase, an initial selection is made based on article titles and abstracts to exclude studies irrelevant to the research objective. Full-text screening is then performed to ensure that the selected studies specifically address the influence of posture, task characteristics, and environmental conditions on upper limb functional space and operational efficiency. The final set of core studies is used for subsequent theoretical analysis.

Through an in-depth summary and analysis of the screened core literature, this study identifies three key factors — posture, environmental conditions, and task demands — that influence upper limb functional space and operational efficiency. It further explores the interaction among these three factors to provide deeper insights into their combined effects.

IMPACT OF POSTURE, ENVIRONMENTAL CONDITIONS, AND TASK DEMANDS ON UPPER LIMB FUNCTIONAL SPACE (ULFS) AND OPERATIONAL EFFICIENCY

Impact of Posture on Upper Limb Functional Space (ULFS) and Operational Efficiency

Different body and visual postures directly affect the size of the functional space, with the fixed position of the eyes and shoulder joint adjustment capability playing key roles. Research on reachable functional space under various body and visual postures indicates that, in gaze fixation posture, functional space is restricted by the fixed eye position, whereas in non-gaze fixation conditions, the freedom of head and trunk movement allows for adjustments in shoulder joint position, thereby expanding the functional space (Liu et al. 2023). Additionally, Nadon et al. found that at 70 different hand positions, higher hand positions resulted in stronger shoulder muscle activation. High-position hand exertion muscle activation rates were 192% higher than low-position exertion, highlighting the importance of scapular and hand stabilizing muscles in maintaining and expanding functional space (Nadon et al., 2016).

Posture affects operational efficiency by influencing muscle load distribution, force transmission efficiency, and fatigue levels. Different hand positions and forearm postures impact muscle engagement. Studies have shown that the highest upward/downward exertion positions occur at 0 degrees above the head and 60 degrees at the shoulder, with maximum operating force observed when the control stick is horizontal (La Delfa et al., 2019). Comparing grip strength across different upper limb postures, findings suggest that standing posture allows for better core muscle engagement to stabilize the upper limb, resulting in a grip strength approximately 10% higher than in a seated position. Conversely, wrist and forearm flexion at 45 degrees leads to excessive muscle contraction or restriction, reducing grip strength by about 15% (Jain et al., 2019). Another study found that in a standing posture, upper limb discomfort decreased, typing speed increased ($p < 0.0001$), and lower trapezius muscle activity exhibited higher variability than in a seated posture (68% higher, $p = 0.003$), facilitating dynamic muscle control and reducing localized muscle fatigue, thereby improving operational efficiency (Fedorowich & Côté, 2018).

Impact of Environmental Conditions on ULFS and Operational Efficiency

Environmental conditions impact functional space by restricting visual information, constraining joint movement range, and reducing hand dexterity. Visual constraints affect the extent of functional space; in visually restricted environments, core upper limb functional space is limited to approximately 67.58°, whereas in visually unrestricted conditions, individuals can freely adjust their head and trunk, significantly expanding functional space to around 180° (Liu et al., 2023). Additionally, in scenarios requiring exoskeletons, shoulder rotation range is affected, reducing functional space to only 68.09% of its full potential ($0.236m^3$) (Castro et al., 2019). Moreover, wearing protective gloves enhances operational safety but reduces finger dexterity and fine motor control, indirectly limiting upper limb functional space (Zare Bidoki et al., 2022).

Environmental factors influence upper limb operational efficiency by altering vestibular perception, hand friction, and muscle activity patterns. Under different gravity environments, the vestibular system's perception accuracy varies, thereby affecting upper limb operational efficiency. In a low-gravity (0.5G) environment, the Position Variability Metric increases by 39.6% ($p = 0.001$), while in a high-gravity (1.33G) environment, the Position Variability Metric decreases by 18.3% ($p = 0.005$). This is due to gravity affecting vestibular signal intensity—compared to low gravity, high gravity enhances vestibular signals, improving perception ability and stabilizing control (Rosenberg et al., 2018). However, as gravity further increases, high gravity leads to an over-perception of roll angles, resulting in over-adjustments. In 1.5G and 2G environments, control accuracy decreases by 26% and 45%, respectively, compared to 1G (Clark et al., 2015). Additionally, a humid environment affects upper limb operational efficiency by altering friction and skin adhesion. Research has found that in finger operation tasks, short-term and long-term immersion reduced task performance by 11% and 8%, respectively ($p < 0.001$), while in bimanual coordination tasks, short-term immersion increased task time by 15% ($p = 0.005$) (Ray et al., 2017). Different ambient temperatures also affect upper limb operational efficiency by influencing hand muscle activity and grip friction. Studies have shown that in a low-temperature environment (5 °C), maximum grip strength decreases by 22.4% compared to normal temperature (25 °C) ($p < 0.0001$), whereas in a high-temperature environment (45 °C), grip strength increases by 8.3% compared to normal temperature ($p < 0.0001$). This is because high temperatures enhance muscle activity and increase nerve conduction velocity, leading to reduced hand dexterity (Ramadan, 2017).

Impact of Task Demands on ULFS and Operational Efficiency

Task demands shape upper limb functional space by regulating interaction distance, altering movement strategies, and influencing muscle load. Different task requirements affect interaction distance control, thereby impacting functional space. For example, studies have found that reachable space(RS)-The maximum anatomical range for limb endpoint positioning-is larger than personal space(PS), which refers to the range where proximity causes discomfort, but smaller than interpersonal space (IPS), which represents the most comfortable interaction distance for social interactions (RS: 91.36cm, IPS: 116.35cm, PS: 53.47cm). This is because individuals tend to maintain a larger space for social interaction tasks than for reaching tasks, while personal safety needs result in a smaller space range. However, when tasks involve multisensory stimulation (visual-tactile integration), functional space undergoes significant expansion—Multisensory Interaction Space (MIS) reaches 127.40cm, exceeding conventional IPS boundaries (Geers & Coello, 2023).

Task demands also alter upper limb functional space by influencing movement strategies and body control methods. Research has found that standardized tasks exhibit a larger and more stable functional space than free tasks ($RW = 91.0\% \pm 8.1\%$ vs. $80.0\% \pm 22.6\%$, $p = 0.006$). This is because task requirements influence upper limb space utilization, and in unguided conditions, different individuals adopt varied movement strategies, leading to changes in functional space (Clément et al., 2018). Additionally, task demands affect functional space by altering muscle load. At high working heights, trapezius and anterior deltoid electromyographic activity increases, subjective fatigue ratings peak, and functional space decreases (Lee et al., 2015).

Task demands influence operational complexity, arm movement range, and muscle coordination patterns, thereby regulating operational efficiency. Research has found that task complexity directly impacts performance. For example, when using tools (instead of direct hand use) to perform tasks, increased movement planning and muscle coordination complexity significantly reduce task completion time ($p < 0.001$). In 2D image tasks, fisheye image perspective tasks show higher accuracy but take longer to complete ($p < 0.01$), indicating that visual distortion may aid target recognition but increases movement planning burden (Batmaz et al., 2017). Another study found that individuals required to undergo upper limb strength training exhibited higher task execution efficiency due to enhanced mobility and reduced muscular asymmetry (Zawadka, 2024). Furthermore, task demands influence upper limb operational efficiency through different arm reach ranges. Studies have found that thrust tasks perform best when the arm is partially extended, with maximum power increasing by approximately 24% ($p < 0.001$), while pull tasks perform best when the arm is fully extended, with maximum power increasing by approximately 29% ($p < 0.001$) (Calé-Benzoor et al., 2016).

Interaction Between Task, Environment, and Posture and Human Factors Implications

Task demands determine the optimal posture and environmental adaptation, affecting functional space and operational efficiency. In thrust tasks, a partially extended arm posture yields the highest efficiency, whereas in pull tasks, a fully extended arm posture is most effective. When the arm is fully close to the body, the power output for both task types decreases by 18–22% ($p < 0.001$) (Calé-Benzoor et al., 2016). Additionally, high-load exercises enhance fine motor control of the non-dominant hand by 7%, but reduce hand dexterity ($p < 0.05$) (Lantis et al., 2024). Maintaining a stable posture is essential for reducing muscle fatigue in precise tasks such as adjusting instrument panels, whereas force-intensive tasks like joystick manipulation are more affected by movement. Therefore, the control interface spatial configuration (depth, height) should be optimized based on biomechanical kinematic thresholds. Specifically, the interface layout should align with the optimal elbow flexion angle to reduce unnecessary muscle load, improve movement efficiency, and optimize the ergonomic layout of the cockpit.

Environmental conditions influence task execution methods by regulating muscle load and fatigue accumulation. Ramadan (2017) found that grip strength in high-temperature environments is 8.3% higher than in normal conditions, whereas in low-temperature environments, maximum grip strength decreases by 22.4%. Therefore, during task execution in high-temperature environments (e.g., aircraft cabins or prolonged exposure to heat), muscle output may temporarily increase, but prolonged exposure leads to fatigue accumulation. In cold environments, such as ground operations in aviation, precision tasks are more susceptible to cold-induced delays in reaction time, necessitating appropriate thermal control in hand operation areas. Furthermore, in humid environments, fine motor tasks exhibit significantly decreased performance (finger task completion time decreased by 11%, $p < 0.001$; bimanual coordination task time increased by 15%, $p = 0.005$), whereas large-scale push-pull tasks are less affected (Ray et al., 2017).

Postural adjustments can compensate for environmental effects, but task demands may lead to posture-environment mismatches. In visually restricted environments, such as virtual reality (VR) settings or laterally offset displays, task completion time increases ($p < 0.001$), but accuracy remains unaffected (Batmaz et al., 2017). This suggests that head and body adjustments can expand functional space and compensate for environmental effects, but prolonged lateral displacement may cause neck fatigue, necessitating reduced body posture constraints. Lee et al. (2015) found that a combination of a high workbench and high component box results in the highest muscle fatigue and subjective fatigue ratings ($p < 0.001$), whereas a low workbench and low component box setup reduces muscle load, making it more suitable for long-duration repetitive hand operations. This further underscores the critical role of posture-perception integration in optimizing spatial adaptability under restricted viewing conditions. By integrating the principles of workstation modular design (Lee et al., 2015) with findings on visual displacement tolerance (Batmaz et al., 2017), interface configurations can be adjusted to reduce operational fatigue and enhance visual interaction efficiency. High-load tasks require optimal posture support, but confined spaces and environmental constraints increase muscle strain and task difficulty. Therefore, in compact cockpit environments, optimizing control interface layouts to align with operational task requirements is crucial.

CONCLUSION

This study systematically explores the impact mechanisms of posture, environmental conditions, and task demands on upper limb functional space and operational efficiency. It provides an in-depth analysis of multi-factor interactions and reveals their complex relationships. The findings indicate that posture affects the size of functional space and the level of operational efficiency by influencing muscle load distribution, force transmission efficiency, and fatigue levels. Environmental conditions directly impact functional space by restricting visual information, limiting joint mobility, and reducing hand dexterity while also affecting upper limb operational efficiency through changes in vestibular perception, hand friction, and muscle activity patterns. Task demands influence upper limb functional space by regulating interaction distance, operational strategies, and muscle load, while optimizing operational efficiency by adjusting task complexity, arm movement range, and muscle coordination patterns.

Additionally, the study reveals that task demands determine the optimal posture for a given environment, while environmental conditions modulate muscle load and operational strategies to influence task performance. Proper posture adjustments can compensate for environmental effects, but inappropriate postures may increase muscle load and task difficulty. Therefore, optimizing control interfaces and workspace layouts is crucial for improving long-term operational efficiency.

Future research should further explore individual differences, anthropometric factors, and additional interaction mechanisms to comprehensively optimize cockpit and workstation designs, enhancing operator performance and comfort in complex interactive scenarios.

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