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Embodiment at Work: A Framework for Human–Technology Interaction in the Future Workplace

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ABSTRACT

Emerging technologies are reshaping work, with tasks increasingly mediated by remote, robotic, and immersive systems. As teleoperation, exoskeletons, and hybrid collaboration tools spread, an underexamined issue remains: how do operators feel embodied in these systems? The sense of embodiment - ownership, agency, and self-location - shapes performance, learning, and well-being, yet it is weakly theorized for applied work. Without a clear framework, systems risk optimizing efficiency over human experience, undermining usability, ergonomics, and inclusion. This paper positions embodiment as a central construct for teleoperated and hybrid work. We synthesize three literatures - (i) perceptual studies of multisensory congruence, (ii) kinesthetic learning on haptic/proprioceptive support for skill acquisition, and (iii) human-factors research on workload and safety - arguing that embodiment links psychological experience to organizational outcomes. We propose a multilayered framework: perceptual (sensory congruence), motor (kinesthetic alignment between operator and device), and social (co-presence, trust, and inclusion in distributed teams). We illustrate implications for surgery, industrial teleoperation, and hybrid setups; outline testable hypotheses and methods (e.g., cross-modal congruency, motion analysis, presence measures); and derive design guidance for adaptive control, wearable interfaces, and immersive platforms that support inclusive, ergonomically sustainable workplaces.

Keywords: Human–technology interaction, Future of work, Embodiment, Ergonomics, Teleoperation, Kinesthetic learning, Hybrid collaboration, Human factors

INTRODUCTION

Across industries, the future of work is being reshaped by emerging technologies such as robotic teleoperation, wearable exoskeletons, and immersive collaboration platforms. These systems promise efficiency, safety, and scalability in fields ranging from remote surgery to industrial maintenance and hybrid education. Yet, as the locus of work increasingly shifts from direct physical engagement to technologically mediated interaction, a critical question arises: how do humans experience embodiment when working through these systems?

The *sense of embodiment* refers to the cognitive and perceptual experience of ownership, agency, and self-location with respect to one's body or a surrogate (Falcone et al., 2023). Research in cognitive science and virtual reality has demonstrated that embodiment can enhance presence, task performance, and learning outcomes (Kilteni et al., 2012, Sanchez-Vives and Slater, 2010, Slater, 2009, Falcone et al., 2024, Van Erp et al., 2022). However, most of this work remains situated in laboratory studies or entertainment applications. By contrast, the integration of embodiment into ergonomics and human factors research has been limited, often focusing on metrics such as workload, fatigue, and safety (Hart and Staveland, 1988, Maravita and Iriki, 2003) without explicitly considering how embodied experience mediates human-technology interaction (Falcone et al., 2022, 2024).

This gap is consequential. If work systems are designed solely around efficiency and output, without attention to the quality of human experience, they risk producing environments that undermine usability, inclusivity, and well-being. A surgeon teleoperating robotic instruments, for instance, may experience misalignment between motor intention and visual feedback, increasing cognitive load and error potential (Pratt and Williamson, 1995). Similarly, a remote worker participating in a hybrid meeting may lack social embodiment cues - such as gaze and turn-taking - that signal inclusion and trust within a team (de Vignemont, 2018). In both cases, performance and organizational outcomes hinge on more than technical specifications; they depend on how workers embody the systems they use.

This paper argues that embodiment should be treated as a structural factor in the future of work, alongside traditional ergonomic concerns. We propose a multi-layered conceptual framework of embodiment in work settings that includes (1) perceptual embodiment, or the sensory congruence that supports presence and effectiveness; (2) motor embodiment, or the kinesthetic alignment that enables skill transfer and reduces physical strain; and (3) social embodiment, or the collaborative dimension that fosters trust and inclusion in distributed teams. By situating embodiment at the intersection of human factors, kinesthetic learning, and immersive systems research, we provide a roadmap for both theorizing and empirically testing its role in shaping the future workplace.

We begin by surveying related work across embodiment, kinesthetic learning, and human factors, then propose a unified framework with perceptual, motor, and social layers. We translate the framework into hypotheses and design guidance for teleoperation, exoskeletons, and hybrid collaboration, and conclude with implications, limitations, and avenues for future research.

BACKGROUND AND RELATED WORKS

Embodiment in Virtual and Immersive Systems

Research on embodiment in cognitive science and virtual reality has established ownership, agency, and selflocation as core components of the embodied self (Kilteni et al., 2012, de Vignemont, 2018, Falcone et al., 2022). Classic illusions demonstrate that temporal and spatial congruence between seen and felt events can re-map body representation (e.g., the rubber-hand paradigm), while contemporary VR studies show that synchrony, low latency, and coherent multisensory cues strengthen presence and influence behavior (Maravita and Iriki, 2003, Slater, 2009, Sanchez-Vives and Slater, 2010). Within immersive systems, embodiment is not merely an epiphenomenon of display fidelity; it depends on cross-modal alignment, visuomotor contingency, and stable sensorimotor predictions that jointly support a sense of being able to act through a surrogate body or viewpoint.

Despite this progress, much of the literature remains oriented toward laboratory demonstrations, therapeutic applications, or entertainment contexts, with comparatively fewer treatments of applied work settings. For example, presence and ownership are seldom linked to task-critical outcomes such as precision, error recovery, or training transfer in safety and time critical environments. Moreover, widely used measures of presence and embodiment (Sanchez-Vives and Slater, 2010, Kilteni et al., 2012) are rarely integrated with ergonomics metrics or organizational key performance indicators (KPIs), limiting actionable guidance for engineering and operations.

Kinesthetic Learning and Motor Control

Parallel lines of work in motor control and kinesthetic learning highlight the importance of proprioceptive and haptic channels for skill acquisition and performance. Internal models and efference-copy mechanisms underpin predictive control, enabling humans to estimate dynamics and compensate for delays or disturbances; such mechanisms are central when interacting with tools, robots, or wearables that alter the operator–world coupling Boaventura and Buchli (2016). In human–robot systems, controller *transparency* (the degree to which the device allows the user's intended motion and forces to pass unimpeded) is a key determinant of precision, effort, and learning. Design levers include impedance/admittance tuning, motion scaling, and gravity compensation (Pratt and Williamson, 1995, Yang et al., 2011, Dos Santos et al., 2022).

Kinesthetic guidance and haptic augmentation can accelerate early learning, shape movement trajectories, and reduce corrective submovements, but benefits may depend on matching assistance to task phase and user proficiency. In exoskeleton contexts, anthropometric fit and load-sharing influence both performance and fatigue, underscoring the need to jointly consider biomechanics and control (Just et al., 2018, Dos Santos et al., 2022). Yet, connections between these kinesthetic constructs and higher-level constructs like agency or body ownership are still under-specified in applied domains, leaving open questions about how motor alignment translates into perceived control and durable skill transfer.

Human Factors and Ergonomics for Teleoperation and Hybrid Work

Human factors research offers mature tools for assessing workload, fatigue, safety, and usability (e.g., NASA–TLX) and has a long history in teleoperation and supervisory control (Hart and Staveland, 1988, Roth and Latoschik, 2020, Hoffmann et al., 2018). Traditional evaluations, however, seldom treat embodiment as a mediating construct that links interface properties to outcomes such as accuracy, error recovery, inclusion, and training efficiency.

In telemanipulation, for instance, latency, registration error, and controller impedance affect both cognitive load and precision (Almeida et al., 2020), but their effects on ownership, agency, or presence are rarely measured alongside performance. Similarly, in hybrid collaboration, social presence and participation equity are central to team effectiveness, yet many systems under-provide gaze, deictic pointing, or floor-control cues that scaffold coordination (Slater, 2009).

Bridging these perspectives suggests a more complete account: perceptual congruence (timing, registration, crossmodal redundancy) and motor alignment (transparency, scaling, fit) condition the operator's embodied experience, which in turn shapes workload, precision, and safety (Nostadt et al., 2020, Toet et al., 2020, Falcone et al., 2023); social embodiment affordances (visibility parity, legible gaze/turn-taking, identity cues) condition trust, inclusion, and coordination. The literature to date provides the building blocks - presence and embodiment in VR (Sanchez-Vives and Slater, 2010, Kilteni et al., 2012, Slater, 2009, Falcone et al., 2022), tool/body-schema extension (Maravita and Iriki, 2003, Nostadt et al., 2020), workload and ergonomics (Hart and Staveland, 1988, Almeida et al., 2020), and transparency in robot control (Pratt and Williamson, 1995, Van Erp et al., 2022) - but lacks an integrative framework that treats embodiment as a first-class variable connecting interface design to organizational outcomes. This paper addresses that gap by articulating a multi-layered model (perceptual, motor, social) and outlining testable pathways to validate it in applied future-of-work scenarios.

IMPLICATIONS FOR RESEARCH AND PRACTICE

Testable Hypotheses and Measures

Building on the proposed framework, we articulate three hypotheses that render embodiment falsifiable in applied work settings and specify corresponding measurement strategies.

H1 (Perceptual—Cross-modal congruency). When multisensory signals are temporally and spatially congruent, participants should exhibit a larger cross-modal congruency effect (CCE) — the difference in reaction times and errors between incongruent and congruent visuo–tactile trials—which is expected to covary with presence and with objective task performance (Verhagen et al., 2020, Falcone et al., 2024, Falcone and Taylor, 2024). Operationally, congruence can be manipulated via motion-to-photon latency (low vs. high), visual–haptic registration (aligned vs. offset), and field of view (restricted vs. wide). Dependent variables include CCE magnitude ($RT_{incongruent}$–$RT_{congruent}$) and error rate, along with task key performance indicators (time-to-completion, precision, count of slips/misses).

H2 (Motor transparency—Impedance matching). In telemanipulation and exoskeleton use, lower impedance mismatch and higher controller transparency should improve spatial accuracy and movement efficiency while reducing perceived workload (Karavas et al., 2015, Parsa et al., 2022, Forouhar et al., 2024, Lieftink et al., 2024). Transparency can be tuned through admittance/impedance parameters, motion scaling, and gravity compensation. Outcomes include endpoint RMS error, path length, normalized jerk (smoothness), correction count, and peak interaction forces; subjective workload can be captured with validated surveys, such as the NASA–TLX. Short calibration blocks can stabilize performance before data collection.

H3 (Social presence—Participation and recovery). Affording social embodiment cues (e.g., gaze indicators, turn-taking scaffolds, and visibility parity between remote and co-located participants) should yield more equitable participation and faster recovery from coordination errors (Xu et al., 2017, Jing et al., 2021). Independent variables include availability of gaze/pointing cues, presence of lightweight floor control (e.g., speaking queue), and parity of views/audio. Dependent variables include talk-time balance (e.g., Gini coefficient), interruption rate, timeto-recover after slips, and perceived inclusion/co-presence. Nevertheless, telepresence remains an active area of inquiry, and current solutions do not consistently achieve high-fidelity co-presence (Van Dijk et al., 2011, Biehl et al., 2015).

Measures and analysis. Perceptual embodiment is probed with standard CCE paradigms and presence/agency questionnaires (de Vignemont, 2018, Peck and Gonzalez-Franco, 2021); motor embodiment with motion-capture kinematics (path length, smoothness), controller logs, and NASA–TLX (Hart and Staveland, 1988); social embodiment with audio/video analytics of turn-taking and inclusion scales. Mixed-effects models with random intercepts for participant (and task item, where applicable) are appropriate for repeated-measures designs, report effect sizes, confidence intervals, and pre-register primary contrasts (Peck and Good, 2023, Wu and Chen, 2024). Where design changes target inclusivity, non-inferiority tests can verify that performance remains within acceptable margins relative to baselines.

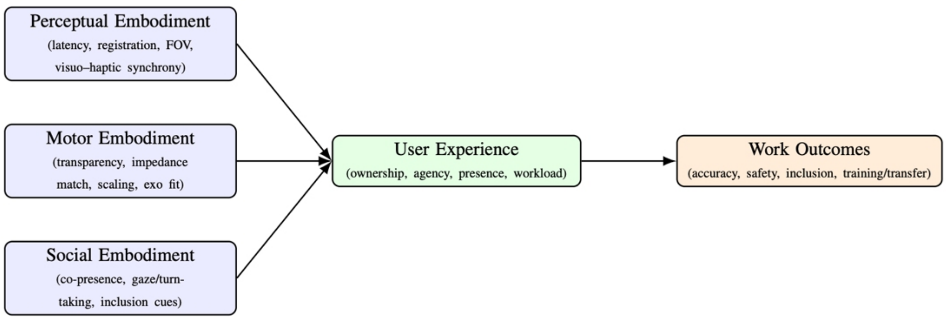

Figure 1: Conceptual framework: perceptual, motor, and social embodiment feed into user experience, which in turn shapes organizational/work outcomes.

DESIGN GUIDELINES

The framework suggests concrete levers for designing embodied work systems. For *perceptual embodiment*, interfaces should minimize end-to-end latency and visual–haptic misregistration, expose quick calibration to prevent drift, and provide multimodal redundancy so that salient events are co-signaled visually, haptically, and/or acoustically (Lieftink et al., 2024). Adjustable field of view and motion gain can help sustain presence without overloading vestibular cues (Falcone et al., 2022; 2024).

For *motor embodiment*, controllers should adapt transparency to task phase, such as higher assistance and damping during coarse transport, and lighter impedance with motion scaling during fine manipulation (Agarwal and Deshpande, 2019). Exoskeletons require anthropometric fit and load-sharing that limit peak forces and cumulative strain; ergonomics indicators (e.g., path inefficiency, grip-force spikes) should be surfaced to operators and supervisors. Routine assessment of workload can trigger micro-breaks or automatic controller retuning when fatigue rises (Mauri et al., 2019, Chung et al., 2025).

For *social embodiment* in hybrid teams, systems should enforce visibility parity (remote participants see what in-room participants see and vice versa), make gaze and pointing cues legible to support joint attention, and provide lightweight turn-taking scaffolds that discourage interruption cascades while preserving spontaneity (Xu et al., 2017, Altmann et al., 2025). Stable identity and status cues (e.g., role, speaking queue position) improve attribution and trust.

Taken together, these practices operationalize embodiment as a first-class design target. By instrumenting perceptual congruence, motor transparency, and social presence alongside conventional human-factors metrics, organizations can link interface choices to safety, performance, training transfer, and inclusion, and iterate toward ergonomically sustainable, human-centered workplaces.

Table 1: Embodiment layers, example design levers, and expected outcomes in work settings.

Layer	Design Levers (Examples)	Expected Outcomes
Perceptual	Latency, registration, FOV, haptic/visual synchrony, audio spatialization	Presence, lower error rates, reduced cybersickness, faster hand–eye coordination
Motor	Admittance/impedance tuning, gravity compensation, exo fit, motion scaling	Productivity, skill transfer, reduced fatigue, safer exertion profiles
Social	Avatar fidelity, gaze cues, turn-taking tools, inclusion affordances	Trust, team cohesion, equitable participation, reduced isolation

DISCUSSION

This paper positions embodiment as a structural factor in the design and evaluation of technology-mediated work. By articulating perceptual, motor, and social embodiment as interdependent layers, we link concrete interface properties (e.g., latency, registration, controller impedance, visibility parity) to experiential states (ownership, agency, presence) and, ultimately, to organizational outcomes (accuracy, safety, inclusion, training transfer). In doing so, we synthesize strands of research that have often progressed in parallel—embodiment and presence in immersive systems, tool-induced body schema extension, transparency and impedance in telemanipulation, workload and safety in ergonomics, and advance a mechanism-centered account that is amenable to empirical testing.

Conceptualizing embodiment as a mediator clarifies how interface manipulations propagate to performance and well-being. Perceptual congruence supports stable sensorimotor predictions that ground ownership and presence; motor alignment reduces error-corrective submovements and cognitive load by harmonizing human and device dynamics; social embodiment affords mutual intelligibility (e.g., gaze, turn-taking), which underwrites trust and equitable participation. The framework also suggests moderators: task phase (transport vs. fine manipulation), user proficiency, environmental complexity, and organizational norms (e.g., meeting etiquette) likely shape the strength of embodiment–outcome links. Importantly, the layers can trade off or interact—for example, aggressive motion scaling may aid precision (motor layer) while degrading visuo-proprioceptive consistency (perceptual layer); conversely, rich social cues can mitigate minor perceptual imperfections by stabilizing coordination.

Operationalizing embodiment requires jointly sampling subjective and objective measures. We advocate batteries that pair (i) CCE-based indices and presence/agency questionnaires for perceptual embodiment, (ii) kinematic and force metrics plus cognitive workload tests for motor embodiment, and (iii) participation analytics (talk-time balance, interruptions, recovery time) for social embodiment. Two validity concerns warrant attention. First, *manipulation checks*: record motion-to-photon latency and visual–haptic registration, log controller impedance/assistance, and verify availability of gaze/turn-taking cues; embodiment inferences are weak without such checks. Second, *ecological linkage*: triangulate lab tasks (e.g., CCE, path-following) with in-situ KPIs to ensure transfer to operational contexts. Mixed-effects models accommodate repeated measures and heterogeneous tasks, while non-inferiority tests are useful when inclusive designs must meet safety or productivity thresholds. Pre-registration and sharing of stimulus code, controller settings, and analysis scripts will improve reproducibility.

Treating embodiment as a design target yields practical levers for how systems are procured, configured, and taught in everyday use. On the perceptual side, teams should plan explicitly for latency and registration budgets, offer rapid calibration to prevent drift, and pair visual events with haptic and auditory confirmations so cross-modal cues reinforce one another. For motor embodiment, controller settings should adapt to task phase—providing more assistance and damping during gross transport, then easing impedance and enabling motion scaling for fine manipulation. Exoskeleton deployments also benefit from anthropometry-aware fitting and load-sharing policies, with simple ergonomics indicators tracking peak forces and cumulative strain; routine workload checks can then trigger short breaks or automatic retuning before fatigue accumulates. Social embodiment in hybrid teams calls for visibility parity between remote and in-room participants, legible gaze and pointing to anchor joint attention, and lightweight floor control to keep turn-taking orderly without throttling spontaneity. At the organizational level, acceptance testing should evaluate embodiment alongside traditional usability and safety criteria, and training curricula should scaffold operators from low- to high-embodiment conditions so that ramp-up time shortens and errors fall as proficiency grows.

Embedding embodiment metrics into workplace systems raises normative questions. Instrumentation that logs gaze, speech turns, or kinematics must respect privacy and avoid punitive surveillance. Inclusion-oriented features (e.g., turn-taking scaffolds) should not inadvertently disadvantage spontaneity or cultural communication styles. Exoskeleton and teleoperation deployments should consider accessibility and differing physical abilities, ensuring that embodiment benefits are not reserved for a narrow subset of workers.

CONCLUSION AND FUTURE WORKS

Embodiment is a structural determinant of safety, performance, inclusion, and learning in technology-mediated work. We proposed a three-layer framework—perceptual, motor, and social—that links interface properties (e.g., latency, registration, controller transparency, visibility parity) to experiential states (ownership, agency, presence) and, through them, to organizational outcomes. We also translated this framework into testable hypotheses and a measurement toolkit that pairs subjective indices (presence, agency, inclusion, workload) with objective signals (kinematics, controller logs, cross-modal congruency, and team-process analytics), enabling embodiment to be treated as an explicit design target. As a conceptual account, our approach has limits: thresholds for "sufficient" congruence or transparency are task- and population-dependent, and interactions among layers may entail trade-offs (e.g., motion scaling improving precision while degrading visuoproprioceptive consistency). Priorities for future work include quantifying inter-layer interactions (for example, whether social cues buffer moderate perceptual misalignment); establishing benchmark tasks and open datasets that link embodiment metrics to operational KPIs; studying longitudinal adaptation and skill transfer in real workplaces; and broadening participant populations and contexts. At the organizational level, procurement and certification should incorporate embodiment thresholds alongside usability and safety criteria to align incentives for human-centered, ergonomically sustainable systems.

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