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Designing Ergonomic Interventions in Socio-Technical Systems: A Cultural Perspective

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ABSTRACT

This review explores the critical role of cultural dimensions in designing ergonomic interventions within socio-technical systems (STS). Employing a systematic literature scan and thematic analysis, it synthesizes frameworks such as Human-Centered Design (HCD), Value Sensitive Design (VSD), and participatory co-design, highlighting their application in emerging technologies like AIoT, human-robot collaboration, and exoskeletons. The review underscores the significance of integrating gender and cultural considerations to enhance social inclusion and safety in diverse contexts. It further examines organizational culture's influence on safety practices and human factors in high-reliability industries, alongside ethical challenges posed by technology adoption, including privacy and digital trust. Through case studies on Industry 4.0/5.0 innovations, the review reveals tensions and opportunities in socio-technical transformations. Finally, it emphasizes inclusive design strategies promoting social sustainability and work inclusion, particularly for marginalized groups. The findings advocate for culturally attuned, ethically responsible ergonomic designs to advance socio-technical systems' resilience and inclusivity.

Keywords: socio-technical systems, cultural considerations, value sensitive design, ergonomic interventions, organizational safety culture, ethical implications, Industry 4.0, inclusive design

1. CULTURAL DIMENSIONS OF ERGONOMIC DESIGN IN SOCIO-TECHNICAL SYSTEMS

Socio-technical systems (STS) represent the intricate interplay among people, technologies, and organizational structures within work environments. Ergonomics plays a pivotal role in these systems by optimizing human well-being and overall system performance through tailored design interventions. By focusing on the fit between workers and their tasks, tools, and organizational contexts, ergonomic approaches contribute to enhanced safety, health, and productivity across diverse industries [1].

Cultural and contextual factors are fundamentally intertwined with the effectiveness of ergonomic interventions in STS. These encompass not only national and regional cultural norms but also workplace-specific social dynamics, gender roles, and organizational culture. For instance, Callari, T. C. et.al highlight the gender-specific perceptions of safety among women cyclists in Tehran, where informal social surveillance outweighs official enforcement in influencing security perceptions [2]. Similarly, in construction and manufacturing contexts, barriers related to gender and ethnicity shape adoption and interaction with technologies such as exoskeletons and collaborative robots [2; 4]. Organizational culture, especially related to safety and human factors, is another vital dimension, as Vink, L.-S., & Walzl, B. demonstrate through integrating occupational safety and operations management to foster a comprehensive safety culture [5].

Given the multifaceted influence of culture and context on ergonomics in STS, this review aims to provide an in-depth examination of cultural dimensions as they pertain to designing ergonomic interventions in complex socio-technical environments. The scope covers a broad range of relevant topics, including value-sensitive design, gender and cultural considerations, organizational safety culture, ethical issues in technology adoption, and emerging socio-technical narratives within Industry 4.0 and 5.0 frameworks.

Table 1 Frameworks for Ergonomic Interventions in Socio-Technical Systems.

Framework / Approach	Key Features	Example Application	Benefits	Challenges
Human-Centered Design (HCD)	User needs, iterative design	AIoT worker assistance	Improved acceptance	Requires stakeholder engagement
Value Sensitive Design (VSD)	Embeds ethics & values	AI-based safety systems	Ethical alignment	Value conflicts
Participatory Co-Design	Stakeholder-driven process	AR for maintenance	Inclusivity	Time-intensive
Goldilocks Work Paradigm	“Just right” job design	Rail driving ergonomics	Balances workload	Context-specific limits

Methodologically, the review employs a systematic literature scanning methodology combined with thematic analysis. Table 1 elaborate the details of potential frameworks for ergonomic interventions in socio-technical systems. This approach enables the synthesis of qualitative and quantitative findings from a diverse set of empirical and theoretical studies drawn primarily from recent high-impact publications. Such comprehensive analysis facilitates identifying prevalent challenges, best practices, and knowledge gaps related to cultural factors in ergonomic interventions across various sectors and technological contexts.

2. HUMAN-CENTERED AND VALUE-SENSITIVE DESIGN APPROACHES

Normal Human-Centered and Value-Sensitive Design (VSD) approaches are pivotal in shaping socio-technical systems that align with human values, ethical considerations, and operational needs. Value Sensitive Design emphasizes embedding human values throughout the design process, particularly in technologies that interact closely with humans such as AIoT (Artificial Intelligence of Things) systems, robotics, and assistive devices. Vernim et al. [6] demonstrated that applying VSD to AI-based worker assistance systems in manufacturing helps address ethical issues arising from Industry 4.0 technologies by systematically incorporating human values, thus enhancing safety and acceptance.

Participatory co-design processes further enhance inclusivity and relevance by engaging diverse stakeholders. Padovano et al. illustrated this through the development of an Augmented Reality (AR) tool for maintenance technicians, where iterative user interviews and design thinking cycles prioritized well-being, skill development, and safety, ensuring the tool met real operator needs [7]. Babapour Chafi et.al reinforced this by applying Cognitive Work Analysis to redesign para-sport systems via multi-staged participatory methods, resulting in socio-technical interventions that recognize complex interdependencies within human and system factors [8].

The Goldilocks Work Paradigm, as introduced by Naweed et al., offers a theoretical framework for designing “just right” jobs, particularly in highly sedentary and inflexible roles such as rail driving [9]. It integrates system thinking, participatory ergonomics, and risk management to

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tailor tasks and environments that optimize worker health and performance without compromising productivity.

Application of these human-centered design (HCD) principles also extends to human-robot collaboration (HRC). Sigcha et al. [10] and Callari et al. [11] developed ethical frameworks for collaborative manufacturing environments emphasizing psychological safety, organizational ethics, and responsible innovation . These frameworks address the paradoxical tensions inherent in integrating automated systems while preserving human autonomy and well-being.
Understanding human adaptation to novel technologies is critical. Gallagher et al. explored the phenomenology of writing with unfamiliar digital tools, uncovering challenges such as surveillance anxiety and situational awareness, which highlight the need for empathetic design that supports user adjustment and trust [12].

Moencks et al. [13] underscored the importance of considering contextual and hierarchical stakeholder perspectives in deploying Operator Assistance Systems, identifying cognitive demands and user reluctance as key considerations for effective human-technology integration.
In the domain of exoskeletons, Okunola et al. identified facilitators and barriers to adoption in construction, emphasizing ethical, social, and psychological risks. Their findings advocate for transparent communication, trust-building, and ergonomic appropriateness as critical factors in design and deployment [14].

Finally, Toorajipour et al. mapped value propositions within AIoT data ecosystems, highlighting customization and control dimensions that can inform human-centric business models to ensure value creation and capture centered on user and stakeholder needs [15].

3. CULTURAL AND GENDER CONSIDERATIONS IN ERGONOMIC INTERVENTIONS

Gender-specific ergonomic needs have emerged as critical considerations across multiple occupational domains, including transportation, healthcare, and construction. Khademi et al. conducted a laboratory experiment using virtual reality to understand women's safety perception as cyclists in Tehran, revealing that informal surveillance by the presence of people strongly enhances women's sense of security, while official police surveillance plays a minor role [2]. This highlights the nuanced societal attitudes towards safety and surveillance that influence ergonomic interventions for women, particularly in contexts where harassment is prevalent. Similarly, Al Salaheen et al. identified key barriers faced by women in construction, such as fear of heights and work-life balance challenges, showing that Industry 4.0 technologies like autonomous construction and advanced building materials can mitigate these issues to support women's career progression [16]. Table 2 summarized the cultural and gender influences on ergonomic design.

Table 2 Cultural and Gender Influences on Ergonomic Design

Context	Country	Cultural / Gender Factor	Ergonomic Implication
Cycling safety	Iran	Informal surveillance stronger than police	Women's sense of safety depends on social presence
Construction work	n.a	Fear of heights, work-life balance for women	Tech like autonomous machinery reduces barriers
Disability employment	Brazil	Ableism, policy gaps	Ergonomic redesign for accessibility

Cultural perspectives further deepen understanding of ergonomic design needs. Rocha, Alonso, and Silva examined employment barriers for people with disabilities in Brazil, emphasizing contextual, organizational, and personal challenges intertwined with societal ableism and

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communication obstacles [17]. They suggested that ergonomics and human factors are instrumental in creating accessible work environments and transforming disability representation. Callari, Curzi, and Lohse addressed human-robot collaboration in manufacturing, noting that ethical frameworks must account for psychological risks and organizational culture variations across European contexts, thus reinforcing that cultural factors shape ergonomic and technological adoption [16].

Studies also extend to informal and marginalized workers, incorporating cultural and social sustainability into ergonomic design. Gadekar, Sarkar, and Gadekar and Sigcha et al. explored health risks and work conditions of waste pickers and informal water vendors in Sub-Saharan Africa, revealing their exposure to injury, environmental pollutants, and social stigma [18; 10]. These findings call for culturally sensitive ergonomic interventions that consider the informal sector's unique socio-economic and environmental factors.

Spatial design research provides additional cultural and gender insights influencing ergonomic outcomes. Askarizad and He demonstrated how urban street furniture influences gendered social activity patterns in Iranian public spaces, noting men's greater use and advocating for designs that reduce visual integration to foster women's social participation [19]. Moreover, Vernim et al. proposed Value Sensitive Design (VSD) as a human-centric approach to AI-based worker assistance systems, implicitly embracing cultural and ethical values that accommodate diverse user needs [6].

4. ORGANIZATIONAL CULTURE, SAFETY, AND HUMAN FACTORS INTEGRATION

The intersection of occupational safety and health (OSH) with organizational management (OM) represents a critical domain for enhancing safety and operational outcomes in socio-technical systems. Hasle, Madsen, and Hansen identify a prevailing divide between OSH and OM due to conflicting logics wherein OSH focuses on risk mitigation and OM emphasizes efficiency [20]. This divide often results in OSH being relegated to a secondary status within operational contexts, limiting its potential impact on day-to-day safety practices. The authors advocate for an integrative institutional logic that aligns responsible and sustainable business practices with worker well-being, proposing synergies that enhance both productivity and safety through coconstitutive logics of risk and efficiency.

Safety culture plays a crucial role in influencing safety consciousness and safety citizenship behavior (SCB). Meng and Chan quantitatively demonstrate that organizational safety culture positively affects construction personnel's safety consciousness and SCB, with personnel engagement and social relationship exchange acting as mediators [21]. These findings highlight the importance of fostering strong interpersonal networks and active engagement to translate safety culture into observable safety behaviors.

In safety-critical sectors such as nuclear power, an integrative approach to human factors and safety culture is essential. Orikpete and Ewim review the mutual reinforcement of human factors, safety culture, and organizational and individual performance [22]. Their synthesis includes lessons drawn from major nuclear incidents such as Three Mile Island and Chernobyl, emphasizing communication, leadership, and error management as pivotal elements. This comprehensive integration is vital for creating resilient organizations capable of managing complex socio-technical risks.

In the forest policy domain, Arnould, Morel, and Fournier illustrate the efficacy of participatory Living Lab approaches in embedding forest owners into policy frameworks [23]. This collaborative model fosters acceptance and innovations that contribute to organizational and environmental sustainability, illustrating the role of stakeholder engagement in shaping safety and operational cultures in natural resource contexts.

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From a manufacturing perspective, Wang, Li, and Freiheit propose a comprehensive technology roadmap for intelligent welding systems grounded in human-cyber-physical systems (HCPS) [24]. This roadmap explicitly accounts for human factors integration, ensuring that advanced automation supports rather than supplants human operators, thus preserving safety and operational performance.

Evaluating human factors practices' maturity, Teperi et al. reveal varying degrees of human factors integration across aviation and railway companies [25]. Their study underscores gaps in systematic implementation, consistent evaluation, and organizational-level buy-in, which must be addressed to fully realize human factors' benefits in high-reliability industries.

5. TECHNOLOGY ADOPTION AND ETHICAL IMPLICATIONS

The incorporation of cutting-edge technologies such as Artificial Intelligence (AI), robotics, exoskeletons, and mobile health (mHealth) applications into socio-technical systems is accompanied by significant ethical and practical challenges. A key concern involves the ethical risks associated with AI and robotics deployment, notably in manufacturing and healthcare. Callari et.al developed a novel ethical framework for human-robot collaboration in manufacturing, emphasizing the importance of psychological safety, ethical awareness, and accountability during innovation processes [26]. This human-centric approach highlights organizational and societal governance beyond simple human-robot interactions, addressing risks inherent in Industry 5.0 transitions.

Trust and privacy are paramount challenges in technology adoption. Fuller et al. investigated robotic-assisted surgery and uncovered barriers related to clinician trust in automation, ergonomic discomfort, and disruptions caused by the built environment [27]. Their study also linked socio-economic status with perceptions towards these technologies, emphasizing the need for design guidelines that consider diverse human factors. Similarly, in the construction sector, exoskeleton technologies raise ethical concerns about informed consent and sensitive data collection, as well as social risks such as unequal access and sharing costs [28]. Users show varying trust levels between active and passive exoskeletons, with stronger trust towards passive variants, illustrating nuanced social acceptance dynamics.

Further, the digital trustworthiness of health-related mobile applications remains a concern. Galetsi, Katsaliaki, and Kumar found that although most mHealth apps for healthcare professionals include privacy policies, less than half are from credible sources, and relatively few employ advanced AI features. Ethical challenges here include maintaining user privacy, ensuring app reliability, and meeting expectations for intelligent features [29].

Inclusivity and social risks in technology adoption extend to informal sectors. Sigcha, et.al applied Social Life Cycle Assessment (SLCA) in informal recycling communities to understand socio-environmental impacts and emphasize stakeholder participation [10]. Their findings reveal challenges in boundary delineation, indicator adaptation, and data validation, suggesting that SLCA must be carefully tailored for informal systems to ensure social sustainability.

Surveillance anxiety emerges as a critical social risk in adopting novel digital tools. Gallagher, Meister, and Russell studied graduate students writing with unfamiliar digital tools in semi-public environments and identified situational awareness challenges and anxiety related to monitoring technologies [11]. These findings stress the importance of addressing psychological and social dimensions alongside technical considerations in technology integration.

Finally, the ethical challenges of emerging neuro-adaptive architectures highlight potential risks to privacy, equity, and autonomy in smart built environments [30]. This points to a broader

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imperative for participatory and empathic design practices to navigate complex ethical landscapes in emerging technologies.

6. SOCIO-TECHNICAL NARRATIVES IN INDUSTRY 4.0 AND 5.0

The evolution from Industry 4.0 towards Industry 5.0 introduces complex socio-technical narratives centered on automation, collaboration, and human augmentation. These narratives reflect ongoing tensions and paradoxes that shape the integration of advanced technologies in industrial and organizational contexts. Hearn et al. explore the diffusion of collaborative robots (Cobots) and uncover a predominant narrative focused on automation as a means of efficiency improvements at the firm level [30]. Their research reveals that cobot adoption tends to emphasize substitutive automation rather than genuine collaborative augmentation at the task level, thus framing socio-technical integration as a challenge requiring richer human-robot interactions beyond prevailing efficiency drivers.

Expanding on these themes, Callari et al. examine the complexities of implementing human-robot collaboration in manufacturing through the lens of Paradox Theory [16]. Their findings articulate paradoxical tensions such as automation versus augmentation and technical efficiency versus human well-being, which manifest across micro, meso, and macro organizational levels. They argue that the transition towards Industry 5.0 is not a linear process but a dynamic journey shaped by emergent tensions that demand adaptive and reflexive management practices.

At the operational level, McLean et al. utilize systems ergonomics frameworks to redesign para-sport systems, exemplifying how socio-technical interventions can generate new processes enhancing multiple system components. Such design approaches illustrate practical engagements with complex system ergonomics that align with the Industry 5.0 focus on human-centric and adaptive systems [30].

Complementing ergonomic and design-oriented narratives, Bouhmoud et al. develop the UniCCC, a novel unified classification system aimed at standardizing construction industry data within an increasingly international and digital collaboration context [31]. This addresses challenges in data heterogeneity and fosters sustainable digital ecosystems, reflecting the digital thread and standardization critical to Industry 4.0/5.0 advances.

Vink and Walzl contribute by redefining human performance within complex socio-technical systems, proposing a multi-layered framework that elevates human performance to a key performance indicator (KPI) [5]. Their approach fosters proactive system design that integrates individual variability, cultural dynamics, and organizational outcomes, directly supporting Industry 5.0 principles emphasizing sustainability, well-being, and resilience.

Technological implementations further illustrate these narratives. Wang et al. present an intelligent welding system framework from a human-cyber-physical systems perspective, underscoring the technical and human integration challenges faced in high-precision industrial settings [32]. Similarly, Askarizad and He explore urban furniture design promoting gender equality and social inclusion, highlighting socio-technical imaginaries that influence public space usability and inclusivity [19].

7. INCLUSIVE DESIGN FOR SOCIAL SUSTAINABILITY AND WORK INCLUSION

Inclusive design for social sustainability and work inclusion necessitates understanding and addressing the multifaceted barriers experienced by marginalized groups, particularly people with disabilities (PwD). Rocha et al. conducted a qualitative investigation into the employment barriers faced by PwD in Brazil, revealing interrelated contextual, organizational, and personal challenges [33]. These included insufficient public policies, pervasive ableism, urban

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inaccessibility, communication restrictions, organizational resistance, and inadequate qualification opportunities. Their findings emphasize the critical role of Ergonomics and Human Factors disciplines in developing accessible work environments and transforming societal representations concerning disability, thus fostering diversity and inclusion at workplaces.

Beyond employment, interventions in sports and community settings offer valuable insights into equity-focused inclusive design. Babapour Chafi and Cobaleda-Cordero applied a complex systems ergonomics framework to analyze and optimize a Para sport system [8]. Their multi-stage approach enabled the identification of interacting factors influencing system performance and guided design interventions that created new processes and improved existing components. This work extends systems ergonomics theory to support inclusion in sport, demonstrating the potential for similarly structured interventions to enhance equity and accessibility.

Community-led innovation further enriches inclusive design strategies. Bhattacharjya et al. explored frugal innovation in a developing country context through an adapted Quadruple Helix model involving academia, industry, government, and society [34]. Emphasizing co-creation with informal actors, their study highlights the importance of intermediary actors and trust-building mechanisms. Such participatory approaches ensure that innovations are contextually relevant, socially sustainable, and broadly empowering, especially in resource-constrained environments.

User experience research methodologies also contribute to social sustainability by facilitating stakeholder dialogue and participation. For example, Sassenou et al. introduced companion modelling as a participatory approach in energy transition planning for Mediterranean cities, immersing diverse stakeholders in co-design processes [35]. Similarly, Pedroso et al. systematically reviewed epidemiological studies on waste pickers, underlining the importance of including vulnerable informal workers in occupational health and social policy research [36].

8. CONCLUSION

This review underscores the significance of cultural factors in shaping ergonomic solutions within socio-technical systems. When looking at frameworks like Human-Centered Design, Value-Sensitive Design, and participatory co-design, it becomes clear that excellent ergonomics must go beyond just technological optimization to encompass social, cultural, and ethical issues. The collection of case studies demonstrates that gender roles, organizational safety culture, and cultural norms profoundly influence the adoption and acceptance of emerging technologies, including AIoT systems, exoskeletons, and human-robot collaborations. Moreover, integrating human elements into management practices has been shown to be essential for cultivating resilience and safety consciousness in high-reliability organizations.

The review found major ethical problems that need to be fixed in order to ensure that technology is adopted in a way that is socially responsible and open to everyone. These problems include fear of monitoring, privacy, digital trust, and fair access. These findings emphasize that socio-technical changes, particularly in Industry 4.0 and 5.0, require a shift to adaptive, reflexive, and human-centered methodologies that align efficiency with well-being.

This study suggests that ergonomics needs to serve as a cultural and ethical channel in socio-technical design, fostering inclusivity for marginalized groups, strengthening organizational resilience, and advancing social sustainability. Subsequent study should improve cross-cultural comparison studies, evaluate the enduring impacts of inclusive design solutions, and develop frameworks that integrate technology, ethics, and social equity. These methods will ensure that ergonomic practices enhance performance while concurrently strengthening the cultural and ethical foundations of socio-technical systems.

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