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Leveraging AI to Enhance Design Ergonomics: A Theoretical Framework and Future Applications

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Abstract
This paper presents a theoretical framework for integrating Artificial Intelligence (AI) into design ergonomics to enhance human–machine interaction. It demonstrates how AI contributes to data-driven ergonomic evaluation through technologies such as digital-twin modelling, computer vision, and wearable sensors. The study highlights AI's role in supporting iterative design processes, cognitive-load analysis, and the creation of intelligent, sustainable workplace environments. Ethical and social implications — including privacy, bias, and accessibility — are also discussed. From a human-centered design perspective, the paper envisions adaptive systems and standardization frameworks that promote innovation, efficiency, and comfort in industrial and workplace design. Ultimately, the framework positions AI as an enabling force that extends ergonomic assessment beyond traditional boundaries, fostering user-centric and ethically aligned design practices.

Keywords: *Artificial Intelligence; Design Ergonomics; Human-Centered Design; Digital Twin Modelling*

Tirer parti de l'IA pour améliorer l'ergonomie de la conception : cadre théorique et applications futures

Résumé

Cet article présente un cadre théorique pour l'intégration de l'intelligence artificielle (IA) dans l'ergonomie de la conception afin d'améliorer l'interaction homme-machine. Il montre comment l'IA contribue à l'évaluation ergonomique basée sur les données grâce à des technologies telles que la modélisation de jumeaux numériques, la vision par ordinateur et les capteurs portables. L'étude met en évidence le rôle de l'IA dans le soutien des processus de conception itératifs, l'analyse de la charge cognitive et la création d'environnements de travail intelligents et durables. Les implications éthiques et sociales, notamment en matière de confidentialité, de partialité et d'accessibilité, sont également abordées. Dans une perspective de conception centrée sur l'humain, l'article envisage des systèmes adaptatifs et des cadres de normalisation qui favorisent l'innovation, l'efficacité et le confort dans la conception industrielle et la conception des lieux de travail. En fin de compte, le cadre positionne l'IA comme une force motrice qui étend l'évaluation ergonomique au-delà des frontières traditionnelles, favorisant des pratiques de conception centrées sur l'utilisateur et conformes à l'éthique.

Mots-clés : *intelligence artificielle ; ergonomie de conception ; conception centrée sur l'humain ; modélisation de jumeaux numériques*

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1. Introduction

Leveraging Artificial Intelligence (AI) to enhance design ergonomics is acquiring increasing attention and relevance within Product Lifecycle Management (PLM) studies (Khani-Shekarab & khani-shekarab, 2021). Ergonomics focuses on making products, systems, and environment compatible with human needs and capabilities while ensuring convenience, safety, and comfort (Asan & Choudhury, 2021). In the context of AI, however, ergonomics now refers to ensuring compatibility between the human performer and the elements of a computer system when interacting with AI tools and devices to guarantee a process that is efficient and safe (Lu et al., 2024). Thus, design ergonomics represents the goal of shaping products and systems that respect and enhance human physical and psychological attributes and interaction with AI.

AI is expected to further revolutionize the future of design, transforming the way ergonomics is observed and practiced. With the rise and evolution of computer-aided design and generative design tools, ergonomic issues have been increasingly considered and are anticipated to gain even higher priority, since decisions on these issues are set very early in the design process. Moreover, with the arrival of post-COVID-19 hybrid work models, home office ergonomics is now more important while designing workspaces that fit these new and diversified modes of working and interacting. To keep pace with these significant transformations in design paradigm and content, an enhanced theoretical framework, grounded upon established theories of human–computer interaction and digital ergonomics, is proposed to augment ergonomics by embracing AI. The framework serves as a solid base upon which a variety of AI+ design ergonomics methods and solutions can be developed or formalized.

1.1. Rationale for AI in Design Ergonomics

The use of artificial intelligence (AI) in product and service establishments aims to provide users with a superior user experience while promoting physical and cognitive ergonomics. Ergonomics prioritizing user comfort has consequential advantages, including augmenting the adoption of products, enhancing customer satisfaction, driving market share growth, fostering product innovation and creativity, and boosting customer retention (Khani-Shekarab & khani-shekarab, 2021). Human-centered AI systems form the theoretical underpinning for employing AI to regulate and augment ergonomics within design practice. Such systems focus on the user, drawing on theories of cognitive load and interaction to systematically identify and reduce extraneous or increase essential load, which subsequently advances task completion (Lu et al., 2024). Following the selection of appropriate data-driven ergonomic metrics, corresponding strategies engage simulation/digital twin modelling and computer vision or wearable sensor analysis, the use of which remains valid throughout based on the human-centered perspective. Ergonomics differs today compared with prior paradigms, notably due to the rise of digital design and interaction media. Yet, it retains paramount relevance, with human-centered AI offering a complementary augmentation of ergonomic assessment and design. These dynamics provide an opportunity for the design community to proactively shape future integration, ensuring effects remain beneficial for users, the wider community, and the planet.

1.2. Defining Ergonomics in the Age of AI

Safety, productivity, technology, and the environment change continuously, yet ergonomics maintains its relevance as it defines the interaction among people, products, tools, and the environment, independent from specific technology. AI is a technology with significant implications for ergonomics, influencing how humans and machines interact and how designs and contexts are represented. AI-enhanced design encompasses methods for assessing and optimizing ergonomic performance, which is why the field retains its relevance today. AI will not replace ergonomics. On the contrary, it offers a chance to rethink and implement function and form while meeting the original ergonomics goal of people-centeredness and restoration.

Human-centredness and ergonomics are two widely used terms. Although both refer to product-user and system-user relations, ergonomics explicitly concerns comfort, productivity, and safety. The applicability of ergonomics to AI-augmented design depends on how people retain these characteristics. Scientific theories about human cognition, workload, and understanding can clarify how AI tools can preserve comfort, safety, and productivity. Human-centered Artificial Intelligence (HCAI) is another contemporary term. The HCAI concept emphasizes working with and understanding users and the environment, and when applied to design, it extends to considering the changing ways in which embodiments and concepts are occupied (Khani-Shekarab & khani-shekarab, 2021).

2. Theoretical Foundations

Modern design practice relies heavily on the creation and evaluation of 'physical' products, with the aim of detecting and minimizing cognitive and physical discomfort for end-users. In the age of evolving or immersive experience-oriented products, supporting comfort and acceptance via ergonomics remains complex and thus challenging for designers. This section favourably discusses the idea of a Human-Centred Capital Ization (HCI) in designing ergonomics that could help integrating Artificial Intelligence services along Design in order to promote ergonomic discomfort assessments.

Human-centered Artificial Intelligence (HCAI) refers to a field of study and a system design objective that leads to the creation of AI-powered systems that are safe, ethical, and responsible. These systems are developed primarily to enhance human capabilities and make human lives better, both for individuals and for society as a whole. HCAI systems should help people in performing their tasks, fulfilling their aims, and achieving their goals. In the context of product design, this viewpoint can also be interpreted as "AI for design" in that the development of such systems is primarily expected to shape the future products or services rather than to create new and independent products based on data-driven algorithms.

2.1. Human-Centered AI for Design

Human-centered artificial intelligence (AI) emphasizes technology design that prioritizes human benefit (Zhou &

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Yu, 2023). Cognitive load theory defines meaningful learning as reducing cognitive overload by developing robust mental models based on the relevant prior knowledge embedded in the abundance of information presented (Lu et al., 2024). This theory relates to AI augmentation in design ergonomics. The design process must accommodate the important perceptual and semantic alignment between user cognition and design systems to promote high-fidelity understanding of AI-supplied data (Naimul Hoque et al., 2024). Human-centered AI for design, cognitive load theory, and convergence to perceptual–semantic alignment justify the need for AI-assisted ergonomic evaluation metrics.

2.2. Cognitive Load and Interaction Models

As computer-aided design (CAD) systems become widely integrated into the design process to assist designers with composition, an AI-augmented ergonomics becomes feasible in the wider applications. The advancement of digital-twin and simulation-based approaches to ergonomics evaluation provides such an adding opportunity. Data-driven and model-based features to assist designers have received growing attention and much effort concentrated on architectural, fashion, industrial and product design. Furthermore, when an integrated-prototyping system is available, allowing designers to revisit and rethink early decisions is still challenging and costly, AI-augmented ergonomics feedback during preliminary design and even early-stage on conceptual sketches will be beneficial. To ensure the ergonomic interfaces with AI-augmented design psychology standards such as BRIEF can be satisfied, quantifiable metrics and digital-twin or simulation methods for wearable-prompt design remain needed. Multiple case studies demonstrate how and what ergonomic standards can be achievable in design of furniture, product, automotive ,or transportation interface. Simulation, mechanical-stress and digital-twin approaches can reduce the time and cost to evaluate and select the wide used efficient design standard prior to user test and validate or final demonstration. Human-centred AI system providing the ergonomic design simulated can effectively bridge the gap among design intention and user experience observed still.

2.3. Semantic and Perceptual alignment in Design Systems

Design begins with the conception of a product and involves its realization, visualization and evaluation through various forms of prototypes, considering both aesthetic quality and ergonomic comfort. Traditional ergonomic assessment marked the completion of the first iteration, but novel design systems foster rapid yet thorough design iteration employing design, visualization or evaluation techniques simultaneously, lengthening the period before ergonomic assessment becomes essential. Evaluation of prototype ergonomics focuses on design integrity, proper interaction representation, or product and user description analysis. Variables incorporate geometrical, kinematic, structural modelling of user/product or product/product interaction, and remain theoretical or empirical, predicting user experience through digital twins, physical interaction modes, and cognitive or emotional modelling contextualized in time.

Recent guidelines for design specify prototypes as means to assess product usability and ergonomics. Utilising

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preliminary ergonomic assessment early in the design process restricts the exploration of radical concepts, while separating ergonomics completely from design process is impracticable. Accordingly, an approach emerges whereby design prototypes accommodate both assessment of user-facing comfort measures and constraints on user-centred design integrity, thus enabling an iterative back-and-forth between high-level design facets and initial ergonomic evaluation of tangible proposals. Prototypes serve to capture user description within design systems, adopting a dual perspective on design actions. As a bridge between dimensionless sketching and focused modelling, these intermediate prototypes inform the specification of ergonomic measures at an unresolved stage of design with freedom and flexibility (Mackeprang et al., 2019). Such a simplistic representation permits investigation of initial user-product compatibility, input-output couplings between user actions or modifications, alternative operating modes influential to task contingency, and comfort measures like postural strain, temporal interaction, or cognitive workload. Interactions unwind an implicit task model shaping product use and emphasising the support of comfort-oriented practices, yet do not conflate task adherence with ergonomics (Holter & El-Assady, 2024).

3. AI-Driven Methods for Ergonomic Assessment

Design Ergonomics Requirements are also addressed by AI-based approaches through the analysis of human behavior and human–machine interaction. The selection of relevant human factors (HF), the identification of significant features, and the exploitation of datasets to generate

Machine Learning (ML) Estimators for the prediction of safety metrics are supported by the application of AI (Khani-Shekarab & khani-shekarab, 2021). These technologies facilitate ergonomic evaluation, contributing to wider adoption of ergonomic techniques. AI design systems adhere to human-centered principles by balancing cognitive load between users and machines in analysis and synthesis tasks. To ensure semantic and perceptual alignment with design intent, unifying representations for geometry, functionality, behaviour, and context are employed, aligning with Interaction Design and Cognitive Load theories. Theoretical foundations govern the establishment of theory-driven ergonomics methods, validating the appeal and effectiveness of AI-driven support technologies.

Data-Driven Metrics for Recording Movement. Activity recognition for Human Activity Recognition (HAR) is imperative in ergonomics, yet inaccuracies persist in lab conditions and the technology remains underrepresented across diverse environments, behaviours, and populations. Challenges arise due to global interaction systems simultaneously engaged by various participants. Commercial markers, ultrasonics, and vision-based motion capture (VMC) are established but constrained by cost and flexibility. Artificial Intelligence (AI)-infused Computer Vision (CV) with topology markers for Skeleton estimation assists analysis in Action Recognition and HAR (Gonzales Marin et al., 2018). CV advancements facilitate detection and tracking with minimal equipment in interfacing, sustaining accuracy across extensive datasets within ergonomic domains. Simulated design as a future-oriented strategy employs Digital Twins for ergonomic investigations, yet data linkage and high-fidelity modelling from virtual to real systems remain constrained, escalating tooling and effort demands when programming datasets physiologically.

Simulation models operationalise ergonomic representation manipulating pose parameters—scalability ceases between virtual and real domains, demanding dedicated analyses per framework. Developers face the dual task of programming and operationalising Action Recognition for video datasets governing intended designs. Wearable sensors acquire information during physical activities operating in unrestricted scenarios.

3.1. Data-Driven Ergonomic Metrics

AI has the potential to augment ergonomics assessments by monitoring and analyzing body posture and movement. Unlike early tools that captured absolute values or coarse temporal features, state-of-the-art data-driven metrics can estimate entire distributions of posture and/or movement characteristics, speed and force of each joint, and contact with supports. Such comprehensive analyses enable advanced ergonomic evaluation of simulated or physical design proposals through avatars, digital twins, and full-space 3D VR prototypes. Data-driven metrics can be particularly effective for AI-augmented ergonomics since they are generally modality-agnostic; regardless of the measurement system employed, if the data remain within specified limits, the same high-fidelity model can be used. The cross-modality independence of the metrics allows AI-augmented ergonomics assessments via a diverse array of measurement modalities.

The metric systems also link closely with—and therefore validate—computational approaches to posture and movement simulation. Physical human–computer interaction (pHCI) models computationally simulate these modalities. By rendering a complete evolution of body posture and movement over time, the pHCI frameworks produce time-series trajectories. Such simulations can therefore be assessed with posture and movement metrics, establishing measurement validity. For avatar-based design exploration, a related configuration enables ergonomic consideration of a broad spectrum of configurations via captured trajectories from motion databases. Multiple, constrained modes can be incorporated.

Rigorous validation of the entire capture–simulation–evaluation pipeline remains critical. Data-driven metrics encapsulate ergonomic principles as actionable design insights. Extensive research characterizing DV–CV mappings and documenting broader generalization patterns supports their completeness. Similarly, characterizations of task–posture and task–movement mappings attest to proper semantic alignment, robustness, and versality. Measurement through simulated trajectories or physical avatar motion thus constitutes valid feedback on semantic ergonomic performance. Evaluating design alternatives at such a granularity enhances comprehension of their broader ergonomic implications across various stages.

Designed for real-world comfort within a dual space, rigorous P/fHCI further reinforces the pipeline's semantic grounding. Constructed around distributing physical efforts in accordance with human physiological limits, pHCI enforces naturally ergonomic solutions and satisfies domain-specific physical constraints, while supporting a diverse selection of interactive patterns and modalities. In turn, every design alternative becomes accessible; the

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encompassing character and yet principles already studied confirm task spectra compatibility. Within the specified scope, simulation at both physical and semantic levels thus satisfies stringent measurement validity, ensuring conversion establishes the desired correspondence.

3.2. Simulation and Digital Twin Approaches

Computational simulations assist the ergonomic analysis of a design by mimicking human-system interactions, in turn enabling the evaluation of associated comfort criteria (Ahmad Malik, 2021) ; (Ahmad Malik & Brem, 2020). Such simulations provide insights that can guide the design of user characteristics, tasks and environments (Wu et al., 2023). Examples encompass digital-twin avatars to visualize modelling parameters and facilitate ergonomic evaluations across diverse designs; evaluations conducted using virtual-reality environments; and testing of form and geometry, material, surface description and assembly features on shape attractiveness through digital-surface designs;.

Distinct from Data-Driven Metrics, which rely on the numerical representation of design attributes, assessment-capability definition and the experimental collection of human responses, simulations-based metrics require a human behaviour model and a characterisation of the human-system interaction. Reinforcement-learning environments, ergonomic-comfort criteria and virtual-reality applications for data collection represent relevant methodologies. Similarly, ergonomics-assessment systems specified in the Prototype and Iterative Evaluation sections leverage wearable sensors, computer-vision methods and digital-twin technology to enhance data-collection and analysis capabilities for associated comfort metrics.

3.3. Computer Vision and Wearable Sensor Analytics

Anthropometric measurements, such as shoulder height, hip circumference, and arm length, are widely used to quantify and describe body shape and size. However, despite comprehensive body measurements being essential in virtually all design industries, detailed anthropometric data is not routinely collected. Consequently, body dimensions are often not incorporated into the design process. Some industries, such as automotive and apparel, use general population statistics to define dimensions. Other industries disregard body dimensions entirely. Alternatively, the practicalities of collecting body measurements, or the availability of alternative systems for acquiring equivalent information, can obviate the need for detailed measurements. Various indirect methods can be adopted too, including the use of full-body avatars, photographs, video footage, and postures to characterize body shape (Lagomarsino et al., 2021). Furthermore, while design systems frequently leverage graphic elements, material choices, and structural definitions, the biobehavioral dimension is only incidental. Analysis tends to be superficial, such as annotating or scaling an image onto a single view, rather than forming an integral part of shape representation. Likewise, specialized sketch drawing or 3D virtual consideration is rare, with sketching instead being limited to description, illustration, or concept generation activities rather than the definition and exploration of shape.

Skeletal attributes provide another indirect method of inferring body shape (Ahuja, 2024). The skeletal system defines the corporeal structure at only a few locations, yet

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these mathematical parameters are widely understood and widely utilized in scientific, artistic, and mathematical analysis, facilitating adaptation even with little design experience. Computational tools, nevertheless, tend to be dedicated to body sketching. Vehicle design, for example, primarily revolves around line projection, shadow, two-and-a-half-dimensional rapid visualization, and methodological rendering of surface shape without reference to three-dimensional inside structural arrangement. Nevertheless, many products can benefit more from a clearer definition of three-dimensional shape and an expanded understanding of the underlying morphology.

4. Design Process Integration

AI-augmented ergonomics can inform design decisions in a user-centered manner throughout the development process. Prototyping and modelling systems enable iterative exploration of ergonomic considerations by interleaving design generation and assessment. AI-assisted ergonomic feedback directs attention to relevant concerns in early concepts, while frameworks for iterative evaluation close the loop between design choices and user comfort feedback. Once the expected design features and a corresponding affordance model are established, evaluation steps can be planned based on the usage scenario and configuration for the target context (Wang & Yoon, 2019). At this stage, both the Data-Driven Metrics and Digital Twins methods specified in earlier sections remain applicable.

Building on affordance-based interaction modelling and various simulation techniques, proximity and reachability can be assessed scenographically within digital-twin environments (Lu et al., 2024). Expected adjustments to the physical workplace can also be evaluated; for example, furniture specifications and other workplace adjustments can be addressed in furniture-oriented design within the broader framework of workplace design.

4.1. Prototyping with AI-Assisted Ergonomic Feedback

Rapidly emerging AI-aided ergonomic analysis and design tools hold significant promise for relieving cognitive load and enriching user experience. Such pervasive analysis might support design efforts where human factors play key roles, notably in large-scale design guidelines or user experience design (Wang & Yoon, 2019). Ergonomics remains among the most critical concerns (Duan et al., 2024). Product design increasingly leverages parametric or generative workflows and computational design exploration; AI can similarly assist by evaluating aesthetic quality or validating fundamental rules for ergonomics or usability. Analyses do not merely seek rules the designer must check before delivery; rather, they guide interaction throughout, flexibly following exploration paths even when broad design theories or precedents are unavailable.

Evaluating comfort, discomfort, or other ergonomic aspects after completing designs via simulation or further steps eludes designers. Tools also consider mass, structure, or light distribution using physical simulation, enhancing yet another design dimension. Focusing on aspects such as anatomy, grasp, or posture associates with explicit subjective elements within the evolving design surface. Closing the loop between design decisions and comfort evaluation is achieved within enterprise contexts.

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4.2. Iterative Evaluation Frameworks

Prototyping is a tool that helps designers turn their ideas into form and structure early in the design process, and AI assistants are beginning to provide suggestions on design proposals. Although these assistants enhance designers' efficiency, ergonomics still depends on human evaluation at the prototyping stage. Therefore, AI-assisted ergonomics needs to be integrated into the rapid prototyping process. Such integration would allow designers to receive real-time ergonomic feedback, helping them make well-informed design decisions sooner, acquire important domain knowledge, and thus improve their ability to design ergonomic products (Lu et al., 2024).

Iterative evaluation frameworks support this integration by designing defining a set of design decisions and corresponding comfort evaluations through a combination of data-driven metrics and digital twins (see AI-Driven Methods for Ergonomic Assessment). Human-centered AI systems offer a broad array of design-ergonomics options during the formative stages of the design process, and to fully exploit these possibilities and provide informative ergonomic feedback, designers utilize iterative evaluation frameworks to specify the expected scope of evaluation and frame critical evalutation questions (Esposito et al., 2024) (see Figure 1).

5. Ethical and Social Considerations

The application of artificial intelligence (AI) to ergonomics raises ethical and social issues of bias, privacy, and consent. While these topics are generally applicable to AI use in design, ergonomics often necessitates handling large user datasets to ensure reliable recommendations. Such practices may further aggravate existing inequalities if the data are skewed towards specific demographic groups. Furthermore, designing ergonomic solutions for young, non-disabled subjects without explicit consent infringes the rights of vulnerable categories. On the contrary, addressing these issues directly leads to inclusivity by design, contributing to universal design principles and other accessible outcomes across age, ability, and disability. The user-centric and context-dependent Flexible Design approach aids the provision of uncovered design support to promote seamless inclusivity across diverse user groups.

The type of content leveraged in AI-driven ergonomics establishes clear obligations regarding data gathering, sharing, and disposal. Such data enabled translational and generative design exploration, delivering user-system-session configurations and unobserved alternative sessions. Considering a similar context, ensuring protectable intellectual property remains paramount. Meanwhile, the availability, scrutiny, and upkeep of design drive recorded via design or activity-monitoring instruments support the reproducibility of state-of-the-art solutions and ease entry for new designers. Data specification interconnected with this ambition refines the supply of relevant, desired, and plentiful data items while cataloguing the merits of the stored material.

Potential ergonomic feedback propositions determined from desk work tackle varying display orientations, from stacked landscape to vertical, and multi-monitor configurations, including laptop integration. Workspace designs pivot around horizontal or vertical-lever height modification and on-side auxiliary space introduction.

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Posture feedback indicates Bending Forward and Position away from Screen also materialises from artificial-lift assistance; assistance thoughts proceed to workspace width or depth alteration, chair augment, legroom supply, or stand-support way-outs when directly articulated (Segkouli et al., 2023). Related existing AI capability entails the fine-tuning of sketch-interface work. While ergonomics receives sensitivity AI accent, tapping into generative design warrants additional requirement to satisfy sketched form quicker. Verifiable screening of session quality, closure stabilisation, and transformation to hybrid modalities represent further elaboration (Vakkuri et al., 2019).

5.1. Bias, Privacy, and Consent in AI Ergonomics

Artificial intelligence (AI) technologies are often perceived as pathbreaking and transformative because they promise to alleviate some of the cognitive burden associated with human design activities (E. Fukumura et al., 2021). Yet, such an expectation conveys a certain level of bias because the original premises underlying design tasks often remain insufficiently explored. In the past decades, considerable attention has been devoted to articulating these fundamental design premises, including cognitive load and the nature of dyadic and group interactions (Newman-Griffis et al., 2022). These efforts have intensified under the guiding principle of inclusivity and universal design, recognizing that design solutions must accommodate specific user qualities since the pursuit of accessible outcomes constitutes an urgent global concern (Chowdhary et al., 2023). In a similar fashion, the computer-aided design (CAD) tools of artificial intelligence (AI) provide the capability to generate highly relevant and technically sound design proposals that contribute to various aspects of ergonomics and are destined to become reliable assistants in the design process. These advanced CAD tools are now being integrated into the design and ergonomics quality-assessment processes.

When assessing ergonomic quality or performance, information perceived by users is often represented as an input. Most practical ergonomic metrics deal with the preparatory phase of eliciting the necessary information prior to the commencement of any design activities. Nevertheless, the relevance of information remains to be ascertained. When ergonomic evaluation is concerned, the assessment of a proposal may be undertaken earlier than anticipated in a hypothetical iterative framework by analyzing what, when, and how users capture data and the precise information signified by geometry and visual texture elements throughout their interaction with specific applications. Artificial intelligence (AI) technologies are increasingly integrated into ergonomics practices. Consequently, examining how such systems impact posture and wellness warrants close attention.

5.2. Inclusivity and Universal Design

The accelerating adaptation of Artificial Intelligence (AI) is reshaping ergonomics practice and education across all design disciplines. While the potential of AI-applications in ergonomics is immediate, critical expectations are already established as future direction on the design of AI-assisted ergonomics tools. The Data-Driven Ergonomics (DDE) framework provides fundamental components to encompass current challenges and inspires anticipated improvements for future utilities (Chemnad & Othman, 2024). As AI-

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powered ergonomics tools are pervasively employed through virtual platforms, addressing bias detection and mitigation in ergonomics datasets is urgently needed to realize fair AI deployment across various user groups (Wald, 2021). The analysis of digital devices within ergonomic contexts remains sparse, although on-going methods focus on perceptual/semantic tools for screen designs and algorithmic modelling of dialogue act distributions embedded in real-time speech data. The widespread integration of AI algorithms into the design ecosystem brings another significant concern to protect users from improper privacy policies and abuse of personal information (Guo et al., 2019).

6. Future Applications and Scenarios

Ergonomics aims to prevent injuries and increase user satisfaction through improved human–computer interaction. Future avenues for AI-augmented ergonomics lie in human-centered adaptive systems, ergonomics-geared workplace design, and sustainability-driven, multifaceted optimization.

The next stage of development envisions systems that learn user PEOU in real time and adapt HMI autonomously to minimize design effort while maintaining PEOU. Such evolution may be supported by data-driven design agents that use ergonomics-aware process formulas to evaluate alternatives, greatly reducing the evaluation space.

Workplace design evolution demonstrates an even broader AI potential footprint. Today, design of items like standing desks contains ergonomic considerations through static analysis of physical interaction in 3D simulations. Future opportunities exist to integrate input on health priorities, demographic group, and preferred material properties, enabling transformation of ideology into other product dimensions. Design agents would systematically alter proposals while monitoring posture and other parameters to meet PEOU targets.

Sustainability challenges further amplify the quest for intelligent ergonomic aids. Many design cycles occur during procurement of items; evaluating prospective purchases remains largely manual. Products may be assessed through usage statistics, life-cycle carbon expenditure, or similar criteria, always factoring user PEOU. Further exploration of intelligent ergonomic aids warrants support from various fields.

6.1. Adaptive Interfaces for Diverse Users

Today's design process is deeply technology-driven; developers and users interact with the same designs through screens, keyboards, and pointing devices. The nature of workplace ergonomics evolves from fitting the tool to the user to aligning tool usage ergonomics with design needs (Ibrahim et al., 2024). Much design today occurs in 3D spaces that evolve and perform over time. This design shift can be modeled in two domains: A) the room, layout, workstation type, component type, and spatial growth of a 3D physical object (Todi & R. Jonker, 2023) ; B) the media type (e.g., document, presentation, dataset), sequence (e.g., forensic), color aesthetics, audience (e.g., emotional bias), and refinement status of screen-based communication material. Further, today's design portfolio and exploration afford realistic switches between family branches. These hybrid forms involve interactions in distinct perceivable

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media, prompting consideration of both design facility ergonomics and cognitive interference.

6.2. AI-Augmented Workplace Design

As digitalization and artificial intelligence (AI) advances modify how people work and live, thus altering the parameters of work efficiency, comfort, safety, and energy consumption, ergonomics design has become an integral part of office facilities and equipment. However, considerations and specifications related to ergonomic design in the early stage of the design process have rarely been systematically studied, thereby potentially affecting the application of AI to ergonomics design. AI-assisted evaluation tools and methods are being developed to analyze relevant data from human participants, digital twins (twinned cyber models of a workspace), and multiple ergonomic-related metrics to closely and efficiently monitor ergonomics status (Khani-Shekarab & khani-shekarab, 2021).

6.3. Sustainability and Ergonomic Optimization

In industry, the growing adoption of collaborative robots (cobots) has resulted in the need to redefine workstation ergonomics in the presence of these systems and to develop tools and techniques to evaluate such ergonomics in human-robot collaboration environments (Lorenzini et al., 2023). Collector stations and marker-placed workbenches allow the adaptation of product design for ergonomic improvement. Taking into account cobot-related actions together with the design of the products handled ensures a wider pre-emptive ergonomic evaluation.

Integration of cobots is an essential future step in industrial ergonomics, especially concerning the development of novel mechanisms to carry products and design parameters of the products being handled. Automated, real-time generation of ergonomic indicators for products according to the directives of cobots acting at postures distance allows the starching of this much-desired integration.

7. Methodological Roadmap

Successful AI-enabled ergonomics demand clearly delineated goals, systematic validation of outcomes, and unbiased reproducibility. The implementation of AI-assisted ergonomic feedback requires recommendations for a validation, standardization, and reproducibility roadmap that benefits all end users by meeting common requirements. Since ergonomics is inherently multidisciplinary, involving design, engineering, psychology, and beyond, successful AI-assisted ergonomics applications in corporate products can derive from individual company pursuit of business success. Advancement of the general field requires these multidisciplinary efforts to be organized in a research-enabling manner.

Computer-vision metrics for ergonomic assessment serve as standards, validating their performance through extensive cross-validation studies across a diverse, task-agnostic test population. Measurement of the target metrics employs phase-related motion capture as a common reference for both cross-validation and the creation of new test data. Cross-validation quality is further enhanced by deployment of distinct sensors in separate laboratories, forcing a choice between mode-code identification of the

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sensing lab or proper quality-testing of the measurements. Moving beyond specific application areas, the resulting data-driven standards and associated requirements also guide new data gathering and testing for other product categories.

7.1. Validation, Standards, and Reproducibility

AI holds promise for augmenting ergonomics through enhanced and data-driven capabilities. AI-mediated interactions and deep learning methods lead to richer ergonomics assessments than are possible through traditional design techniques. Consequently, an ideal ergonomic modelling framework should offer deep learning and data-driven assessments on human activities, ergonomics, and utilization in tandem with other modelling elements (Asan & Choudhury, 2021). Publication frequencies around human factors and ergonomics have increased since 2016, alongside a broadening of interest in human-centric topics, augmented and virtual reality, and AI support for UX design and evaluation (Lu et al., 2024). Frameworks describing data-driven and simulation approaches enable understanding of ergonomic requirements and a digital twin offer insights to anticipate human performance and ergonomics in other domains.

7.2. Interdisciplinary Collaboration

Designing user-friendly products often poses challenging trade-offs and can feel like a dark art. Nevertheless, the emergence of artificial intelligence (AI) offers the promise to illuminate important ergonomic issues throughout the design process. AI-driven methods can help measure ergonomic properties early in the trajectory—from concept through prototyping—providing guidance about physical fit, ease of use, and user comfort. Advances in data-driven metrics, virtual representations, and human behavior analysis enable AI to assess ergonomic issues in designs with unprecedented scope, speed, and automation. These developments offer the potential to reshape current strategies for ergonomic evaluation (Asan & Choudhury, 2021). Yet, to fully realise that promise, design practice must still evolve in the near term.

Research in AI-augmented ergonomics tends to focus on building, testing, or applying specific methodologies, often neglecting critical aspects of validation, benchmarking, and standards. In addition to establishing clear requirements for data quality, computational capacity, and reproducibility, a rich opportunity exists to advance rigour in the design and assessment of AI-enabled ergonomics methods. Further, increasing engagement across the disciplinary spectrum with architecture, safety, psychology, and other areas can tighten the synergy between ergonomics and AI. Collectively, these measures will strengthen the foundations of AI-enhanced design ergonomics and enable more effective and sustainable uptake of current methodologies (Holter & El-Assady, 2024).

8. Implementation Challenges

Data quality and accessibility pose critical barriers to implementation for human-centered AI, particularly for ergonomic analysis where detailed data underpin virtually every algorithm. For example, computer-vision techniques rely on images illustrating how a user interacts with a system (E. Fukumura et al., 2021) , while simulation

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approaches progress toward high-fidelity digital twins of the user-product combination (Lu et al., 2024). Consequently, two high-level strategies can promote resilience: prioritization of the most data-hungry algorithms and adoption of readily available datasets, tools, and architectures for the remaining methods. Furthermore, resource-intensive methods tend to require extensive computational infrastructure—a second challenge common throughout the design AI landscape. In ergonomics, the progression from broad strategies to narrowly scoped methods serves the analogous purpose of identifying approaches amenable to incremental deployment. The initial focus is accordingly placed on data-driven metrics capable of capturing general ergonomic properties with modest datasets; only once semi-automatic evaluation has been established for diverse objects is attention diverted to simulation-based digital twins requiring highly detailed models. Building clout in provisional settings sustains momentum and exploration of design-altering innovations. Such gradual adoption facilitates eluding major up-front investments in either perspective.

Experiments involving traditional ergonomic assessments illuminate another obstacle linked to operability, influencing the formulation of exhaustive feedback. Recent advances enable automated evaluation of comfort without proffering corrective suggestions precisely because human-centric AI, for design systems, encompasses various aspects and permits diverse augmentation paths; curtailing complimentary feedback risks obscuring foundational understanding and guidance for further embedding ergonomics. A framework illustrating the breadth of potentially AI-augmented ergonomic dimensions, alongside material and ergonomics metrics akin to materiality and manufacturability, constitutes essential tooling for guiding the next-broadest exploration horizon following completion of data-driven metrics for comfort. Such schema consequently accompany remaining challenges and ongoing work.

Individual adoption of AI-driven ergonomic methods typically necessitates collection of fresh user data much like their traditional counterparts since ergonomics-centric characteristics remain largely inaccessible for general-purpose design datasets encompassing graphics, CAD models, and 3D meshes. Research thus seeks means to identify such algorithms without supplementing an already extensive data catalog, leveraging information inherent to widely applied modelling techniques pooled from considerable industrial experience. Upon securing installations across genuinely varied designs addressing comfort, an intriguing avenue emerges: how design regimes characterise and impart ergonomic properties, thereby facilitating cross-regime analysis within yet another qualification dimension.

8.1. Data Quality and Accessibility

The increasing accessibility of AI-augmented ergonomic tools brings new challenges arising from low data quality or narrow availability (E. Fukumura et al., 2021). Resource constraints, including limited personnel or computation, compel organizations and disciplines to prioritize systemic deployment of ergonomic solutions across scales. Restrictions often entail a stochastic approach. Macro elements receive initial consideration, even for applications

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closely tied to specific forms, functions, or settings; thereby establishing productive ergonomic awareness at a foundational level. Figuring out which AI-driven analyses to undertake next predominantly depends on users' observed comfort or satisfaction; disconnections may point to deficiencies that the current design fails to address adequately.

Challenges of data performance, accessibility, and computational constraints remain interconnected. Cross-discipline solutions demand cooperation among developers, practitioners, content curators, and infrastructure maintainers, synchronizing data at design or operational nodes. Formally defining allowable modifications before scaling access facilitates multiscale adjustments without formulating the specifications from scratch anew.

8.2. Computational Resources and Scalability

A common characteristic of many existing AI-augmented approaches is a heavy computational cost and subsequent reliance on appropriately sized resources. For example, a Full-Combination Algorithm Quantifying the Mutual Information between the Image and Other Data at Different Levels demonstrates its applicability for testing specific models and improving solution space during key image classification tasks, given sufficiently large image datasets. As AI-augmented methods become increasingly diverse, the requirement for resource-intensive evaluation becomes increasingly likely. High-level strategies for broadening resources could include suitable co-location with specialist resources whenever possible, investigation of collaboration opportunities with broader resource availability, detailed analysis of performance requirements, and progressive scaling of evaluation resources, starting with smaller-scale options whenever feasible.

This consideration could also be tied to Discussion point 1 regarding influencing factors as an extension of initial resource availability beyond data itself. Reliance on Data-Driven Ergonomic Quality Metrics also offers guidance regarding underpinning AI techniques, with proper validation of the results remaining a necessary prerequisite for practical adoption.

9. Case Studies and Illustrative Scenarios

AI-driven ergonomics offers far-ranging virtual opportunities. In furniture and product design, ergonomics establishes how AI affects form, function, and user experience; figure-ground generalizations emerge from 3D geometry and user-centered mechanisms. Automotive and transportation interfaces explore ergonomic involvement with task-driven interaction and time-shared activity management; task structure analysis and saliency graph extraction generates understanding of activity operability, structural organization, and occluded content.

9.1. Furniture and Product Design

Design ergonomics aims to facilitate effective human interaction with design objects. Ergonomic aspects vary with the artefact type, for example, among products, furniture, and vehicles; different body parts are engaged; the time and nature of engagement vary. This section illustrates AI-assisted design ergonomics for furniture, an intrinsic material form of design. An omnipresent human requirement, it remains under-researched, offering rich AI

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opportunities through undeveloped ergonomic assessment, modelling, and design strategies (Leimer et al., 2020). Furthermore, illustrating product ergonomics extends the theory through additional AI-ergonomics principles.

Furniture serves a primarily functional role, structuring time and place during mobility. Ergonomic functions thus ease transient and prolonged interactions. Supporting posture during these phases ensures quality of clear-minded, spontaneous reflection and creativity, vigilance in time-critical decisions, technology mediation or purification, and other parallel or sequential actions. Manufacturers currently focus on hygienic surfaces satisfying body-contact areas over posture. Prioritising the overall transitional journey by defining preceding and following gestures, extracting expected body states, and similarly modelling user-object mutuality during, pre-, and post-transition would permit AI-supported furniture design circumventing bodily contact specification and enhancing overall ergonomic accommodation.

Automotive-transportation user-phase comprehension parallels furniture-transitory-understanding extension: enabling mobility across trips inside public or shared transport, appliances condition access or relaxation. Design materials—shaping artefact control during journey through grasping, pressing, tilting, rotating—operate on contact states. Transport-and-furniture AI ergonomics model parallel user-gesture comprehension, seeding additional principles widening AI application across sectors.

9.2. Automotive and Transportation Interfaces

Cognitive ergonomics examines significant shifts in human-automation communications with the advent of AI and seeks to enrich this dialogue: a Design Support Approach better connects humans to machine models of reality. The rapid adoption of Terms-of-Service AI agents—for example, OpenAI's ChatGPT—illustrates a transition from passive to active copying of human meanings in creating new texts, codes, calculations, and drawings. Early AI programs like ELIZA were limited to simple text manipulation. The arrival of large-language models has accelerated cognitive ergonomics' parallel interest in understanding an increasingly automated world (Ramm et al., 2019). A first example explores sentiment expressions; a second concerns grammatical intricacies; and a third addresses the automatic generation of knowledge and science. Cognitive ergonomics focuses on design specifications for both human and AI authors—on "combined intelligence"—across an array of modes (speech, text, symbol, code, sketch, 2D, 3D) and media (video, illustration, performance, software) (Eom & Hun Lee, 2015). The need for new quantitative models presents prospects for meta-sciences that ultimately generate architecture for either human or AI participation on Demand Processing through a Supply Offering System. AI facilitates a metasizing function by explicating nature and practice across extensive varieties of human activity, skills, and productive tendencies.

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Conclusion

A central tenet of this exploration has been the proposition that the design ergonomics discussion should not be dismissed or overshadowed by the rise of artificial intelligence. Instead, the complementary pairing of AI and design ergonomics forms a rationale for devising frameworks that encode ergonomic considerations into design processes and systems. Such frameworks should accommodate a variety of existing approaches to ergonomics, whether these focus on individual attributes, on end-user physical or psychosocial experience, or on cognitive load. Furthermore, a human-centered artificial intelligence approach to design amounts to a distinctive opportunity.

To advance hijack-proof design, humans remain central to design, meaning that contemporary models of how people engage with products provide the foundation for articulating ergonomics. An interaction model delineating the paths along which information flows between user and product, and a cognitive load model highlighting the element of effort involved in transferring information, together offer a consistent basis for evaluative metrics and for identifying ergonometric issues and opportunities. For design that promotes durability, classifying physical materials according to their sustainability equivalence emerges as a relevant ergonomic framework. Addressing such ergonomic considerations elucidates the practical and theoretical benefits of AI-assisted design.

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