

Publication status: This preprint has not been published elsewhere.

A Conceptual Framework for Integrating Cognitive, Emotional, Behavioral, and Motor Adaptation Across Human-Centered Research Domains

Amelia Kowalska

<https://doi.org/10.1590/SciELOPreprints.16736>

Submitted on: 2026-06-30

Posted on: 2026-10-08 (version 1)

(YYYY-MM-DD)

A Conceptual Framework for Integrating Cognitive, Emotional, Behavioral, and Motor Adaptation Across Human-Centered Research Domains

Amelia Kowalska
AGH University of Science and Technology
Warsaw, Poland
kowalska.amelia@yahoo.com
ORCID: 0009-0009-8895-1962

Abstract

Human adaptation is a fundamental process that shapes how individuals respond to cognitive, emotional, behavioral, and physical challenges. Despite its centrality to human functioning, adaptation-related knowledge remains fragmented across affective computing, neuroergonomics, digital phenotyping, rehabilitation engineering, and human digital twins. These fields have advanced the assessment, monitoring, and prediction of human conditions, yet adaptation is frequently treated as a secondary outcome rather than the primary phenomenon of interest. This paper introduces *Human Adaptation Engineering* (HAE), a conceptual framework that positions adaptation as the integrative construct linking diverse human-centered research areas. A literature-based conceptual synthesis was conducted using fifty highly cited review, survey, and framework papers published between 2015 and 2026. Qualitative analysis identified recurring processes—disruption, response, adjustment, stabilization, and long-term outcome—across cognitive, emotional, behavioral, and motor dimensions. The HAE lifecycle model and five conceptual propositions provide a domain-agnostic scaffold for theory development, interdisciplinary collaboration, and adaptation-centered system design. The paper discusses theoretical and practical implications, acknowledges limitations of citation-based synthesis, and outlines a future research agenda for operationalizing and empirically validating adaptation as a cross-domain engineering target.

Keywords: human adaptation engineering; adaptation processes; conceptual framework; affective computing; neuroergonomics; digital phenotyping; rehabilitation engineering; human digital twins; interdisciplinary synthesis

1 Introduction

Humans continuously adapt to changing conditions. Students adapt to new learning demands; workers adapt to increasing workload and fatigue; patients adapt during recovery from injury or disease. Routine life likewise requires ongoing adjustment across physical, cognitive, emotional, and behavioral domains. Research over the past two decades has produced powerful technologies for observing and modeling human states: affective computing for emotion and affect [1, 3, 4]; neuroergonomics for workload, attention, and performance [6, 7]; digital phenotyping for longitudinal behavior and mental-health indicators [10, 12]; rehabilitation engineering, including virtual reality (VR), for motor and functional recovery [14, 15, 16]; and human digital twins for personalized representation and simulation [19, 20].

Although these fields differ in methods and objectives, each investigates how humans respond when internal or external conditions change. Most frameworks nevertheless emphasize *detection*—emotion labels, workload indices, digital biomarkers, clinical recovery metrics, or twin-based forecasts—rather than *adaptation* as a coherent process spanning multiple dimensions. Knowledge therefore

remains siloed: separate terminologies, datasets, validation protocols, and success criteria impede cross-domain theory.

Highly cited review literature reinforces this pattern. Synthesis of top-cited reviews from 2015–2026 shows heavy concentration in affective computing and emotion recognition, with comparatively fewer integrative reviews on adaptation as a generalized construct (see Section 4). Stroke rehabilitation exemplifies domain-specific adaptation research [16, 17], while occupational stress monitoring illustrates physiological adaptation to sustained demand [25, 26]. Contexts differ, but the underlying structure—challenge, response, adjustment, and outcome—recurs.

This paper proposes **Human Adaptation Engineering (HAE)** as a conceptual framework that treats adaptation as the primary unit of analysis. HAE does not replace domain sciences; it provides a shared lifecycle and propositions for organizing their findings. The contributions are fourfold:

1. A reproducible, citation-ranked synthesis of fifty review-level papers across six adaptation-related domains (2015–2026).
2. Identification of a cross-domain adaptation lifecycle (disruption → response → adaptation → stabilization → outcome).
3. Five conceptual propositions linking domain-specific evidence to general adaptation mechanisms.
4. A structured discussion of implications, limitations, ethics, and future empirical priorities for adaptation-centered human systems.

2 Background and Related Studies

2.1 Affective Computing

Affective computing examines emotion and affect through computational models, progressing from unimodal cues (face, speech) to multimodal fusion with physiological signals [1, 5, 2, 3]. Surveys document rapid growth in deep learning and wearable-based recognition [4, 3]. The dominant objective remains *classification* of emotional state at a time point. Longitudinal models of how affective responses evolve under sustained disruption—and how interventions reshape that trajectory—are less developed at the review level.

2.2 Neuroergonomics and Mental Workload

Neuroergonomics studies the brain and body at work, emphasizing mental workload, vigilance, fatigue, and operator performance [6, 7, 9]. Systematic reviews confirm that cardiovascular, ocular, and electroencephalographic measures can discriminate workload changes, though validity is task- and domain-dependent [6, 7]. Adaptive automation triggered by physiological indices illustrates closed-loop human–system coupling [8]. Nevertheless, reviews typically stop at measurement and prediction rather than theorizing multi-session adaptation to chronic demand.

2.3 Digital Phenotyping

Digital phenotyping quantifies individual-level phenotypes in situ using smartphones and wearables [10, 11]. Reviews show feasibility for monitoring mood disorders, anxiety, and schizophrenia through passive features (mobility, sleep, heart rate, activity) [12, 13]. Adaptation appears implicitly in relapse prediction and behavioral drift, but phenotyping reviews foreground *monitoring* and *forecasting*, not a general adaptation ontology.

2.4 Rehabilitation Engineering

Rehabilitation engineering, including VR-mediated training, addresses functional recovery after neurological and orthopedic impairment [14, 15, 16, 17, 18]. Meta-analyses report small-to-medium effects on motor and cognitive outcomes. VR enables progressive, feedback-rich practice environments. This literature is closest to treating adaptation as a first-class process (learning, compensation, re-stabilization), yet outcomes remain clinical and population-specific.

2.5 Human Digital Twins

Human digital twins (HDTs) aim at dynamic, individualized computational representations for simulation and decision support [19, 20, 21, 22]. Roadmaps emphasize sensing-to-decision pipelines and ethical deployment [20]. Scoping reviews note that few implementations satisfy strict digital-twin criteria (personalization, dynamic updating, verified prediction) [22]. HDT reviews center on anatomy, physiology, and clinical twins; cross-domain cognitive-affective-behavioral adaptation is largely aspirational.

Recent studies have also explored adaptation-related phenomena in immersive environments. Virtual reality has increasingly been used as a platform for observing how individuals respond to changing task demands and environmental stressors. Behavioral indicators such as hesitation, task performance changes, and physiological reactions provide valuable insight into adaptation processes. Rah and Chen demonstrated that behavioral patterns captured in immersive VR environments can reveal meaningful changes associated with cognitive and behavioral adaptation under stress conditions [23]. Their findings suggest that adaptation can be observed through evolving behavioral responses rather than solely through physiological measurements.

Similarly, rehabilitation research highlights adaptation as a progressive recovery process rather than a single clinical outcome. Rah and Chen showed that the detection of weak plantar activation signals can support earlier intervention and feedback during stroke rehabilitation, facilitating gradual motor recovery and functional improvement [24]. Although these studies originate from different application domains, both illustrate how adaptation emerges through repeated interaction between individuals and changing environmental demands. Together, they support the central premise of Human Adaptation Engineering, namely that adaptation is a cross-domain process spanning cognitive, behavioral, emotional, and motor dimensions.

2.6 Gap Statement

Across domains, reviews excel at state assessment and condition-specific prediction. None offers a single framework that explains how disruption propagates across cognitive, emotional, behavioral, and motor channels toward stabilized function or decline. HAE addresses that integrative gap.

3 Methodology

3.1 Study Design

This study employed a *literature-based conceptual synthesis*—appropriate for theory-building when the goal is integrative abstraction rather than effect-size estimation [5]. No new human-subjects data were collected.

3.2 Corpus and Selection

Six domains were targeted: affective computing, neuroergonomics/workload, digital phenotyping, rehabilitation engineering (emphasis on VR and motor recovery), human digital twins, and occupational stress/fatigue adaptation. Inclusion criteria were:

- Publication years 2015–2026;

- Document type: systematic review, scoping review, meta-analysis, narrative survey, roadmap, or explicit conceptual framework;
- Peer-reviewed journal or major archival survey (preprints noted separately);
- Relevance to human state measurement, adaptation, recovery, workload, behavior monitoring, or personalized human modeling.

Primary empirical trials were excluded to emphasize field-level consolidation. Fifty papers were retained by ranking candidate reviews on citation counts (Semantic Scholar and OpenAlex, cross-checked June 2026), with domain-relevance filtering to exclude unrelated high-citation reviews (e.g., generic methodology papers).

3.3 Analysis Procedure

The procedure comprised: (1) domain tagging; (2) extraction of stated objectives, constructs, and limitations; (3) thematic coding for adaptation-related mechanisms; (4) cross-domain comparison; (5) iterative framework drafting. Figure 1 summarizes the workflow.

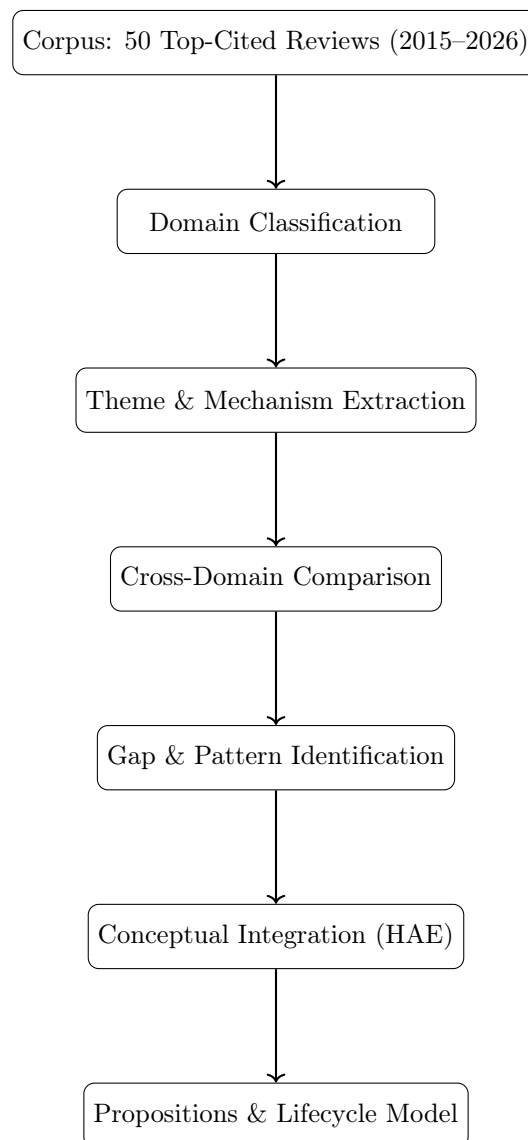


Figure 1: Conceptual synthesis methodology for Human Adaptation Engineering (HAE).

3.4 Theoretical Foundations

HAE rests on three foundations. **(1) Process-oriented adaptation:** psychology, human factors, and rehabilitation treat functioning as temporally extended adjustment to perturbation [14, 16, 25]. **(2) Systems thinking:** cognitive, affective, behavioral, and motor channels interact; change in one dimension constrains others. **(3) Human-centered measurement:** sensing and modeling traditions from affective computing, phenotyping, and digital twins supply observable indicators, which HAE reinterprets as inputs to an adaptation lifecycle rather than as isolated classification targets [1, 10, 20].

4 Results and Conceptual Synthesis

4.1 Cross-Domain Pattern

Synthesis yields a recurrent structure: *disruption* (task load, stressor, injury, symptom exacerbation) elicits measurable *response*; repeated interaction produces *adaptation* (compensation, learning, regulation); *stabilization* of new patterns follows; and *outcomes* emerge (recovery, resilience, performance gain, or decline). Figure 2 formalizes this lifecycle.

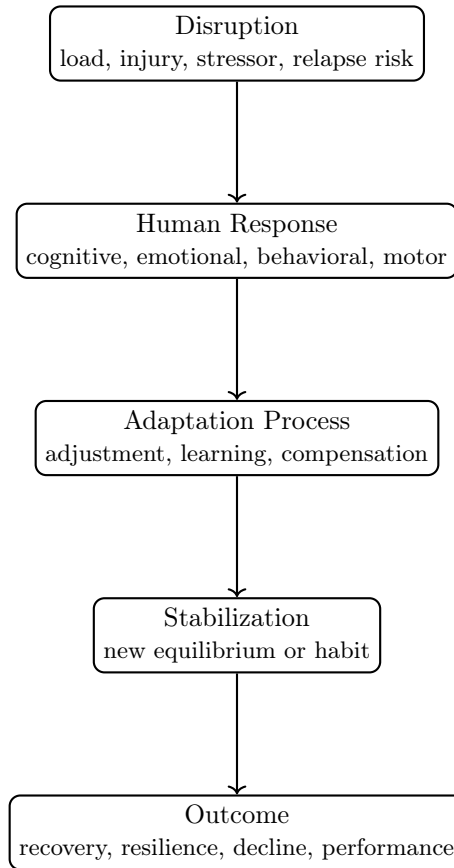


Figure 2: Human Adaptation Engineering (HAE) lifecycle model.

4.2 Domain Contributions

Table 1 maps major fields to HAE dimensions. Each domain supplies partial evidence; none alone specifies cross-domain transition dynamics. Collectively, however, these research areas reveal a common pattern: human adaptation unfolds as a continuous process rather than a sequence of isolated states. Existing studies typically focus on specific outcomes such as emotion recognition,

Table 1: Research domains and their contributions to Human Adaptation Engineering (HAE).

Domain	Typical focus	HAE contribution
Affective computing	Emotion/affect recognition	Emotional response dynamics; regulation trajectories
Neuroergonomics	Workload, fatigue, performance	Cognitive demand; adaptive automation exemplars
Digital phenotyping	Passive behavior monitoring	Longitudinal behavioral adaptation; relapse drift
Rehabilitation engineering	Motor/cognitive recovery	Learning, compensation, functional re-stabilization
Human digital twins	Personalized simulation	Individualized state trajectories; what-if adaptation
Occupational stress/fatigue	Wearable stress/fatigue	Sustained-demand adaptation; safety outcomes

workload estimation, rehabilitation progress, or behavioral monitoring, yet they rarely model how individuals transition between these conditions over time.

4.3 Research Landscape

Table 2 summarizes thematic coverage in the top-fifty review corpus.

Affective computing dominates citation-ranked reviews; neuroergonomics and HDT are under-represented in that ranking despite high field impact—a limitation discussed in Section 5.

Table 2: Distribution of the top-fifty cited review papers (2015–2026) by thematic area.

Research area	Number of reviews
Affective computing	32
Digital phenotyping	7
Rehabilitation engineering	7
Neuroergonomics / workload	2
Human digital twins	2
Occupational stress / fatigue	2

4.4 Conceptual Propositions

The following propositions summarize cross-domain inferences. They are intended as theory-generating statements subject to empirical test, not as proven laws.

P1 (Multi-channel response): Disruption in one dimension (e.g., cognitive overload) routinely co-occurs with measurable changes in other dimensions (affect, behavior, motor variability), implying that adaptation should be modeled as a vector state rather than a single construct [6, 1, 12].

P2 (Process asymmetry): Detection accuracy of instantaneous state does not imply understanding of adaptation trajectory; fields optimized for classification under-sample stabilization and long-horizon outcome formation [10, 14].

P3 (Closed-loop gap): Domains with adaptive intervention (neuroadaptive automation, VR difficulty tuning, clinical alerting) demonstrate that *optimization* requires feedback from state estimates, yet most reviews stop at open-loop monitoring [8, 16, 12].

P4 (Individualization): Human digital twins and phenotyping indicate that adaptation pathways are person-specific; universal thresholds on physiology or behavior will misclassify adaptation stages for substantial subgroups [19, 22, 10].

P5 (Maladaptive stabilization): Stabilization can represent either functional recovery or entrenched maladaptation (chronic stress encoding, learned non-use, affective avoidance); outcome valence must be evaluated explicitly, not inferred from equilibrium alone [25, 15].

5 Discussion

5.1 Theoretical Implications

HAE reframes human-centered technology research around a single question: *How does a human system move from disruption to a new functional state?* This shifts emphasis from static labels (emotion class, workload level, symptom score) to *trajectories* and *transition mechanisms*. For theory, HAE encourages borrowing control-theoretic and developmental concepts—set-points, compensatory reorganization, and attractor states—without reducing adaptation to any single modality.

The propositions in Section 4 imply that interdisciplinary models should represent cross-coupling explicitly. For example, digital phenotyping’s behavioral features may lag cognitive overload experienced in occupational settings; affective computing may detect emotional dysregulation before behavioral relapse in mental-health monitoring. Integrative models should therefore specify time scales and cross-channel delays.

5.2 Practical Implications for Human-System Design

For practitioners, HAE suggests a design checklist: (1) define the disruption class; (2) select multi-modal indicators of response; (3) model adaptation dynamics (not only snapshots); (4) implement stabilization-aware interventions; (5) evaluate outcomes on functional, not proxy, criteria. Rehabilitation VR, adaptive automation, and digital therapeutic alerting already implement fragments of this pipeline; HAE argues for explicit lifecycle documentation and shared evaluation metrics across domains.

Human digital twins may eventually serve as simulation testbeds for adaptation policies—e.g., predicting recovery trajectories under alternative training schedules—provided twins meet verification, validation, and uncertainty quantification standards [22, 20].

5.3 Critical Perspectives

A central critique is that HAE risks being perceived as terminological integration without new empirical content—a “rebrand” of existing silos. The framework’s value hinges on whether it generates falsifiable predictions (e.g., cross-channel delay profiles, maladaptive stabilization signatures) and standardized reporting of adaptation stages in primary studies.

A second critique concerns construct validity: “adaptation” in motor learning, affect regulation, and workload recovery are not guaranteed to be commensurate. HAE mitigates this by defining *lifecycle stages* at a coarse grain while allowing domain-specific operationalizations within each stage.

A third critique involves ethics and power: continuous phenotyping and workplace physiological monitoring can surveil rather than support adaptation [12, 6]. HAE-compatible systems must em-

bed consent, purpose limitation, worker/clinician governance, and transparency about intervention triggers.

5.4 Relation to Adjacent Frameworks

HAE complements, rather than supersedes, domain frameworks. Neuroergonomics supplies operator-performance theory; digital phenotyping supplies ecological measurement; rehabilitation supplies plasticity and practice effects; affective computing supplies affect models; HDT supplies personalization infrastructure. Related integrative ideas—human performance modeling, closed-loop neuromodulation, and human-state engineering pipelines emphasizing sense–infer–act—share the lifecycle logic articulated here but differ in scope and primary audience [5, 8].

5.5 Limitations

This conceptual synthesis has limitations. First, citation-ranked selection biases toward affective-computing surveys with high bibliometric velocity; neuroergonomics and HDT landmarks with moderate citation counts may be underweighted. Second, exclusion of primary studies omits recent empirical advances not yet surveyed. Third, qualitative coding by a single analyst limits inter-rater reliability; future work should apply structured coding with multiple reviewers. Fourth, the top-fifty corpus is a heuristic, not a PRISMA-registered systematic review; supplementary materials should publish the full paper list and search audit trail. Fifth, HAE is descriptive at this stage: formal dynamical systems or causal models are not yet specified.

5.6 Future Research Agenda

Priority directions include: (1) operational definitions and measurement batteries for each lifecycle stage; (2) cross-domain datasets with aligned labels for cognitive, affective, behavioral, and motor channels; (3) intervention studies that compare open-loop monitoring versus adaptation-stage-aware closed-loop policies; (4) twin-based simulation studies with explicit adaptation policies and VVUQ; (5) normative and regulatory analysis for occupational and clinical deployment. Empirical demonstration that lifecycle-stage models outperform snapshot classifiers in predicting long-term outcomes would constitute strong validation of HAE’s utility.

6 Conclusion

Human adaptation is not peripheral to human-centered science—it is the process that links momentary response to lasting change. Yet highly cited review literature from 2015–2026 remains dominated by condition-specific detection and monitoring, especially in affective computing, while integrative adaptation theory spans domains only implicitly. Human Adaptation Engineering (HAE) offers a conceptual response: a five-stage lifecycle, domain contribution map, and five propositions that organize existing evidence without claiming a new sensor, algorithm, or clinical protocol.

HAE is intentionally modest in epistemic status. It is a framework for synthesis and hypothesis generation, not a finished theory. Its success will be measured by whether researchers and designers adopt shared language for disruption, response, adaptation, stabilization, and outcome—and whether subsequent empirical work falsifies or refines the propositions advanced here. By centering adaptation rather than classification, Human Adaptation Engineering aims to support the next generation of interdisciplinary human systems that measure change, understand adjustment, and intervene with respect for individual trajectories and ethical boundaries.

Conflict of Interest

The author declares that there are no conflicts of interest regarding the publication of this manuscript.

Research Data Statement

No new research data were generated for this study. This article presents a conceptual framework developed through the synthesis and analysis of previously published scientific literature. All sources used are cited in the References section.

References

- [1] S. Poria, E. Cambria, R. Bajpai, and A. Hussain. A review of affective computing: From unimodal analysis to multimodal fusion. *Information Fusion*, 37:98–125, 2017.
- [2] S. Li and W. Deng. Deep facial expression recognition: A survey. *IEEE Transactions on Affective Computing*, 2020. doi:10.1109/TAFFC.2020.2981446.
- [3] S. Khare, V. Blanes-Vidal, E. Nadimi, and U. Acharya. Emotion recognition and artificial intelligence: A systematic review (2014–2023) and research recommendations. *Information Fusion*, 102:102019, 2023.
- [4] M. Shu, T. Zhu, and H. Yang. A review of emotion recognition using physiological signals. *Sensors*, 18(7):2074, 2018.
- [5] S. K. D’Mello and J. Kory. A review and meta-analysis of multimodal affect detection systems. *ACM Computing Surveys*, 47(3):43:1–43:36, 2015.
- [6] R. L. Charles and J. Nixon. Measuring mental workload using physiological measures: A systematic review. *Applied Ergonomics*, 74:221–232, 2019.
- [7] D. Tao, H. Tan, H. Wang, X. Zhang, X. Qu, and T. Zhang. A systematic review of physiological measures of mental workload. *International Journal of Environmental Research and Public Health*, 16(15):2716, 2019.
- [8] R. Parasuraman and G. F. Wilson. Putting the brain to work: Neuroergonomics past, present, and future. *Human Factors*, 50(3):468–474, 2008.
- [9] P. A. Hancock et al. Brain at work and in everyday life as the next frontier: Grand field challenges for neuroergonomics. *Frontiers in Neuroergonomics*, 1:583733, 2020.
- [10] Y. Liang, X. Zheng, and D. Zeng. A survey on big data-driven digital phenotyping of mental health. *Information Fusion*, 52:290–307, 2019.
- [11] J.-P. Onnela and S. L. Rauch. Harnessing smartphone-based digital phenotyping to enhance behavioral and mental health. *Neuropsychopharmacology*, 41:1691–1696, 2016.
- [12] P. Bufano et al. Digital phenotyping for monitoring mental disorders: Systematic review. *Journal of Medical Internet Research*, 25:e46778, 2023.
- [13] J. P. M. Mendes et al. Sensing apps and public data sets for digital phenotyping of mental health: Systematic review. *JMIR Mental Health*, 9(2):e28735, 2022.
- [14] M. C. Howard. A meta-analysis and systematic literature review of virtual reality rehabilitation programs. *Computers in Human Behavior*, 70:317–327, 2017.
- [15] G. López et al. What do randomized controlled trials say about virtual rehabilitation in stroke? A systematic literature review and meta-analysis. *Journal of NeuroEngineering and Rehabilitation*, 15:74, 2018.
- [16] J. Chen, C. Or, and T. Chen. Effectiveness of VR-supported exercise therapy for upper extremity motor rehabilitation in stroke: Systematic review and meta-analysis. *Journal of Medical Internet Research*, 24:e24111, 2022.
- [17] M. Soleimani, M. Ghazisaeedi, and S. Heydari. Efficacy of VR for upper limb rehabilitation in stroke: Systematic review and meta-analysis. *BMC Medical Informatics and Decision Making*, 24, 2024.
- [18] M. Maier et al. VR-mediated stroke rehabilitation with physiological computing: Systematic review. *Frontiers in Virtual Reality*, 3:889271, 2022.
- [19] Q. He et al. From digital human modeling to human digital twin: Framework and perspectives in human factors. *Chinese Journal of Mechanical Engineering*, 2024.
- [20] C. Tang et al. A roadmap for the development of human body digital twins. *Nature Reviews Electrical Engineering*, 1:199–207, 2024.
- [21] B. Kamel et al. Human digital twin: A survey. arXiv:2212.05937, 2022.
- [22] S. Elkefi et al. A scoping review of human digital twins in healthcare applications and usage patterns. *npj Digital Medicine*, 2025.

- [23] Rah, A. and Chen, Y. Virtual Reality as a Stress Measurement Platform: Real-Time Behavioral Analysis with Minimal Hardware. *Sensors*, 25(17):5323, 2025. doi:10.3390/s25175323. PMID: 40942750; PMCID: PMC12430991.
- [24] Rah, A. and Chen, Y. Stroke Rehabilitation in Virtual Reality Through Enhanced Plantar Pressure Detection Using Sensor Resolution and Adaptive Thresholding. *Algorithms*, 19(5):368, 2026. doi:10.3390/a19050368.
- [25] S. Greene, H. Thapliyal, and A. Caban-Holt. A survey of affective computing for stress detection. *IEEE Consumer Electronics Magazine*, 2016.
- [26] S. Anwer et al. Fatigue monitoring through wearables: A state-of-the-art review. *Sensors*, 21(3):814, 2022.
- [27] R. W. Picard. *Affective Computing*. MIT Press, Cambridge, MA, 1997.
- [28] A. A. Rizzo and G. J. Kim. A SWOT analysis of the field of virtual reality rehabilitation and therapy. *Presence: Teleoperators and Virtual Environments*, 14(2):119–146, 2005.

This preprint was submitted under the following conditions:

- The authors declare that the necessary Terms of Free and Informed Consent of participants or patients in the research were obtained and are described in the manuscript, when applicable.
- The authors declare that the preparation of the manuscript followed the ethical norms of scientific communication.
- The authors declare that they are aware that they are solely responsible for the content of the preprint and that the deposit in SciELO Preprints does not mean any commitment on the part of SciELO, except its preservation and dissemination.
- The authors declare that the data, applications, and other content underlying the manuscript are referenced.
- The deposited manuscript is in PDF format.
- The authors declare that the research that originated the manuscript followed good ethical practices and that the necessary approvals from research ethics committees, when applicable, are described in the manuscript.
- The authors declare that once a manuscript is posted on the SciELO Preprints server, it can only be taken down on request to the SciELO Preprints server Editorial Secretariat, who will post a retraction notice in its place.
- The authors agree that the approved manuscript will be made available under a [Creative Commons CC-BY](#) license.
- The submitting author declares that the contributions of all authors and conflict of interest statement are included explicitly and in specific sections of the manuscript.
- The authors declare that the manuscript was not deposited and/or previously made available on another preprint server or published by a journal.
- If the manuscript is being reviewed or being prepared for publishing but not yet published by a journal, the authors declare that they have received authorization from the journal to make this deposit.
- The submitting author declares that all authors of the manuscript agree with the submission to SciELO Preprints.