

Predictive Modeling of Human Fatigue and Recovery in Industrial Systems

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Abstract

Human fatigue and recovery are fundamental yet poorly quantified processes governing performance and safety in labor-intensive and hybrid human-machine systems. Despite decades of ergonomics research, current models cannot predict fatigue evolution or recovery across varying work conditions, particularly when human performance degradation and restoration occur simultaneously. This study defines the analytical and methodological challenges of modeling human fatigue and recovery and demonstrates, using evidence from a controlled order-picking experiment, the need for continuous, data-driven representations of competing fatigue and recovery dynamics under uncertainty.

The analysis highlights key barriers including nonlinear dynamics, multimodal and asynchronous data, uncertainty quantification, interpretability, fairness, and privacy that constrain existing reliability and machine learning frameworks. Addressing these barriers opens new research opportunities in Industrial and Systems Engineering (ISE), including reliability theory, hierarchical and causal learning, uncertainty-aware decision analytics, and ethical data infrastructures for human digital twins. Collectively, these directions articulate a convergent ISE vision with human-centric analysis and decision-making systems in which humans, AI, and machines co-evolve, adapt, and respect each other's limits to achieve resilient, safe, and ethically grounded intelligent operations.

Keywords

Human Fatigue, Recovery Dynamics, Uncertainty Quantification, Ethical AI, Resilient Industrial Systems.

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Biographies

Dr. Sahand Hajifar is an Assistant Professor in Information Systems and Business Analytics at Park University, Parkville, MO, USA. He earned his Ph.D. in Industrial Engineering from the University at Buffalo in 2022. His research focuses on human factors, including wearables, Internet of Things, and fatigue modeling, as well as network analytics and signal processing. Dr. Hajifar has actively contributed to the professional community as a member of INFORMS and IISE. He has received several awards for his research, including the IISE QCRE Best Student Paper Competition, second place in the 2025 INFORMS Data Mining Society Data Challenge, and finalist in the 2024 INFORMS Manufacturing AI Case Competition. His work has been supported by funding from the New York and New Jersey Education and Research Center's Pilot Projects Research Training Program. He has collaborated with industry partners, including General Electric and the Electric Power Research Institute, on applied projects. Dr. Hajifar also serves as a reviewer for prominent journals, including *IISE Transactions*, *Applied Ergonomics*, and *Journal of Quality Technology*.

Dr. Setareh Kazemi Kheiri is an Assistant Professor in Industrial Engineering at the University of Pittsburgh, Pittsburgh, PA, USA. She earned her Ph.D. in Industrial Engineering from the University at Buffalo in 2025. Her research focuses on applied machine learning, forecasting, occupational health, manufacturing, and quality and reliability. Dr. Kazemi Kheiri has received multiple recognitions for her research and professional contributions, including being named Student of the Year at the 2024 Applied Ergonomics Conference, the 2024 Dieter W. Jahns Student Practitioner Award, and second place in the 2025 INFORMS Data Mining Society Data Challenge. Her work has been supported by funding from the New York and New Jersey Education and Research Center's Pilot Projects Research Training Program. She also serves as a reviewer for *IISE Transactions*. She is an active member of INFORMS, Women in Statistics and Engineering (WiSE), and the Human Factors and Ergonomics Society (HFES).

Dr. Fadel M. Megahed is the Raymond E. Glos Professor and a Professor of Information Systems & Analytics at Miami University, Oxford, OH, USA. He received his Ph.D. and M.S. in Industrial and Systems Engineering from Virginia Tech and a B.S. in Mechanical Engineering from the American University in Cairo. His main research streams include applied artificial intelligence (AI) and statistical surveillance, with applications in manufacturing, public health, and occupational health & safety. His work in these areas has been funded by Aflac, the American Society for Safety Engineers (ASSE) Foundation, GE Research, Gore, the National Institute for Occupational Safety and Health (NIOSH), and the National Science Foundation (NSF). He is currently the Editor of the Case Study Section for the *Journal of Quality Technology*.

Dr. Lora A. Cavuoto is a Professor of Industrial and Systems Engineering at the University at Buffalo, Buffalo, NY, USA. She received her Ph.D. in Industrial and Systems Engineering from Virginia Tech, Blacksburg, VA, in 2012. Her research focuses on physical ergonomics, occupational safety and health, human factors in healthcare, and surgeon ergonomics. Dr. Cavuoto's research has been supported by funding from the CDC National Institute for Occupational Safety and Health (NIOSH), the National Institutes of Health (NIH), the US Army, and the American Society of Safety Professionals Foundation. She currently serves as a Scientific Editor for *Applied Ergonomics*.

Dr. Hongyue Sun is an Associate Professor in Mechanical Engineering in the College of Engineering at the University of Georgia, Athens, GA, USA. Prior to joining the University of Georgia, he was an Assistant Professor in Industrial Engineering at the University at Buffalo. He has a multidisciplinary background, holding a B.E. in Mechanical Engineering, an M.S. in Statistics, and a Ph.D. in Industrial Engineering. Dr. Sun's research focuses on data analytics and artificial intelligence for advanced manufacturing, occupational safety, and healthcare systems. His work has been supported by the National Science Foundation (NSF), the National Institute for Occupational Safety and Health (NIOSH), United States Department of Agriculture (USDA), the U.S. Navy, and MxD. His research has received several best paper awards from INFORMS and IISE. He is the recipient of the Outstanding Young Manufacturing Engineer Award from SME and the University at Buffalo's Exceptional Scholar: Young Investigator Award in 2023. Dr. Sun is an active member of IISE, INFORMS, and ASME.