Editorial: Special Issue: Towards a Transdisciplinary Approach to the Development and Control of Haptic Devices for Human-in-the-Loop Applications

Building haptic interfaces for human-in-the-loop applications is a profound scientific and technological challenge. It requires developing methods to intuitively channel sensorimotor information between afferent and efferent neural pathways of a human user and inputs and outputs of an external system. In such applications, artificial touch may serve as a virtual extension of the human body to a remote location (e.g., teleoperation) or it can create a perception that an external system is a part of the body (e.g., prosthetics).

The integration of haptic technologies into human-in-the-loop systems requires deep understanding of sensorimotor control from multiple perspectives. This Special Issue brings together contributions from diverse fields to explore how advanced haptic interfaces can seamlessly integrate with human cognition and motor control.

Seven manuscripts have been accepted and published within this Special Issue, addressing design, sensor data processing, and control of haptic systems. Overall, these papers showcase a variety of innovative approaches — from closed-loop feedback systems in prosthetics, to novel interfaces that convert sensor data into tactile perceptions for enhanced object manipulation. Contributions also include studies on compensatory control in teleoperation, frameworks for programming collaborative robots via wearable sensors, and intelligent haptic feedback systems for automated driving environments. Collectively, these works underscore the critical need to integrate advanced sensor technologies, algorithmic data processing, and bio-inspired design principles in creating next-generation haptic devices.

Shi et al. [A1] designed and developed a fully hydraulic closed-loop haptic system, which is lightweight, battery-free, and controller-free. The system includes a sensor placed on the fingertip of a prosthetic hand and an actuator located on the human body (e.g., residual limb) to provide tactile sensation. In this system, the prosthetic fingertip receives external mechanical stimuli and transfers them to a feedback actuator through an incompressible fluid, providing directional force guidance. Their work demonstrates how fluidic mechanisms can be harnessed for mechano-tactile feedback, contributing to the development of more intuitive and responsive prosthetic devices.

Carducci et al. [A2] investigated the effects of various teleoperator coupling dynamics—including mechanical, unilateral, and bilateral—on visual-motor pursuit tracking performance with a 1-DoF testbed. The teleoperator system consists of a leader, a follower, and the coupling dynamics between them. The system allows the user to control the virtual pointer to track a virtual ball with predefined rotational movements. The user controls the angle of the virtual rotational pointer by pronating or supinating their wrist on the leader input. Their findings reveal that humans can develop compensatory control strategies to adapt to different coupling conditions. This study highlights the importance of understanding human motor adaptability in teleoperated systems, paving the way for improved design and control of human-in-the-loop haptic interfaces.

In [A3], Ivani et al. described the assessment of a novel interface to convey artificial tactile feedback to a prosthesis user, focusing on contact and texture detection. Using two accelerometers on the thumb and index finger of a prosthetic hand, the sensor data were processed and translated into vibrations delivered to the forearm (residual limb). The system was evaluated in able-bodied participants and a person with amputation, for whom the feedback was fully integrated inside the socket. The results showed that the feedback improved texture recognition and increased the feeling of ownership. This contribution emphasizes the potential benefits of well-designed haptics in improving subjective experience and interaction between the user and their bionic limb.

In [A4], Meattini et al. proposed an enhanced framework for programming by demonstration, which allows for intuitive programming also accessible to non-expert users. By using a wearable EMG-based human-robot interface that measures muscle co-contraction, programming inputs are conveyed via hand stiffness modulations. Complemented by vibrotactile feedback, the system enhances operator confidence and accessibility for non-expert users, opening new avenues for human-robot collaboration.

Peters et al. [A5] developed a soft robotic seat equipped with 12 custom fiber-reinforced pneumatic actuators designed to provide haptic feedback for human intervention requests and situational awareness in highly automated vehicles. The authors describe the design and fabrication of the soft pneumatic actuator with fiber and fabric reinforcement to achieve an enhanced structural integrity. The authors used an analytical model for the actuator and characterized the elongation, force, and adaptable stiffness of the actuator. User evaluations reveal positive acceptance and usability, suggesting that such haptic systems can

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effectively communicate alerts and facilitate transitions between automation levels in a driving context.

The study of Ujitoka et al. [A6] titled "Effect of normal force intensity on tactile motion speed perception based on spatiotemporal cues" examined how variations in the normal force between skin and surface affect the perception of the speed of motion. Using a novel pin-array device that allows normal force to be altered without affecting shear force or vibrations from lateral slip on the skin, the authors demonstrated that increased normal force leads to higher perceived speeds and that the force level does not affect speed discriminability. The results are interpreted in terms of the mechanical interactions between skin and surface and their effects on sensory neurons within the skin. Potential applications of these results are also discussed.

The study by Duan et al. [A7] describes a robotic system for endovascular interventions featuring an advanced haptic interface on the surgeon's side. Key innovations include a dynamic load hysteresis compensation model for reducing the discrepancies between desired and actual forces, and a psychophysically based haptic perception model to improve the transparency and safety of teleoperation. During the system development, the authors considered surgeons' operational skills and ergonomic needs. The suitability of the system was validated through different experiments, showing better performance compared to the state-of-the-art interfaces for endovascular interventions.

A central theme throughout this Special Issue was the call for a transdisciplinary approach to haptics through integration of pioneer innovation, engaging engineering, computational neuroscience, human motor control, cognitive sciences, and philosophy of mind. Indeed, the above summaries demonstrate such an integrative approach, where technical contributions were inspired by insights from human motor control and neuroscience, to develop novel systems for the application of haptics in the context of online control with the human-in-the-loop. Still, there are even broader perspectives, for instance, philosophical and computational models and viewpoints, which are not included in this Special Issue. Nevertheless, such approaches take time to mature and settle, and we believe the present contributions have introduced valuable insights that can be considered as a first attempt towards transdisciplinarity in haptics. We hope this collection stimulates further research and fosters fruitful dialogue across disciplines, paving the way for the next generation of human-centered haptic technologies.

Editorial board:

The composition of the editorial board is an extension of the original editorial board of the Special Session entitled "Human-in-the-loop control of haptic devices: now and the future" at the SysInt international conference (https://sysint-conference.org/), from which this proposal derived.

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Appendix: Related Articles

[A1] G. Shi, J. Shi, A. Shariati, K. Motaghedolhagh, S. Homer-Vanniasinkam, and H. Wurdemann, "Design and characterisation of multi-cavity, fluidic haptic feedback system for mechano-tactile feedback," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 6–19, Jan.-Mar. 2025, doi: 10.1109/TOH.2024.3454179.

[A2] J. Carducci, N. J. Cowan, and J. D. Brown, "Teleoperator coupling dynamics impact human motor control across pursuit tracking speeds," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 20–31, Jan.-Mar. 2025, doi: 10.1109/TOH.2025.3546522.

[A3] A. S. Ivani, F. Barontini, M. G. Catalano, G. Grioli, M. Bianchi, and A. Bicchi, "Characterization, experimental validation and pilot user study of the vibro-inertial bionic enhancement system (VIBES)," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 32–44, Jan.-Mar. 2025, doi: 10.1109/TOH.2024.3435588.

[A4] R. Meattini et al., "Neuromuscular interfacing for advancing kinesthetic and teleoperated programming by demonstration of collaborative robots," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 45–57, Jan.-Mar. 2025, doi: 10.1109/TOH.2024.3484373.

[A5] J. Peters, B. Anvari, J. Licher, M. Wiese, A. Raatz, and H. A. Wurdemann, "Acceptance and usability of a soft robotic, haptic feedback seat for autonomy level transitions in highly automated vehicles," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 58–72, Jan.-Mar. 2025, doi: 10.1109/TOH.2024.3392473.

[A6] Y. Ujitoko, Y. Takenaka, and K. Hirota, "Effect of normal force intensity on tactile motion speed perception based on spatiotemporal cue," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 73–79, Jan.-Mar. 2025, doi: 10.1109/TOH.2024.3352042.

[A7] W. Duan et al., "Development of an intuitive interface with haptic enhancement for robot-assisted endovascular intervention," *IEEE Trans. Haptics*, vol. 18, no. 1, pp. 80–92, Jan.-Mar. 2025, doi: 10.1109/TOH.2023.3346479.