Theory and Practice of Science and Technology
2026, VOL. 7, NO. 2, 136-140
DOI: 10.47297/taposatWSP2633-456927.20260702

Applications of Haptic Feedback – Based Human – Machine Interaction Technologies in Assistive and Rehabilitation Fields: A Review

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ABSTRACT

Haptic feedback – based human – machine interaction (HMI) has become an important direction in assistive and rehabilitation technology. By providing tactile or force-related cues, haptic interfaces can compensate for sensory loss, support motor control, and improve coordination between users and devices. Recent progress in flexible sensors, wearable actuators, closed-loop control, and intelligent algorithms has expanded the use of haptic HMI in rehabilitation robotics, prosthetic control, sensory substitution, and wearable assistance. This review outlines the foundations of haptic perception and interface design, summarizes key technological advances such as sensor integration, multimodal interaction, and adaptive feedback, and discusses representative applications in rehabilitation and assistive systems. Current barriers, including limited tactile realism, wearability constraints, power demand, and user variability, are also considered, together with future directions in artificial intelligence, bio-inspired tactile systems, and personalized design.Overall, haptic HMI is moving from proof-of-concept devices toward more practical and clinically relevant systems. Further progress will depend on how effectively sensing, feedback, and user adaptation can be integrated into reliable real-world platforms.

KEYWORDS

Haptic feedback; Human – machine interaction; Assistive technology; Rehabilitation robotics; Sensory substitution; Prosthetic control

1 Introduction

Human-machine interaction (HMI) is evolving from command-based operation toward multisensory communication. Within this shift, haptic feedback has become increasingly important because it conveys touch, pressure, vibration, and force information, complementing or partially replacing visual and auditory input in tasks requiring continuous control and physical coordination [1-2].

Progress in flexible electronics, wearable sensing, skin-conformal materials, miniaturized actuators, and low-latency control has accelerated the development of haptic interfaces. Systems once limited to rigid laboratory settings are now moving toward lightweight, body-compatible, bidirectional platforms that can both sense user states and deliver real-time feedback [1-2]. At the same time, haptic technology is expanding from engineering prototypes to medical and health-related applications, particularly rehabilitation and assistive support [3].

This trend is especially relevant to rehabilitation and assistive technology. In rehabilitation, haptic feedback can strengthen sensorimotor training, improve movement awareness, and support error correction. In assistive systems, particularly prosthetics and mobility-related devices, tactile cues may compensate for missing sensory input, reduce visual dependence, and improve usability in daily tasks [4-6]. Haptic feedback is therefore becoming a functional element rather than an optional interface feature.

However, important barriers remain, including limited tactile realism, incomplete hardware integration, wearability constraints, power demand, and user-specific adaptation [2-3,6]. Thus, the key issue is no longer whether haptic feedback can be implemented, but how it can be translated into reliable, user-centered, and clinically useful HMI systems.

This review summarizes recent advances in haptic feedback-based HMI for assistive and rehabilitation applications. Section 2 outlines the foundations of haptic interaction, and Section 3 discusses emerging technologies for sensory augmentation.

2 Fundamentals of Haptic Feedback in Human–Machine Interaction

Haptic feedback transmits information through touch-related sensation, including pressure, vibration, stretch, motion, and force. In HMI, it acts as a core interaction layer linking device states, environmental signals, and user perception, especially in systems requiring continuous bodily coordination [7].

2.1 Forms of Haptic Feedback

Haptic feedback is commonly divided into tactile and kinesthetic components. Tactile feedback mainly stimulates

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cutaneous receptors and conveys local information such as contact, pressure, vibration, slip, or surface change, whereas kinesthetic feedback relates to force, limb position, and movement [7]. In practice, many systems combine both forms to improve interaction quality.

Among tactile modalities, electrotactile stimulation has received particular attention because it can encode diverse information while remaining relatively compact and wearable. A recent review and meta-analysis showed its promise in hand- and arm-related interactions, although effectiveness still depends on stimulation strategy, placement, and user adaptation [2]. This highlights that useful haptic design depends not only on technical output, but also on perceptual interpretability.

2.2 Physiological and Technological Foundations of Haptic Interaction

The performance of haptic systems depends on how well artificial stimuli match human sensory physiology. Touch perception relies on multiple skin receptors and is integrated with proprioceptive and visual input for object recognition, motor correction, and environmental awareness [7]. As a result, even technically advanced systems may perform poorly if their spatial, temporal, or intensity patterns do not fit perceptual capabilities.

Recent skin-integrated wireless interfaces illustrate the growing importance of perceptual encoding. These systems can deliver spatially distributed tactile information across the hand while supporting wearable form factors, showing that the design challenge is not merely to add feedback, but to encode tactile information in ways users can readily interpret [8].

2.3 Device Architecture: Sensors, Actuators, and Closed-Loop Control

Modern haptic HMI systems generally combine sensors, actuators, and control algorithms. Sensors detect information from the user, device, or environment; actuators convert commands into physical stimuli; and control modules determine how feedback is delivered [7]. Interaction quality therefore depends on system integration rather than on any single component.

This is increasingly evident in wearable systems. Skin-integrated stretchable actuators enable body-conformal closed-loop interaction, while active electronic skin platforms combine sensing and feedback within the same material system [9-10]. Such advances show that haptic HMI is shifting from discrete output devices toward distributed, body-compatible interaction architectures.

Overall, the fundamentals of haptic HMI now involve perceptual physiology, wearable device engineering, and adaptive information encoding. This broader framework underlies current progress in rehabilitation and assistive applications.

3 Human–Machine Interaction Technologies for Sensory Augmentation

Sensory augmentation uses artificial interfaces to extend, reinforce, or substitute aspects of human perception. In haptic HMI, this means converting environmental, biomechanical, or device-derived information into tactile cues that users can interpret in real time. The goal is not simply to generate sensation, but to improve performance, safety, or control without overloading the user [1,7].

Recent progress shows three major trends: more wearable and distributed sensing, more adaptive closed-loop feedback, and more multimodal interaction.

3.1 Sensor Integration as the Basis of Sensory Augmentation

Sensory augmentation depends first on what a system can detect. For this reason, recent haptic platforms increasingly embed sensing into wearable, body-conformal systems. This allows force, motion, deformation, and contact information to be captured more naturally during use.

Digitally embroidered smart gloves, for example, show how tactile interaction can be integrated into flexible textile-based systems while maintaining wearability and adaptive communication between the hand and the device [11]. Likewise, wireless haptic interfaces capable of generating programmable touch patterns across large skin areas demonstrate that feedback can be distributed across the body rather than confined to small rigid modules [12]. These developments make sensory augmentation less intrusive and more practical for real-world use.

3.2 Closed-Loop Feedback and Adaptive Control

Another important trend is the move from single-channel stimulation to multimodal haptic interaction. Earlier systems often relied on one form of tactile output, whereas newer platforms increasingly combine multiple feedback modes or integrate touch with other sensory channels.

Skin-integrated multimodal haptic interfaces exemplify this direction by providing richer tactile experiences while preserving flexibility and wearability [13]. Such systems are valuable because they better match natural perception, which depends on combined sensory streams rather than isolated signals. In practice, multimodal feedback may reduce ambiguity, improve salience, and support more intuitive learning.

This principle is also evident in sensory substitution and mobility assistance. A wearable obstacle-avoidance device for

visually impaired users showed that haptic feedback, combined with cross-modal learning, can support safer and more effective navigation [14].

3.3 Adaptive, Intelligent, and Context-Aware HMI Systems

A further development is the rise of adaptive and intelligent haptic HMI. Fixed feedback rules are often insufficient because users differ in sensitivity, preference, movement patterns, and cognitive load, while real-world environments are dynamic.

Wearable full-body motion tracking and haptic feedback systems supported by deep learning demonstrate how haptic communication can be linked to real-time motion understanding instead of simple preset mappings [4]. Similarly, wearable technologies for assisted mobility in real-world settings suggest that future haptic systems must operate reliably outside controlled laboratory conditions [5].

Overall, sensory augmentation in haptic HMI is moving beyond proof-of-concept stimulation toward integrated systems that can sense relevant information, convert it into meaningful tactile cues, and adapt feedback to users and tasks. This is why haptic HMI is becoming increasingly important in rehabilitation and assistive technology.

4 Applications in Rehabilitation

Haptic feedback has become increasingly relevant in rehabilitation because it can restore task-related sensory information during movement, helping patients detect errors, adjust performance, and engage more actively in training. This value is especially evident in neurological rehabilitation, where impaired sensorimotor integration often limits recovery [15-16].

4.1 Motor Rehabilitation

In motor rehabilitation, haptic feedback is most useful when it acts as a corrective cue rather than a simple technical addition. After stroke or other neurological injury, patients often have difficulty judging loading symmetry, movement trajectory, or movement quality. Under these conditions, tactile and kinesthetic cues can compensate for reduced intrinsic sensation and support more structured practice [15-16]. Current evidence suggests benefit for gait, balance, and postural control, although outcomes remain influenced by protocol design and user variability [15-16].

4.2 Neurorehabilitation and Sensorimotor Reinforcement

In neurorehabilitation, the importance of haptic input lies in rebuilding the sensory component of motor recovery. For patients with post-stroke upper-limb dysfunction, tactile reinforcement may help restore a more effective sensorimotor loop. Recent evidence linking tactile-feedback-assisted training to altered functional connectivity and cortical activation supports the view that haptic stimulation may influence neural engagement rather than serving only as an external prompt [17]. This also helps explain why haptic feedback is increasingly integrated into immersive rehabilitation platforms [15-17].

4.3 Rehabilitation Robotics and Home-Based Systems

Rehabilitation robotics remains a major application area because robotic systems can deliver repetitive, quantifiable, and assist-as-needed training. Once haptic feedback is incorporated, these systems can also communicate timing, resistance, and error information back to the user, thereby supporting more active participation [15]. At the same time, recent work suggests that future clinical value will depend less on robotic complexity alone than on portability, comfort, personalization, and sustained usability. This is why wearable and home-deployable biofeedback systems are attracting increasing interest for gait retraining, arm movement correction, and task practice beyond the clinic [16]. Overall, the systems most likely to matter clinically are those that provide interpretable feedback in forms patients can continue to use over time [15-17].

5 Applications in Assistive Technologies

In assistive technology, the function of haptic feedback is primarily compensatory rather than restorative. Haptic interfaces convert signals such as contact force, obstacle position, or body instability into tactile cues that users can interpret quickly without excessive visual dependence [6,18].

5.1 Haptic Feedback in Prosthetic Systems

Prosthetic systems remain one of the clearest examples of why haptic feedback matters in assistive design. Many users can control an artificial limb motorically but still lack meaningful sensory return, which increases cognitive effort and visual reliance. Recent reviews suggest that vibrotactile and electrotactile strategies can improve control and user experience in lower-limb prosthetic systems, although long-term usability and perceptual naturalness remain limiting factors [6]. More broadly, wearable mobility technologies indicate that effective assistance depends not only on control accuracy, but also on comfort, reliability, and real-world adaptability [5-6].

5.2 Sensory Substitution for Visual Impairment

Sensory substitution for visual impairment is another important application. Here, visual or spatial information is translated into tactile cues to support navigation and obstacle avoidance. Compared with auditory-only solutions, haptic systems preserve access to environmental sounds and may therefore be better suited to real-world mobility. Recent reviews document the growing use of wearable tactile interfaces, haptic vests, and directional cueing systems in this area, while also noting persistent challenges related to comfort, battery life, and environmental robustness [18-19]. In this context, the key practical question is no longer only whether tactile navigation is feasible, but whether it can be delivered in forms that are acceptable, reliable, and suitable for sustained use in daily life [18-19].

6 Technical Challenges and Limitations

Although haptic HMI has shown clear promise in rehabilitation and assistive technology, many systems remain closer to technical prototypes than mature practical tools. Once devices move from controlled environments into wearable or real-world use, limitations in fidelity, comfort, and robustness become much more apparent [20-21].

6.1 Limited Tactile Resolution and Sensory Realism

A persistent challenge is the gap between artificial stimulation and natural touch. Human tactile perception is highly sensitive to spatial pattern, temporal variation, and subtle contact change, whereas many existing interfaces still produce relatively coarse signals. As a result, many current systems still face difficulties in reproducing fine texture, realistic force transitions, and rich contact perception with sufficient realism and stability [21-22]. In practice, feedback that is detectable but ambiguous may increase user effort without meaningfully improving performance.

6.2 Wearability, Power Demand, and Human Factors

A second limitation concerns long-term usability. Many current systems still rely on components that are bulky, rigid, or energy-intensive, which restricts comfortable extended use. This is particularly problematic in rehabilitation and assistive contexts, where devices may need to be worn repeatedly in therapy or daily life [21,23]. In addition, technical performance alone does not determine acceptance. Users differ substantially in tactile sensitivity, cognitive tolerance, and adaptation speed, so even technically strong systems may fail if they are difficult to learn or uncomfortable to wear [20-21,23].

6.3 System Integration, Closed-Loop Robustness, and Practical Translation

Another major barrier lies in integrating sensing, actuation, and control into robust closed-loop systems. As haptic platforms become more sophisticated, they also become more dependent on stable coordination among sensors, actuators, wireless communication, and feedback algorithms [20,22]. Greater capability often brings greater fragility. At the same time, advances in tactile scanners and flexible tactile sensors suggest that hardware performance is improving, but practical translation still depends on whether these gains can be converted into reliable, low-burden systems for real users [24-25]. For healthcare applications, translation is therefore not a final step after development, but the main criterion by which system quality should be judged [20-25].

7 Conclusion and Future Perspectives

Haptic feedback-based human-machine interaction is becoming increasingly important in rehabilitation and assistive technology because it can restore or augment meaningful information loops among the user, the device, and the environment. Across current studies, its value is clearest when feedback is not treated as an isolated output, but as part of an integrated system linking sensing, control, and perception.

Even so, technical progress alone does not guarantee practical impact. Limitations in tactile realism, wearability, power efficiency, system integration, and user adaptation continue to restrict broader deployment [20-25]. Future progress will likely depend on the development of lighter wearable interfaces, more reliable closed-loop systems, and AI-assisted rehabilitation platforms that may better integrate real-time sensing, adaptive feedback, and personalized intervention within a more unified framework [26]. If these advances can be translated into robust real-world systems, haptic HMI is likely to play a growing role in next-generation assistive and rehabilitation technologies.

Funding

This work was supported by the College Students' Innovation and Entrepreneurship Training Program (NO: 202510752011 and S202510752001).

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