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Recent Advances in Supplementary Haptic Feedback for Human-Machine Interfaces in Upper Limb Assistance and Rehabilitation

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***Abstract*—Despite the rapid technological advancements we witnessed in the last few decades, effective regaining or substituting the impaired sensorimotor function of the upper limb is still a dream for many patients and researchers worldwide. While technology-aided motor therapy and advanced human-machine interfaces have significantly evolved, the efforts to integrate supplementary sensory feedback (SSF) to promote sensorimotor restoration after neurological or orthopedic damage became relevant only in recent years. In this review, we examine emerging strategies for encoding and delivering somatosensory information to users of prosthetic, orthotic, and rehabilitation systems, highlighting advances in electrotactile, vibrotactile, mechanotactile, and neurostimulation-based approaches. We synthesize cross-disciplinary findings from neuroscience, haptics, and clinical bioengineering to outline how SSF influences embodiment, motor learning, user acceptance, and real-world performance. Despite rapid technical progress, major gaps persist, including limited long-term evaluation, narrow user representation, and a lack of standardized methods for characterizing sensations and benchmarking device performance. We discuss the scientific and translational barriers that currently constrain widespread adoption of SSF technologies and identify promising directions for future research, including unified assessment frameworks, personalization strategies, and the development of richer haptic vocabularies to enhance the functionality and clinical relevance of next-generation sensorimotor interfaces.**

***Index Terms*— Assistive technologies, Haptic Interfaces, Human-Machine Systems, Rehabilitation robotics, Tactile Feedback.**

I. INTRODUCTION

MILLIONS of people around the world experience significant sensorimotor impairments due to spinal cord injury (SCI), peripheral nerve injuries, neuropathies, stroke, and other neuromuscular disorders [1]. Missing proprioceptive or tactile signals and/or their altered processing hinders the relearning of fundamental motor functions such as control of balance, walking and grasping [2]. This is because sensory information is essential for human motor control. Thanks to the internal models formed in the cerebellum, the central nervous system (CNS) predicts movements and their sensory consequences based on an efferent copy of the motor command [3], [4]. When the actual sensory feedback differs from these predictions, a prediction error arises, prompting the intact CNS to refine motor actions and improve internal models, thereby closing the control loop [5]. A partial or complete loss of somatosensory inputs may impair such adaptations and ultimately prevent the recovery [6]. In addition, impaired temperature and pain sensations, balance, or proprioception can impact the safety of people with neuromotor damage, even after adequate motor recovery [7]. Therefore, restoring the missing sensory function may actively support and enhance motor performance and facilitate rehabilitation.

Tactile sense allows for the perception of surface properties and contact events and relies mainly on the mechanotactile receptors present in the glabrous skin. These receptors vary in their response characteristics, including adaptation rate, receptive field size, and temporal and spatial resolution, allowing them to encode a wide range of tactile stimuli with high specificity [5]. In contrast, kinesthesia and proprioception enable the perception of applied forces, movements, and position [8]. When this *intrinsic feedback* - naturally arising during interactions - is unavailable (e.g., in people with severe somatosensory impairments), *supplementary feedback* can be delivered to compensate for the missing sensory input [9].

Haptic stimulation, which transmits information through the sense of touch, is a commonly used approach to provide supplementary feedback. Literature studies revealed that targeted haptic stimulation can enhance motor performance by increasing corticospinal excitability and expanding cortical representations of stimulated body parts [10]. Most commonly,

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haptic feedback is used for sensory substitution, as when force feedback is conveyed in the form of vibrations delivered to the skin [11]. However, it can also be modality matched, such as when force information is transmitted through direct application of force or pressure [2]. Modality-matched haptic feedback allows users to focus their visual attention on the task, potentially reducing the cognitive burden during rehabilitation exercises or while using assistive devices, especially when compared to screen-based visual feedback [2]. Although it is generally agreed that supplementary haptic feedback, delivered by a human therapist or through an artificial device, can support motor (re-)learning, the most effective way for its integration with rehabilitative or assistive technologies is still debated [12].

In the context of rehabilitative and assistive technologies, the patient is connected to the external system via a human-machine interface (HMI). The HMI interprets user inputs (such as gestures, biosignals, or button presses) to decode their intention and send commands to the assistive system. Ideally, to close the control loop, the HMI should be bidirectional. It should provide feedback (such as tactile or kinesthetic cues) during and/or after the action was executed to inform the user about the system's internal status and/or its interaction with the environment (Fig.1).

This review systematically examined the development of supplementary haptic feedback strategies in HMIs for upper-limb assistive and rehabilitation devices from the year 2017 onwards. The progress in the developments of sensory feedback for prostheses and neuroprostheses up to that year was summarized in two influential reviews [13], [14], and some feedback modalities, such as osseoperception, emerged in the meantime [15]. Unlike previous reviews, which typically focus on a single device class (e.g., prosthetics) or a single feedback modality [13], [14], [16], [17], this review aims to provide three novel perspectives: (i) a cross-domain synthesis across diverse assistive systems, including prostheses, neuroprostheses, exoskeletons, and rehabilitation devices; (ii) a modality-level comparison supported by meta-analysis; and (iii) a translational perspective on technological maturity and clinical readiness. In this sense, the present work is intended as a comprehensive, comparative and translational synthesis of the field.

The review is organized as follows: Section I introduces the topic; Section II explains the systematic methodology employed for selecting papers; Section III presents a systematic mapping of feedback modalities; Section IV reports a meta-analysis of study characteristics; Section V provides a comparative synthesis and translational perspective, outlining future directions.

II. METHODOLOGY OF SYSTEMATIC REVIEW

This study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA), a methodical approach to gathering and filtering research items relevant to the topic. The literature search was conducted from January 1st, 2017, to December 31st, 2024, on four digital databases: (1) *IEEE Xplore Digital Library*; (2) *Scopus*; (3) *PubMed*; and (4) *Web of Science,* to ensure a comprehensive collection of relevant studies. The terms included in the research string concerned both the nature of the supplementary feedback and the technologies used to provide it to the users of upper-limb assistive or rehabilitation devices (See Table I). The database screening was conducted on titles, abstracts, and keywords. After removing duplicates, records related to the lower limb, animal studies, technologies without

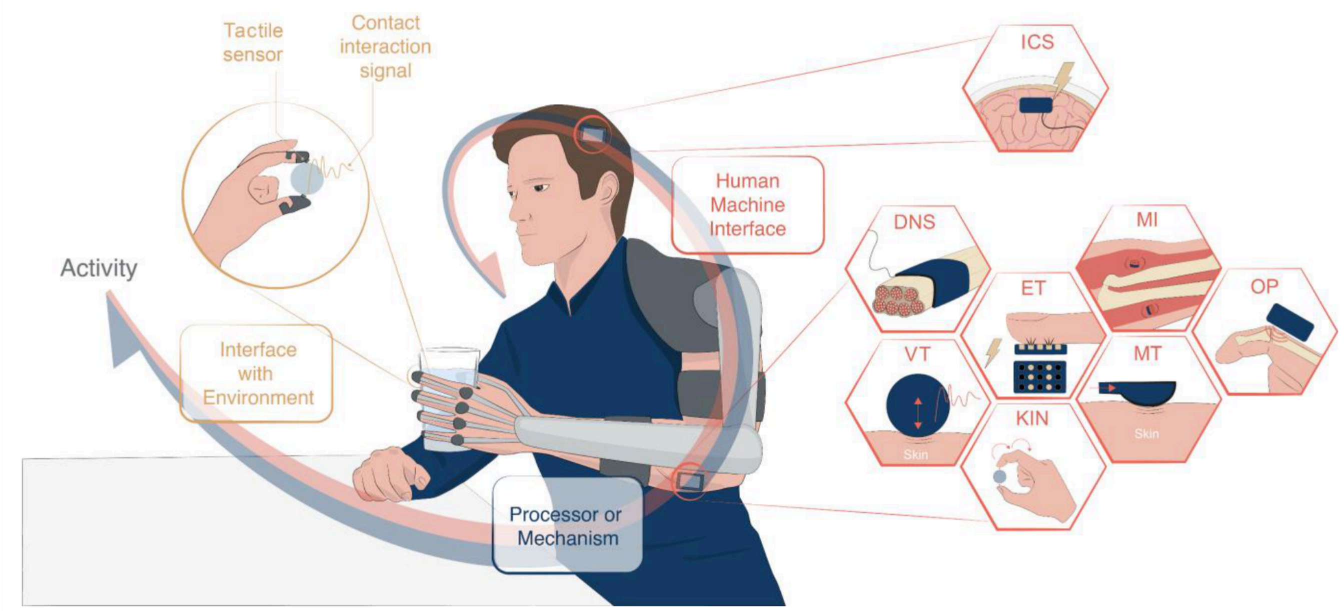

Fig. 1. Diagram of a human-machine interface (HMIs) in assistive technologies. Bidirectional HMIs link users to rehabilitative and assistive devices by decoding tactile inputs and providing augmented feedback through various stimulation modalities. Invasive Cortical Stimulation (ICS), Direct Nerve Stimulation (DNS), Vibrotactile (VT), Electrotactile (ET), Mechanotactile (MT), and Kinesthetic (KIN) stimulations have been explored in the past in multiple studies. Myokinetic Implants (MI) and Osseoperceptive Feedback (OP) are more recently proposed approaches.

TABLE I

RESEARCH STRINGS USED FOR EACH DATABASE

Database	String
IEEE Xplore, Scopus, Web of Science	TITLE-ABS-KEY ((((haptic OR tactile OR vibrotactile OR sensory) AND (perception OR feedback)) OR (bone AND conduction) OR (osseoperception OR osseointegr*)) AND (prosthe* OR neuroprosthe* OR orthosis OR exoskelet* OR implant OR robot) AND (rehabilit* OR assistance OR assistive OR (((human-machine OR body-machine OR man-machine) OR ((human OR man OR body) AND machine)) AND interface* OR interaction))))
PubMed	TITLE-ABS ((((haptic OR tactile OR vibrotactile OR sensory) AND (perception OR feedback)) OR (bone AND conduction) OR (osseoperception OR osseointegr*)) AND (prosthe* OR neuroprosthe* OR orthosis OR exoskelet* OR implant OR robot) AND (rehabilit* OR assistance OR assistive OR (((human-machine OR body-machine OR man-machine) OR ((human OR man OR body) AND machine)) AND interface* OR interaction))))

rehabilitative or assistive purposes, and systems that did not provide supplementary feedback to the user were excluded. We excluded gray literature (technical reports, preprints, and theses), as well as review articles, opinion pieces, and publications not written in English. The results exported were screened by title and abstract by two reviewers (namely the first and second authors of this manuscript) to determine their relevance. Articles that met the inclusion criteria during the title and abstract screening were selected for full-text review. Any discrepancies between the reviewers were resolved by a third reviewer, namely the fifth author. The remaining records underwent full-text screening. They were deemed eligible if they i) included strategies to provide supplementary haptic feedback to the user, ii) were applied during the use of devices for upper limb motor assistance or rehabilitation, and iii) were evaluated in studies involving human participants. Studies involving “sensory substitution” by using auditory and visual cues to feed back tactile information were excluded.

In total, 135 studies were retained and analyzed after the screening and eligibility assessment process (Fig. 2). For each study, we noted the device and the modality used to provide feedback.

III. SUPPLEMENTARY HAPTIC FEEDBACK FOR SENSORIMOTOR REHABILITATION AND ASSISTANCE

We classified the devices into four categories: hand prostheses, exoskeletons, neuroprostheses, and hand-worn technologies. Active hand prostheses (henceforth referred to as prostheses) are intended to replace the function of the missing biological counterpart and can be myoelectric or body powered. Their mechatronic design can be customized to accommodate different amputation levels, as well as individual preferences and activity requirements. Powered exoskeletons (henceforth referred to as exoskeletons) are wearable robotic devices that typically integrate sensors and actuators to provide assistive or resistive forces, thereby enhancing or opposing the user's movements. Neuroprostheses target the nervous system, interfacing directly with the brain, spinal cord, or peripheral nerves to capture and/or stimulate neuronal activity. Hand-worn technologies are wearable devices equipped with sensors to monitor tactile interactions, as well as actuators (e.g., vibrators and/or tactors) to provide haptic cues without imposing motion.

The techniques to provide supplementary haptic feedback were clustered into invasive and non-invasive (Fig. 3) [2]. Invasive techniques include intracortical and spinal stimulation, direct intra or extra-neural nerve stimulation, and myokinetic implants, whereas non-invasive techniques were further subdivided into modality-matched or -mismatched. The former implies delivering stimuli using the same sensory modality as the natural information they are intended to render (e.g., a pressure stimulus to render contact force), whereas the latter refers to stimuli that does not match the modality of the original stimulus (e.g., increasing vibration amplitudes to render increasing levels of grasping forces) [17]. These approaches can also be combined leading to mixed modality feedback.

Kinesthetic and mechanotactile feedback are the two categories of the modality-matched approach [18]. The CNS uses kinesthetic awareness or proprioception to deduce location, motion and the feeling of tension of the body parts, while the tactile sense, also referred to as exteroception, is employed to infer environmental information. We can further make a distinction between implicit (movement-based) and explicit (sensory-based) haptic feedback [2]. The devices that

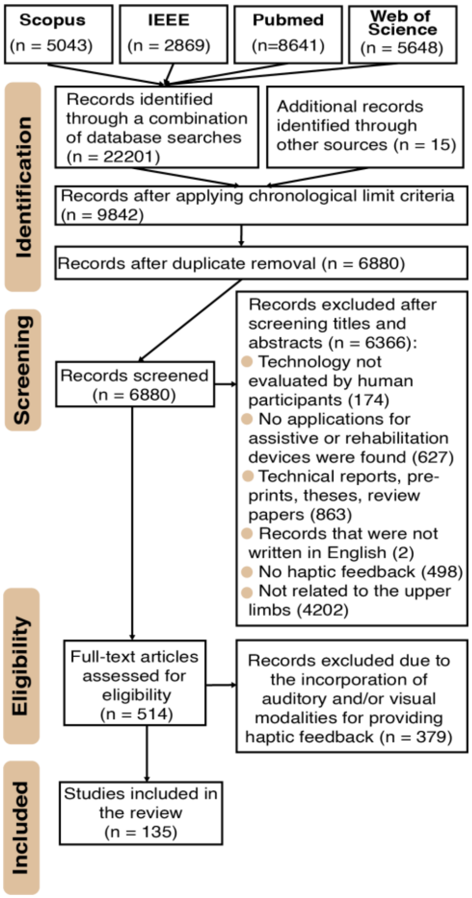

Fig. 2. PRISMA workflow to amass and filter the studies.

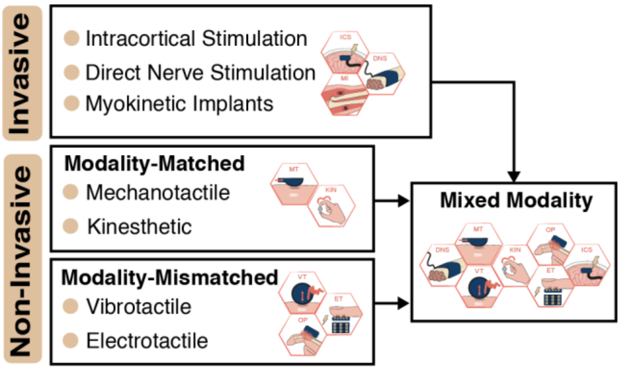

Fig. 3. Supplementary haptic sensory feedback approaches for rehabilitation or assistance, grouped by modalities

actively impose motion, such as exoskeletons, can promote rehabilitation and lead to the restoration of sensory functions by facilitating the intrinsic sensorimotor integration mechanisms, even when they did not provide explicit somatosensory feedback [10]. However, such systems were not included in the present review. On the other hand, devices that target sensory function by providing explicit somatosensory feedback, but without imposing motion, were included in this review.

The literature grouped by invasiveness and sensory modality are summarized in Table II. In the remainder of this section, we will discuss each of the aforementioned groups in more detail.

A. Invasive approaches

1) Intracortical Stimulation

Intracortical stimulation can evoke artificial somatosensory perceptions by delivering electrical pulses through high-resolution electrodes implanted in specific regions of the primary somatosensory cortex (S1) [19]. For example, by stimulating localized cortical areas, researchers have been able to elicit sensations, such as vibrations, buzzing, electrical tingling, and trembling, on the palm and fingers of individuals with essential tremors [20], epilepsy (Fig. 4A) [19], [21] and SCI [22].

However, clarity and resolution of these sensations depend on precise electrode placement, which is not a trivial task [23]. To address this challenge, the researchers from the Johns Hopkins APL introduced the use of high-density electrocorticography to enhance electrode implantation accuracy. This technique combines pre-, intra-, and post-operative recordings to accurately map finger representations in real-time on the S1 cortex [23]. After this method was used for electrode positioning, a SCI participant was able to distinguish tactile sensations from each finger when receiving intracortical stimulation [24].

The proper tuning of stimulation parameters is another important factor for the delivery of effective somatosensory feedback using this approach. A strong linear relationship has been reported between current amplitude and the perceived intensity of the sensation elicited on the hand, tongue, and fingers [25]. Several works have shown that participants suffering from epilepsy and SCI can reliably distinguish stimuli delivered at different frequencies. They reached accuracies of up to 98%, particularly when discriminating the frequencies of 50 Hz and 100 Hz, while detecting sensations in different areas of the hand covering nearly 65% of the whole hand [19], [26], [27].

Electrocortical stimulation have been applied to provide somatosensory feedback in closed-loop HMIs, where electrodes implanted in the motor cortex detected movement intention to control an actuator, while the stimulation of S1 provided real-time feedback. For example, in [28], a tetraplegic participant controlled the direction of a virtual airplane via motor cortex signals, while S1 stimulation indicated trajectory deviations. Over three sessions, the task completion success rate increased from 78% to 94%, demonstrating the potential of intracortical feedback for guiding virtual control tasks. A study from the University of Pittsburgh used a similar methodology in which brain signals controlled a robotic arm, while intracortical stimulation provided proportional feedback about the torque applied by the robotic hand's fingers [29]. In this case, tasks involving grasping and transferring objects were performed by a tetraplegic participant, demostrating a 12% improvement in object transfer rate compared to the no-feedback condition, along with a 50% reduction in completion time. A similar setup, presented by Johns Hopkins University [30], applied this bi-directional HMI strategy to evaluate the ability of an SCI participant to recognize the softness of three different objects. The participant achieved the identification accuracy of nearly 70%.

2) Direct Nerve Stimulation

Direct nerve stimulation involves applying electrical impulses to peripheral nerves, to elicit and/or modulate sensory perception, including touch [14]. Epineural interfaces, such as cuff or Flat Interface Nerve Electrodes (FINE), do not pass through the nerve but instead surround it [31]. In contrast, intraneural interfaces, such as the Longitudinal Intra-Fascicular Electrode (LIFE) or Transverse Intra-Fascicular Multi-Channel Electrode, penetrate the nerve's protective sheaths, allowing intimate electrical contact with the peripheral nerve fascicles [32].

Direct nerve stimulation can be used in neural interfacing and prosthetics to restore or enhance sensory functions, especially when peripheral pathways still retain some functionality [14], [32]. Peripheral stimulation applied to the forearm of transradial amputees has been shown to evoke localized phantom hand sensations, felt as tingling, vibration, and pressure [33]. Pioneering work at the University of Utah demonstrated that when using this configuration, participants were able to feel the change in stimulation parameters, including frequency and amplitude modulation, with accuracies approaching 75% and 46% when discriminating 4 and 8 levels of intensity/frequency [34]. Building upon these findings, a closed-loop system enabled a transradial amputee to regulate grip force more effectively during object manipulation, improving compliance detection and object transfer performance by 44% and 46%, respectively, compared with no-feedback conditions [35]. The

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same group further refined their approach by introducing biomimetic feedback strategies [35], where stimulation was designed to mimic natural sensory encoding mechanisms, demonstrating that this enabled more intuitive use of the prosthesis. Such biomimetic approaches allowed participants to handle fragile objects more successfully (46%), respond more quickly to tasks (56%), and improve discrimination of object size and compliance (44%), when compared to standard sensory

TABLE II

SENSORY FEEDBACK STRATEGIES FOR UPPER-LIMB HMI FOR REHABILITATION OR ASSISTANCE

Studies	**Feedback Modality: Invasive (I), Non-Invasive (NI)**		**Sample size range: Healthy (H); Non-able bodied (NA)**	**Domain of application**	**Sensing technology**	**Stimulation Location**	**Advantages**	**Disadvantages**
[19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30]		Intracortical stimulation (I)	1-17 (NA)	Neuroprosthesis	None; ECoG	S1	• Natural sensation • High resolution • Low latency	• Highly Invasive • Low Stability • Regulatory barriers
[31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51]		Direct Nerve stimulation (I)	1-6 (NA)	Neuroprosthesis	Load cells; pressure; iEMG; ECoG	Nerves forearm;	• Somatotopic • Intuitive cues • Low latency	• Surgical risk • Long-term drift • Long-term evaluation missing
[52], [53], [54]		Myokinetic implants (I)	1 (NA)	Prosthesis	Electromagnetic sensors	Forearm	• Stable sensing • Natural proprioception • High resolution	• Full evaluation missing • Alignment issues
[55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66]	Modality-matched	Mechanotactile (NI)	1-30 (H); 1-44 (NA)	Exoskeleton; Prosthesis; Gloves	IMU; Pressure	Fingers; Palm; Forearm Upper arm	• Intuitive pressure • Low power • Wearable	• Bulky hardware • Low resolution • Slow dynamics
[67], [68], [69], [70], [71], [72], [73], [74]		Kinesthetic (NI)	1-40 (H); 1-7 (NA)	Exoskeleton; Neuroprosthesis; Prosthesis	Encoders; EEG; sEMG; Artificial reflex arc	Forearm; Upper arm; Hand	• Natural proprioception • Precise guidance • Immersiveness	• Non portable • Mechanically complex
[15], [75], [76], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113], [114], [115], [116]	Modality-mismatched	Vibrotactile (NI)	1-70 (H); 1-14 (NA)	Prosthesis; Exoskeleton; Glove; Neuroprosthesis	Bend; Force; Angle; Servomotor; sEMG; Pressure; EEG; Piezoresistive	Upper arm; Wrist; Shoulder; Elbow; Fingers; Forearm; Palm	• Low cost • Easy integration • Multi-tactor arrays	• Unnatural • Cognitive load • Limited resolution • Distracting
[118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138], [139], [140], [141], [142], [143], [144]		Electrotactile (NI)	1-26 (H); 1-5 (NA)	Prosthesis	Force; Electronic skin; Cutaneos ionogel mechanoreceptor; Flexible neuromorphic tactile; sEMG; Proximity	Forearm; Upper arm; Hand; Fingers; Palm	• High resolution • Lightweight • Versatile sensations • Multi-electrode arrays	• Impedance variability • Comfort issues • Cognitive load
[145], [146], [147], [148], [149], [150], [151], [152], [153], [154], [155]	Mixed Modality	Vibrotactile; Electrotactile; Mechanotactile; Kinesthetic; Direct Nerve Stimulation; Intracortical stimulation	1-40 (H); 1-9 (NA)	Prosthesis; Exoskeleton; Neuroprosthesis; Glove	sEMG ; EEG ; Force ; Angle ; Strain gauges ; Encoders ;	Hand; Fingers; Upper-Arm; Palm; Elbow; Wrist; Forearm; S1; Nerves	• Rich cues • Complementarity among channels • Higher accuracy	• Complex design • Hardware-intensive • Burdensome integration

Abbreviations: Primary sensorimotor cortex (S1); Electrocorticography (ECoG); Intramuscular Electromyography (iEMG); Inertial Measurement Unit (IMU); Electroencephalography (EEG); surface Electromyography (sEMG) feedback schemes. Similarly, investigators at the University of Michigan delivered electrical stimulation with amplitude proportional to prosthetic hand force, enabling participants to identify four objects of two different sizes and stiffness without visual feedback at accuracies above the chance level (≈54%) [36].

Building on this concept, researchers at the Università Campus Bio-Medico di Roma applied proportional stimulation to address more complex control demands and provided users not only with information about grip force but also about object slippage [37]. Participants performed grasp-and-transfer tasks involving precision, cylindrical, and lateral grips, moving objects from one side to another while blindfolded. Under feedback conditions, users demonstrated enhanced manipulation stability, with slippage errors reduced by 27% compared to the no-feedback condition. Moreover, performance improvements were consistent across grasp types, indicating that multi-parameter encoding can enhance both dexterity and reliability in prosthetic control.

Research groups at the University of Texas and the University of Minnesota have also reported progress in closed-loop neural interfacing using LIFEs implanted in the forearm of transradial amputees [32], [38], [39]. In these studies, the amplitude of electrical stimulation was proportional to grasping force, enabling users to regulate the grip force and discriminate up to seven distinct force levels. Similarly, Case Western Reserve University, in collaboration with University Hospital Cleveland Medical Center, demonstrated that direct nerve stimulation could convey phantom finger position information to transradial amputees. Using such feedback, participants could successfully identify between four and seven hand gestures with the accuracy of 75–94% [40]. Beyond functional improvements, participants reported increased prosthesis acceptance and greater ease of interaction in social contexts, highlighting the psychological benefits of artificial sensory feedback (Fig. 4E) [31], [41]. Extending this work, the same group combined direct nerve stimulation with intracortical brain signals in a tetraplegic patient, where brain activity was decoded to trigger forearm nerve stimulation. This approach restored both movement and finger-specific tactile sensations with good tolerability [42]. While these results underscore the potential of multimodal neuroprosthetic feedback, further studies are needed to evaluate long-term functionality and scalability.

At Scuola Superiore Sant'Anna (SSSA), researchers demonstrated that invasive sensory feedback could substantially improve prosthetic control. In initial studies, transradial amputees using this approach showed better regulation of grip when handling fragile objects (25%), as well as more efficient motor coordination (34%), with clear reductions in the delay between gripping and lifting compared to no-feedback conditions [43]. Meanwhile, at Chalmers University of Technology in Sweden, investigators advanced the field by integrating sensory feedback into osseointegrated neuromusculoskeletal prosthetic systems [44], [45]. By combining implanted electrodes with osseointegration, they enabled transradial and transhumeral amputees to experience restored sensory perception during everyday tasks. The users reported improved grasp precision and increased sense of prosthesis embodiment, reflecting the practical benefits of this long-term interface [45]. The two institutions then collaborated, combining SSSA's expertise in sensory feedback with Chalmers' neuromusculoskeletal platform [46]. They demonstrated that artificial sensory input could be mapped to individual prosthetic fingers, allowing an amputee to execute more accurate and dexterous grasping movements during daily activities. Functional assessments showed measurable improvements in prosthetic control —by 13% in the Assessment of Capacity for Myoelectric Control and 23% in the Southampton Hand Assessment Procedure — and also reduction in pain perception. A follow-up study with additional participants validated these results [47], demonstrating enhanced coordination during tasks such as pick-and-lift, thereby confirming that the integration of invasive sensory feedback into neuromusculoskeletal prostheses offers both functional and quality-of-life benefits.

Other efforts at SSSA, in collaboration with the École Polytechnique Fédérale de Lausanne (EPFL), have focused on refining intraneural stimulation and developing biomimetic encoding strategies [48], [49]. Tests with two transradial amputees showed that linearly modulated amplitude signals were more intuitive than frequency modulation, improving performance in force control and shape recognition tasks by 5–10%. Building on this, the same group introduced neuromorphic approaches inspired by cutaneous mechanoreceptors. In [50], a morphological artificial fingertip encoded spatial texture information using spike-based neuromorphic detection, enabling participants to identify up to five distinct textures with 90% accuracy. In a subsequent study [51], the team implemented a hybrid encoding scheme emulating the responses of slowly adapting type I (SAI), rapidly adapting type I (RAI), and rapidly adapting type II (RAII) afferents. During stimulation discrimination and dexterity tasks such as the virtual egg test, participants doubled the number of successfully transferred objects relative to the no-feedback condition and reported significantly greater perceived naturalness than amplitude modulation. Together, these works highlight the progression of DNS—from basic force encoding toward biomimetic, neuromorphic stimulation capable of delivering intuitive and lifelike tactile feedback.

3) Myokinetic Interface

The Myokinetic Interface is an emerging technique, introduced by investigators from SSSA, to control prosthetic systems through magnets implanted within the residual muscles [52]. As the muscles contract and relax, the magnets shift position, producing changes in the surrounding magnetic field that can be detected by external sensors. Initial research has focused on using this information to decode user intentions for device control (Fig. 4I) [52], [53]. However, implanted magnets can also be used to provide proprioceptive and tactile feedback. This can be achieved through electromagnetic actuation, where external coils remotely induce controlled vibrations in the implanted magnets [52]. This vibration can activate mechanoreceptors in the muscles, thereby eliciting natural kinesthetic or vibrotactile sensations [53]. This principle was explored in [54], where a real-time system was developed to assess the effects of the vibrating magnets when embedded in a silicone phantom structure.

B. Non-Invasive approaches

1) Modality-matched

a) Mechanotactile

Mechanotactile feedback is implemented by stimulating the skin mechanically to replicate natural tactile sensations, such as pressure or skin stretches [11]. A common strategy to deliver mechanotactile feedback involves pneumatic cuffs or soft armbands placed on the forearm or upper arm. In prosthetic applications, such systems are typically used to produce pressure proportional to the grasping force exerted by the artificial hand. For instance, in [55], investigators from the University of Pisa (UniPi) developed a soft armband to convey force feedback from the index finger and thumb, increasing the pressure when both fingers are engaged (see Fig. 4B). Similar air-chamber-based bracelets have been used to improve grasp force regulation [56], [57] and enhance dexterity when manipulating fragile objects [58]. Another group at UniPi, in collaboration with University College London (UCL) and SSSA, designed a fluidic haptic interface driven by water flow—without electronic actuation—to deliver mechanotactile feedback directly to the fingers. Preliminary tests with healthy participants showed that thinner membranes (3 mm) produced a wider detectable force range than thicker ones (7 mm), confirming the feasibility of low-power, mechanically driven feedback for wearable applications [59].

Beyond static pressure, spatially distributed mechanotactile feedback has also been explored to convey directional information. In [60], researchers at Stanford and Rice University created air chambers that produced distinguishable pressure shifts across the forearm in up to four directions. Participants demonstrated high recognition rates in direction discrimination, suggesting that this could be an intuitive method for conveying multi-dimensional sensory information. Likewise, [61] presented a forearm-mounted device with three servomotors that applied pressure in distinct patterns, allowing participants to identify hand gestures of the prosthetic hand with high accuracy, even in the absence of vision. Additionally, UniPi researchers presented a skin-stretch-based system on the forearm to provide proportional information about prosthetic hand aperture. This system was used to enhance the recognition of object features such as shape, size, and stiffness, especially when visual cues were unavailable [62]. Similarly, in [63], skin-stretching on the forearm was used to simulate wrist flexion and extension. Participants reported perceiving movement-related sensations consistent with the intended wrist motion direction, although the feedback did not replicate a natural proprioceptive experience. In [64], another skin-stretch system, created in collaboration between UniPi and Rice University, was used for conveying the overall aperture of a multi-DOF prosthetic hand. Experiments demonstrated improved perception of hand opening without a significant increase of cognitive load in both able-bodied participants and a prosthesis user. Overall, these studies demonstrate that mechanotactile feedback can improve prosthetic users' ability to perceive hand posture, object properties, and movement, in the absence of visual cues.

Mechanotactile feedback has also been integrated into training and rehabilitation. In [65], upper-arm cuffs were used bilaterally in transhumeral amputees to train prosthesis grip force control, showing performance improvements after several sessions. In [66], investigators at Rice University in collaboration with UniPi implemented a multimodal feedback scheme within a serious game, combining kinesthetic cues generated by resistive torques of an exoskeleton with forearm squeeze and skin-stretch feedback to convey interaction forces and trajectory errors. Preliminary results on healthy participants showed that real-time feedback could reduce errors and enhance interaction while performing the therapy task.

b) Kinesthetic

Kinesthetic feedback refers to the perception of forces and torques acting on the musculoskeletal system. Researchers have explored the integration of this feedback modality into upper-limb rehabilitation games. In a study conducted at Kyung Hee University, an exoskeleton provided resistive torque during elbow flexion to simulate lifting different weights in a virtual environment, thereby increasing muscular effort and enhancing therapy intensity [67]. Similarly, the team at Delft University, in collaboration with the researchers at Erasmus University Rotterdam and the University of Bern, have employed virtual objects interaction with movement resistance for rehabilitation purposes [68], [69], [70], [71], [72]. For example, participants trained to invert a virtual pendulum using a robotic exoskeleton, where forces corresponding to the pendulum dynamics were applied through the joystick or exoskeleton interface to guide movement [68], [69]. Providing this feedback led to reduced errors compared to conditions without feedback. In another study [70], tactile and kinesthetic feedback were jointly delivered when interacting with virtual objects, enabling users to identify them more accurately than with kinesthetic cues alone. Additionally, these investigators have applied kinesthetic feedback in rehabilitation games to simulate real-world activities, such as bartending, where users manipulated virtual objects through resistive forces or exoskeleton assistance (see Fig. 4C) [71], [72]. Results with post-stroke patients indicated that haptic interaction enhanced engagement, which could, in turn, improve rehabilitation outcomes [2].

Beyond physical rehabilitation, kinesthetic feedback has also been combined with EEG-based HMIs to enhance realism and engagement in cognitive tasks. In [73], EEG signals were used to detect hand-opening intentions, triggering a robotic glove that provided feedback about the success of the mental task. The same approach was later applied to enable finger movements through an exoskeleton [74]. Preliminary results with healthy participants showed increased cortical activity when kinesthetic feedback was present. Such effects may be particularly valuable

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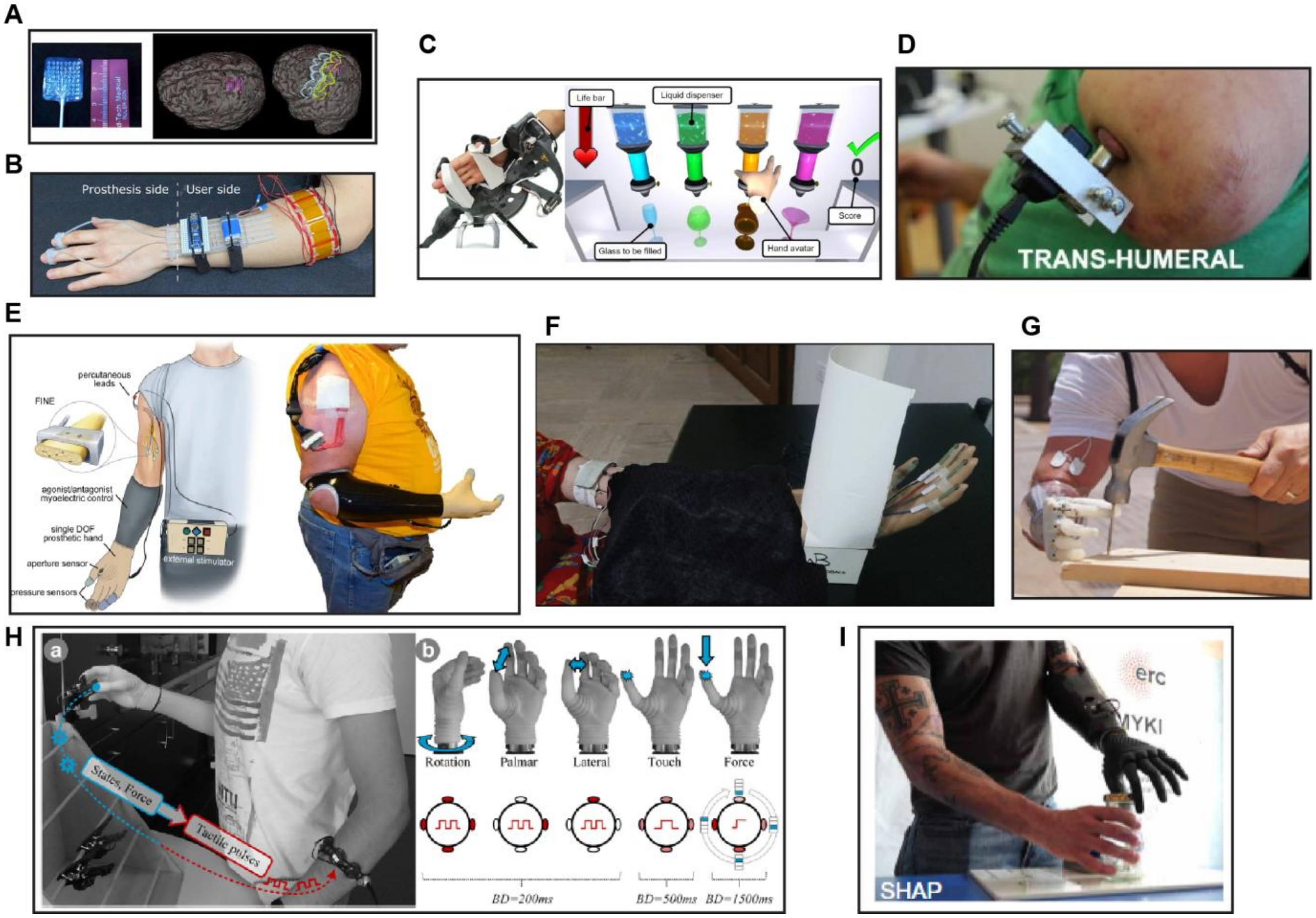

Fig. 4. Representative examples of augmented sensory feedback systems per type: (A) intracortical stimulation [21]; (B) mechanotactile [55]; (C) kinesthetic [72]; (D) Vibratory stimulation of bone [15]; (E) Direct nerve stimulation [31]; (F) vibrotactile [110]; (G) electrotactile [144]; (H) Vibrotactile [80]; (I) Myokinetic implants [53].

when combined with standard rehabilitation interventions, as already demonstrated when using active exoskeletons to deliver repetitive movements [2].

2) Modality-mismatched

a) Vibrotactile

Vibrotactile stimulation is one of the most explored methods to provide augmented feedback due to its ease of use [11], [75]. The selection of actuator technology depends on the requirements of a specific application in terms of power, response time, and frequency range. Eccentric rotating mass (ERM) motors are cost-effective and simple to control, and hence most used, but they have slower response times and coupled stimulation parameters (i.e., intensity and frequency cannot be modulated independently). Conversely, piezoelectric actuators offer high precision and fast response but require higher voltages [76]. Linear resonant actuators (LRA) offer a balance between efficiency and control, though they have limited bandwidth. A major common limitation of vibrotactile actuators is their low spatial resolution, as vibrations tend to spread across the skin, making it difficult to deliver highly localized tactile information [77].

In prosthetic applications, vibrotactile feedback is most often used to convey contact-related information. Typically, contact forces are measured via sensors embedded in the prosthetic fingertips or palm, and vibration intensity modulated to reflect parameters such as object stiffness [78], [79], [80], textures [81] or grasping force [80], [82]. For example, groups at the University Medical Center Göttingen, Imperial College London, and Aalborg University (AAU), have demonstrated that such feedback can support myoelectric prosthesis control by encoding grasp force, touch events, and wrist rotation [80] (See Fig. 4H). However, performance benefits are strongly task dependent [17]. In conventional dexterity tests such as the Box and Blocks or Clothespin Relocation tests—when performed with rigid objects—vibrotactile feedback often provides little benefit, as these tasks can be completed using maximal force without precision demands [80]. In this context, feedback may even prolong completion times due to increased cognitive processing demands. In these cases, feedback may even increase task completion time due to additional cognitive processing. Thus, vibrotactile grasp-force feedback is ineffective for tasks that do not require force modulation and may introduce unnecessary cognitive load.

By contrast, when tasks involve fragile or sensorized objects that require fine force regulation, vibrotactile feedback has been shown to improve accuracy [80], [83]. Subjective evaluations in these contexts frequently report an enhanced sense of

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embodiment (≈15–20%), accompanied by a modest increase in perceived cognitive load (≈5–10%) [80]. Neurophysiological evidence further refines this picture: functional near-infrared spectroscopy (fNIRS) studies at Johns Hopkins University showed that vibrotactile feedback during stiffness recognition tasks reduced cortical indicators of mental effort relative to no-feedback conditions, suggesting that workload may decrease once feedback is successfully integrated [84]. Together, these findings indicate that the effects of vibrotactile stimulation on performance and embodiment are highly task dependent. While feedback can enhance accuracy and promote embodiment in tasks requiring fine modulation of grip force or object discrimination, its benefits may diminish – or even hinder performance – in simpler tasks that do not demand such precision [16]. Similarly, the impact on cognitive load varies: it may initially increase due to the need to interpret additional sensory cues but tends to decrease as users adapt and the feedback becomes integrated into their motor control processes [85] .

Beyond tactile substitution, vibrotactile feedback has been widely used to convey proprioceptive information, such as joint position or movement. Collaborative work by the Italian Institute of Technology, AAU, the University of Genova, and the University Medical Center Göttingen explored spatial encoding strategies in which wrist angle was mapped onto activation patterns across vibrotactor arrays wrapped around the forearm or residual limb [86], [87]. These approaches enabled users to estimate wrist rotation with moderate accuracy, achieving success rates close to 80% [86], or angular errors around 20% [87]. Similar performance was reported at the University of North Carolina, where upper arm vibrotactor arrays conveyed prosthetic finger joint angles using combined spatial and intensity encoding [88]. Furthermore, wearable vibrotactile bracelets tested in hand-position and movement-guidance tasks further demonstrated that participants could reliably estimate limb position without visual input [89], [90], [91]. In these cases, the feedback was provided by distributing vibration patterns across multiple actuators, highlighting the potential of wearable vibrotactile arrays for enhancing proprioceptive awareness in assistive systems.

Vibrotactile feedback has also been employed to support higher-level control functions, including error signaling, predictive guidance, and biofeedback. Error-based schemes, such as those developed at the University of Bologna, used vibration cues proportional to force deviations and improved accuracy in reaching target force levels by approximately 25% [92]. Predictive feedback approaches, including work at the University of Alberta, conveyed impact anticipation through vibration, enabling smoother movement adjustments [93]. Spatial guidance has been demonstrated with multi-actuator bracelets, such as the Harbin Institute of Technology's system that encoded proximity to objects through vibration frequency and intensity, assisting visually impaired amputees in reach-and-grasp tasks [94]. Vibrotactile biofeedback linked to sEMG classification further reinforced motor intent during virtual grasping tasks in a study made at McGill University [95]. Further, AAU and the University of Novi Sad used arrays of vibrotactile feedback linked to EMG levels to enhance predictive control of grasping force [83]. Then, EMG and conventional force feedback were combined to facilitate both predictive and corrective control, improving grip force regulation by 20%-25% [96]. Overall, this demonstrates the effectiveness of vibrotactile feedback when it is used to facilitate feedforward or predictive control mechanisms rather than replacing sensory feedback alone [17].

An important dimension in vibrotactile design concerns the temporal structure of feedback. Continuous proportional feedback can convey rich information but may become redundant or distracting during certain task phases. To address this, researchers at SSSA explored discrete burst-based feedback to signal salient events such as contact or slippage, reporting improvements in intuitiveness, coordination, and dexterity of approximately 25–40% relative to no feedback [85], [97], [98]. Similarly, transient or fading feedback strategies preserved performance benefits while reducing distraction and discomfort [99]. These findings suggest that event-based or time-limited vibrotactile feedback may offer a better balance between information content and cognitive demand than continuous stimulation.

Vibrotactile stimulation has also been used to evoke kinesthetic illusions by vibrating muscles or tendons to induce a sensation of limb movement. At the Lerner Research Institute, stimulation of reinnervated residual muscles enabled amputees to reduce grasping errors to approximately 5%, accompanied by increased agency and perceived motion [100]. Complementary studies at the University of Pittsburg demonstrated that modulating vibration intensity across multiple sites could reliably encode movement amplitude [101]. In the clinical domain, colleagues at SSSA tested vibrotactors applied to agonist muscles in post-stroke patients performing reaching tasks [102]. Vibration-induced proprioceptive feedback led to measurable improvements in smoothness and accuracy of movement. These results highlight vibrotactile illusions as a promising strategy for enhancing motor learning and proprioceptive awareness in rehabilitation.

Longer-term studies suggest that vibrotactile feedback can contribute to the refinement of internal sensorimotor models. Work at the University of Birmingham and the University Medical Center Göttingen showed that force feedback facilitated the development of inverse models for prosthetic control, enabling users to reproduce desired force levels even after feedback removal [103]. Home-use studies by researchers of the University of California, further demonstrated that transhumeral amputees could integrate vibrotactile touch feedback into daily prosthesis use, reporting improved manipulation performance and embodiment over time [104]. Thus, these studies reinforce that vibrotactile feedback can aid motor learning and internal model formation beyond immediate task performance and show that this effect is preserved even in subjects with high level amputations.

In rehabilitation, vibrotactile feedback has been integrated into diverse virtual setups to support motor re-education and engagement. Arrays of vibrotactors on the upper arm were used to guide elbow flexion/extension [105], fingertip vibrators on the thumb and index supported grasping in children with cerebral palsy [106], and multiple vibrotactors placed on the forearm provided feedback during wrist/hand movements in post-stroke patients using exoskeletons [107] or joystick interfaces [108]. In these studies, haptic cues consistently enhanced accuracy and user involvement, highlighting their potential for improving motor function in serious games, potentially facilitating rehabilitation and recovery.

A key approach in rehabilitation and assistive contexts has been embedding sensors into gloves or armbands to detect contact events or applied force and deliver corresponding vibrotactile cues [11]. At SSSA, fabric gloves incorporating fingertip piezoelectric sensors and forearm actuators provided discrete feedback during object contact, enabling participants with sensorimotor deficits to improve coordination in fine manipulation tasks [109]. Similarly, researchers at Manchester Metropolitan University developed a forearm armband with five-coin motors linked to fingertip force sensors (Fig. 4F) [110]. Vibration intensity scaled with applied force, improving participants' ability to discriminate stiffness levels with accuracy rates above 80%. Expanding beyond contact and force feedback, the University of Southampton demonstrated that wrist-based vibrotactile cues could convey proximity information, increasing accuracy in distance estimation [111]. More advanced interfaces, such as the fingertip-mounted electromagnetic actuator array developed at Stony Brook University, could render multiple tactile modalities (force, vibration, angular cues, and skin drag), with healthy users successfully identifying surface structures and directional information, pointing to applications in motor guidance [112]. Together, these works have showed that wearable vibrotactile systems can effectively support rehabilitation, motor guidance, and complex manipulation, with clear functional benefits for users with sensorimotor deficits.

While vibrotactile feedback is most commonly delivered to the skin, recent work has explored bone-conducted stimulation exploiting osseoperception. Studies at SSSA and Chalmers University of Technology showed that vibrations applied to osseointegrated prosthetic abutments could evoke tactile or auditory percepts depending on frequency [15] (see Fig. 4D). Extending this approach, at the University of Melbourne, non-invasive bone-conduction interfaces targeting the olecranon further demonstrated reliable discrimination of vibration parameters and stimulation localization in both able-bodied and amputee participants [113], [114], [115]. Importantly, osseoperceptive feedback allowed for discrimination of virtual objects during augmented reality prosthetic tasks, achieving success rates of approximately 86–92% compared to visual-only conditions [116]. Collectively, these studies have shown that osseoperception can be a promising alternative or complement to skin-based vibrotactile stimulation, capable of providing robust perceptual cues while also being compatible with osseointegrated interfaces.

b) Electrotactile

Electrotactile interfaces deliver low-intensity electrical current to the skin, directly stimulating underlying nerve fibers and bypassing natural mechanoreceptors. The current travels through the subdermal space between the anode and cathode, activating cutaneous afferents and evoking tactile sensations in targeted areas [14]. Although the sensations differ from those produced by natural stimuli due to the artificial mode of activation (i.e., the direct stimulation of the nerves rather than the transduction of energy from mechanical to electrical), the broad range of tunable parameters of the stimulation enables the generation of diverse and informative tactile cues [16], [117]. Human perception of electrotactile stimulation has been studied in terms of sensation types, such as buzzing, vibration, or warmth, and the ability to distinguish them by modulating its parameters, such as frequency and amplitude [118], [119], [120].

Electrotactile feedback has been widely used to enhance grasp control in myoelectric prosthetic hands. Stimulation parameters modulated by contact or force sensors have been shown to improve grip force regulation and object feature recognition. For example, feedback has enabled users to discriminate object stiffness [121], [122], [123], [124], [125], size [126], and shape [124], [127]. Some studies presented by Università Campus Bio-Medico di Roma, University of Genoa, and AAU have mapped the output of piezoresistive sensors placed on the palm and fingers of robotic hands to electrotactile stimulation on the forearm, enabling users to identify static and dynamic mechanical interaction patterns delivered to the hand with an accuracy of around 90%. This allowed the participants to differentiate contact locations and recognize object properties [125], [128]. In [125], the feedback was implemented using a high-density matrix of recording and stimulation points, demonstrating the potential of electrotactile interfaces to establish a compact and yet high-bandwidth feedback interface.

Electrotactile feedback can support perceptual learning and seamless integration into the sensorimotor loop. For instance, repeated exposure to specific electrotactile patterns improves users' ability to discriminate them [119]. At AAU, researchers showed that multichannel electrotactile stimulation proportional to grip force is processed similarly to natural tactile feedback, indicating that such feedback can be seamlessly integrated into the sensorimotor loop [129].

Encoding schemes determine how electrotactile information is interpreted, influencing both perceptual clarity and task performance. For instance, a study by IIT and AAU compared spatial versus combined spatial-and-frequency encoding for low- and high-resolution discrete feedback of myoelectric signals (EMG biofeedback), showing that combined encoding improved performance for low-resolution arrays but degraded it at higher resolution [130]. The same group also used a joystick-based compensatory tracking task to compare frequency- and pulse-width-modulation encoding strategies, providing insights into which parameter encoding approach can optimize control performance [131]. Together, these studies illustrate the importance of systematically comparing different encoding methods, as the choice of encoding can significantly influence control performance and perceptual clarity.

Beyond tactile perception, electrotactile interfaces have been explored to enhance proprioception using sensory substitution. At Chongqing University, a multichannel system delivered stimulation proportional to wrist angles, improving participants' perception of limb position [132]. Similarly, researchers at AAU encoded hand aperture, wrist rotation, and grasping force of a hand prosthesis using spatially distributed stimulation around the forearm. The proposed feedback was designed to provide information about the complete state of the prosthesis (3 feedback variables) in an intuitive manner congruent with prosthesis motion, and the experiments demonstrated that the feedback reduced angular errors by 46–50% compared to no-feedback conditions when vision was blocked [133].

Electrotactile feedback has shown benefits in motor learning and skill acquisition. AAU investigators have demonstrated how spatially encoded grasping force feedback can facilitate the learning of grasping force control when applied over multiple sessions [134]. The difference in performance with and without feedback consistently decreased across sessions, showing that the participants were becoming less and less dependent on the artificial feedback. Beyond force control, electrotactile feedback can facilitate perceptual skill acquisition: at the University of Bern, a virtual game delivering texture-based stimulation enabled participants to recognize surface properties without visual input [135]. Collectively, these studies demonstrated that electrotactile feedback could enhance both motor precision and perceptual discrimination, with improvements sustained over repeated sessions and, in some cases, retained after feedback removal.

Beyond electrotactile stimulation, transcutaneous electrical nerve stimulation (TENS) provides a complementary strategy for restoring somatosensory feedback [136]. TENS is a non-invasive approach that delivers electrical currents to superficial nerves, producing somatotopic sensations that can be referred to missing fingers in transradial amputees [137]. Functional neuroimaging and EEG studies have shown that when stimulation—whether via TENS or electrotactile input delivered to phantom maps on the residual limb—is somatotopically organized, it can activate cortical regions corresponding to the phantom hand [138], [139], [140], [141] . This indicates that preserved somatosensory representations can still be accessed non-invasively in some amputees. In contrast, conventional electrotactile stimulation applied to non-somatotopic skin areas typically elicits localized sensations on the stump and does not produce the same cortical activation pattern. Moreover, TENS applied during motor imagery tasks in healthy participants enhances cortical activation relative to visual-only or no-feedback conditions, suggesting that artificial nerve stimulation can engage neurocognitive processes [142]. Similarly, a study by Shanghai Jiao Tong University used TENS during object exploration to convey tactile sensations emanating from the missing fingers [143]. Participants were able to perceive object properties such as length and softness while visual feedback was occluded, demonstrating that non-invasive nerve stimulation can provide finger-specific somatosensory cues.

A key limitation of electrotactile feedback is variability in perceived sensations due to fluctuating skin impedance in time and between locations, which reduces consistency across users and sessions. To address this, adaptive controllers have been developed; for example, researchers at the University of Illinois implemented an impedance-adaptive system that adjusted stimulation parameters in real time to maintain consistent sensations, enabling amputees to manipulate virtual objects using electrical stimulation feedback delivered at the skin over the biceps muscle (Fig.4G) [144]. These findings underscore that both adaptive control of stimulation parameters and careful electrode design are critical for maintaining reliable, interpretable electrotactile feedback across users and tasks.

3) Multimodal

Combining multiple stimulation modalities presumably enables richer and more intuitive haptic feedback by potentially engaging distinct somatosensory pathways. Investigators at the University of North Carolina-Chapel Hill and NC State University developed a multimodal myoelectric hand with supplementary feedback combining vibrotactile cues for contact events with electrotactile stimulation for stiffness and size, achieving object identification success rates of above 80% in a transhumeral amputee [145]. At the Lerner Research Institute, vibrators on reinnervated muscles were combined with pressure tactors to convey hand aperture and touch, respectively, yielding >81% success in stiffness recognition and object transfer tasks [146]. Other studies at IIT, Hannover Medical School and National Research Center for Rehabilitation Technical Aids integrated mechanotactile (pneumatic cuffs) and vibrotactile feedback to encode texture, hardness, and slippage, enhancing grip force control [147], [148].

Collaborations between the EPFL and the SSSA demonstrated that invasive (direct nerve stimulation, DNS) and non-invasive (electrotactile) modalities can be combined to convey complementary tactile and proprioceptive information [149]. In experiments with transradial amputees using myoelectric robotic hands, this hybrid approach enabled participants to discriminate object size and compliance—such as distinguishing small–soft or small–hard items—with an average accuracy of 75%. Moreover, users reproduced the target prosthetic joint angles with a median precision error of 9.1°, confirming that hybrid electrical feedback can effectively integrate multiple sensory channels to enhance perception and control.

In rehabilitation, vibrotactile and resistive feedback have been shown to enhance motor performance and engagement. Devices developed at the University of Michigan delivered both resistive and vibrotactile cues to individuals with muscle weakness, reducing hand positioning errors by 12–26% and increasing engagement [150], [151]. For elbow rehabilitation, researchers at the University of Tokyo demonstrated that combining force and vibration feedback improved movement accuracy in serious-game exercises [152]. Additionally, an illusion-based study at the University of Georgia showed that integrating kinesthetic and mechanotactile feedback enhanced embodiment of artificial limbs more effectively than when applying either modality alone [153].

Electrotactile, kinesthetic, and intracortical feedback have been shown to modulate cortical activity and reduce cognitive load during motor tasks. Investigators at the University of Tübingen demonstrated that both electrotactile and kinesthetic feedback during EEG-based motor imagery tasks enhanced cortical activation and decreased mental effort [154]. Complementing this, Johns Hopkins University reported that tactile vibration and intracortical stimulation elicited comparable neural responses in a post-SCI participant, suggesting that multimodal or alternative stimulation strategies can effectively engage somatosensory pathways for functional sensory restoration [155]. Together, these studies indicate that artificial sensory feedback can influence cortical processing in ways that may support improved motor control and rehabilitation outcomes.

IV. META-ANALYSIS

To provide the reader with a better grasp on this topic, we analyzed and categorized the aforementioned studies as well as summarized their main characteristics into relevant variables. More specifically, we have analyzed the field of application of supplementary sensory feedback, the population characteristics, the techniques to provide it, and possible technological limitations [16].

A. Field of application

To facilitate the visualization of recent research trends related to upper-limb sensorimotor rehabilitation and assistance, we analyzed the frequency of keyword occurrences in the included papers using VOSviewer[1] . Subsequently, we classified the application domain of each paper, distinguishing between the device types, i.e. prosthesis, exoskeleton, neuroprosthesis, and hand mounted devices.

Based on the density map derived from the keyword frequency across the analyzed studies, we identified approximately nine primary clusters (Fig. 5). The following list outlines the different types of graphics published in IEEE journals. They are categorized based on their construction, and use of color / shades of gray: The most frequently occurring keywords included *tactile feedback*, *stimuli*, *robotics*, *progress*, *prosthetic limb*, *perspective*, *virtual reality*, *somatosensory feedback*, *variability*, and *intensity*. Additionally, smaller interconnected clusters emerged, indicating recent advancements and deepened focus areas. These smaller clusters included terms such as *machine learning*, *grip*, *naturalness*, *sensory stimulation*, *haptic feedback*, and *user experience*, among others. Taken together, these clusters suggest that current research is strongly oriented toward improving sensory feedback and embodiment in prosthetic and robotic systems, while emerging areas such as machine learning and user experience reflect a growing emphasis on adaptive, personalized, and human-centered feedback approaches. Overall, the field appears to be shifting from purely mechanical assistance toward integrative sensorimotor restoration and intuitive control.

Analysis of the studies categorized by the device type reveals that those focusing on prosthetics are the most prevalent, accounting for approximately 57% of the total. Neuroprostheses follow at 27%, exoskeletons at 10%, and hand-worn technologies at nearly 6% (Fig.6A). This shows that closing the sensorimotor loop by providing explicit sensory feedback is relatively unexplored in the domain of exoskeletons and neuroprosthetics, which so far mostly focused on restoring motor functions.

B. Study populations

The included studies were counted and categorized based on the type of participants enrolled, distinguishing between studies with healthy participants and studies with disabled participants. Within the disabled participant group, included studies were further categorized by medical condition (e.g., SCI, stroke, amputation). For all studies, we also classified them by sample size as either pilot studies (N < 10) or evaluation studies (N ≥ 10). Counting was performed per study, allowing us to analyze how study size related to participant type—for example, how many evaluation studies included participants with disabilities [16].

The analysis of the population characteristics indicates that 49% of the studies included healthy participants, while the remaining 51% involved volunteers with disabilities (Fig. 6B). Among the latter, transradial amputees were the most commonly represented group (29%), followed by transhumeral amputees (7%), and individuals with SCI (6%). Studies involving patients with epilepsy and post stroke for 2% each. Other conditions such as essential tremors, partial hand amputations, wrist amputations and visual impairements each represented equal or less than 1% (Fig. 6B). Finally, regarding the sample size and study type, 43% of the studies were classified as evaluation studies - 27% involving healthy

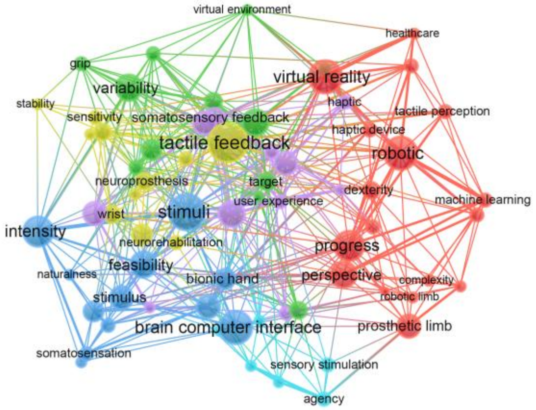

Fig. 5. Density visualization map of the occurrences found in the keywords of the included studies

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[1] [Online]. Available: https://www.vosviewer.com/

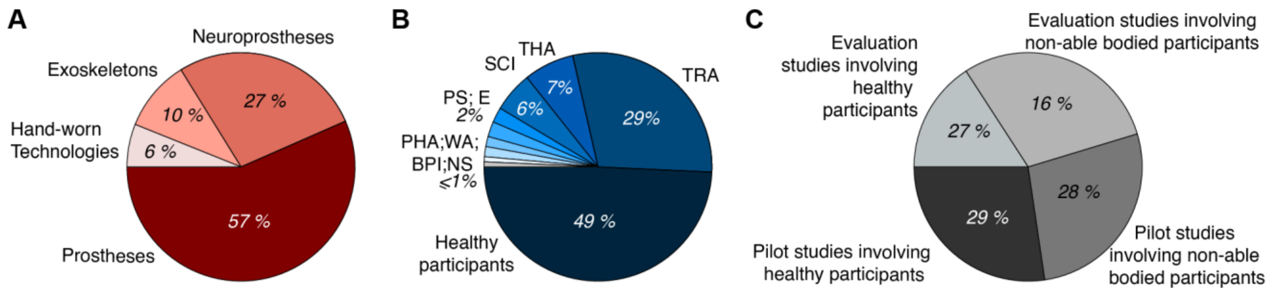

Fig. 6. Overview of included studies. (A) Proportion of studies grouped by type of rehabilitation and assistive devices. (B) Participant conditions across the included studies. (C) Population size distribution across the included studies **Note**: TRA - Transradial Amputation, THA - Transhumeral Amputation, SCI - Spinal Cord Injury, E - Epilepsy, PHA - Partial Hand Amputation, WA - Wrist Amputation, BPI - Brachial Plexus Injury, ET - Essential Tremor, NS – Non-sighted, PS – Post Stroke.

participants and 16% involving non-able-bodied volunteers. The remaining 57% of the studies were pilot studies, with 29% involving healthy participants and 28% involving non-able-bodied volunteers (Fig. 6C). Overall, these results indicate that research in upper-limb sensorimotor interfaces remains evenly divided between proof-of-concept experiments with healthy participants and preliminary validations with patients. The balanced distribution suggests that the field is steadily moving from experimental demonstrations toward clinically relevant testing, though large-scale trials are still limited.

C. Sensory feedback techniques

We further classified the studies based on relevant aspects of sensory feedback, such as locations of stimulation on the upper limb (excluding studies related to intracortical stimulation), level of invasiveness (invasive/non-invasive), and feedback modality.

Mapping the stimulation sites on the upper limb (Fig. 7) unveiled that the forearm is the most frequently targeted area, featured in 53% of the studies. This is followed by the upper arm (17%), the fingers (13%), and the hand (9%). Stimulation of joint areas is less common, with the elbow and wrist, targeted both in 4% of the studies, and the shoulder in only 1%.

Finally, regarding the invasiveness of the feedback methods, 27% of the studies employed invasive techniques, 73% non-invasive ones (Table II). These findings highlight the dominance of non-invasive feedback methods, particularly vibrotactile and electrotactile stimulation, reflecting a strong emphasis on user safety, comfort, and accessibility. The comparatively low number of invasive and kinesthetic studies indicates that technical and ethical barriers still limit their broader adoption.

V. DISCUSSION AND FUTURE DIRECTIONS

With this systematic review and meta-analysis, we aimed to offer a comprehensive overview of recent advancements in the use of supplementary sensory feedback for human-machine interfaces in upper limb rehabilitation and assistive technologies. We identified a variety of approaches to deliver somatosensory information, through both invasive and non-invasive techniques, and our findings highlighted certain shortcomings/several limitations that warrant further investigation in future research.

A. Quality of assessment and participant representation

A predominance of pilot studies (sample size < 10 participants) was observed, accounting for approximately 57% of the reviewed works. This continues to pose a challenge when proposing novel systems, as such limited sample sizes often do not guarantee the generalizability of outcomes or the statistical significance of findings [16]. Notably, 43% of the studies included participants with sensorimotor impairments, indicating progress in inclusive recruitment and the evaluation of devices' feasibility for their intended assistive or rehabilitation purposes. However, only 16% of the studies involved more than 10 participants from the target user population (see Fig 6C), underscoring a key limitation in much of the existing research. Therefore, despite known challenges in the patient recruitment, especially in some fields (e.g., upper limb amputations), future studies should prioritize recruiting larger cohorts from the intended end-user population to enhance the validity and applicability of their findings.

In addition, the reviewed literature shows a clear overrepresentation of individuals with transradial amputation. This bias likely reflects both practical considerations (e.g., easier recruitment and fitting) and experimental advantages, such as preserved residual musculature and more intuitive mappings between motor commands and artificial feedback [17]. While this focus has enabled meaningful progress, it limits the extent to which current findings can be generalized to users with more proximal amputations or, more generally, other neurological conditions. For instance, research into the impact of artificial feedback on rehabilitation of stroke subjects [109] or on the use of an exoskeleton by paralyzed patients [71], [72]

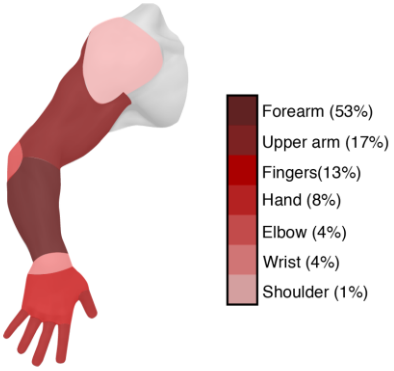

Fig. 7. Areas of stimulation on the upper limb used to provide supplementary haptic feedback.

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is still in a very early stage. Overall, these trends indicate that, despite encouraging progress toward inclusive testing, larger and more diverse cohorts are still needed to establish the reliability and clinical relevance of supplementary sensory feedback systems.

B. User- and device-dependent effectiveness of sensory feedback

Beyond sample size considerations, the effectiveness of supplementary sensory feedback depends strongly on user-specific factors and device context. In particular, the level of limb loss or neurological impairment plays a critical role in determining how feedback is perceived and utilized. In more proximal amputations, the reduced availability of residual sensory pathways often requires feedback to be delivered to proximal body regions (e.g., upper arm or trunk), which limits available stimulation sites and may affect perceptual sensitivity [83], [156]. In contrast, individuals with partial-hand amputations can often rely on residual natural sensation or incidental feedback, reducing the relative benefit of artificial cues. As a result, users with higher-level amputations may require more comprehensive or multimodal feedback strategies to compensate for the greater loss of proprioceptive and tactile information [80].

The role of sensory feedback is also shaped by the type of assistive or rehabilitative device. In prosthetic hands, feedback is most beneficial for tasks requiring precise force modulation, object discrimination, or slip detection. Conversely, in exoskeletons and rehabilitation systems, feedback often serves a guiding or corrective function to support motor relearning, coordination, and engagement rather than high-fidelity perceptual restoration [66]. Hand-worn devices and virtual rehabilitation platforms prioritize usability, motivation, and training efficiency [106].

Taken together, these observations underscore that sensory feedback strategies cannot be universally prescribed as one-fits-all solution. Instead, their design and expected benefits must be interpreted considering the user’s impairment level, residual capabilities, task demands, and assistive device characteristics. Explicitly accounting for these factors is essential for translating laboratory findings into clinically meaningful and user-acceptable solutions [157].

C. Comparison Across Sensory Feedback Modalities

Across the reviewed literature, no single sensory feedback modality consistently outperforms others across all tasks, user populations, or device types. Instead, the effectiveness of supplementary sensory feedback reflects trade-offs between perceptual richness, intuitiveness, invasiveness, and practical constraints such as wearability, calibration effort, and cognitive load (Table II) [80], [157].

Invasive approaches, including direct nerve stimulation and intracortical stimulation, show the potential to provide more naturalistic and somatotopically matched sensations, supporting sensorimotor integration and promoting the feeling of embodiment [1], [45], [122]. These characteristics suggest potential advantages for prosthetic applications requiring fine force modulation or object discrimination [46], [51]. However, their broader clinical applicability remains limited by surgical risks, regulatory constraints, and the relatively small number of users evaluated to date. Other emerging invasive techniques, such as myokinetic interfaces, have shown promise in restoring proprioceptive cues via implanted magnetic elements; however, these approaches remain exploratory, and their clinical translation is still under validation [53].

Among non-invasive techniques, vibrotactile feedback is the most widely adopted modality due to its robustness, low cost, and ease of use and integration across prostheses, exoskeletons, and rehabilitation platforms [80]. Vibrotactile cues have been successfully employed for grasp event detection, proprioceptive substitution, force regulation, object property discrimination, and motor training [83], [85], [106], [134], [147]. However, the stimulation parameters (frequency and intensity) are intrinsically coupled, which limits the perceptual resolution and richness. While multi-tactor arrays can be used to provide spatially distributed stimulation, they increase system complexity and setup requirements and may elevate attentional demands [87], [96].

Electrotactile feedback enables high spatial resolution and compact, lightweight implementations, making it well suited for wearable applications [131], [158]. By modulating the electrical waveform, this modality can evoke a range of sensations, including discrete touches, flutter, vibration- and even temperature-like cues, and supports biomimetic stimulation through dense, configurable electrode arrays [125], [158]. However, the elicited sensations are affected by skin impedance variability, and if not properly adjusted, the stimulation can lead to uncomfortable and even painful sensations. This complicates calibration, especially in interfaces with many pads, and thereby long-term use [144]. Importantly, if surface electrodes are placed at locations where peripheral nerves are superficially located, electrical stimulation can elicit somatotopic sensations without the need for surgery [149], but this approach is yet to be investigated more systematically. Mechanotactile feedback provides intuitive pressure-based cues, which can be used to convey modality matched feedback, for instance, using pressure to transmit grasping force information. This approach was integrated into several prosthetic systems, but is often constrained by bulkier hardware, limited spatial resolution, and slower actuation dynamics [56], [57]. Kinesthetic feedback, while typically less portable and mechanically complex, offers continuous and intuitive cues related to limb loading and motion, making it well suited for guidance-based and rehabilitation-oriented applications [66], [72].

Mixed-modality systems combine complementary feedback channels to increase perceptual richness and task performance, leveraging multisensory integration mechanisms. While these approaches often improve discrimination accuracy and robustness, they introduce additional design, integration, and calibration complexity [124], [146].

The reviewed evidence indicates that the selection of a sensory feedback modality should be guided primarily by task

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demands, user characteristics (e.g., level of impairment, residual sensory function), and device type, rather than by technological capability alone. Overall, supplementary sensory feedback is most beneficial in tasks requiring force modulation, object discrimination, proprioceptive adjustments in the absence of vision, or motor learning, whereas its advantages may be limited in simple grasping tasks that can often be accomplished using incidental feedback or feedforward control [80].

D. Wearability and functionality

Several studies have identified persistent challenges related to the wearability and functional integration of sensory feedback systems, particularly those involving small tactors, cuffs, or superficial electrodes [8], [58], [62], [66], [89], [90]. These shortcomings in wearable device design are closely tied to issues of user comfort, embodiment, and overall system usability. In prosthetic applications, both non-invasive and invasive sensory feedback interfaces are often integrated within the prosthetic socket [58], [87], while rehabilitation systems often embed feedback components into textile-based wearables or 3D printed housings [66], [106]. The use of compact actuators in such designs enhances portability and discretion. However, more complex systems—particularly those relying on high-power actuators or sophisticated control hardware—often require external components that reduce portability and increase the overall device weight [69]. This limits their suitability for daily use, especially among individuals seeking lightweight and unobtrusive assistive technologies.

Despite the functional benefits of supplementary sensory feedback, its integration into commercially available assistive devices remains limited, partly due to reliance on external actuators that are difficult to embed within compact systems. This highlights the need for miniaturized, energy-efficient, and low-cost feedback technologies that improve wearability and interoperability. Open-source hardware and software initiatives are emerging as promising enablers of dissemination and reproducibility, providing accessible platforms for prototyping vibrotactile and multisensory interfaces [64], [159], [160]. By lowering development barriers and encouraging standardization, such resources, together with industry–academic collaboration, may accelerate translation of sensory feedback solutions toward scalable and clinically viable deployment.

E. User needs

Although many included studies emphasize the user perspective—often through questionnaires or psychometric evaluations [31], [104] —the development of assistive and rehabilitation technologies remains largely technology-driven or curiosity-driven rather than user-centered. Prior perspectives highlight that insufficient integration of lived user experience into early design stages can hinder adoption and long-term usability of assistive technologies [161]. This gap underscores the need for participatory and co-design approaches of haptic feedback solutions, where end users contribute throughout development rather than only during evaluation phases.

Furthermore, most evaluations assess subjective perception, such as increased proprioception, reduced mental effort, or greater motivation to use the device [46], [84], [154]. While these findings are encouraging, they rely heavily on self-report methods, which can be prone to bias and variability. Furthermore, the "optimal" feedback modality—whether vibrotactile, electrotactile, or mechanotactile—may differ substantially between individuals, depending on personal preferences, residual limb characteristics, or neurological conditions [26], [89], [98], [103], [105].

These insights underscore a critical gap: without adaptive, user-tailored systems and more robust evaluation tools, HMIs may fail to meet the nuanced needs of end users. Future research should move beyond standard questionnaires, incorporating more objective and longitudinal assessments of usability and comfort. For example, this can be achieved using physiological workload measures (e.g., fNIRS, EEG) [84], [154] or in-home trials that capture long term adaptation [31], [45], [104]. Importantly, design processes must involve users early and continuously—through participatory or co-design methods—to ensure that feedback systems align with the lived experiences of those who depend on them.

Emerging modalities, such as thermal feedback, have been explored as modalities to enhance sensory realism. Researchers at SSSA [162] demonstrated that controlled thermal stimuli delivered through the abutment of amputees could evoke stable phantom thermal sensations corresponding to hot and cold. Similarly, a system developed at Seoul National University [163] integrated thermo-haptic actuators into a glove, allowing participants to perceive. While these modalities could have a positive effect in terms of embodiment and realism, some perspectives have reported that users consistently prioritize reliability, comfort, and functional utility over the addition of sophisticated sensory features, highlighting the importance of balancing innovation with practicality [161].

From a clinical and design perspective, these observations indicate that supplementary sensory feedback should be implemented flexibly, adapted to the target application context, rather than as a fixed or universal solution. Systems intended for daily assistive use should prioritize comfort, reliability, low cognitive demand, and minimal calibration burden, whereas rehabilitation and training platforms may accommodate technically more ambitious solutions, where advanced high-fidelity feedback is used to support motor learning and engagement. Importantly, feedback architecture should be modular and configurable, allowing clinicians to adjust modality, encoding, and intensity according to user preferences, residual function, and rehab stage. Such user-centered and adaptable designs are likely to improve acceptance, long-term adherence, and clinical relevance of haptic HMIs.

These considerations align with broader challenges identified in prior reviews of wearable and multisensory haptic interfaces across domains such as virtual reality, teleoperation, and navigation [8], [157]. Common limitations include the limited realism of artificial tactile stimulation, incomplete understanding of multisensory integration, and variability in

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perception due to anatomical differences and interface placement. In addition, ergonomic constraints such as long-term wearability and social acceptance, together with practical demands for miniaturized, lightweight, and energy-efficient hardware, remain critical barriers. Demonstrating clear functional benefits with minimal system complexity is therefore essential, particularly for clinical translation, where safety, reliability, and regulatory requirements impose additional constraints.

F. Challenges and future developments in HMIs for haptic feedback restoration

While many studies report the beneficial effects of supplementary sensory feedback on user experience, non-invasive approaches —particularly those delivering feedback to non-somatotopic locations—also highlight some limitations. These include increased cognitive load and delayed response times during task execution [83], [131], [133], underscoring the challenge of integrating supplementary feedback into motor control processes [16]. Users must learn how to interpret and incorporate this novel sensory input into their motor schemes, which introduces additional complexity and delays in computing the action [155]. To address this, researchers have developed encoding strategies that are clear to perceive and easy to interpret [87], [117] or those that prioritize intuitiveness and reduce cognitive burden—for example, delivering discrete bursts at key events like contact or slippage rather than continuous proportional signals [85], [97], [109]. However, making the feedback more intuitive often involves simplifying it, sacrificing the inherent richness of natural somatosensory input, such as the ability to perceive object properties [96]. Indeed, human mechanoreceptors are capable of detecting various tactile cues— such as contact forces, texture, shape or stiffness [78], [132], [148] — and simplified feedback may fail to fully replicate these dimensions.

To bridge this gap, multimodal feedback strategies have been also proposed. By combining different modalities (e.g., vibrotactile and electrotactile cues), these approaches leverage the brain’s ability to integrate information from different channels [145]. This can enrich the provided input, potentially improving feedback discrimination and overall usability [12]. A notable example is *osseoperceptive feedback*, which transmits vibratory stimulation through the bone and can concurrently evoke both tactile and auditory sensations. First demonstrated in 2017, osseoperceptive feedback opened a new avenue for sensory feedback restoration, enabling users with osseointegrated prostheses to perceive contact and vibration through the skeletal system itself [15]. Although the phenomenon requires further investigation, these early findings have inspired renewed interest in exploiting multimodal or cross-modal feedback mechanisms that bypass the skin entirely.

Altogether, these findings highlight the importance of achieving a careful balance: supplementary sensory feedback should be rich enough to convey meaningful information, yet intuitive enough to be seamlessly integrated into natural motor control processes.

Another major challenge in the field is the lack of systematic comparisons between different sensory feedback approaches. Current studies employ a wide variety of modalities, encoding strategies, and feedback variables, but standardized evaluation protocols and/or direct comparison between the methods are rare [16]. As a result, it remains unclear which methods are more effective, which variables are most informative, or which approaches are preferred by end-users [80]. This lack of consensus on stimulation modality, encoding, and relevant feedback features limits the ability to establish best practices and hinders the direct translation of research findings into practical, high-performing prosthetic or rehabilitation systems.

In response to some of these limitations, there has been growing interest in invasive feedback systems, such as direct nerve stimulation and intracortical stimulation [23], [30], [45], [46], [47]. By interfacing directly with the peripheral or central nervous system, these approaches can provide more natural and timely sensory feedback, mitigating issues such as delayed responses, cognitive demand and reduced realism [51], [149]. In fact, invasive systems have demonstrated faster response times and enhanced biomimetism in prosthetic control compared to their non-invasive counterparts [36], [43], [48], [52]. Emerging techniques such as spinal cord stimulation have demonstrated somatotopically matched sensations and object discrimination in early case studies [165]. Although promising, this technique remains in very early stages of investigation and was therefore not included in detail in this review. Overall, although current approaches still fall short of fully replicating natural tactile sensations, ongoing exploration of underutilized nerve targets holds promise for improving perceptual fidelity [51]. Nevertheless, the development and deployment of these systems remain constrained by significant ethical, surgical, and regulatory barriers, which continue to limit their adoption.

VI. CONCLUSION

This review highlights how feedback modalities contribute to restoring haptic perception, improving motor control, and enabling more intuitive human-machine interaction. While advances in HMIs continue to improve user experience and functional outcomes, several critical challenges remain. These include the design of intuitive and meaningful feedback modalities, the replication of natural sensory characteristics, and the broader integration of sensory feedback into rehabilitation strategies—not just prosthetic control. Beyond the technical aspects, future research must also prioritize wearability, user comfort, and validation through larger, more diverse population studies. Addressing these issues will be essential to translating current technological advances into clinically viable, user-centered solutions.

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