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A hierarchical sensorimotor control framework for human-in-the-loop robotic hands

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Human manual dexterity relies critically on touch. Robotic and prosthetic hands are much less dexterous and make little use of the many tactile sensors available. We propose a framework modeled on the hierarchical sensorimotor controllers of the nervous system to link sensing to action in human-in-the-loop, haptically enabled, artificial hands.

Summary sentence: Principles of hierarchical human sensorimotor control promise improved human-in-the-loop control of sensate robotic hands.

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Introduction

Humans with intact motor function but insensate fingertips have substantial difficulty performing dexterous grasping and manipulation, indicating that tactile sensing is necessary for human dexterity. Commercially available robotic and prosthetic hands have increasingly sophisticated articulations (*1*) but generally lack tactile feedback, despite the large variety of engineered sensors available. Bioinspired design suggests that understanding and applying lessons from human haptics could enhance the currently limited dexterity of artificial hands. The haptic capabilities and strategies of humans and robots can provide a common testbed to integrate action and perception with decision-making at multiple levels and across applications.

Recently developed tactile sensing technologies can be incorporated into a general concept of "electronic skins", which include dense arrays of normal-force-sensing tactile elements (taxels), fingertips with comprehensive force perception providing a directional force-distribution map over the entire sensing surface (*2*), and complex three-dimensional architectures mimicking the mechanical properties and multimodal sensing of human fingertips (*3*, *4*). Tactile sensing systems mounted on mechatronic limbs could therefore endow robotic systems with complex contact-state representations needed to characterize, identify and manipulate objects (*5*).

It is a challenge to effectively interface humans with such touch-enabled robotic hands, however. It remains largely unclear how to manage agency and task assignment, and maximize the utility and user experience in human-in-the-loop systems such as bionic limbs, virtual avatars and telerobots endowed with high-bandwidth tactile streams. Particularly challenging is how to exploit varied and abundant tactile data generated by haptic devices, only some of which may require direct transmission to the operator.

To address this challenge, we take inspiration from the hierarchical principles of sensorimotor control in humans to propose a conceptual framework in which the paradigm of shared control is used to integrate bioinspired touch-enabled robots with humans. The overall aim of this Viewpoint is to establish a research agenda for natural closed-loop control with touch-enabled robotic agents in human-in-the-loop systems across multiple applications.

Human tactile sensing, haptics and dexterity

Human hands are embedded with a dense network of receptors responsive to both static and time-varying aspects of mechanical events. Processing the abundance of tactile data provided by these receptors is straightforward for humans (in contrast to robotic devices), as evidenced by the fact that we can use our hands effortlessly for various tasks, from dexterous manipulation to haptic exploration of the environment. In this section, we outline some fundamental principles underlying the functioning of the biological sensorimotor loop that can serve as an inspiration for the development of haptically enabled human-in-the-loop systems.

Hierarchical organization and parallel processing

When the hand interacts with objects, afferent tactile information from mechanoreceptors in the hand is processed in parallel and integrated by neural networks at multiple levels of the central nervous system (CNS). Such processing is highly intertwined with the efferent components of movement generation (*6*). At the lowest level of the hierarchy are the intrinsic biomechanical properties of the human hand and muscles that can be used to facilitate sensorimotor control and allow automatic reactions without any neural computation (*7*), (*8*). Higher in the hierarchy is the neural circuitry in the spinal cord (neural "middleware" (*9*)), comprising feedback loops with variable gains that can be adjusted by the CNS to affect the behavior of a single actuator (the homonymous stretch reflex) or regulate more complex event-driven actions such as the response to incipient slip. Somatosensory information from the spinal cord is further processed by subcortical structures such as the cuneate nuclei in the medulla oblongata and the thalamus. The highest levels of control are reserved for supraspinal neural networks that are responsible for movement planning and execution, task sequencing, interactive perception, and interpersonal communication (passive and affective touch), where motivation is integrated with prior experience for the achievement of strategic goals. Hierarchical control is well represented by grasping, which progresses from cortical structures responsible for the goal (to grasp an apple, for instance) to subcortical structures including the cerebellum, basal ganglia, brainstem reticular formation, and spinal cord, which compute the detailed motor plan and contingent reflexive corrections as well as regulating online movement execution (*10*).

Integration of feedforward and feedback control

The speed and dexterity of human reaching and grasping are enabled by a combination of feedforward programming and feedback-driven control (*11*). According to a well-known motor control theory of grasping (*12*) a principal role of the hand mechanoreceptors is to provide the timing that governs the unfolding motor plan. More specifically, the mechanoreceptors detect critical phases of grasping such as loading, lifting, and releasing, triggering phase-specific feedforward controllers. The neural control centers that contribute to feedforward and feedback muscle activation send "efference copies" of their outputs back to higher centers including the cortex and cerebellum. These information transmissions entail substantial delays due to the relatively slow conduction of action potentials (approximately 20-80 m/s) over substantial distances (approximately 1 m). The important inference is that feedback does not need to be processed continuously to achieve effective control.

Dynamic balance between subconscious and conscious processing

Not only can humans reach and grasp dexterously, but they do so effortlessly, with much of the sensorimotor processing performed subconsciously. High-level actions such as target object selection normally require at least some conscious involvement, whereas the lower levels of control can be programmed to operate without conscious attention, provided that the movement unfolds as expected. However, a mismatch between expectations and the information detected by the mechanoreceptors (fingertip micro-slip on a surface, for example) is a warning signal to activate feedback-driven corrections (*12*). In this case, the grasping action is suddenly "revealed" to the person, as the tactile information reaches consciousness and demands attention to recover (*13*).

Importantly, although most of the processing proceeds below the level of consciousness, humans can also decide to direct attention to the afferent stream, and activities such as deliberate haptic exploration (*14*) demand ongoing attention to haptic stimuli. A dynamic interplay between afferent and efferent haptic activity, processed subconsciously or consciously depending on the context, is therefore an intrinsic characteristic of human manipulation and exploration.

Robotic tactile sensing and control

High-density tactile sensing in robotics

Similar to biological mechanoreceptors, robotic mechanosensors are mostly strain gauges that detect the deformation of a substrate, which can also be retrieved through optical tactile sensing. The location and mechanical properties of that substrate determine how that deformation and strain relate to a state variable such as the location or direction of contact force or vibration. Tactile information inevitably requires many such sensors (see open challenges in Box 1), which may generate many separate electrical signals (*3*) or may be interrogated as a video stream of the deformations (*4*). Those signals may require substantial combination and processing to extract exhaustive information on state variables required for control such as tangential forces (*15*) or the surface contours and texture of a contacted object (*3*).

Distributed sensing for control

Dexterous manipulation of objects generally requires understanding their overall shape and loading at multiple contact points. Tasks such as grasping an object require knowledge and control of the relative locations and applied forces of multiple fingers. If the object is unfamiliar, the controller must maintain a stable grasp while simultaneously identifying the object and its handling properties from sensors in the electronic skin and in the actuators and their mechanical linkages (corresponding to biological proprioception), as well as other modalities such as vision. Stability usually requires fast, automatic responses to events such as incipient slip (*16*); object identification may require more deliberative sequences of exploratory movements (*14*). Despite considerable research on sensors and control algorithms, current technological solutions are still far from human capabilities.

Signal processing as a bottleneck for closed-loop control

Although electronic transmission of information is almost instantaneous compared to neural action potentials, digital protocols and signal processing of large amounts of data can result in substantial delays in robotic systems. In humans, the entire process of collecting, transmitting, and elaborating information is particularly critical when rapid force adjustments are needed, such as when avoiding slippage or accidental contact. Biological sensors transmit information over large numbers of relatively slow but parallel channels, whereas artificial sensors more commonly aggregate many information channels for serial transmission. Efforts to implement continuous data processing may encounter limitations even with a few hundred sensors, which is far less than the many thousands in a human hand. Autonomous robots typically have battery power budget limitations for transducers, signal conditioning and transmission, for example, and deep neural networks (used to extract high-level percepts and actionable information) are typically implemented as serial software simulations that require power-hungry computers.

Strategies for robots to handle high-density tactile data

Different approaches are possible for managing complex sensing systems with limited computational resources. At any moment, only a subset of tactile sensors is likely to be active. Also, high spatial resolution can be obtained by using interpolation across a small number of low-noise sensors. Indeed, in some cases a single sensor might provide the required control information, as has been demonstrated for slip detection (*17*). Biological sensorimotor processing can also inspire strategies for processing high-density tactile data in robotic systems, as summarized in Box 1, for instance within the framework of "sensory synergies" (*18*) or taking inspiration from the model of the thalamus as a dynamically adjustable filter between sensors and cortex (*19*). More recent interpretations of thalamocortical function emphasize the recruiting of additional cortical processing to deal with unanticipated or novel stimuli (*20*), with implications for how computational demands might be distributed between limited local processors in the robot and dedicated servers outside. Another bioinspired approach would be to filter out self-generated tactile data to enhance information coming from the environment (*11*).

Data redundancy in complex electronic skin is useful for dealing with manufacturing variations, damage, soft-material degradation and noise. Neural networks and other machine learning methods are being developed to translate such high-density information into manageable control inputs, but these approaches are still far from performing as well as humans (or other animals) in tasks that require embodied intelligence. In humans, temporal resolution is extremely high for fast, transitory signals and decreases for slower inputs, consistent with event-driven organization. Neuromorphic computing has already inspired the development of hardware-implemented neuromorphic skin (*21*). Such neuromorphic approaches, with compact size, low power requirements, and robustly parallel operation, offer an alternative to more traditional robotic methods and technologies. They are also more likely to generate signals that can be shared with human operators, as discussed in the next section.

Box 1: Open challenges of high-density tactile sensing and processing

- Flexible and stretchable electronic skin technologies could be used to embed various sensors in an elastic material at different positions and depths, and to better map the mechanical state of the electronic skin on the robotic hand for enhanced tactile perception. Biology can inspire solutions to reduce the complexity of the sensing system by suggesting regions where higher tactile acuity is needed (such as fingertips) and where relatively impoverished acuity is sufficient (such as palm).
- The real-time processing of high-density and multimodal sensor data is still a bottleneck for closed-loop control of robotic hands endowed with electronic skin. Biological strategies for dealing with the high complexity of tactile information, such as filtering, hierarchical organization, and parallel processing, might act as a source of inspiration to design biomimetic robot controllers.

Shared perception and action in human-machine systems

Enhancing haptic robots with high-density tactile sensing can substantially improve their capabilities. This enhancement, however, raises questions about how best to transmit these signals to a human controller, and more generally how to integrate the human with the device in human-in-the-loop systems.

The limitations of direct interfacing

A natural solution would be to establish bidirectional communication directly between the user's nervous system and the mechatronic device. In the sensory domain, this means translating the data recorded from advanced tactile sensors into electrical or mechanical stimulation profiles delivered non-invasively to the skin, or invasively, to its subdermal layers, peripheral nerves, or somatosensory cortex (*22*). The biggest challenge is to achieve sufficient temporal and spatial resolution so that the evoked neural activity generates a recognizable percept of the haptic event. Unfortunately, the overall spatial selectivity, and hence the achievable information bandwidth, is still low (*23*), and the salient aspects of neural encoding are not fully understood. In addition, haptic perception is necessarily closely integrated with motor control, both to explore and identify unknown objects and to achieve dexterous manipulation of them. Recording motor commands from the human operator and converting them into useful actions by the robot requires another communication interface whose signals are difficult to record chronically and whose biological codes are poorly understood (*24*).

Shared control to accommodate high-density tactile data

The spatiotemporal demands on this interface might be reduced by employing some level of shared control, whereby some low-level functions are automatically controlled independently of human agency. In fact, some biological processes, for example, human slip control, embody such a hierarchical model, where fast and subconscious reflexive responses can be supplemented by slower volitional reactions. Ideally, to achieve intuitive and natural interaction when the control is shared between the human and artificial system, the autonomous controller should be "invisible" to the human user, who would experience full agency over the device and not the intelligence embodied in the robotic end-effector (*25*). The hierarchical organization of the human sensorimotor system summarized earlier suggests that this could be obtained if the artificial system takes over the sensorimotor functions that are normally performed subconsciously.

The concept of shared control in the context of a haptically enabled human-in-the-loop system is illustrated in Fig 1. The high-bandwidth sensing information recorded by an electronic skin placed on a robotic end-effector can be processed in the local loop for low-level autonomous behavior of the artificial hand (subconscious processing) (*26*), (*27*). In addition, shared control provides flexibility regarding the transmission (and use) of tactile data within hybrid human-in-the-loop systems because, contrary to direct interfacing, not all data need to be conveyed to the human operator. Instead, part of the data is consumed by the local feedback loops implementing automatic functions.

A framework to organize bidirectional control in haptically enabled human-in-the-loop systems

This approach (Fig. 1), however, imposes a new challenge: deciding how to share not only the control but also the haptic feedback streams between the automatic and human controllers. Again, human sensorimotor processing can inform these decisions. One option would be to convey to the user only the information that requires conscious processing, and encapsulate the other tactile signals in the automatic controller. In this case, the data flow between the automatic controller and the human agent ultimately depends on the level of autonomy of the robotic system, as indicated

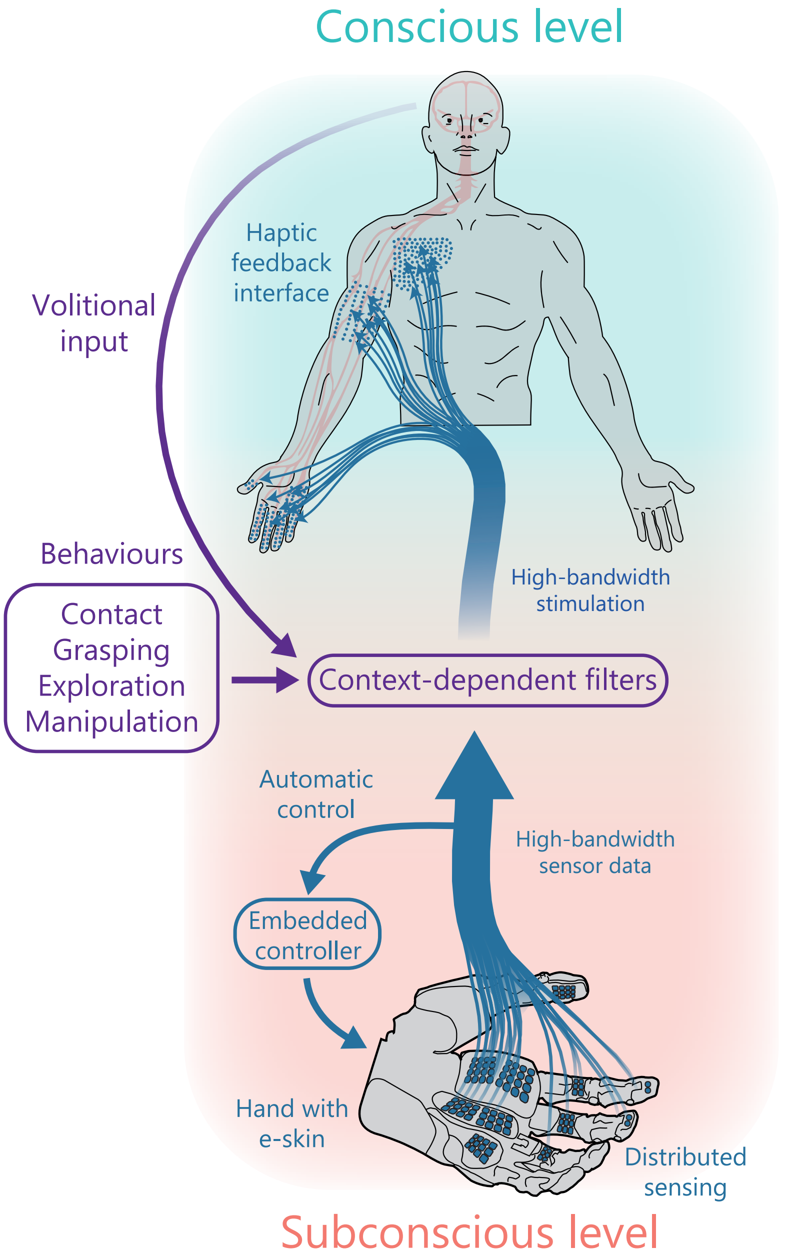

Figure 1: **The proposed flow of high-bandwidth sensor data in human-in-the-loop haptic systems.** The distributed nature of high-density sensing is shown on the artificial hand at the bottom of the picture. Sensing information is processed locally for automatic control of the artificial hand, mimicking human-like subconscious processing. Depending on the nature of current interactions (behaviors), context-dependent filters regulate the amount of haptic data conveyed to the human user as feedback. The stimulation interface, which can be invasive or non-invasive, needs to support tactile communication with variable bandwidth, whereas the location of stimulation delivery depends on the specific application. For example, stimulation can be delivered to the hand in teleoperation scenarios or to the arm (residual limb) in prosthetics applications.

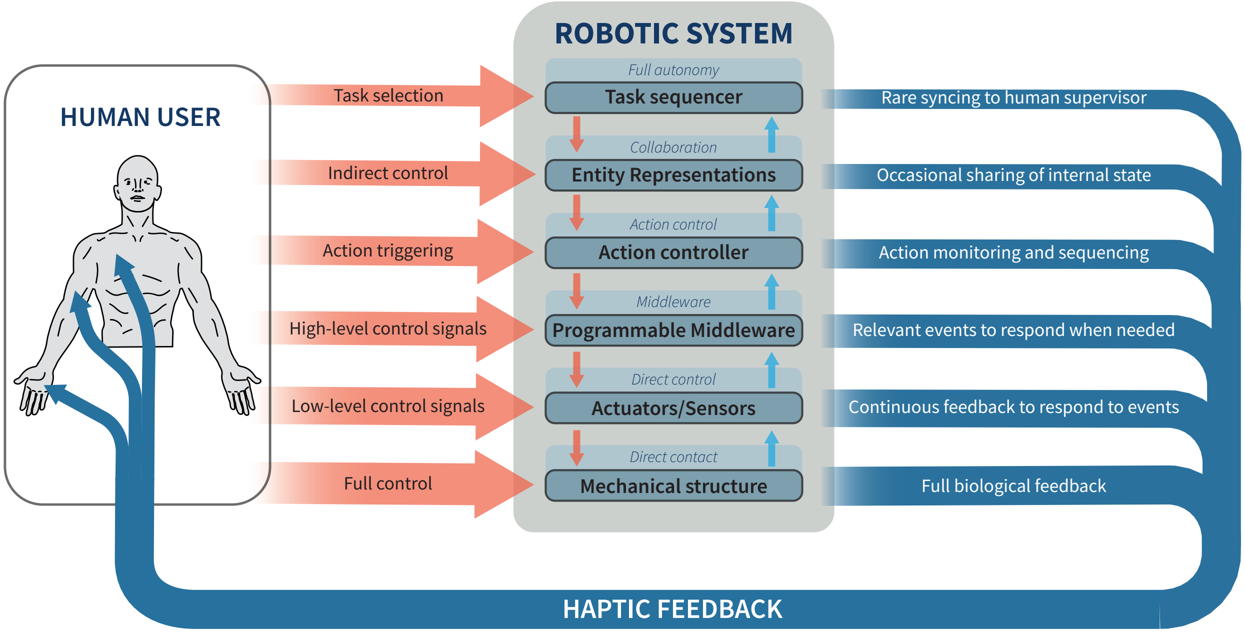

Figure 2: **A framework to guide the implementation of human-in-the-loop systems enhanced with high-density tactile data.** The robotic system is a model of a robotic agent that can incorporate different levels of autonomy, from no autonomy (direct contact or control) to collaborative and fully autonomous behavior. The darker rounded rectangles (from task sequencer to mechanical structure) are the layers of the hierarchically organized robot controller, the light blue shapes indicate the level of interfacing of the human user with the machine (from full autonomy to direct contact), whereas red and blue arrows are the command and feedback signals exchanged between the human operator and the robotic system. The shared control paradigm allows for the reduction in the "pressure" on the human-machine interfacing channel carrying command and feedback signals. The higher the level of interfacing, the smaller the communication bandwidth between the human and the system that is required to achieve an equivalent functionality and performance, as indicated by the changing thickness of the red and blue lines. The level of interfacing also determines the specific nature of control and feedback signals as shown in Table I.

in Fig. 2 and Table I. Figure 2 starts from a biomimetic model of hierarchical robot control proposed earlier (*9*), adding the human agent that can interface with the robotic system at different levels depending on the amount of intelligence embodied by the robot (autonomous capabilities). The level of interfacing defines a flow of both control and feedback information between the human and robotic agent. The general principle could be summarized as follows: as the robotic system is enhanced with advanced autonomous capabilities, shifting the responsibility of control towards the robotic agent, more and more of the sensor data could be consumed locally, decreasing the amount of data that needs to be conveyed to the human operator and tolerating longer latency of transmission.

In direct interfacing (direct control in Fig. 2) the responsibility of the robot controller is only to detect and translate the intentions of the user (no intelligence in the device), and therefore we have no option but to convey the high-density tactile data to the user. The requirements for the feedback interface are in this case stringent, as the user needs to employ the feedback to react to and compensate for disturbance, for instance detecting slip and increasing the grasping force. If, alternatively, the robot is equipped with "middleware", including local loops that operate as artificial reflexes, the requirements for feedback can be relaxed because the device can react to

Table I: **A framework for the implementation of closed-loop haptically enabled human-in-the-loop systems**

Increasing autonomy

Decreasing feedback

Level of interfacing	Representative examples	Haptic feedback flow and sensor data sharing	Haptic feedback content and role	Requirements for the haptic feedback loop
Full autonomy: device functions autonomously, and the user sends high-level goals	Autonomous mobile robotics that is responsive to the user	Most feedback to the device to support autonomous functioning	Occasional syncing between the two autonomous agents (user and device)	Rare, non-critical, optional component
Collaboration: device assists the user by monitoring and responding to user behavior	Collaborative and smart assistive robotics	Most feedback to the device to support autonomous functioning and user interaction	Inform the user about the internal state of the cobot to understand its behavior and decision making	Occasional, non-critical, optional component
Action control: device can accomplish well-defined actions, the user triggers actions	Semi-autonomous prosthesis, smart telerobot	Feedback is "equally" shared between the user and action controller in the device	Inform the user about the progress and results of initiated actions the device is executing	The feedback is triggered intermittently during action execution to allow the user to supervise the action execution
Middleware: user commands but the device can respond to external stimuli	Prosthesis with reflexes, impedance-controlled telerobot	Most feedback to the user, the reflex controller in the device reacts to stereotyped sensor inputs	Inform the user about relevant events that were potentially already reacted to by the robot	The feedback triggered by events enables the user to react fast and supplement the initial response of the device
Direct control: user commands all aspects of the device	Myoelectric prosthesis, leader/follower telerobotics, telepresence	No intelligence in the device, all feedback to the user	Sensor data is conveyed to the user for continuous processing and reacting	Continuous feedback to enable the user to act instantaneously
Direct contact: the user holding a device	Passive or powered mechanical tool	No intelligence in the device, all feedback to the user	Biological and augmented feedback	Continuous feedback to enable the user to act instantaneously

disturbance automatically (middleware in Fig. 2). The role of feedback is now to inform the user about events to which he/she can still decide to react, typically over longer latencies, and more generally to convey the state of the system to the user (providing information about grasping force, for instance). When the robot controller includes enough embodied intelligence (action control in Fig. 2) to perform high-level actions, feedback becomes even less critical and can be used to indicate the progress of action execution. Finally, with fully autonomous robots that collaborate with humans or operate independently (collaboration and full autonomy in Fig. 2), feedback can be reduced to occasional periodic synchronization of the internal states of the two agents.

An example that integrates the insights presented so far could start from a robotic end-effector equipped with high-density sensing (Fig. 1) and an action controller (Fig. 2, Table I). The smart gripper operating as a prosthetic hand, for instance, is commanded by high-level signals such as “close the hand”, whereas the low-level details of the movement such as individual finger trajectories unfold largely outside the user’s awareness. In this mode, the system provides simple feedback to the user that “gently” paces the normal progression of the movement by, for example, indicating object contact and release (*29*). Given an unpredictable event, a distinctive feedback signal alerts the human operator to attend to and recover the behavior via the high-level strategies learned over a lifetime. Such interplay between “subconscious” processing by the local controller and a conscious reaction of the user reflects human sensorimotor processing, as explained before. In addition, at any moment the user can allocate conscious attention to the information that was otherwise processed subconsciously. Enhanced feedback may then be invoked, for example, augmenting binary object-contact signals with the spatially distributed pressure pattern registered by the electronic skin (*28*, *30*).

Finally, the human ability to learn and adapt are crucial for developing effective interaction with the environment. Even if the robotic system does not have such capabilities, the human agent is intrinsically capable of internalizing the dynamics of the controlled system and, as already shown in prosthetics (*31*), these capabilities can critically affect the use and potential benefits of feedback. If the robot can also learn and adapt, which requires at least some awareness of the environment (Fig. 2, action controller and higher levels), feedback might become even less critical for the overall performance of the human-in-the-loop system, as the robot controller becomes increasingly more reliable. Humans learn continuously, across all levels of control and over an exceptionally long timespan. How to implement such learning in a robotic system is still an open challenge.

Stimulation technologies for flexible tactile feedback

As discussed above and shown in Fig. 1, an ideal stimulation interface to convey tactile feedback to the user should be capable of providing communication with variable bandwidth, from simple feedback of important events and phases to comprehensive feedback of spatially distributed tactile interactions. Several representative examples of interfaces that can be used to establish high-bandwidth tactile channels are shown in Fig. 3. Electrotactile and vibrotactile interfaces are non-invasive and microelectronic technologies can support dense matrices of electrode pads and miniature mechanical “tactors” (*30*, *32*). Such interfaces can therefore deliver spatially distributed stimulation to the skin, but the sensation fidelity and quality cannot match the natural tactile experience. Invasive approaches also exist, for example, the stimulation of peripheral nerves or sensorimotor cortex using dense arrays of needle electrodes (*33*). Such approaches are currently

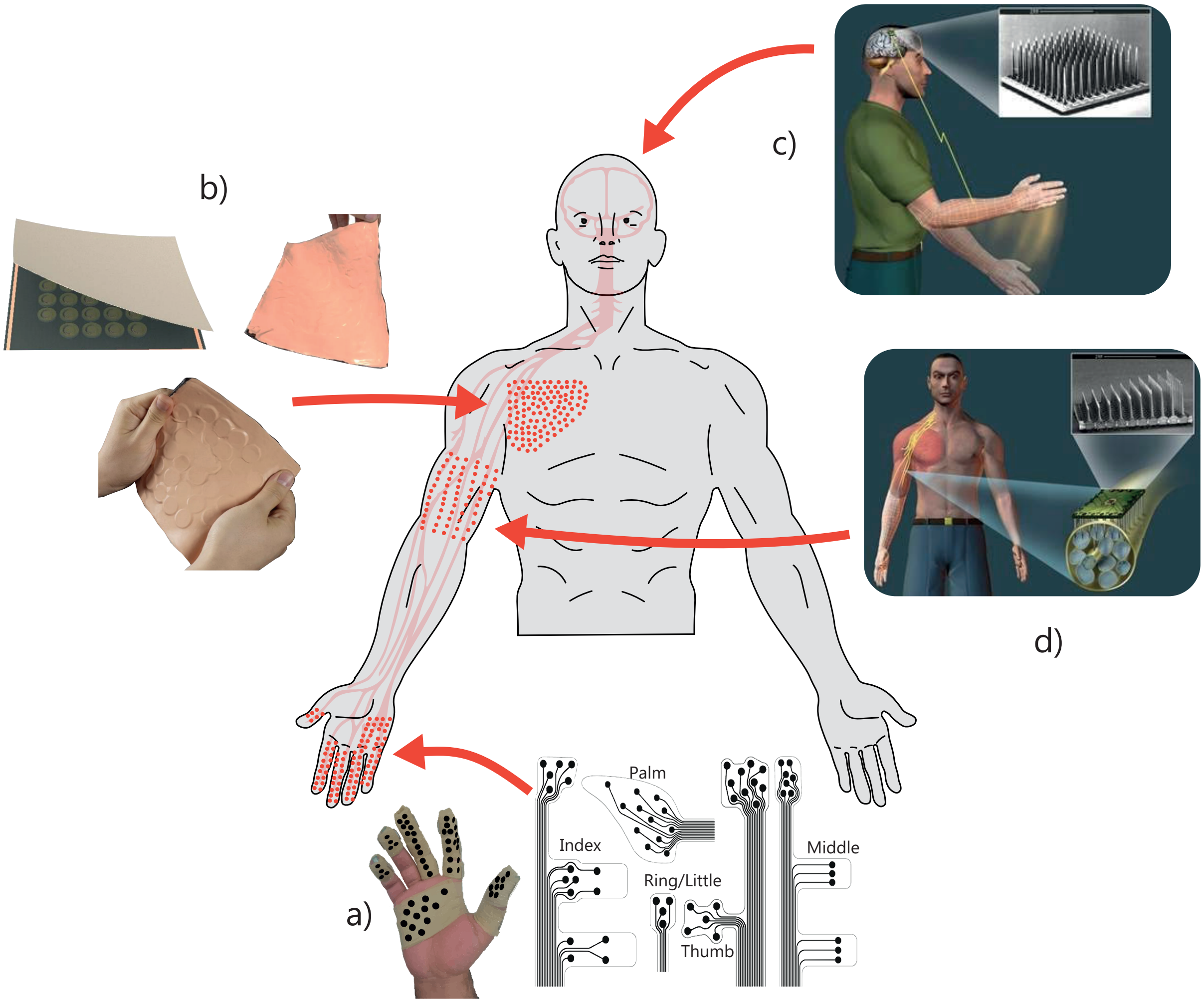

Figure 3: **Representative examples of interfaces that can provide high-bandwidth tactile stimulation**: a) High-density matrix electrodes for electrotactile stimulation (*30*), b) Skin-integrated multichannel vibrotactile interface (*32*), c) Utah electrode arrays for brain stimulation (*33*), and d) Utah slanted electrode arrays for peripheral nerve stimulation (*33*).

reserved for specific clinical applications, however, such as the restoration of somatosensory feedback in highly disabled patients. Nevertheless, the effective information throughput that can be achieved with such invasive and non-invasive interfaces is still likely to be substantially below that of natural tactile feedback.

Overall, the onlife digital era (*34*) provides a testbed where the distinction between human, machine, and nature is blurred. Information and communication technologies are becoming environmental forces that affect our self-conception, mutual interactions, and interactions with both virtual and physical worlds. Technology for tactile feedback is a critical element for humans to effectively extend their bodies and minds across physical distances (see ANA Avatar XPRIZE (*35*)). Such technology is much more demanding and less developed than existing technologies for visual and auditory acquisition and display. Yet tactile feedback must be successfully integrated with those extra-personal senses to enable an immersive and dexterous interaction. A long path is ahead, but the nature of the challenges is becoming apparent (see Box 2).

Box 2: Open challenges of interfacing with high-density tactile systems

- Despite promising developments, we still lack effective and reliable technology to transmit high-density tactile information from a robot to an operator with the fidelity that matches the natural tactile experience.
- We do not know to what extent we can rely on brain plasticity to learn to interpret tactile data, and this poses a dilemma between conveying the “raw” information (spatially distributed sensations) versus “pre-digesting” the data for the user by extracting high-level features to simplify perception and interpretation.
- Robotic systems still largely lack sophisticated algorithms for local use of the rich tactile data available from currently available sensors. Biological strategies to deal with the high complexity of tactile information might inspire solutions, but they also require dynamic bidirectional control in which the central controller (the human in a hybrid system) selects the currently desired, local behavior of the robot according to the operator's learned control strategy.
- The organization of human sensorimotor processing can be used as a guideline to define the models of interaction between humans and robotic agents, as proposed in this Viewpoint, but many questions are still open. For instance, what is processed subconsciously versus what needs to reach consciousness, and the mechanisms that govern such “gating” of sensory information, are still not elucidated clearly across tasks and functions.
- The models for shared control must consider both objective performance and subjective user experience in diverse applications, from industry to prosthetics, which have radically different requirements that are yet to be fully revealed and understood.

Conclusions

Advanced technologies now provide mechatronic, sensing and computational components for fully functional anthropomorphic limbs. The limiting factor in achieving haptically informed and dexterous machines is how to close the sensorimotor control loop locally, within the robotic system, as well as externally with the human user. This includes the identification of salient sensory modalities, the extraction of actionable information from such sensors, and the integration of such information to inform and/or adjust goal-directed behaviors. As we have shown in this Viewpoint, human performance provides inspiration for design strategies for mechatronic systems that can function like humans, alongside humans, and even as replacement parts for humans. The shared control and context-dependent filtering of tactile information, organized hierarchically to mimic the allocation of the subconscious and conscious processing in human sensorimotor control, is a promising approach to organizing the flow of high-density tactile data within human-in-the-loop systems. Conversely, such engineered systems can be used to test theories of biological function that are difficult to confirm from the limited data obtainable from biological systems.

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Authors' Contributions

All authors contributed to the scientific discussion initiated and moderated by LS, MB, FM, and SW, which led to this paper. LS, SD and GEL drafted the manuscript. All authors revised the draft and approved the submitted version.

Competing interests

G.E.L. is the founding director of SynTouch Inc., a manufacturer of tactile sensors for prosthetic and robotic hands. The other authors declare that they have no competing interests.

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