

## From surface signals to subsurface intelligence in wearable hand tracking

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### A SHIFT FROM SURFACE SENSING TO BIOMECHANICAL INTELLIGENCE

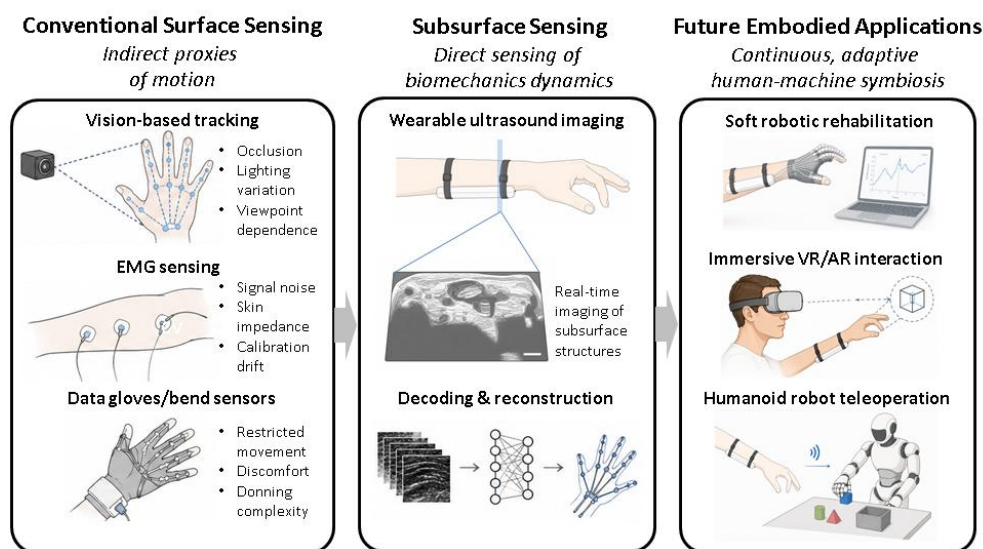
The ability to accurately and continuously track human hand motion remains a central challenge for robotics, human-computer interaction, and emerging spatial computing systems. For decades, dominant approaches have relied on surface-level sensing modalities, including vision-based tracking systems and electromyography (EMG), to infer hand kinematics, often restricting tracking to discrete gestures or limited degrees of freedom, alongside alternative wearable modalities such as strain and inertial sensors that impose mechanical constraints on natural hand motion<sup>[1,2]</sup>. While these methods have enabled important advances, they fundamentally depend on indirect proxies of motion, inferring intent from surface electrical or kinematic signals rather than directly observing biomechanical actuation<sup>[3]</sup>. This often limits robustness, precision, and generalizability across environments and users<sup>[4,5]</sup>.

In this context, the recent work by Lu *et al.*<sup>[6]</sup> represents a significant conceptual and technological departure, enabling continuous reconstruction of all 22 degrees of



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freedom (DOFs) of the hand with high accuracy and low latency. By integrating wearable ultrasound imaging with machine learning, the authors introduce a wrist-mounted system capable of directly observing subsurface anatomical structures, including tendons and muscles, in real time, as illustrated in Figure. This approach bypasses the ambiguity inherent in surface measurements and instead captures the biomechanical processes that generate motion. The result is a continuous, high-dimensional representation of hand kinematics derived directly from subsurface tissue dynamics that enables accurate reconstruction of complex gestures without reliance on external cameras or restrictive instrumentation.



**Figure 1. From surface sensing to subsurface intelligence for wearable hand tracking.** Comparison of conventional hand-tracking approaches (left), including vision-based systems, electromyography (EMG), and instrumented gloves, with a wrist-mounted ultrasound sensing paradigm (centre) that captures real-time subsurface dynamics of tendons and muscles. Ultrasound image sequences are processed through an image-to-kinematics learning pipeline to reconstruct continuous, full-DOF hand kinematics (22 DOFs). This enables robust, camera-free interaction across applications such as virtual/augmented reality interfaces, quantitative motion monitoring for soft robotic rehabilitation, and intuitive teleoperation of robotic systems (right).

This shift from indirect surface sensing to direct biomechanical imaging fundamentally redefines how human motion can be measured. Rather than inferring intent from electrical activity or external appearance, the system observes the physical actuation

mechanisms of the hand itself. In doing so, it aligns closely with the broader paradigm of embodied intelligence, where sensing, control, and physical structure are tightly integrated<sup>[7]</sup>. This new sensing modality directly captures actuation mechanisms, rather than relying on indirect electrical or visual proxies. Hence, the wrist becomes not merely a measurement site, but a window into the coordinated dynamics of human movement.

Importantly, this approach also addresses persistent limitations in existing hand-tracking systems. Vision-based methods, while powerful, are susceptible to occlusions, lighting variability, and viewpoint constraints<sup>[8]</sup>. EMG-based systems, though wearable, often suffer from signal variability due to electrode placement, skin impedance, and user-specific physiology<sup>[5]</sup>; these systems are typically limited to recognizing predefined discrete gestures rather than continuously reconstructing arbitrary hand configurations<sup>[9]</sup>. By contrast, ultrasound imaging provides a stable and anatomically grounded sensing modality, capable of capturing deep tissue motion with high fidelity across diverse conditions. This positions the work of Lu *et al.*<sup>[6]</sup> as a potential inflection point in the evolution of wearable sensing technologies.

## **ENABLING CONTINUOUS AND NATURAL HUMAN-MACHINE INTERACTION**

Beyond its sensing novelty, the system introduced by Lu *et al.*<sup>[6]</sup> enables a qualitatively different mode of interaction between humans and machines. Traditional gesture-based interfaces often rely on discrete classification of predefined hand poses, limiting expressiveness and responsiveness. In contrast, the continuous reconstruction of hand motion afforded by ultrasound imaging supports fluid, real-time interaction, where subtle variations in movement can be captured and interpreted. This capability has profound implications for emerging domains such as virtual and augmented reality, teleoperation, and assistive technologies. In immersive environments, natural hand tracking is essential for intuitive manipulation of virtual objects<sup>[10]</sup>, including continuous pinch-based scaling and multi-axis object control demonstrated in real time. Current solutions often require external cameras or instrumented gloves, which can constrain usability and scalability. A compact, wrist-worn system that operates independently of environmental infrastructure could significantly lower these barriers, enabling seamless integration into everyday settings.

Similarly, in robotic teleoperation, continuous hand motion tracking can enhance the fidelity of human-robot interaction, as evidenced by real-time control of robotic hands for dexterous tasks. Learning-based control frameworks increasingly rely on rich demonstration data to train visuomotor policies<sup>[11]</sup>. High-resolution, temporally continuous hand kinematics, captured directly from the user, could provide valuable supervision signals, improving both the efficiency and generalization of such systems, particularly in data-driven manipulation frameworks<sup>[12]</sup>. In this sense, wearable ultrasound sensing may serve not only as an interface, but also as a high-resolution data-generation platform for learning from demonstration and imitation-based control<sup>[13]</sup>. Crucially, the robustness of subsurface sensing also opens the door to deployment in unstructured, real-world environments. Unlike vision-based systems, which degrade under occlusion or poor lighting, ultrasound-based tracking remains invariant to external visual conditions. This resilience is particularly important for applications in healthcare and rehabilitation, where consistent performance is essential.

## **IMPLICATIONS FOR SOFT ROBOTICS AND WEARABLE REHABILITATION**

The implications of this work are especially compelling when viewed through the lens of soft robotics and wearable rehabilitation, which are fields that have long sought to bridge the gap between human intent and assistive actuation. Soft robotic gloves, in particular, have emerged as promising devices for restoring hand function in individuals with neurological impairments, leveraging compliant materials to enable safe and adaptive interaction with the human body<sup>[14,15]</sup>. However, a central challenge in these systems lies in accurately sensing user intent. Many existing devices rely on EMG signals or simple motion sensors, which provide limited resolution and can be difficult to calibrate across users. The integration of wearable ultrasound imaging offers a fundamentally richer sensing modality, capable of capturing the underlying biomechanical processes that drive hand motion. This could enable more precise and responsive control of assistive devices, enhancing both functionality and user experience.

Notably, prior studies have demonstrated the feasibility and translational potential of soft wearable robotic gloves across a range of clinical and engineering contexts. For

instance, MRI-compatible soft robotic gloves have been developed to enable simultaneous rehabilitation and brain imaging, facilitating the study of neuroplasticity during therapy<sup>[16]</sup>. In parallel, fully fabric-based bidirectional gloves have been introduced to improve wearability, scalability, and bidirectional assistance for hand-impaired patients<sup>[17]</sup>. These advances highlight the importance of integrating sensing, actuation, and user-centered design in the development of next-generation rehabilitation technologies. The work of Lu *et al.*<sup>[6]</sup> complements and extends these efforts by providing a high-fidelity sensing layer that could be seamlessly integrated into soft robotic systems. Although prior studies have explored ultrasound-based sensing for muscle activity and gesture recognition, they have largely been limited to discrete classification or low-dimensional tracking<sup>[18,19]</sup>.

Ultrasound-based sensing opens the door to adaptive, closed-loop rehabilitation systems that respond in real time to the user's biomechanical state, enabling truly personalized assistance beyond predefined motion patterns. This convergence of subsurface sensing and soft actuation signals a shift toward embodied human-machine systems, where sensing, control, and physical interaction are intrinsically coupled.

## **CHALLENGES AND THE ROAD TOWARD EMBODIED INTELLIGENCE**

Despite its promise, several challenges must be addressed before wearable ultrasound-based hand tracking can achieve widespread adoption. First, ensuring robustness and generalization across users remains a key concern, particularly given the current reliance on user-specific model training. Variations in anatomy, tissue composition, and sensor placement can affect signal quality and model performance. Addressing these challenges will likely require the development of large-scale datasets and more generalizable learning frameworks, potentially drawing on recent advances in foundation models for sensorimotor intelligence. Second, while ultrasound provides rich biomechanical information, translating these signals into accurate and interpretable motion representations is nontrivial, particularly due to ambiguity between joint configuration and muscle force. The relationship between internal tissue dynamics and external kinematics is complex and context-dependent, necessitating sophisticated modelling approaches. Integrating physics-informed models with data-driven learning may offer a promising path forward, enabling systems that are both accurate and interpretable.

Third, practical considerations related to hardware miniaturization, power consumption (~5 W), and long-term wearability constraints must be addressed. For wearable systems to achieve real-world impact, they must be unobtrusive, comfortable, and capable of operating continuously over extended periods. Advances in flexible electronics, low-power ultrasound transducers, and integrated system design will be critical in this regard. Looking ahead, three directions will be pivotal: (1) cross-user generalization via large-scale learning; (2) multimodal sensing for disentangling force and motion; and (3) miniaturized, low-power wearable ultrasound systems. Together, these developments will determine whether such systems evolve from compelling laboratory demonstrations into ubiquitous human-machine interfaces.

Ultimately, the work of Lu *et al.*<sup>[6]</sup> points toward a future in which human motion is no longer inferred indirectly but reconstructed directly from subsurface biomechanical dynamics. By bridging the gap between sensing and embodiment, wearable ultrasound technologies may redefine how humans interact with machines, thereby enabling more natural, adaptive, and high-fidelity human-machine interfaces.

## **DECLARATIONS**

### **Authors' contributions**

RY conceived and contributed to the original draft of the manuscript.

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Not applicable.

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### **Conflict of interest**

The author declares that he has no competing interests.

### **Ethical approval and consent to participate**

Not applicable.

**Consent for publication**

Not applicable.

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