Cyborg robots: From wearable robotics to embodied human–machine symbiosis

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FROM WEARABLE ROBOTS TO CYBORG ROBOTS

Wearable robots have shown that robotic systems can restore, assist, and extend human physical capability. Prosthetic limbs mainly serve people with limb loss by substituting missing motor and sensory function; exoskeletons assist users with motor impairments or high physical demands by sharing joint torques and postural support; and supernumerary robotic limbs expand reachable action space and degrees of freedom for users who may already have intact limbs. These systems therefore differ in users, control targets, sensory-feedback needs, safety risks, and ethical questions, yet all must transmit force, motion, and information through the human body. This physical coupling has improved through lightweight, soft, and compliant interfaces,[1] but most wearable robots remain externally worn systems: they act on the body without yet being controlled, perceived, or trusted as part of the body.

In this commentary, the term *cyborg robot* does not refer to literal human–machine fusion, nor simply to a neural-interface wearable robotic system[2] or a shared-control system that distributes control authority between human and robot.[3] It denotes a functional stage of wearable robotics in which the device forms a stable closed loop among human intention, bodily state, robotic action, and sensory feedback. Under this view, prostheses, exoskeletons, and supernumerary robotic limbs approach the cyborg-robot stage only when they move beyond device-mediated function and become low-burden, bidirectional, and trustworthy extensions of sensorimotor function. Soft and compliant interfaces may facilitate this transition by improving comfort and force transmission,[4] but softness alone does not define a cyborg robot. The defining feature is whether the machine's function and feedback can be progressively internalized into human motor and sensory capability through intention recognition, state estimation, adaptive actuation, sensory feedback, and long-term co-adaptation (Figure 1).

CYBORG ROBOTS: EMBODIED HUMAN-MACHINE SYMBIOSIS

Wearable robots are becoming lighter, stronger, more responsive, and more adaptive. Recent advances in actuation, embedded sensing, soft structures, and learning-based control continue to improve wearable robots in strength, speed, precision, and endurance. However, improved machine capability does not automatically produce sensorimotor integration with the human body. Human movement is an embodied process shaped by intention, proprioception, muscle state, balance regulation, environmental perception, cognitive load, and trust. The need for cyborg robots therefore arises not from insufficient machine power, but from the difficulty of making that power predictable, controllable, and bodily integrated.

Whether a device restores lost function, assists movement, or extends bodily degrees of freedom, a central barrier is often insufficient human–machine coupling. Intention recognition degrades outside controlled settings, sensory feedback is often too sparse to support embodiment,[5] and control interfaces can impose attention, calibration, and trust burdens. As a result, many wearable robots help users perform actions without becoming internalized as reliable bodily capability. The cyborg-robot concept should therefore be understood as a pathway for connecting machine performance with human intention, perception, and adaptation.

CORE TRANSFORMATION: FROM WEARABILITY TO INTERNALIZATION

For wearable robots to become cyborg robots, the central challenge is to transform device-mediated function into internalized sensorimotor capability. Internalized control does not mean that the machine replaces human motor decision-making. It means that the user can rely on the machine without continuously monitoring, correcting, or negotiating its behavior. Observable signs include lower cognitive workload, shorter or less frequent calibration procedures, stable task performance across environments, improved trust and agency, discriminable feedback, comfortable interfaces, and fewer safety interventions. This transformation depends on two linked capabilities: bidirectional perception makes human and machine mutually legible, while internalized control turns this shared perception into continuous action, co-adaptation, and real-world robustness.

Bidirectional perception

The first capability is bidirectional perception rather than isolated sensing or one-way feedback. In one direction, the robot must perceive the user's intention, bodily state, physical interaction, and environment with informative and robust sensing. Electromyographic and neural signals are close to motor intention, but sensitive to placement, perspiration, fatigue, and inter-user variability. Pressure, force-myography, and interaction-force signals reveal assistance, discomfort, slippage, and compensatory effort at the physical interface. Inertial measurement units identify posture, movement phase, and balance, while vision can provide information about terrain, obstacles, and manipulation targets. In the other direction, the user must perceive the robot's action, contact state, output level, uncertainty, and potential risk through feedback that is timely and easy to interpret. Tactile, force, auditory, or visual cues can convey machine states to the user, but their location, intensity, timing, and encoding must support shared awareness without increasing cognitive burden. Bidirectional perception should therefore follow minimal sufficient coupling: using the smallest stable set of sensing and feedback channels that preserves safety, robustness, comfort, and usable information during daily activity.

Internalized control

The second capability is to convert bidirectional perception into continuous, predictable, and low-burden control. Instead of treating user input as isolated commands, the robot should update actions as intention, bodily state, contact condition, and environment change. In the resulting sensorimotor loop, intention recognition connects the robot to motor goals; bodily-state estimation constrains action according to posture, load, fatigue, balance, contact condition, and context; adaptive actuation converts these estimates into assistance, substitution, or extension of movement; and sensory feedback keeps the user aware of motion, force, contact, task state, and risk. This shifts control from predefined modes to adaptive regulation of torque, impedance, support, or motion guidance. Over repeated use, the control policy should also support co-adaptation: the user learns how to incorporate the device into motor strategy, while the robot updates assistance and feedback according to individual behavior.

Practically, internalized control must be implemented with low-latency sensing and actuation, online detection of sensor drift and poor contact, user-specific adaptation that does not require excessive recalibration, power-aware computation, and fail-safe modes that reduce assistance or alert the user when confidence is low. Daily use also requires privacy-preserving handling of neural, muscular, motion, and video data; validation in clinical and community environments; and robustness to stairs, crowds, skin condition, fatigue, clothing changes, and unexpected contacts. At the fast timescale, the

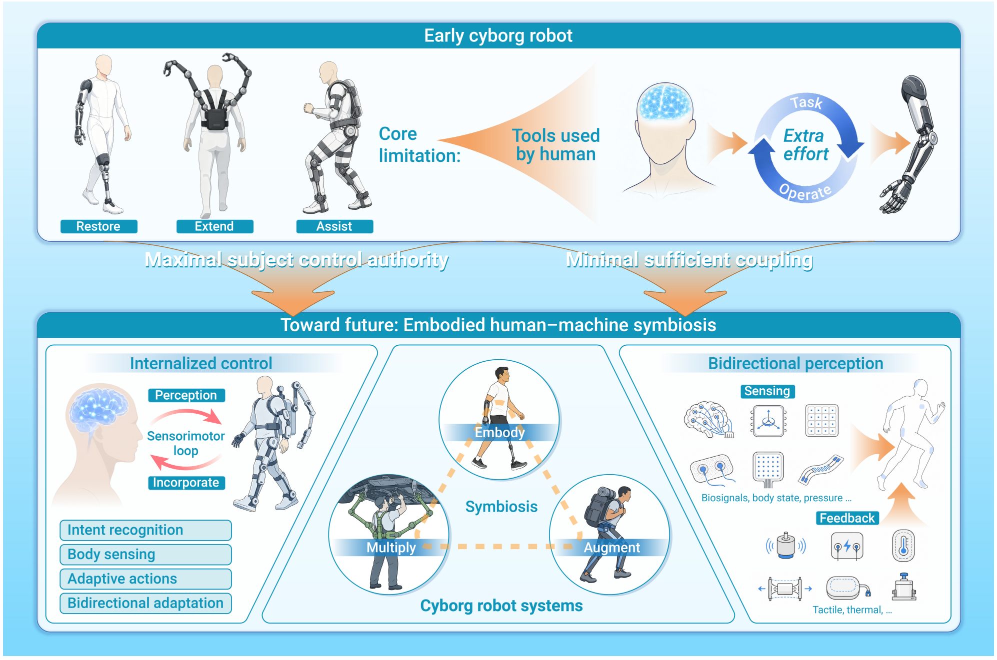

Figure 1. From wearable robots to cyborg robots The transition is shown as a closed loop linking intention recognition, bodily-state estimation, adaptive actuation, and sensory feedback, with bidirectional signals allowing the device to move from externally provided function toward internalized human–machine coupling.

robot must respond to intention, movement, contact, and environment without constant supervision. At the slow timescale, both user and robot must adapt so that wearable-device function can become internalized sensorimotor capability.

Diverse forms of a shared cyborg-robot future

The cyborg-robot future will not take a single mechanical form. Prosthetic limbs, exoskeletons, and supernumerary robotic limbs all point toward internalized human–machine capability, but each begins from a different relation to the body. Prostheses seek to make an artificial limb feel available for action and sensation; exoskeletons must coordinate assistance with residual movement, balance, fatigue, and task context; and supernumerary robotic limbs add new degrees of freedom that users must learn to coordinate without excessive cognitive load. These differences matter because the goal is not simply greater autonomy, output power, or task performance. It is the reliable incorporation of device-mediated function into the user's sensorimotor repertoire. Evaluation should therefore ask whether users can more easily anticipate, regulate, trust, and adapt to the system over time, while still respecting the specific function it restores, supports, or extends.

CONCLUSION AND OUTLOOK

Wearable robots have demonstrated the possibility of restoring, augmenting, and extending human capability, but most still function as external devices rather than internalized body extensions. The main bottleneck is not mechanical performance alone, but the lack of stable, low-burden, and trustworthy coupling among intention, bodily state, robotic action, physical interaction, and sensory feedback. Advances in neural and neuromuscular intention decoding, tactile and force feedback, interaction-force sensing, and human-in-the-loop optimization provide foundations for this transition. The next step is to build bidirectional human–machine coupling that users can gradually incorporate into their own motor and sensory capability, while preserving comfort, safety, privacy, accessibility, and accountability in daily environments. When wearable robots can sense intention, estimate bodily state, regulate physical interaction, adapt their action, and return meaningful feedback with minimal burden, they can move from external wearable devices toward internalized body extensions.

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AUTHOR CONTRIBUTIONS

Yuanwen Zhang and Yuquan Leng conceived the topic and developed the central argument of the commentary. Yuanwen Zhang and Guotong Zhang wrote the original draft. Haolan xian and Bailun Li contributed to the discussion of wearable robotics, cyborg robots, human–machine interaction, and embodied sensorimotor coupling. Yuanwen Zhang, Guotong Zhang, and Yuquan Leng reviewed and edited the manuscript. Yuquan Leng and Donghao Zhangsupervised the work. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.