From Intention to Action: An Invasive BCI-Driven Wearable Framework for Everyday Hand Assistance in SCI Patients

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Abstract

Hand paralysis resulting from cervical spinal cord injury (SCI) limits independence in daily life. Existing assistive wearable devices rely on residual muscle capabilities that are unreliable in severe paralysis. We present a BCI-wearable framework that envisions a modular wrist-worn wearable device interfacing with an invasive brain-computer interface (BCI) platform, closing the sensorimotor loop from voluntary cortical intention to physical hand actions, such as grasping. This framework integrates intracortical motor decoding, functional primitive classification, modular cable-driven finger actuation, and intracortical microstimulation (ICMS) tactile feedback into a pipeline that operates independently of residual hand functions.

Keywords

Brain-computer interface; spinal cord injury; wearable; hand motor assistance; intracortical decoding; somatosensory feedback; assistive technology

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1 Introduction

Motor paralysis from stroke and spinal cord injury (SCI) profoundly limits functional independence [20]. More than 60% of stroke survivors experience persistent motor deficits that compromise their ability to perform activities of daily living (ADLs) [9], and hand paralysis is particularly consequential: the hand underlies nearly all object manipulation — grasping, eating, dressing, personal hygiene — making its loss a critical barrier to autonomy [6, 20]. Existing assistive technologies, including rigid hand exoskeletons [3, 24] and soft robotic gloves [22], have made progress towards restoring grasp function, but share a fundamental mechanical limitation. When the user places them over paralyzed hands, they must align actuators with finger joints that are no longer in predictable positions. However, Cervical SCI patients commonly hold their hands in fixed postures, for instance, fingers passively curled inward due to lost muscle control, or the wrist drawn toward the forearm. Thus, it's difficult for their hands to be safely forced into the alignment these devices assume, risking pain, spasticity, and injury [1, 2, 20]. Stacking actuators over paralyzed fingers also increases distal weight, reduces wearability, and complicates independent donning [24]. Wrist-mounted modular design avoids this direct finger-joint contact, positioning robotic finger modules on the wrist to assist grasp without imposing forces on the hand [11]. However, most existing wrist-mounted designs infer intent from surface electromyography (sEMG) or residual wrist motion, signals that are unreliable or absent in individuals with severe paralysis [14, 20, 25]. Therefore, cervical SCI patients require an intent signal that is robust to the severity of the paralysis.

Invasive intracortical brain-computer interface (BCI) technology provides direct, high-fidelity access to cortical motor signals with the spatial resolution needed to decode individual finger-group intentions without relying on residual muscle activity [4, 10, 18]. Recent work has shown that these signals carry sufficient resolution to distinguish individual finger-group intentions, allowing real-time decoding of flexion and extension across thumb, index–middle, and ring–little groups [18, 21]. Moreover, the same implanted electrode array can also be used in reverse. By delivering precisely patterned electrical pulses to the somatosensory cortex — a technique called intracortical microstimulation (ICMS) — the system can evoke artificial sensations of touch and texture, allowing a user to *feel* what their hand is holding [7, 8]. Together, motor decoding and ICMS create the substrate for a closed sensorimotor loop: the brain sends movement commands out, and tactile information comes back in, as it would in an uninjured hand.

In this workshop paper, we propose a framework that realises this loop for cervical SCI patients. Voluntary motor intention encoded in primary motor cortex is captured by intracortical arrays, decoded into continuous kinematic parameters, classified into functional hand primitives, and executed by a wrist-worn modular robotic finger system. Simultaneously, a wristband camera infers contact state and surface properties from the object being manipulated; these signals are encoded and delivered as ICMS to somatosensory cortex, completing the loop by returning tactile percepts to the brain.

2 BCI-Wearable Framework

Our proposed framework couples an invasive intracortical BCI with a wrist-worn modular robotic hand system to enable voluntary, sensation-aware hand motor assistance in individuals with

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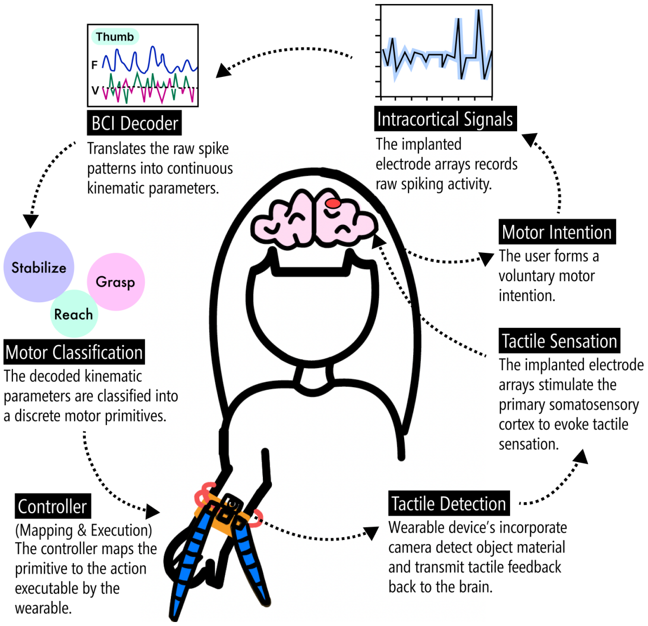

Figure 1: Closed sensorimotor loop of the proposed invasive BCI-wearable framework for hand assistance in SCI patients.

cervical SCI (Figure 1). The framework defines a closed sensorimotor loop comprising five interdependent components: intracortical signal capturing, motor-intention decoding, motor classification, wearable actuation, and cortical tactile feedback. Decoded cortical intent drives physical hand action, and sensory signals detected by the wearable return to the brain as artificial tactile percepts, restoring the bidirectional neural engagement that underpins natural sensorimotor function.

2.1 Core Framework Components

Motor Intention and Intracortical Signals. When the SCI user forms a voluntary movement intention, patterned neural activity is observed in the primary motor cortex (M1) and associated premotor areas [12, 19]. Voluntary movements involve hierarchical motor planning in which the cortex first encodes a movement goal in extrinsic coordinates—including the target location, desired trajectory, and movement direction—and subsequently generates descending commands that encode the parameters required to execute that trajectory, including joint angles, movement velocity, and activation signals to the muscles acting across each joint [12, 19]. Specifically, instead of issuing a single discrete trigger, these motor commands are continuous. M1 activity persists throughout movement execution, which encodes the ongoing kinematic state [12]. The intracortical microelectrode arrays that are implanted in the brain of the SCI patient record raw spiking activity and local field potentials from M1 neurons at millisecond temporal resolution, capturing the neural correlates of intended movement even in the complete absence of overt limb motion [4, 5, 10].

BCI Decoder. The recorded spike trains are processed by a trained neural decoder that translates the activity of the high-dimensional neural population into low-dimensional continuous kinematic parameters, updated at approximately 20 ms intervals to maintain real-time responsiveness [18, 21]. In our framework, we focus on a space of hand-motor parameters defined by three complementary dimensions derived from the existing intracortical decoding literature [18, 21]: (i) *finger group identity*, distinguishing the thumb (T), index–middle (IM), and ring–little (RL) groups; (ii) *movement direction*, classifying each group's intended motion as flexion (F) or extension (E); and (iii) *motion magnitude*, capturing continuous finger translation velocity (FV) and grasp contact force (GF).

Motor Classification. Rather than mapping the raw decoder output directly to actuator commands, we use an machine learning-based intermediate classification layer to provide a context-aware interpretation of the decoded kinematic output. This classification matches the continuously updated parameter estimates against a taxonomy of functional motor primitives drawn from upper-extremity motion analysis, including *idle/stabilize*, *point-to-point reach*, *reach-to-grasp*, *transport*, and *reposition* [15, 17]. With the classifier, the wearable device will predict the functional action the user intends to perform. For example, lift a cup, zip a jacket, or turn a door handle. The classifier and the prediction provide the wearable device with the current motor command and goal-directed sequence of the intended action. This context enables the controller to select appropriate finger configurations proactively, smoothly transitioning between successive primitives with the most contextually plausible action [17].

Wrist-Worn Robotic Hand-Assisted System. The wearable device consists of four integrated sub-components: a forearm-mounted controller, a modular wristband, plug-in cable-driven robotic finger units, and a dorsal-mounted sensing camera (Figure 2).

Controller. The controller module, worn on the forearm, implements two operational modes tailored to different SCI presentations. In cervical SCI, the injury level — denoted C4 through C7 for the relevant vertebrae — determines which muscles remain under voluntary control; higher levels (C4–C5) result in complete hand paralysis, while lower levels (C6–C7) preserve partial function such as tenodesis grip, a passive hand-closing motion produced when the user extends their wrist. The two modes are designed to align with this clinical spectrum. The *assist mode*, appropriate for users who retain partial voluntary finger function (*e.g.,* C6–C7 injury), coordinates the actuation of the robotic finger synergistically with the residual movement of the user, increasing the strength and range of motion without overriding the residual volition (Figure 2). *Active mode*, for users with complete hand paralysis (*e.g.,* C4–C5 injury), executes the full classified motor primitive through the robotic finger modules, acting as a complete motor substitute (Figure 2). In both modes, the controller receives primitive commands from the classification layer and maps them to per-finger cable actuation patterns in real time.

Wristband and Robotic Finger Modules. The wristband serves as the mechanical foundation of the system, featuring a set of standardized mounting positions distributed around its circumference. Each position accepts a modular cable-driven robotic finger unit that can be installed, removed, or repositioned without tools, allowing clinical configuration to the user's specific hand presentation.

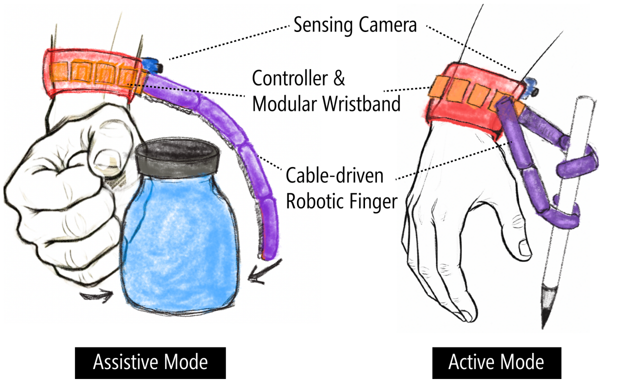

Figure 2: Two operational modes of the forearm-mounted controller.

Each finger unit contains two micro-motors that independently tension two pairs of orthogonal cables, generating a four-way drive of the multi-directional tendon structure through a single lightweight module. This multi-directional capability enables the artificial finger to conform to irregular object surfaces and to produce the range of grasp patterns required for ADLs [23].

Sensory Camera and Detection. A camera embedded in the wristband continuously captures the object being manipulated, enabling real-time inference of contact state, object material, and surface texture. It determines the relative position of the wearable and the interactive object to decide the gripping direction, and provides sensory data from which tactile feedback stimuli can be derived for cortical transmission.

Tactile Sensation. Sensory signals acquired by the wristband camera are encoded as patterned electrical stimulation parameters and delivered to the primary somatosensory cortex via the implanted electrode array, evoking artificial tactile percepts through ICMS [7, 8]. This artificial somatosensory feedback allows the user to perceive the texture of a grasped object, where the user receives real-time perception of hand-object interaction, enabling SCI patients to restore a form of tactile agency.

2.2 Design Considerations for BCI-Wearable Co-Design

Designing a wearable device that functions as a BCI effector, we identify five co-design considerations (CDC) that could guide the development of BCI-integrated assistive wearables for SCI populations.

CDC#1: Wearability and Safety. SCI patients frequently experience heightened skin sensitivity due to altered autonomic and sensory regulation below the injury level [20], making prolonged contact with rigid or high-pressure surfaces a clinical risk. Moreover, cervical SCI commonly produces fixed hand presentations. Spastic finger flexion and wrist palmar flexion mean that the hand is often held in a contracted posture that cannot and should not be forcibly corrected by the device [1, 2]. Rather than wrapping around or between fingers, the design should avoid direct finger-joint coverage entirely, using modular robotic units positioned at the wrist or dorsal surface to assist grasp without imposing forces against fixed joint postures. Device materials should be lightweight, soft, and durable where they contact skin, and total worn weight should remain minimal to avoid accelerating fatigue in proximal muscle groups that SCI patients rely on for compensation [13, 16].

Beyond contact safety, the electronic components embedded in the wristband introduce additional wearability tradeoffs. For example, Micro-motors generate vibration and acoustic noise during actuation, which may be perceptible to the user and bystanders. Power supply also needs more consideration, as a device that runs out mid-task undermines the independence it is meant to restore.

CDC#2: Patient-Adaptive Configurability. Patient configurability addresses the diverse clinical reality of hand manifestations resulting from cervical spinal cord injury, ranging from tendon-fixed postures to claw deformities due to the loss of intrinsic muscles [cite relevant papers on hand development in spinal cord injury]. This means that no single, fixed finger layout can meet the needs of all users. Our robotic finger unit's modular plug-in design allows clinicians and users to select the fingers to be controlled and their configurations, thereby customizing the device based on each patient's residual function and the ADL goals.

CDC#3: ADL-Relevant Grasp Coverage. Devices supporting only a single grasp pattern impose task and object constraints that can negate their independence gains [13, 17]. The diversity of ADL-relevant manipulation requires a wearable that can produce meaningfully different finger configurations on demand [15, 17]. Multi-directional cable actuation per finger module expands this reachable configuration space without proportionally increasing device weight.

3 Envisioned Scenarios

We present three envisioned scenarios that ground the framework in concrete ADL and creative contexts.

Scenario#1: Assistive Mode — Hygiene Tasks. A person with C6 SCI reaches for a comb on the bathroom counter. Their preserved wrist extension initiates a natural tenodesis grasp around the handle; the decoder detects a GRASP primitive and the finger modules close further, augmenting grip force without overriding the user's own closing movement. As the comb moves through hair, the wrist camera detects surface resistance; a corresponding tactile percept arrives at somatosensory cortex, and the user feels the drag and modulates stroke pressure through continuous BCI output. To hold a washcloth next, the user forms an intention to press. The system reconfigures the finger modules to a flattened posture that sustains a stable contact force against the face.

Scenario#2: Active Mode — Playing a Hand Drum. A person with C6 SCI retains partial wrist extension in one hand but has no voluntary function in the other. They wish to play a hand drum, which they have abandoned since the injury. With the wrist system in *active mode*, the device acts as a complete motor substitute that the user's cortical intent is the only signal driving hand action. Each intended strike is decoded from motor cortex as a rapid EXTENSION–GRASP sequence, driving the robotic finger modules to release and re-grip the drumstick in time. The camera detects each stick-to-drum-head contact; ICMS feedback delivers a tactile pulse at the moment of impact, restoring a rhythmic perceptual loop the user draws on to regulate timing.

Scenario#3: Mode-Switching — Preparing a Drink. A person with C6 SCI is making tea. Their preserved wrist extension supports tenodesis grip for light objects, but the full cylindrical grasp required to lift a full kettle exceeds what residual function can produce. As they reach for the kettle, the motor classifier identifies a *reach-to-grasp* primitive with high contact force magnitude; the controller enters *active mode* and the finger modules execute a full cylindrical grasp, lifting the kettle and pouring into a cup. Once the cup is filled and the user's wrist repositions it on the table, the classifier detects a *transport/stabilise* primitive with lower force demands; the controller transitions to *assistive mode*, amplifying the tenodesis grip to hold the cup during drinking without overriding the wrist extension the user is actively producing. This scenario illustrates that mode boundaries in real ADL use are not user-selected switches but emergent transitions driven by task context, and that the motor classification layer must manage them fluidly and without perceptible interruption.

4 Conclusion and Future Work

This workshop paper presented a closed-loop, invasive BCI-driven modular wearable framework for hand assistance in individuals with cervical SCI. In future work, we will build and evaluate a physical prototype with SCI participants in ADL tasks. We will also explore how the BCI-wearable co-design principles identified here transfer to other body segments, such as ankle dorsiflexion or elbow support, where intracortical decoding of the relevant motor representation could drive analogous modular actuators for broader daily-assistance coverage.

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