Healthcare and Rehabilitation 2 (2026) 100066

Contents lists available at ScienceDirect

Healthcare and Rehabilitation

journal homepage: www.keaipublishing.com/en/journals/hcr/

A rehabilitation design concept based on brain–computer interface and McKibben artificial muscle

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ARTICLE INFO

Keywords:
Haptics
Brain–computer interface
Wearable device

ABSTRACT

This perspective proposes a restrained rehabilitation design that reframes an electroencephalography (EEG)-based brain–computer interface (BCI) from continuous motor control to an intention-gating signal that determines when and how strongly haptic cues should be delivered. A McKibben artificial-muscle haptic navigation module encodes task deviation into a small, semantically consistent directional codebook, enabling intuitive "coach-like" guidance while minimizing visual/verbal dependence. This concept emphasizes safety-biased thresholds, low-intrusion feedback, protocol-level reporting of gating reliability, and cue-dose tapering to promote autonomy and skill transfer under real-world variability and drift.

Background and motivation

The central difficulty of rehabilitation training often lies not in whether a patient can execute a specific movement, but in whether the patient can repeat it correctly in real settings, gradually internalize it, and retain it after leaving the device. In clinical and home contexts, visual demonstrations, onscreen instructions, and verbal cues constitute the primary feedback channels. These channels readily compete for attentional resources and outsource learning to external guidance, which fosters dependence on watching and listening.[1] At the same time, brain-computer interfaces (BCI) are expected to deliver continuous and fine-grained motor control in rehabilitation. However, under wearable and everyday conditions, signal noise, inter-individual variability, and day-to-day drift make it difficult to reproduce such goals reliably. System goals should therefore return to providing clear and intuitive error information within critical time windows when patients actively attempt to move.

Intention-gated BCI and directional haptic navigation

This perspective has motivated the development of a restrained and implementable design concept. The BCI should not be positioned as a controller that drives the body, but rather as an intention-gating module. The essential output is whether the patient is initiating motor intention or a coarse estimate of the intention strength. In wearable real-world rehabilitation, intention gating can rely on low-latency electroencephalographic markers, including movement-related cortical potentials (e.g., the readiness potential) and changes in sensorimotor rhythm power (e.g., event-related desynchronization [ERD] and event-related synchronization [ERS]) during motor preparation and initiation. These signals can be estimated from short time windows using a small number of electrodes. Algorithmically, intention detection can be implemented using conventional pipelines—such as bandpower or temporal features of ERD, ERS, or Movement related cortical potentials (MRCPs) combined with Linear Discriminant Analysis (LDA), Support Vector Machine (SVM), or logistic regression—to produce a low-latency probability of intention onset or strength from short windows. Deep learning approaches, such as compact Convolutional Neural Network (CNN), Recurrent Neural Network (RNN), or Transformer variants, are also feasible; however, we emphasize that whichever model is used should be calibrated for cross-day robustness and conservative decision thresholds, because the output serves gating rather than continuous command generation. The value of BCI lies in providing temporal information that determines when a cue should appear, how long it

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https://doi.org/10.1016/j.hcr.2026.100066
Received 24 January 2026; Received in revised form 5 March 2026; Accepted 9 March 2026

should persist, and how strong it should be, rather than directly prescribing joint angles or continuous trajectories. Importantly, electroencephalography (EEG)-based gating can exploit preparatory cortical markers, including MRCP and ERD, to align cue delivery to pre-movement intention windows, whereas Electromyography (EMG)- or kinematics/performance-threshold gating typically becomes reliable only after muscle activation or overt deviation is already expressed. This earlier, intention-level access is particularly consequential in neurorehabilitation populations with weak/atypical EMG patterns or compensatory movements, where peripheral or kinematic thresholds may conflate execution noise with genuine intent. Compared with prevalent BCI-robot rehabilitation systems that use MI decoding for continuous online control and often combine multimodal feedback to improve engagement and decoding performance,[2] our concept deliberately avoids continuous command generation. Instead, aligned with the trends summarized in recent reviews of BCI–robot hand rehabilitation,[3] BCI is positioned as an intention gate that modulates when and how much haptic navigation feedback is delivered, thereby prioritizing robustness and semantic consistency under real-world variability. This gating formulation offers a concrete advantage: it turns an error-prone continuous decoder into a binary/graded permission signal. Thus, occasional EEG uncertainty changes the cue timing and intensity rather than imposing erroneous kinematics. Consequently, it improves the safety and transfer of motor learning by delivering feedback only during genuine voluntary attempts and enabling principled tapering of the cue dose across sessions. In parallel, McKibben artificial muscle haptic navigation should not assume responsibility for substituting force generation or mechanically pulling the body to complete a task.[4] Its role is to translate deviation into a directional sensation. Through haptic cues that resemble a coach's touch, such as gentle pulling, compression, or slight torsion, it conveys simple and unambiguous navigation information, including left and right, forward and backward, and up and down.[5] The combined objective is not to make the device perform the movement more accurately on the patient's behalf but to help the patient learn the movement more stably at the right moments.

Relation to assist-as-needed and personalized rehabilitation

Although our rationale is consistent with individualized closed-loop neurorehabilitation, it is conceptually distinct from assist-as-needed (AAN) and generic "personalized rehabilitation" in that the adapted variables are the gating policy and cue dose (rather than an assistive control policy), and the delivered intervention is non-assistive directional haptic guidance (rather than physical movement assistance). Table 1 delineates shared elements (closed-loop individual calibration) versus the genuinely new aspects emphasized here: EEG as a safety-biased intention gate, low-cardinality semantically stable directional cueing, and protocol-level cue-dose tapering with explicit reporting of gating reliability/cue-dose metrics.

System architecture

This design concept, depicted in Fig. 1(a), emphasizes the effectiveness of a minimal closed loop rather than the complexity of stacked functions. The proposed wearable devices, Funabot-Suit (Fig. 1(b)) and Funabot-Sleeve (Fig. 1(c)), were proven to communicate information between humans and machines via the torso and forearm. The BCI first identifies the time window in which the intention emerges. A gating module then determines whether haptic cues are permitted and sets the cue intensity. The haptic encoding module maps the task deviation to a directional haptic pattern. In its simplest form, this mapping is manually specified as a small set of discrete rules that quantizes the deviation vector (e.g., left/right, forward/backward, and up/down) into a single, semantically consistent haptic pattern. Alternatively, the mapping can be learned or individualized from short calibration data but should remain constrained to this low-cardinality codebook to preserve interpretability and stable cue semantics across sessions. McKibben artificial muscle haptic navigation applies this pattern to locations that readily support a spatial reference frame, such as the torso or proximal upper limb. Inertial sensors or task performance metrics then return the movement state information used to slowly update the gating thresholds and haptic intensity. Here, "slowly update" refers to conservative, bounded calibration, potentially under clinician supervision. For example, compensating for baseline drift and maintaining cue intensity within an individualized comfort range. This does not imply a reward-driven human-in-the-loop reinforcement learning policy; rather, any adaptation follows simple safety-constrained rules with a fail-safe default to release. In this closed loop, the algorithmic sophistication is not a core issue. The core lies in the semantic consistency and restraint of the cue dosage. The haptic cues should be few and stable, and each pattern should have a single clear meaning. The same stimulus should not carry different meanings across training stages, which reduces the learning burden and supports transfer across tasks. Cue intensity should be gradually reduced as training progresses so that patients can reclaim error correction from the device through their own perception and motor planning, thereby reducing the risk of long-term dependence.

Table 1
Conceptual positioning relative to assist-as-needed and personalized rehabilitation paradigms.

Dimension	assist-as-needed / Personalized rehabilitation	This Perspective
Rehabilitation objective	Optimize task-level performance via individualized assistance, difficulty titration, and/or adaptive feedback	Prioritize volitional engagement and skill acquisition/transfer via minimally sufficient, intention-timed cueing with planned cue tapering
Control variable being adapted	Assistance magnitude/trajectory/control policy; task parameters; feedback dosage	Gating policy and cue dose, rather than kinematic assistance
Function of neural/intention signals	When used, contributes to state estimation and/or adaptive assistance for performance enhancement	EEG provides a high-level permissive/triggering signal (intention gate), not a continuous command stream for low-level control
Role of actuation modality	Delivers assistive torques/forces/trajectories (physical assistance) to reduce error or effort	McKibben actuation is constrained to directional haptic guidance, explicitly non-assistive in terms of movement execution
Safety and failure characteristics	Mis-estimated intent or controller error can impose maladaptive kinematics; safety depends on controller constraints and limits	Conservative gating and fail-safe release: uncertainty modulates cue delivery (timing/intensity) rather than imposing incorrect motor output
Evaluation and reporting emphasis	Assistance profiles, controller performance, clinical outcomes, dose–response at the intervention level	Protocol-level reporting: gating reliability + cue-dose descriptors

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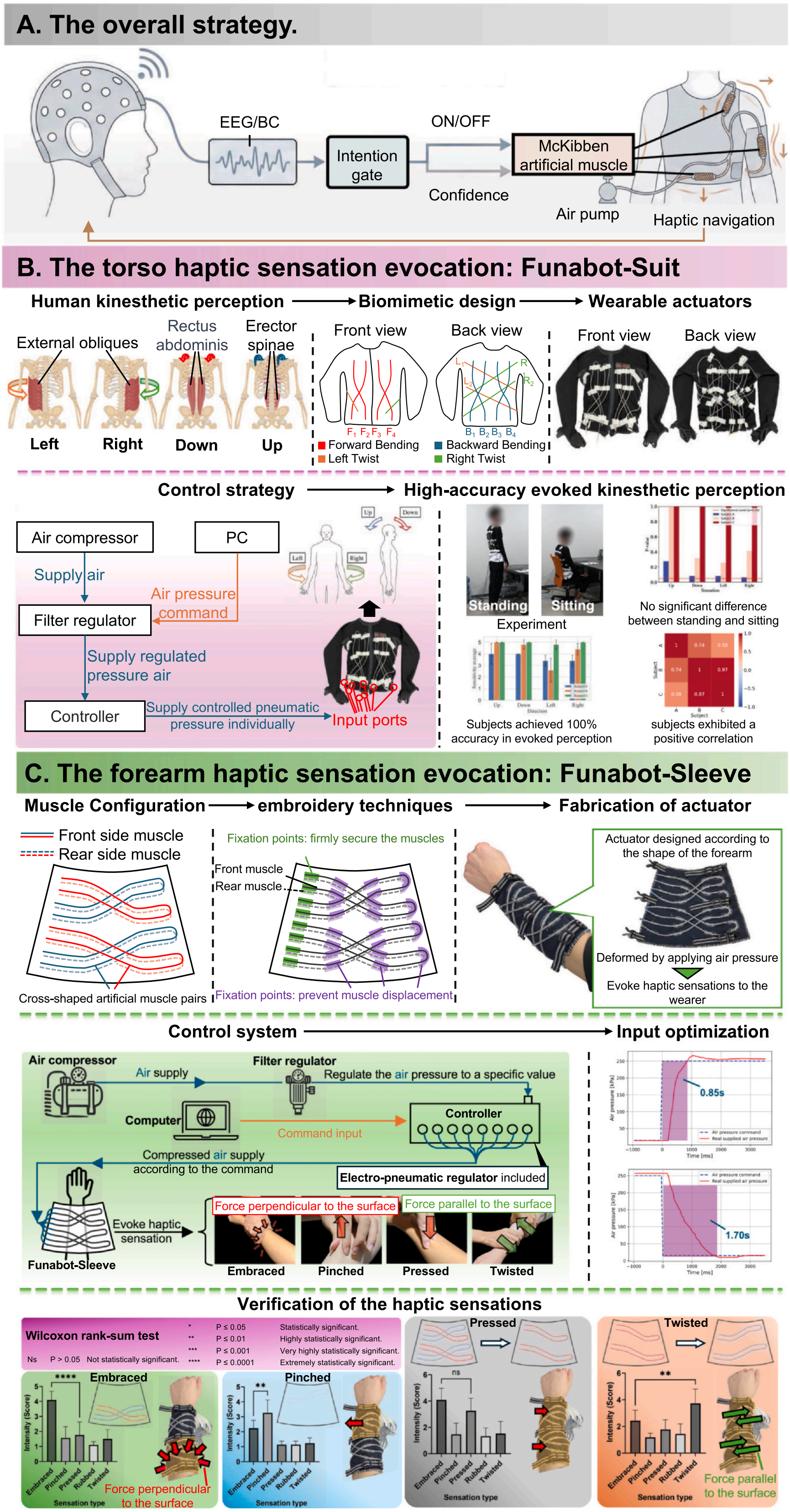

Fig. 1. Rehabilitation design concept of the proposed intention-gated EEG/BCI-driven McKibben artificial-muscle haptic navigation system. A, The overall strategy. B, Torso wearable haptic sensation evocation: Funabot-Suit [5]. C, Forearm wearable haptic sensation evocation: Funabot-Sleeve [4]. Abbreviations: EEG, electroencephalography; BCI, brain–computer interface; PC, personal computer.

Intended populations and use scenarios

The framework is primarily intended for neurological rehabilitation populations, such as stroke survivors, who retain detectable voluntary motor intentions but exhibit impaired movement quality and a high reliance on external cues, spanning the subacute to chronic stages. The boundary conditions include users with severe cognitive or attention deficits that prevent cue interpretation, absent or unreliable intention signals, or contraindications to wearable haptics such as skin fragility or intolerable discomfort, for whom the proposed gated haptic strategy may be less applicable. When this concept is applied to concrete tasks, the most direct entry points are training paradigms that rely heavily on external cues yet critically require movement quality and strategy internalization. In upper limb rehabilitation practice, patients often correct errors by repeatedly checking the screen and following verbal commands.[6] Performance can be sustained in the short term; however, movement strategies are difficult to consolidate. Intention gating ensures that haptic cues occur only when the patient attempts to initiate and adjust movements.[7] Directional haptic cues can shift correction from visual tracking to fine-tuning by feeling, which redirects attention from external displays toward bodily sensation and action planning.[8] Postural control and turning training also align with directional haptic cues because the torso and proximal segments more readily provide stable spatial reference frames.[9] Haptic navigation delivers immediate alignment information without consuming visual resources, whereas gating reduces the disruptive effects of unnecessary cues on balance control. In home-based training, environmental noise, fragmented attention, and practical barriers further amplify the value of low-demand and low-intrusion feedback. Gated haptic cues are more likely to be accepted over time than are persistent reminders.

Risks and boundary conditions

This design concept also requires a clear view of risks and boundary conditions. Cross-day drift and inter-individual variability in BCI still lead to false triggers and missed detections. Practical mitigation in future systems involves a brief per-session calibration (baseline normalization and conservative thresholds) and ongoing monitoring of false trigger and miss rates. As a feasibility envelope, intention gating is assumed to yield a permissive decision within a short pre-/peri-movement window, typically within a few hundred milliseconds of movement initiation, so that cue onset remains temporally coupled to action planning rather than late error correction. False triggers are acceptable only if they are sufficiently rare to preserve stable cue semantics; practically, this motivates imposing an explicit cap on spurious cue rate and favoring cue suppression over potentially misleading directional information. Missed detections primarily reduce effective training dose rather than impose erroneous kinematics, but when frequent they erode functional relevance; therefore false-trigger and miss rates should be reported together with cue-frequency and taper parameters as protocol-level feasibility indicators. If additional data are available, lightweight transfer, domain adaptation or bounded online updating can be explored but should remain safety-biased because the BCI output serves as intention gating rather than continuous control. When the role of the BCI is limited to gating rather than continuous control, the system can adopt more conservative and robust decision rules and can, when needed, incorporate lightweight fusion with electromyography or inertial information to improve reliability.[10] The primary risks of haptic cues arise from unstable semantics and learning interference caused by incorrect cues. Design should, therefore, prioritize stable and consistent meaning and should reduce cue frequency rather than provide unreliable directional information. The engineering translation of the McKibben artificial muscle haptic navigation must contend with practical constraints, including pneumatic supply, noise, weight, maintenance, and wearing comfort. These constraints support a role centered on navigational prompting rather than actuation for task execution, along with a safety principle in which failure defaults to release. Individual differences in sensitivity to haptic stimulation are also important. The rapid calibration of detection thresholds and comfort ranges should be the default procedure that allows for individualized intensity adjustment without compromising semantic consistency.

Outlook and reporting recommendations

Therefore, a combination of BCI gating and McKibben artificial muscle haptic navigation provides a route for a closed-loop rehabilitation design. Looking forward, this restrained design philosophy suggests a protocol shift from maximizing assistance to prescribing a minimal intention-timed cue dosage with planned tapering, thereby embedding autonomy and skill transfer as explicit clinical endpoints. It also motivates future rehabilitation strategies to standardize haptic cue semantics and report gating reliability and cue-dose metrics, such as false-trigger rate, cue frequency, and taper schedule, as protocol-level parameters rather than purely algorithmic details. It does not aim to use a BCI to directly control fine-grained continuous movements. Instead, it uses the temporal structure of intention derived from BCI to manage the timing and dosage of cues, and uses McKibben artificial muscle haptic navigation to deliver intuitive and interpretable directional information.

Ethics approval

This study proposes a theoretical design concept and framework for rehabilitation devices, and no human or animal experiments were conducted in the research process. Therefore, no ethical approval was required for this work in accordance with the relevant research ethics guidelines. For the potential clinical translation of the proposed design in the future, the implementation of human trials will strictly comply with the Declaration of Helsinki and obtain ethical approval from the institutional review board (IRB) of the host institution, as well as written informed consent from all participants.

Funding information

This work was supported by the Innovative Research Group of the Chongqing Municipal Education Commission (CXQT19026), Cooperative Project between the Chinese Academy of Sciences and the University in Chongqing (HZ2021011), Young Project of Science and Technology Research Program of the Chongqing Education Commission of China (KJQN202501166), and Chongqing Municipal Human Resources and Social Security Bureau (CSTB2025YCJH-KYXM0046).

CRediT authorship contribution statement

Zhen Tian: Supervision, Writing – review & editing. **Zhanwei Wang:** Writing – original draft. **Shaojie Gu:** Writing – original draft. **Zihao Zuo:** Writing – original draft. **Yang Jiang:** Writing – original draft. **Yanhong Peng:** Writing – original draft, Writing – review & editing, Conceptualization, Funding acquisition. All the authors have read and approved the final version of this manuscript.

Data availability

No empirical data were generated for this theoretical design concept; thus, data availability is not applicable.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

ChatGPT (GPT-5.2) was used to review manuscript grammar. All authors reviewed and edited the content and take full responsibility for the final manuscript. No other generative AI tools were used in the preparation of this work. (explicitly state no other AI use).

Acknowledgments

None.

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