Wrist-Based Haptic Rehabilitation Device for Stroke using Body-Grounded Haptic Concept: A Review

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ABSTRACT

Stroke is a major cause of long-term disability, and impaired wrist and hand function can greatly limit independence in daily activities. Conventional rehabilitation remains important, but it is often constrained by therapist availability, limited training intensity, and reduced patient motivation during repetitive exercises. Haptic and robotic-assisted rehabilitation devices have been introduced to support repetitive, measurable, and feedback-driven therapy. However, many existing systems are bulky, costly, or designed mainly for clinical and laboratory settings, limiting their wider use in home-based or low-resource rehabilitation settings. This paper reviews selected wrist-based haptic and rehabilitation devices and proposes the development of a compact body-grounded haptic device, named H³-WristKit, for post-stroke wrist rehabilitation. The proposed device focuses on wrist flexion-extension movement and is designed to deliver adaptive assistive and resistive feedback using impedance control. Existing interfaces, including Hapkit, H³Kit, pneumatic wrist rehabilitation robots, low-cost wrist robots, and RiceWrist-S, were compared in terms of design, portability, advantages, and limitations. The review shows a clear gap between high-performance grounded systems and portable educational haptic devices. The proposed H³-WristKit aims to address this gap by combining a lightweight body-grounded structure, low-cost fabrication, and rehabilitation-oriented control. Future work should include prototype fabrication, control validation, safety testing, usability evaluation, and preliminary testing with post-stroke users to assess practical feasibility, patient adherence, and user satisfaction. This work provides an early design direction for a more accessible wrist rehabilitation device that may support continuous upper-limb therapy after stroke.

Keywords: body-grounded haptics, haptic feedback, rehabilitation robotics, stroke rehabilitation, wrist rehabilitation

INTRODUCTION

Stroke remains one of the most significant global health challenges, ranking among the leading causes of long-term disability and mortality worldwide. According to epidemiological projections, the global incidence, mortality, and disability-adjusted life years (DALYs) associated with ischemic stroke are expected to rise steadily through 2030, particularly in developing regions where healthcare access and rehabilitation infrastructure remain limited [1]. A stroke occurs when the blood supply to part of the brain is interrupted or reduced, preventing brain tissue from receiving sufficient oxygen and nutrients. Within minutes, brain cells begin to die, leading to neurological impairments that may affect motor, sensory, cognitive, or speech functions [2]. Among these, upper-limb motor dysfunction, especially in the wrist and hand, has been consistently identified as one of the most disabling consequences of stroke [3]–[6].

The restoration of wrist and hand function plays a pivotal role in regaining independence in daily living activities such as grasping, reaching, and manipulating objects. However, recovery of upper-limb motor function is often limited and slow due to the complex neuromuscular coordination required for wrist movements [7]. Stroke survivors typically exhibit reduced range of motion, muscle weakness, spasticity, and impaired coordination in the affected limb [8]. These deficits restrict their ability to perform activities of daily living (ADLs), ultimately affecting their quality of life and social reintegration [9], [10].

Stroke rehabilitation aims to restore motor control and functionality through repetitive, task-specific, and goal-oriented exercises that engage both the musculoskeletal and nervous systems [3], [11], [12]. Such interventions are grounded in the concept of neuroplasticity, the brain's intrinsic ability to reorganize its structure and function to compensate for lost neural connections [7], [13]. Neuroplastic recovery is experience-dependent: it relies heavily on the intensity, frequency, and quality of sensorimotor training provided during the rehabilitation process. Clinical studies, such as the Graded Repetitive Arm Supplementary Program (GRASP), have demonstrated that patients who perform hundreds of daily wrist and arm repetitions achieve significantly better functional outcomes than those undergoing conventional low-repetition therapies [14]. This evidence underscores that rehabilitation effectiveness is directly correlated with repetition intensity, variability of tasks, and patient engagement [4], [15].

However, despite the strong theoretical foundation and proven efficacy of repetitive training, conventional therapist-based rehabilitation faces substantial practical constraints. The availability of trained therapists is often limited, particularly in low- and middle-income countries such as Malaysia, where healthcare workforce shortages are well-documented [9], [8]. Even in well-resourced clinical environments, therapy intensity is constrained by therapist fatigue, patient compliance, and institutional time limitations [16], [17]. Furthermore, repetitive manual exercises are physically demanding for therapists and monotonous for patients, leading to reduced motivation and adherence over prolonged treatment periods [10]. These systemic and motivational barriers hinder patients from achieving the high-intensity, continuous practice necessary to stimulate lasting neuroplastic recovery.

To address these limitations, robot-assisted rehabilitation has emerged as a transformative approach to motor recovery. Robotic systems enable precise, repeatable, and quantifiable movement training while providing real-time feedback on performance and progress [3], [11], [18]. Such systems can deliver consistent therapy doses, reduce therapist workload, and facilitate data-driven treatment personalization. Numerous studies have confirmed that robot-assisted therapy can enhance motor outcomes compared to traditional therapy, particularly when used as a supplement rather than a replacement for human supervision [4], [12], [19].

Two primary categories of robotic rehabilitation devices have evolved: end-effector-based systems and exoskeleton-based systems. End-effector robots, such as the MIT-Manus, apply forces at a single point of contact, for example, the hand or wrist, allowing simplified control of limb trajectories [11]. In contrast, exoskeleton robots like the RiceWrist-S align mechanically with human joints to provide multi-degree-of-freedom (DOF) movement with higher precision and torque [20]. Both architectures have proven effective in clinical rehabilitation, yet they present notable limitations. End-effector robots lack precise joint alignment, leading to reduced kinematic fidelity, while exoskeletons are typically bulky, expensive, and confined to controlled laboratory or hospital environments [21], [16], [22]. As a result, their widespread deployment, particularly for home-based therapy, is impractical.

In response to these shortcomings, recent research has explored portable and body-grounded haptic devices, designed to provide haptic or kinesthetic feedback without external mechanical grounding [23], [24]. The term "body-grounded" refers to systems that use the user's own body as the reaction frame for force feedback instead of attaching the device to an external structure or fixed base. Devices such as the Hapkit [25] and H^3Kit [26], [24], [27], originally developed for haptics education, have demonstrated the feasibility of delivering meaningful force feedback through lightweight, low-cost mechanisms. Their compact and modular architecture allows users to feel virtual environments such as springs, walls, or dampers using simple impedance-based control algorithms [22]. These devices emphasize active participation, a crucial factor in promoting motor learning and neuroplasticity [4], [5].

While educational haptic devices like the H³Kit are not designed to generate the higher torque levels required for rehabilitation, their core principles, simplicity, portability, and interactivity, can be leveraged to design clinical-grade, affordable rehabilitation tools [26], [24]. The challenge lies in adapting such systems to meet the rigorous demands of post-stroke therapy: ensuring ergonomic alignment with human anatomy, implementing adaptive control strategies, and maintaining safety during physical interaction [22], [28], [29]. Achieving this balance requires interdisciplinary collaboration between biomedical engineers, clinicians, and neuroscientists to translate haptic design concepts into medically effective rehabilitation technologies.

The Need for Wrist-Focused Rehabilitation

Upper-limb recovery after stroke typically follows a proximal-to-distal progression, in which shoulder and elbow movements often recover earlier than wrist and hand function [5], [12]. This hierarchical recovery pattern underscores the importance of targeted wrist rehabilitation, as the wrist serves as a biomechanical and neurological bridge between gross arm movement and fine motor control. Impairments in wrist flexion and extension can severely restrict the ability to grasp, release, or manipulate objects, directly compromising activities such as eating, dressing, and writing [10].

Traditional wrist rehabilitation exercises often include passive stretching, active-assistive movement, and resistive strengthening [8], [30]. However, these exercises require continuous therapist supervision to ensure correct movement trajectories and avoid compensatory strategies that may reinforce abnormal motor patterns. Without real-time feedback, patients may perform exercises incorrectly, potentially impeding recovery. Haptic and robotic devices can overcome these barriers by guiding wrist trajectories, adjusting resistance based on user performance, and providing sensory feedback that reinforces motor learning [18], [15], [31].

Moreover, incorporating force feedback into wrist rehabilitation can enhance the user's ability to perceive and respond to movement errors. Psychophysical research suggests that haptic feedback stimulates proprioceptive senses that are critical for accurate motion control [32]. By integrating controlled force feedback into rehabilitation exercises, patients may regain kinesthetic awareness and improve coordination between visual and tactile cues. Therefore, a wrist-based haptic rehabilitation device is well positioned to restore both strength and sensory integration in post-stroke patients.

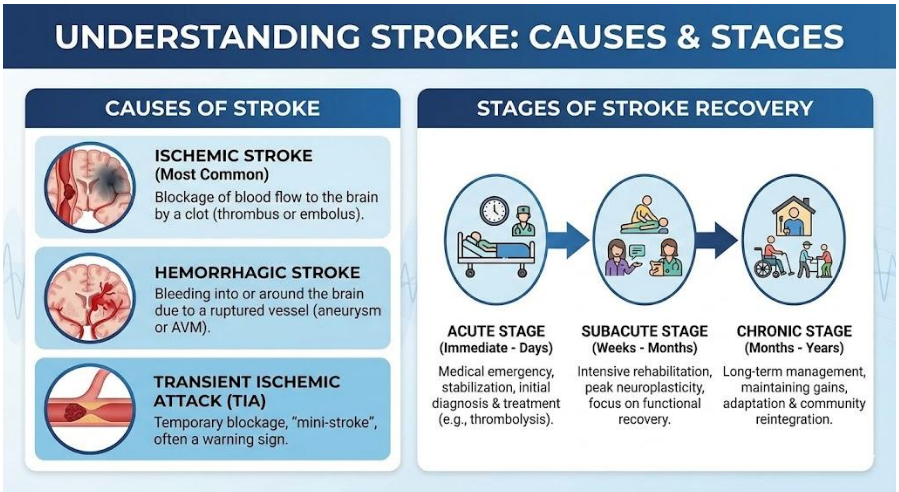

Figure 1: Understanding Stroke- Causes and Recovery Stages

The Role of Impedance Control in Haptic Rehabilitation

Haptic systems rely on sophisticated control algorithms to simulate virtual mechanical properties such as stiffness, damping, and inertia. Among these, impedance control is one of the most widely adopted frameworks in rehabilitation robotics because of its stability, safety, and adaptability [22], [33]. This control strategy allows the device to regulate the relationship between force and motion, thereby replicating the sensation of interacting with physical objects. In rehabilitation contexts, impedance control can be tuned to either assist or resist user movement, depending on the patient's current functional capacity [15], [21].

For example, during early-stage recovery, or assistive mode, the device can function as a guiding mechanism by moving the wrist through a predefined trajectory to stimulate neural activation in patients with limited voluntary control. As recovery progresses, or in resistive mode, the same system can provide variable resistance, challenging patients to overcome virtual loads and enhance muscle strength. This dual-mode capability encourages active engagement, which is a key driver of neuroplastic adaptation [4], [5], [31].

However, achieving stable and responsive impedance control in lightweight, body-grounded systems poses technical challenges. These include minimizing delays in force feedback, preventing unwanted oscillations, and ensuring accurate position sensing despite mechanical flexibility [22]. To address these issues, modern rehabilitation devices incorporate high-resolution magnetic encoders and current-controlled DC motors to achieve precise torque modulation [23], [24]. The proposed body-grounded haptic system adopts these design principles while optimizing for portability and user comfort.

Limitations of Current Rehabilitation Devices

Despite significant advancements, current robotic rehabilitation technologies still face several limitations that restrict their widespread use. First, most systems remain clinic-bound and require stationary setups with external frames for grounding and high-torque actuators [16], [20]. This limits accessibility for patients who are unable to attend frequent therapy sessions because of mobility, financial, or logistical constraints [9], [34]. Second, cost and complexity remain major barriers. Commercial robotic systems can cost tens of thousands of dollars, placing them beyond the reach of many healthcare institutions in developing countries [9], [34].

Beyond the initial purchase cost, maintenance and operational requirements may further limit adoption in routine rehabilitation settings. Robotic rehabilitation systems often require technical support, calibration, replacement of mechanical or electronic components, and user training for therapists or caregivers. These requirements may be difficult to sustain in low-resource healthcare settings, where rehabilitation services are already limited by staffing, equipment, and infrastructure constraints. Therefore, affordability should not only refer to the cost of fabrication, but also to long-term maintenance, ease of use, durability, and the ability to function with minimal technical support.

Third, the limited adaptability of many devices may reduce their clinical effectiveness. Fixed-force control systems can provide excessive assistance, causing users to rely passively on the robot, a phenomenon commonly referred to as “slacking” [31]. This passivity may reduce cortical engagement and undermine the neuroplastic benefits of active participation. Studies emphasize that rehabilitation outcomes improve when robotic assistance is adaptive and responds dynamically to the patient’s effort level [15], [35]. Finally, portability and ergonomic alignment are often overlooked in device design, leading to bulky or uncomfortable interfaces that may discourage prolonged use [28], [29].

Given these gaps, there is a pressing need to develop compact, user-friendly, and cost-effective devices that maintain clinical relevance while enabling home-based rehabilitation. Such systems should combine mechanical simplicity with advanced control strategies capable of delivering adaptive assistive and resistive feedback safely and effectively.

Towards a Body-Grounded Wrist-Based Haptic Device

The concept of a body-grounded haptic rehabilitation device represents a shift from traditional grounded robotics to wearable or self-contained systems [23], [24]. By using the human body as the mechanical reference frame, these devices eliminate the need for external supports while maintaining the ability to generate controlled feedback forces. The H^{3}Kit, developed at the University of California San Diego, exemplifies this concept by demonstrating that high-quality haptic interaction can be achieved through a handheld, low-inertia platform [24], [26], [27].

Based on the limitations identified in current wrist rehabilitation devices, this paper proposes a compact body-grounded haptic device named H^3-WristKit. The device is intended to adapt the educational H^{3}Kit concept for post-stroke wrist rehabilitation by integrating impedance-based assistive and resistive feedback. This proposed adaptation is important because existing educational haptic kits are generally designed for basic haptic interaction or teaching purposes, whereas rehabilitation use requires greater attention to safety, ergonomics, control stability, and therapeutic relevance.

The proposed H³-WristKit is designed as a single-degree-of-freedom (DOF) wrist-based haptic rehabilitation device that focuses on wrist flexion-extension, a fundamental movement for upper-limb function. By integrating 3D-printed lightweight structures, low-cost electronic components, and adaptive control algorithms, the device aims to offer a more affordable and portable option for stroke rehabilitation.

Unlike traditional exoskeletons, the H³-WristKit is compact, portable, and body-grounded, allowing patients to conduct therapy sessions independently at home or under minimal supervision. Its dual-mode control framework is intended to guide movement during early recovery and provide resistance-based strengthening during later stages. This adaptive functionality, combined with ergonomic design and low manufacturing cost, positions the device as a potential solution to the accessibility gap in stroke rehabilitation technology [19], [29], [30].

Summary of Research Motivation

In summary, stroke rehabilitation continues to demand innovative solutions that merge clinical efficacy with accessibility and affordability. The increasing stroke burden in Malaysia and globally [1], [9] underscores the urgency of developing portable technologies that enable continuous, intensive therapy outside hospital settings. Existing robotic systems have demonstrated the potential of haptic feedback in restoring motor function, yet their high cost, size, and complexity limit practical deployment.

By introducing a body-grounded, impedance-controlled wrist rehabilitation device, this research aims to contribute a novel approach to post-stroke therapy. The proposed system not only addresses mechanical and control challenges but also aligns with current clinical objectives of promoting active, patient-centered rehabilitation. Through careful design and validation, such devices may ultimately support long-term neuroplastic recovery, improve patient motivation, and reduce healthcare burdens by shifting rehabilitation from the clinic to the home environment.

Study Aim and Rehabilitation Context

Study Aim

This paper reviews selected wrist-based haptic and rehabilitation devices and proposes the development of a compact body-grounded haptic device, capable of delivering adaptive assistive and resistive force feedback to facilitate post-stroke motor recovery.

Background on Stroke Rehabilitation

Stroke rehabilitation is a long-term therapeutic process that capitalizes on neuroplasticity to restore lost motor control and functionality [7], [13]. Recovery is often most responsive during the subacute phase, from weeks to months after stroke, when structured and high-intensity training can maximize neuroplastic recovery [36], [37]. Conventional physiotherapy remains the foundation of post-stroke rehabilitation because it allows therapists to assess movement quality, guide patients manually, adjust exercises according to impairment level, and monitor safety during therapy [8], [17]. Therapist involvement is especially important because stroke survivors may present with different levels of severity, spasticity, weakness, fatigue, and cognitive or motivational challenges. These patient-specific factors influence how much assistance, repetition, and progression can be safely provided during rehabilitation.

The Graded Repetitive Arm Supplementary Program (GRASP) trial demonstrated that hundreds of additional wrist and arm repetitions daily can improve muscle coordination and dexterity [14]. However, achieving this level of repetition through therapist-supervised sessions alone can be difficult because of time, staffing, and resource limitations [8], [17]. As a result, robotic and haptic devices have become useful complementary tools for delivering consistent, task-specific movement therapy [3], [11], [12].

These technologies should not be viewed as replacements for conventional physiotherapy, but as supportive systems that may extend therapy intensity and provide feedback outside regular supervised sessions. Assist-as-needed and resistive training paradigms can help patients re-engage affected limbs and strengthen residual motor pathways [4], [15]. A wrist-based rehabilitation device specifically targeting flexion-extension motion can therefore provide additional support for functional upper-limb recovery, particularly when used alongside therapist-guided rehabilitation [10].

Rehabilitation Robotics

Robotic rehabilitation systems have been shown to enhance upper-limb recovery by enabling controlled, repetitive, and data-driven movement exercises [3], [11], [12]. Devices such as the MIT-Manus and RiceWrist-S have achieved clinical success, but they remain impractical for home-based use because of their bulk, cost, and need for external grounding [16], [20].

Recent advancements in lightweight, body-grounded devices such as the Hapkit and H³Kit have shown that effective kinesthetic feedback can be delivered without complex infrastructure [24]–[27]. These devices rely on impedance control mechanisms to simulate virtual spring-damper environments that enhance user interaction and engagement [22], [33].

However, challenges remain in terms of force accuracy, joint alignment, and long-term stability [28], [29]. To translate educational prototypes into therapeutic devices, further refinement in ergonomics, feedback calibration, and adaptive control is necessary [21], [35].

Design Requirements for a Wrist-Based Haptic Rehabilitation Device

Based on the literature [21], [22], [24], [29], several essential design requirements were established:

1. Single-DOF wrist flexion-extension capability
   This enables focused rehabilitation of the primary wrist movement that is critical for daily function.
2. Low mass and inertia
   A lightweight design ensures safety, reduces fatigue, and allows more natural wrist motion [4].
3. Adaptive assistive and resistive feedback
   Customizable control modes support recovery progression from limited voluntary movement to more active wrist motion [15].
4. Compact and portable design
   A compact structure facilitates home-based therapy with minimal setup [23], [24].
5. Stable impedance control with accurate sensing
   Stable control and accurate sensing are required to ensure smooth force rendering and safe human-device interaction [22], [33].

These principles guide the mechanical and control design of the proposed body-grounded device, referred to as the H³-WristKit.

METHODOLOGY

A structured literature review was conducted to assess existing haptic and robotic wrist rehabilitation devices. Database searches were performed using IEEE Xplore, ScienceDirect, and PubMed with the following keywords: “wrist haptic device,” “stroke rehabilitation robot,” “assist-as-needed control,” and “impedance-based feedback.”

Studies were included if they met the following criteria: they were peer-reviewed publications from 2000 to 2025, addressed upper-limb or wrist rehabilitation, and reported device design, control methodology, or experimental results. Studies were excluded if they were theoretical-only papers or non-haptic designs. Out of 75 identified publications, 22 met the criteria for detailed review. Comparative analysis focused on device configuration, portability, sensing mechanisms, control strategies, and therapeutic outcomes.

RESULTS AND DISCUSSION

Comparative Analysis of Wrist Haptic Interfaces

Several wrist-based haptic and rehabilitation interfaces were reviewed to understand their design approaches, strengths, and limitations. The comparison considered practical aspects such as degree of freedom, portability, actuation method, control strategy, and potential use in clinical or home-based rehabilitation. This helped identify the gap for a simpler, lower-cost, and more adaptable wrist rehabilitation device.

Table 1: Comparative Analysis of Wrist Haptic Interfaces

No.	**Author and year**	**Device name**	**Primary design**	**Advantages**	**Limitations**
1	Okamura et al. [25]	Hapkit	1-DOF friction-drive, desk-mounted haptic device	Open-source, low-cost, and minimal gear backlash	Stationary, low torque, and not designed for intensive rehabilitation
2	Rehmat and Culbertson [24]	H^3Kit	Handheld, portable haptic device for STEM education	Highly portable, tactilely engaging, and accessible for teaching and prototyping	Designed for education and not intended to produce clinical rehabilitation forces
3	Al-Fahaam et al. [29]	Wrist rehabilitation robot	3-DOF device using pneumatic muscle actuators	Lightweight actuation, safe interaction, and impedance control capability	Requires an external air supply, which reduces portability
4	Bu [30]	2-DOF wrist rehabilitation robot	Low-cost, 2-DOF wrist robot for flexion-extension and ulnar-radial deviation	Supports multi-axis movement and provides kinematic/static performance evaluation	Grounded structure and less suitable for compact home-based use
5	MAHI Lab [20]	RiceWrist-S	3-DOF cable-driven, grounded wrist exoskeleton	High torque capability, multiple DOFs, and low-backlash transmission	Bulky, costly, and mainly suitable for clinical or laboratory settings

Advantages and Limitations of Existing Interfaces

Existing designs show clear trade-offs between torque output, system size, and portability. High-torque exoskeletons such as the RiceWrist-S offer advanced control and precision, but they remain impractical for home use because of their weight and cost [20]. In contrast, portable body-grounded devices such as the H^3Kit provide better mobility and ease of handling, but they may not generate sufficient torque for full rehabilitation exercises [24], [26].

When compared with conventional physiotherapy, haptic and robotic devices offer several practical advantages. They can deliver repeated movements more consistently, provide measurable feedback, and reduce the physical burden on therapists during repetitive training. However, they cannot replace the therapist’s role in assessing movement quality, adjusting exercise difficulty, monitoring compensatory movement, and ensuring patient safety. In real rehabilitation settings, the effectiveness of any device will also depend on patient motivation, stroke severity, comfort, ease of use, and whether the patient can continue using the device regularly.

The proposed H^3-WristKit attempts to address some of these gaps by combining the ergonomic simplicity of the H^3Kit with enhanced control dynamics for rehabilitation. By implementing impedance control strategies [22], [31], it can dynamically transition between assistive and resistive modes, supporting both early and later stages of stroke recovery. In addition, the use of 3D-printed lightweight materials can reduce the overall mass of the device, improving comfort and accessibility. Nevertheless, further testing is still needed to confirm whether the device can provide adequate torque, stable feedback, and safe interaction for post-stroke users.

Summary of Key Findings

The reviewed devices show that there is still no simple solution for wrist rehabilitation that can balance force output, portability, cost, and adaptability. High-performance systems are useful for controlled clinical or laboratory use, but they are often too large and costly for routine home-based therapy. Portable haptic devices are easier to handle and more affordable, but many of them were originally developed for education or basic haptic interaction rather than rehabilitation. This shows that portability alone is not enough; the device must also be able to provide safe, meaningful, and adjustable feedback for patients with different levels of wrist impairment.

Based on this comparison, an effective wrist rehabilitation device should be compact, comfortable, and easy to use, while still providing sufficient assistive and resistive feedback for training. The proposed H^3-WristKit attempts to address this gap by adapting the body-grounded haptic concept into a rehabilitation-oriented device. However, its actual value will depend on further testing, especially in terms of torque output, control stability, safety, usability, patient adherence, and suitability for different stages of stroke recovery. This is important because a device that works well technically may still have limited clinical use if it is difficult to wear, uncomfortable, or not practical for repeated use in real rehabilitation settings.

Practical Considerations for Clinical Translation

For a wrist-based haptic device to be useful in rehabilitation, its success should not be judged only by its mechanical design or control performance. In practice, the device must also fit into the daily routine of patients, therapists, and caregivers. Patients after stroke may differ in muscle strength, spasticity, fatigue level, cognition, motivation, and ability to follow instructions. Therefore, the device should allow adjustable assistance, clear feedback, and simple operation so that training can be matched to each user’s ability and recovery stage.

Therapist involvement remains important, especially during the early stage of device use. A therapist can determine whether the movement is safe, whether compensatory patterns are occurring, and whether the exercise intensity is appropriate for the patient. For home-based use, the device should ideally include clear instructions, basic safety limits, and performance tracking so that progress can be reviewed during follow-up sessions. These features may help improve adherence, because patients are more likely to continue training when the device is comfortable, easy to use, and provides visible feedback on their effort or progress.

Future development of the H³-WristKit should therefore include not only prototype testing, but also usability and acceptance studies involving post-stroke users and rehabilitation professionals. Real-time feedback, adaptive training protocols, and artificial intelligence-based adjustment may further improve the system by allowing the level of assistance or resistance to change according to user performance. However, these features should be introduced carefully to ensure safety, reliability, and ease of use. Larger clinical studies will eventually be needed to determine whether the device can improve functional wrist recovery, patient adherence, and satisfaction in real rehabilitation settings.

CONCLUSION

This study reviewed several wrist-based haptic rehabilitation systems and discussed the development of a body-grounded, impedance-controlled device for post-stroke wrist rehabilitation. The review shows that existing devices have different strengths and limitations. Grounded robotic systems and exoskeletons can provide better force output and control accuracy, but they are often bulky, costly, and more suitable for clinical or laboratory settings. In contrast, portable haptic devices are simpler and more accessible, but most are not specifically designed for rehabilitation use.

Based on these findings, the proposed H³-WristKit is intended to provide a more compact and affordable option for wrist rehabilitation. The device focuses on wrist flexion-extension movement and aims to deliver assistive and resistive feedback using impedance control. However, further work is needed to fabricate the prototype and test its control performance, torque output, safety, comfort, usability, and user acceptance. Future studies should also examine whether the device can support regular training, patient adherence, and therapist-guided monitoring in real rehabilitation settings. Overall, this work provides an early design direction for a body-grounded haptic device that may support more accessible upper-limb rehabilitation after stroke.

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REFERENCES

1. L. Pu, L. Wang, R. Zhang, T. Zhao, Y. Jiang, and L. Han, “Projected global trends in ischemic stroke incidence, deaths and disability-adjusted life years from 2020 to 2030,” *Stroke*, vol. 54, no. 5, pp. 1330–1339, 2023, doi: 10.1161/STROKEAHA.122.040073.
2. Centers for Disease Control and Prevention, “About stroke,” May 22, 2024. [Online]. Available: https://www.cdc.gov/stroke/about/index.html
3. J. M. Veerbeek, E. E. H. van Wegen, J. van der Heijden, and G. Kwakkel, “Robot-assisted therapy for the upper limb after stroke: A systematic review and meta-analysis,” *Gait & Posture*, vol. 39, no. 2, pp. 682–687, 2014, doi: 10.1016/j.gaitpost.2013.09.018.
4. D. J. Reinkensmeyer and J. Patton, “Robotics, motor learning, and neurologic recovery,” *Annual Review of Biomedical Engineering*, vol. 11, pp. 249–277, 2009, doi: 10.1146/annurev-bioeng-060908-150139.
5. V. S. Huang and J. W. Krakauer, “Robotic neurorehabilitation: A computational motor learning perspective,” *Journal of NeuroEngineering and Rehabilitation*, vol. 6, article 5, 2009, doi: 10.1186/1743-0003-6-5.
6. J. Roh et al., “Assessment of upper-limb function in patients with chronic stroke using kinematic measures during robot-assisted therapy,” *Journal of NeuroEngineering and Rehabilitation*, vol. 10, article 109, 2013, doi: 10.1186/1743-0003-10-109.
7. J. A. Kleim and T. A. Jones, “Principles of experience-dependent neural plasticity: Implications for rehabilitation after brain damage,” *Journal of Speech, Language, and Hearing Research*, vol. 51, no. 1, pp. S225–S239, 2008, doi: 10.1044/1092-4388(2008/018).
8. C. J. Winstein et al., “Guidelines for adult stroke rehabilitation and recovery: A guideline for healthcare professionals from the American Heart Association/American Stroke Association,” *Stroke*, vol. 47, no. 6, pp. e98–e169, 2016, doi: 10.1161/STR.0000000000000098.

9. K. S. Tan and N. Venketasubramanian, “Stroke burden in Malaysia,” *Cerebrovascular Diseases Extra*, vol. 12, no. 2, pp. 58–62, 2022.
10. Flint Rehab, “10 helpful hand exercises for stroke patients of all ability levels,” Dec. 13, 2022. [Online]. Available: https://www.flintrehab.com/hand-exercises-for-stroke-patients/
11. B. T. Volpe et al., “Intensive sensorimotor arm training mediated by therapist or robot improves hemiparesis in patients with chronic stroke,” *Neurorehabilitation and Neural Repair*, vol. 22, no. 3, pp. 305–310, 2008, doi: 10.1177/1545968307313489.
12. B. T. Volpe, H. I. Krebs, N. Hogan, L. Edelstein, C. Diels, and M. Aisen, “A novel approach to stroke rehabilitation: Robot-aided sensorimotor training,” *Neurology*, vol. 54, no. 10, pp. 1938–1944, 2000, doi: 10.1212/WNL.54.10.1938.
13. S. C. Cramer, “Treatments to promote neural repair after stroke,” *Journal of Clinical Investigation*, vol. 128, no. 1, pp. 77–86, 2018, doi: 10.1172/JCI94464.
14. J. E. Harris, J. J. Eng, W. C. Miller, and A. S. Dawson, “A self-administered Graded Repetitive Arm Supplementary Program improves arm function during inpatient stroke rehabilitation: A multi-center randomized controlled trial,” *Stroke*, vol. 40, no. 6, pp. 2123–2128, 2009, doi: 10.1161/STROKEAHA.108.544585.
15. Y. Li, J. Chen, H. Chen, R. Huang, and X. Ma, “A greedy assist-as-needed controller for end-effector upper limb rehabilitation robot based on 3-DOF potential field constraints,” *Frontiers in Neurorobotics*, vol. 17, 2023, doi: 10.3389/fnbot.2023.1118182.
16. S. Kwok et al., “A systematic review of neurorehabilitation robotics: A practical guide for clinicians,” *Brain Injury*, vol. 31, no. 4–5, pp. 527–534, 2017, doi: 10.1080/02699052.2017.1302834.
17. D. O. Kleindorfer et al., “2021 guideline for the prevention of stroke in patients with stroke and transient ischemic attack,” *Stroke*, vol. 52, no. 7, pp. e364–e467, 2021, doi: 10.1161/STR.0000000000000375.
18. S. Pezeshki, M. Poursina, A. Khosravi, D. Al-Jumeily, and S. Lughmani, “A comprehensive review of control challenges and methods in end-effector upper-limb rehabilitation robots,” *Sensors*, vol. 20, no. 22, article 6432, 2020, doi: 10.3390/s20226432.
19. K. Boardsworth et al., “Upper limb robotic rehabilitation following stroke: A systematic review and meta-analysis investigating efficacy and the influence of device features and program parameters,” *Journal of NeuroEngineering and Rehabilitation*, vol. 22, article 164, 2025, doi: 10.1186/s12984-025-01662-4.
20. MAHI Lab, “Human motion assessment for rehabilitation,” Rice University. [Online]. Available: https://mahilab.rice.edu/research/human-motion-assessment-rehabilitation
21. A. Agarwal and A. D. Deshpande, “An improved adaptive robotic assistance methodology for upper-limb rehabilitation,” *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 3624–3631, 2018, doi: 10.1109/LRA.2018.2851748.
22. N. J. Cowan et al., “Control, analysis, and implementation of haptic systems,” *IEEE Control Systems Magazine*, vol. 29, no. 3, pp. 70–81, 2009, doi: 10.1109/MCS.2009.932918.
23. M. O. Martinez et al., “Evolution and analysis of Hapkit: An open-source haptic device for educational applications,” *IEEE Transactions on Haptics*, vol. 13, no. 2, pp. 354–367, 2020.
24. S. Rehmat and H. Culbertson, “H^{3}Kit: Hand-held haptic kit for STEM education,” in *2019 IEEE World Haptics Conference*, 2019, pp. 401–406.
25. Stanford University, “Build one,” *Hapkit*. [Online]. Available: https://hapkit.stanford.edu/build.html
26. R. Bloom, Z. Huang, K. Lavarias, M. Ren, and T. K. Morimoto, “H^{3}Kit: Hand-held haptic kit for STEM education,” in *Proceedings of the IEEE Haptics Symposium*, 2024.
27. UCSD Morimoto Lab, “H3Kit,” GitHub. [Online]. Available: https://github.com/UCSDMorimotoLab/H3Kit
28. M. B. Näf, K. Junius, M. Rossini, C. Rodriguez-Guerrero, B. Vanderborght, and D. Lefeber, “Misalignment compensation for full human-exoskeleton kinematic compatibility: State of the art and evaluation,” *Applied Mechanics Reviews*, vol. 70, no. 5, article 050802, 2018.
29. H. Al-Fahaam, S. Davis, and S. Nefti-Meziani, “Mechanical design, fabrication, kinematics and dynamics modeling, multiple impedance control of a wrist rehabilitation robot,” 2016. **[Details to verify]**
30. S. Bu, “The 2-DOF wrist rehabilitation robot,” 2018. **[Details to verify]**
31. E. T. Wolbrecht, J. Leavitt, D. J. Reinkensmeyer, and J. E. Bobrow, “Control of a pneumatic rehabilitation robot for optimizing plastic recovery after stroke,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 16, no. 3, pp. 294–304, 2008.

32. L. A. Jones and H. Z. Tan, “Application of psychophysical techniques to haptic research,” *IEEE Transactions on Haptics*, vol. 6, no. 3, pp. 268–284, 2013, doi: 10.1109/TOH.2012.12.
33. F. A. Mussa-Ivaldi and D. J. Reinkensmeyer, “Physical human-robot interaction in rehabilitation and assistive robotics,” in *Biomedical Engineering Handbook*, CRC Press, 2008.
34. Ambitious Impact, “What are DALYs and are they a good metric?” Jan. 23, 2014. [Online]. Available: https://www.ambitiousimpact.com/post/what-are-dalys-and-are-they-a-good-metric
35. L. Masia, M. Casadio, P. Giannoni, G. Sandini, and P. Morasso, “Performance adaptive training control strategy for a 2-DOF wrist exoskeleton,” *Medical & Biological Engineering & Computing*, vol. 47, no. 2, pp. 155–166, 2009. **[Journal/details to verify]**
36. W. J. Powers et al., “Guidelines for the early management of patients with acute ischemic stroke: 2019 update to the 2018 guidelines,” *Stroke*, vol. 50, no. 12, pp. e344–e418, 2019, doi: 10.1161/STR.0000000000000211.
37. J. Bernhardt et al., “Agreed definitions and a shared vision for new standards in stroke recovery research: The Stroke Recovery and Rehabilitation Roundtable publication strategy,” *International Journal of Stroke*, vol. 12, no. 5, pp. 444–450, 2017, doi: 10.1177/1747493017711815.