A Platform Technology for XR Biofeedback Training under Operant Conditioning for Functional Limb Weakness

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Abstract

Background: Functional Neurological Disorder (FND) is a complex condition causing significant, debilitating symptoms comparable in impact to epilepsy and multiple sclerosis. FND encompasses various types, including functional seizures, movement disorders, persistent perceptual postural dizziness, and cognitive disorders, each arising from an interplay of neurological and psychiatric mechanisms. However, only half of UK health boards have established treatment agreements for FND, highlighting substantial gaps in care. Advancements in understanding FND pathophysiology, such as abnormal sensorimotor processing, have led to the development of neurotechnologies, including extended reality (XR) biofeedback, which may support rehabilitation for functional limb weakness through haptic and visuo-motor tasks.

Objective: This study aimed to evaluate the usability of an early-stage XR biofeedback platform designed for FND rehabilitation. The platform combines bottom-up haptic feedback with top-down visuo-motor tasks.

Methods: Three patient representatives with lived experience of FND and three healthcare workers participated in a mixed-methods study. Initially a Delphi survey was completed to share insights on XR technology requirements and therapeutic needs, followed by usability testing during a workshop. System Usability Scale (SUS) scores were collected for tasks including position feedback control, relaxation, and force feedback control. Qualitative data from freeform feedback were analyzed using thematic coding in NVivo.

Results: Qualitative analysis revealed themes around XR experience, technology relevance, and design needs. Many participants had recreational XR experience but limited familiarity with haptic feedback, valuing features such as customization, real-time feedback, and ease of use. Concerns were raised about accessibility and affordability. Usability scores were high for position feedback control and hypnotic relaxation tasks, with SUS scores above 85, indicating positive user satisfaction. However, force feedback control yielded more variable results, with some users, particularly those with functional dystonia, finding it challenging.

Conclusions: The XR platform demonstrated strong usability for position feedback control and hypnotic relaxation, though mixed responses to force feedback suggest the need for adaptation to diverse user needs. Improvements in comfort, immersion, personalization, and affordability are essential to maximize the platform's effectiveness and accessibility in FND care. The study underscores the potential of neurotechnological interventions in FND rehabilitation, while highlighting areas for design enhancement to support inclusivity and address the complex needs of FND patients.

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Background

Functional Neurological Disorder (FND) is a complex condition causing significant, debilitating symptoms comparable in impact to epilepsy and multiple sclerosis. FND encompasses various types, including functional seizures, movement disorders, persistent perceptual postural dizziness, and cognitive disorders, each arising from an interplay of neurological and psychiatric mechanisms. However, only half of UK health boards have established treatment agreements for FND, highlighting substantial gaps in care. Advancements in understanding FND pathophysiology, such as abnormal sensorimotor processing, have led to the development of neurotechnologies, including extended reality (XR) biofeedback, which may support rehabilitation for functional limb weakness through haptic and visuo-motor tasks.

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Keywords: extended reality; haptic; functional neurological disorder; biofeedback training; system usability scale.

Introduction

Functional Neurological Disorder (FND) is a complex, debilitating condition impacting individuals with symptoms comparable in severity and societal cost to epilepsy and multiple sclerosis (1). FND is associated with four main types: functional seizures, functional movement disorders, persistent perceptual postural dizziness, and functional cognitive disorder, all which stem from the interplay between neurological and psychiatric mechanisms. Yet only 50% of UK health boards have established agreements for FND treatment, as highlighted by FND Hope UK, underscoring significant gaps in care (https://www.fndhope.org.uk/freedom-of-information-project-aimed-to-explore-issues-reported-by-nhs-clinicians-and-the-fnd-community-regarding-accesses-to-treatment-for-people-with-fnd/). Recent advancements in neurotechnologies and breakthroughs in understanding FND's pathophysiology reveal shared pathways, such as abnormal sensorimotor processing and disruptions in agency, which provide promising avenues for novel therapeutic strategies (2). Notably, neurotechnological interventions, including extended reality (XR) biofeedback for functional limb weakness, are being explored within a stepped-care framework (3) based on severity to support rehabilitation from clinic to home settings. These neurotechnologies employ haptic feedback and visuo-motor tasks aimed at engaging patients in bottom-up and top-down processing, respectively, to enhance system usability and patient engagement.

A survey of 527 individuals revealed high rates of co-morbid symptoms among FND patients, including pain (78.1%), fatigue (78.0%), and sleep disturbances (46.7%), with symptom severity often worsening post-diagnosis (4). Effective FND management emphasizes the importance of transparent diagnosis explanations to foster patient understanding and improve treatment adherence (5).
Further, the National Institute of Mental Health's (NIMH) Research Domain Criteria (RDoC) framework offers a dimensional perspective, guiding the development of targeted neurotechnologies and biomarkers for improved phenotyping of FND heterogeneity (6). However, ethical considerations surrounding identity, autonomy, and patient privacy remain, necessitating patient and stakeholder engagement to align neurotechnological interventions with healthcare economic objectives and ethical standards. The objective of this research was to investigate system usability of an early-stage platform neurotechnology for XR biofeedback training for functional limb weakness combining bottom-up haptic feedback with top-down visuo-motor tasks (see Figure 1) (7) for multidisciplinary treatment and rehabilitation. The goal is to ensure that these neurotechnologies are not only precise and technically effective, but also sustainable, and usable by the FND patients.

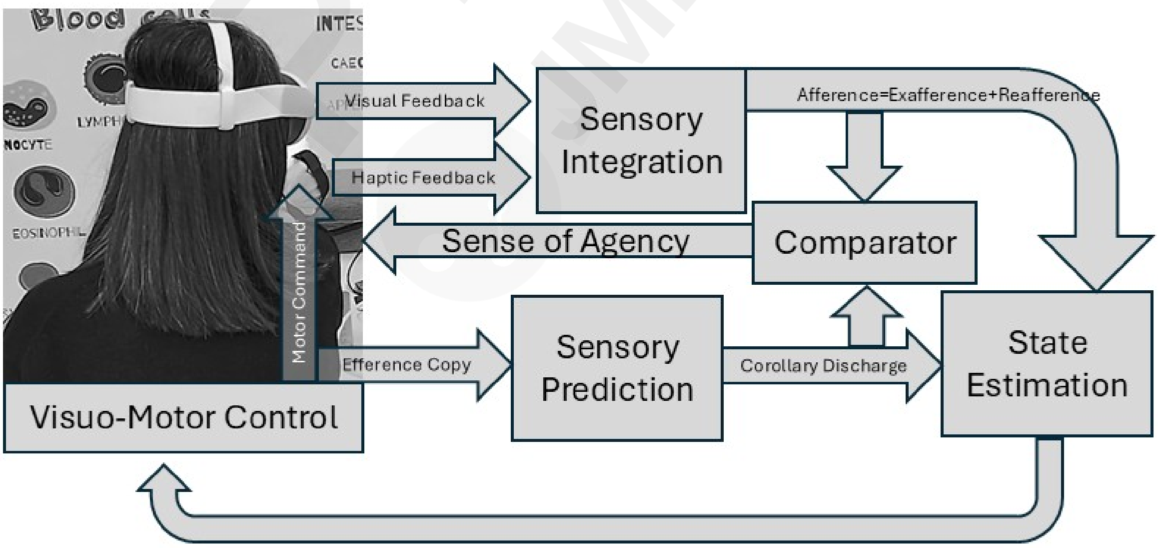

Figure 1: Based on the comparator model, when a motor command is issued, an accompanying Efference Copy is generated, which allows the brain to predict the expected sensory outcome of the action. This predicted outcome is then compared to the actual sensory feedback upon action completion. A strong sense of agency is experienced if there is a close match between predicted (Corollary Discharge) and actual sensory information (Afference) from the environment. This comparator model can also explain sense of agency in virtual XR environments where a virtual representation mimics the user's physical movement providing Exafference that when combined with Reafference

Methods

Participants

3 FND patient representatives (1 female, 2 males) and 3 healthcare workers (2 females, 1 male) participated in Delphi survey followed by system usability testing during a collaborative workshop. (see Supplementary Materials for details). All the patient representatives have been included as co-authors in this paper.

Data Collection and Analysis

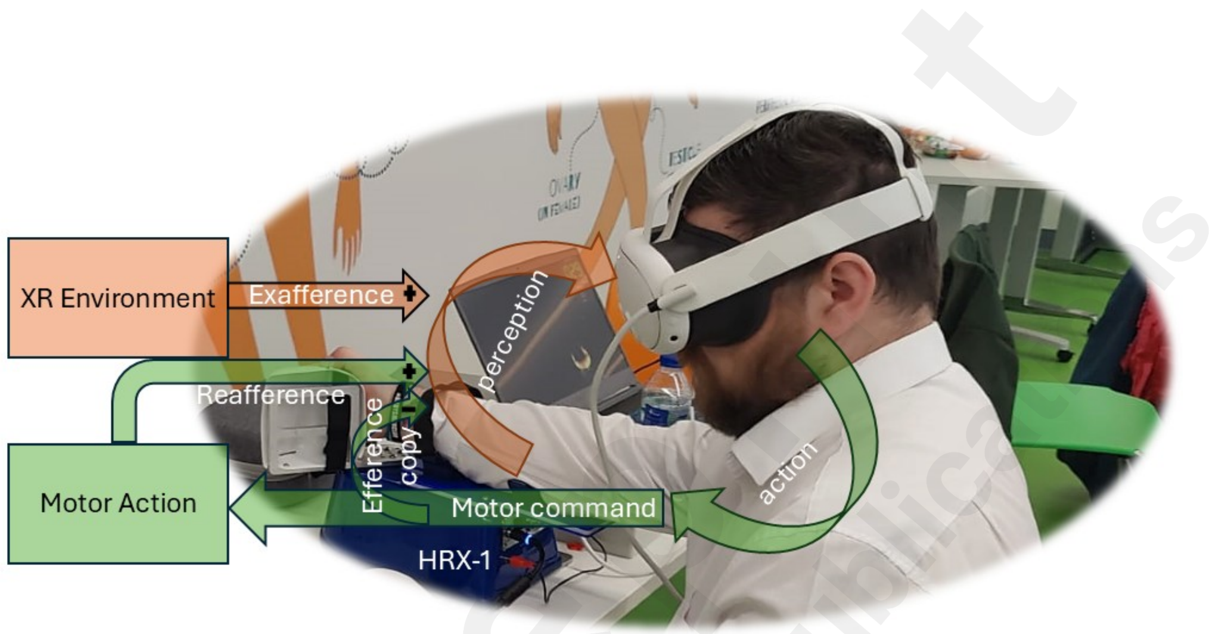

Figure 2: Perception-Action coupling for XR biofeedback training to modulate bottom-up reafference with exafference through a haptic wrist robot (HRX-1, Human Robotix) to support movement in cases of functional weakness. Top-down modulation is influenced by guided visual and verbal suggestions presented via XR feedback. A distinction can be made between efference copy—an internal brain duplicate of motor commands used for predictive control—and corollary discharge, which involves signals that adjust sensory processing based on these predictions.

System Usability

The usability testing using System Usability Scale (SUS) (8) for the XR biofeedback platform (see Figure 2) involved guiding participants through key tasks, including setup, navigation, biofeedback tasks (hypnotic relaxation, position feedback control, force feedback control), adjusting settings, and ending the session with debriefing. Participants were encouraged to think aloud, sharing on paper writing any challenges or feedback as they progressed. Follow-up questions explored their overall experience, ease of use, and suggestions for improvement. This freeform written feedback was used for QDA to find the needs of individuals with FND. (see Supplementary Materials for data).

Delphi Survey

Individuals with lived experience of FND participated in an online survey as "experts by experience" (EbyE), offering insights on XR technology requirements and therapeutic needs. The first-round questionnaire included open and closed-ended questions about familiarity with XR, perceptions of XR haptics for biofeedback, and expectations or concerns for FND rehabilitation. Following the survey, a workshop with 3 FND patient representatives and 3 healthcare workers tested system usability to further refine the XR haptics technology. Qualitative data analysis (QDA) of freeform written feedback from the Delphi survey was conducted using NVivo software (see Supplementary Materials for data).

Results

Qualitative

QDA identified key themes including Participant Demographics and Identity, Experience and Perception of VR and Haptics Technology, Expected Relevance and Impact, Barriers and Challenges, and Design and Customization Needs. Delphi survey results presented at the National Rehabilitation Centre's Conference on Rehabilitation Technologies 2024 (9), the QDA showed that while many participants had some experience with XR technology (mostly for recreation), knowledge of haptic feedback was limited. Participants valued customizable features like exercises and real-time feedback, found VR haptics biofeedback highly relevant, and hoped it could improve functionality affected by FND. Common concerns included affordability, accessibility, insurance coverage, and potential overstimulation, which could worsen symptoms. Participants emphasized the need for a comfortable, user-friendly design, especially to support non-technical users and address VR discomfort. (see Supplementary Materials for the raw text).

QDA of freeform written feedback from the usability testing workshop highlighted key themes for improvement, including comfort, technical quality, personalization, accessibility, and overall concept acceptance. Users found the headset's weight uncomfortable, recommending a lighter design with added padding. Visual and audio issues, such as pixelation and fast-paced sounds, disrupted immersion, with suggestions for smoother visuals and softer, slower audio for a more calming experience. Personalization options, like adjustable visuals and interactive elements, were asked for enhancing engagement. While our XR concept was well-received, particularly for potential FND healthcare applications, users expressed concerns about cost and accessibility, suggesting flexible pricing models and options for shared use. Overall, refining comfort, audio-visual quality, personalization, and affordability would enhance the VR experience's appeal and usability, especially in FND healthcare. (see Supplementary Materials for the raw text).

Quantitative

Basic usability testing typically benefits from 5-10 participants, and here, most scores shown in Table 1 were high for the position feedback control task, with several above 85, indicating excellent usability. Specifically, participants 1, 3, 4, and 5 rated it between 85 and 100, showing a strong positive response. Similarly, hypnotic relaxation also scored well, with participants 2 and 4 achieving 90 and 87.5, respectively. However, the force feedback control task had a broader range of scores, from a high of 95.0 (participant 5) to a low of 27.5 (participant 3), who has functional dystonia and may have found force feedback challenging. These mixed experiences suggest variability in usability for the force feedback control in individuals with different pathophysiologies, while position feedback control and hypnotic relaxation tasks received consistently positive feedback, highlighting their strong usability and user satisfaction.

Table 1. SUS score was calculated for each participant across XR tasks, including hypnotic relaxation, position feedback control, and force feedback control, using standard methodology (https://hell.meiert.org/core/pdf/sus.pdf).

	XR force feedback control	XR position feedback control	VR hypnotic relaxation

	SUS score	SUS score	SUS score
Participant 1	80.0	95.0	47.5
Participant 2	62.5	72.5	90.0
Participant 3	27.5	92.5	45.0
Participant 4	82.5	100.0	87.5
Participant 5	95.0	90.0	45.0
Participant 6	87.5	85.0	-

Discussion

Principal Results

This study, the first in our knowledge to use a mixed-methods approach to evaluate an XR biofeedback training platform for FND, found high usability for tasks involving position feedback control and hypnotic relaxation, with most participants scoring above 85, indicating excellent usability and high user satisfaction. QDA suggests that further improvements in comfort, immersive experience, personalization, and accessibility will be essential to enhance user satisfaction.

Limitations

This study has several limitations. The small sample size (5-6 participants for usability testing) may restrict the generalizability of the findings, as a larger sample could offer more robust insights. Individual conditions, such as functional dystonia, also impact usability, especially in force feedback control, which may not accurately reflect broader user experiences. Focusing on specific XR tasks (hypnotic relaxation, position feedback control, and force feedback control) could overlook usability aspects of other XR functionalities. Additionally, the reliance on subjective SUS scores introduces potential bias, as individual expectations or familiarity with XR can influence ratings. Portable brain imaging, such as functional near-infrared spectroscopy and electroencephalography, could provide deeper insights into individual responses to XR biofeedback tasks by capturing efference copy and corollary discharge via the supplementary motor area (10), as shown feasible in prior studies with healthy subjects (11). Also, task-specific factors, like varying comfort levels with force feedback, may also affect scores, suggesting that a broader evaluation would strengthen the applicability of the usability findings.

Comparison with Prior Work

Most existing XR research centers on sensor setups for motor rehabilitation in conditions with organic causes, such as stroke. Studies have also started exploring XR technology's potential in neurological rehabilitation, with a focus on usability and cognitive engagement. Janeh et al. (12) underscore XR's value in enhancing sensorimotor processing, but it is essential to assess usability specifically for FND, where limb weakness is not due to an organic cause. Early user involvement in the design process for FND can help identify unexpected user experience issues, thereby improving engagement and adoption. This study applied a generative framework to categorize technological advancements as either incremental improvements or revolutionary changes, aiming to enhance FND rehabilitation through iterative progress and transformative innovations. Importantly, there are currently no published usability evaluation of XR biofeedback systems tailored specifically to FND.

Conclusions

In conclusion, the study's findings indicate high usability for the XR tasks of position feedback control and hypnotic relaxation, with consistently strong scores from participants, highlighting these features as well-designed and well-received. However, the force feedback control task showed more variable results, suggesting mixed usability experiences, particularly for participants with specific conditions like functional dystonia. This variation points to potential areas for improvement in adapting force feedback control to accommodate diverse user needs. Despite these limitations, the results provide valuable insights into the strengths of the XR platform's usability, particularly in position feedback control and hypnotic relaxation, while identifying opportunities to enhance inclusivity and accessibility in force feedback applications.

Acknowledgements

Our first co-creation workshop, focused on exploring the biofeedback design space for managing Functional Neurological Disorders (https://www.lancashireneuroscience.co.uk/events/co-creation-of-digital-health-technologies-for-management-of-functional-neurological-disorders-fnd-a-workshop) was funded by the N-CODE, an EPSRC funded network plus. This was followed by EPSRC Rehabilitation Technologies Network+ funding for co-production (https://www.rehabtechnologies.net/fundedprojects) that will be presented at Royal Society funded Discussion meeting (https://royalsociety.org/science-events-and-lectures/2024/11/digital-healthcare/)

Conflicts of Interest

The authors declare the following potential conflicts of interest: Alastair Buchanan, CEO of Nudge Reality Ltd., UK, and Ildar Farkhatdinov, CEO of Human Robotix Ltd., UK, served as industry partners in this study, providing technologies and contributing to the co-production efforts focused on real-world implementation and strategic insights driven by industry innovation.

CRedit Author Contribution Statement

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Data curation – Lindsey Rickson (equal), Katerina Hatjipanagioti (equal), Matthew Newsham (equal)
Funding acquisition – Anirban Dutta (lead), Alastair Buchanan (supporting), Ildar Farkhatdinov (supporting), Abhijit Das (supporting)
Investigation – Lindsey Rickson (equal), Katerina Hatjipanagioti (equal), Matthew Newsham (equal), Lewis Leyland (equal), Jacqueline Twamley (equal), Abhijit Das (equal)
Methodology – Anirban Dutta (lead), Alastair Buchanan (supporting), Ildar Farkhatdinov (supporting)
Project administration – Anirban Dutta (equal), Abhijit Das (equal)
Resources – Jacqueline Twamley (lead), Alastair Buchanan (supporting), Ildar Farkhatdinov (supporting)
Supervision – Anirban Dutta (equal), Abhijit Das (equal)
Validation – Abhijit Das
Visualization – Anirban Dutta
Writing – original draft – Anirban Dutta
Writing – review & editing – Anirban Dutta (lead), Abhijit Das (supporting), Alastair Buchanan (supporting), Ildar Farkhatdinov (supporting), Jacqueline Twamley (supporting)

References

1. O'Mahony B, Nielsen G, Baxendale S, Edwards MJ, Yogarajah M. Economic Cost of Functional Neurologic Disorders. *Neurology*. 2023;101(2):e202-e214. doi:10.1212/WNL.0000000000207388

2. Hallett M, Aybek S, Dworetzky BA, McWhirter L, Staab JP, Stone J. Functional neurological disorder: new subtypes and shared mechanisms. *The Lancet Neurology*. 2022;21(6):537-550. doi:10.1016/S1474-4422(21)00422-1

3. Taing M, Sztainert T, Harley M, Allen K, Moore F. Applying a Stepped-Care Framework for Functional Neurological Disorder Management. *Canadian Journal of Neurological Sciences*. Published online March 1, 2024:1-3. doi:10.1017/cjn.2024.32

4. Ducroizet A, Zimianti I, Golder D, et al. Functional neurological disorder: Clinical manifestations and comorbidities; an online survey. *Journal of Clinical Neuroscience*. 2023;110:116-125. doi:10.1016/j.jocn.2023.02.014

5. Stone J, Carson A, Hallett M. Explanation as treatment for functional neurologic disorders. *Handb Clin Neurol*. 2016;139:543-553. doi:10.1016/B978-0-12-801772-2.00044-8

6. Spagnolo PA, Garvey M, Hallett M. A dimensional approach to functional movement disorders: Heresy or opportunity. *Neurosci Biobehav Rev*. 2021;127:25-36. doi:10.1016/j.neubiorev.2021.04.005

7. A Platform Technology for VR Biofeedback Training under Operant Conditioning for Functional Lower Limb Weakness - [v1]. Accessed November 3, 2024. https://www.preprints.org/manuscript/202407.2520/v1

8. Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale - JUX. JUX - The Journal of User Experience. May 7, 2009. Accessed November 3, 2024. https://uxpajournal.org/determining-what-individual-sus-scores-mean-adding-an-adjective-rating-scale/

9. Das A, Newsham M, Hatjipanagioti K, Buchanan A, Farkhatdinov I, Dutta A. VR Haptics Biofeedback Training for Functional Limb Weakness: Insights from the First Round of a Delphi Survey. In: ; 2024.

10. Haggard P, Whitford B. Supplementary motor area provides an efferent signal for sensory suppression. *Brain Res Cogn Brain Res*. 2004;19(1):52-58. doi:10.1016/j.cogbrainres.2003.10.018

11. Kamat A, Makled B, Norfleet J, et al. Directed information flow during laparoscopic surgical skill acquisition dissociated skill level and medical simulation technology. *npj Sci Learn*. 2022;7(1):1-13. doi:10.1038/s41539-022-00138-7

12. Janeh O, Matsumto K, Horsak B. Editorial: The role of perceptual manipulations of XR in neurological rehabilitation. *Front Virtual Real*. 2024;5. doi:10.3389/frvir.2024.1472756