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Combining augmented reality with functional electrical stimulation for independent therapy: assessing technology acceptance among individuals with cervical spinal cord injury

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Abstract (250 words)

Introduction: Functional electrical stimulation (FES) can improve functional outcomes for individuals with cervical spinal cord injury (cSCI). While wearing augmented reality (AR) headsets, automated hand tracking can be leveraged to automate FES delivery and control stimulation patterns to assist independent hand exercises. The current study assessed the perceived usefulness and feasibility of using a combined AR-FES system for individuals with cSCI.

Methods: 12 individuals with cSCI tried a custom AR-FES application for a single 30-minute session in a supervised clinical environment. While wearing the headset, the system compared actual to target hand postures during hand exercises with real objects, with a closed-loop linear scaling of FES amplitudes to help participants achieve correct grasping patterns. Immediately after, participants completed a custom questionnaire, the System Usability Scale (SUS), and a 30-minute semi-structured interview analyzed using a hybrid inductive-deductive thematic analysis informed by the Technology Acceptance Model.

Results: Positive usability metrics (i.e., mean SUS = 75; SD = 12) were complemented by three themes: 1) Perceived Ease of Use (subthemes: perceived complexity, technological and physical limitations), 2) Perceived Usefulness (subthemes: potential impact on recovery, addressing limitations of previous therapies, person dependent), and 3) Behavioural Intention to Use (subthemes: attitudes towards use, using the system in different environments and ways).

Conclusion: Individuals with cSCI perceived that the AR-FES system was useful toward recovery, potentially feasible for independent use, and provided suggestions to increase both. Thus, the study demonstrates the potential to increase the dosage of neuromodulation-based rehabilitation via independent use of an AR-FES system.

Keywords: augmented reality, functional electrical stimulation, spinal cord injury, rehabilitation, hand function, technology acceptance model

Introduction

Individuals with cervical spinal cord injury (cSCI) commonly have impaired upper limb function, and report regaining that function as a main priority contributing to independently engaging in activities of daily living[1,2]. To support recovery, massed practice of functional tasks[3,4] and the incorporation of neuromodulation interventions such as functional electrical stimulation (FES) have shown efficacy in improving upper limb function[5,6]. However, the amount of therapy individuals with cSCI complete is limited by the duration of inpatient stays after cSCI (i.e., mean length of stay in Canada after traumatic SCI: 108 days[7]), limited dosage of upper limb exercises during inpatient therapy[8], and barriers to outpatient care including availability of one-on-one therapist time[9,10]. Further, access to neuromodulation-based interventions are limited by additional barriers to using FES in clinical environments (e.g., lack of FES-related expertise among clinicians, long setup times which can limit clinical utility)[11]. Thus, rehabilitation solutions that can allow individuals to engage in FES based therapy independently can promote massed practice while incorporating neuromodulation techniques.

A potential avenue for developing rehabilitation tools that allow for independent therapy is using mixed reality head mounted displays (HMDs). While individuals wear a HMD, it can track hand and joint positions in real-time and provide virtual cues or elements directly to the user[12–14], providing an integrated, highly portable and more immersive solution compared to motion capture solutions positioned in the surrounding environment. In recent work using an augmented reality (AR) HMD, individuals with cSCI tried an AR application that provided grasping guidance and grasping posture

feedback while they performed grasping exercises with real objects[15]. After trying the application for a single session, participants perceived that the application provided useful guidance and feedback, increased motivation during hand exercises, and had the potential to increase exercise compliance[15]. The advantages of mixed reality applications can also be used in combination with neuromodulation therapies such as FES. For example, the sensors from mixed reality HMDs (e.g., hand tracking, voice detection, etc.) can be leveraged to trigger the onset and control the amplitude of electrical stimulation delivered to the user. This combination would be particularly useful because during FES therapy the therapist is responsible for triggering stimulation onset and setting or adjusting stimulation intensities, preventing the user from independently engaging in the therapy[5]. Further, the stimulation intensity set at the start of a session typically produces a maximum tolerable contraction on every attempt[5], which can potentially limit individuals' active engagement in the task and contribute to muscle fatigue. Previous work that has combined mixed reality applications with FES of upper limb muscles has relied on non-immersive virtual reality environments (e.g., serious gaming on an external monitor) and the FES assisted with hand opening and closing[16] or upper limb reaching tasks[17] for individuals with stroke. Thus, although the FES was automatically triggered by either muscle activity[16] or arm kinematics[17], the tasks did not involve functional real object interactions and the stimulation intensities were not scaled or adjusted during a trial (i.e., open-loop stimulation). Using an AR platform to control closed-loop FES (i.e., adjusting or scaling stimulation intensity based on individual performance) has the potential to fill these gaps and enable individuals with cSCI to complete functional neuromodulation-assisted exercises more independently.

The goal of the current study was to assess perceptions of using a prototype version of a novel AR-FES system among individuals with cSCI. Specifically, the novel AR-FES system provides grasping guidance to individuals via augmented visual cues, allows individuals to independently initiate FES via voice commands, modulates stimulation amplitude in real-time via differences between actual and target hand postures, and provides a means to track hand exercise repetitions. At the current stage of development, individuals with cSCI tried the system in a supervised clinical setting and provided feedback on its perceived usefulness towards rehabilitation goals and potential for future home-based rehabilitation, including recommendations that would inform future iterations of the system. The discussion was framed around potentially using the tool in a home environment to assess a scenario requiring complete or almost complete independence with the system. This approach is consistent with recommendations of Musselman and colleagues[18] in which assessing rehabilitation technology in a staged manner (i.e., assessing elements of feasibility and meaningfulness of technology prior to efficacy) can potentially lead to more successful clinical translation for individuals with SCI. We hypothesized that individuals with cSCI would perceive the system as potentially useful towards their recovery, potentially usable in independent environments and provide specific recommendations to improve future iterations of the system. At the current stage of development, positive perceptions of the AR-FES system paired with achievable recommended changes would provide a strong rationale for continuing along a staged manner of application development and testing.

Methods

Participants

12 individuals with cSCI participated in the study (see Table 1 for demographic details). All male participants identified as men and all female participants identified as women. Sensory and motor assessments were completed using version 1 of the Graded Redefined Assessment of Strength, Sensibility and Prehension (GRASSP[19]). All participants provided written informed consent, and all protocols were approved by the Research Ethics Board of the University Health Network (#23-5249). All participants in the current study also participated in a previously reported study in which they tested a standalone AR rehabilitation application[15]. We recruited individuals with sub-acute or chronic cSCI of any level or severity, traumatic or non-traumatic, with visible hand impairment (Table 1). Exclusion criteria included any disease or injury other than the SCI that may be affecting grasping performance, inability to understand the study procedures, and muscles required for grasp production not being responsive to neurostimulation.

Table 1. Demographic and clinical information of the participants (AIS: American Spinal Injury Association Impairment Scale; T/NT: Traumatic/ Non-Traumatic). Prehension scores refer to the Prehension Performance sub-score from the GRASSP assessment for the right and left hand.

Participant	Age - years	Sex	Injury level	AIS grade	Type of injury	Months since injury	Prehension Score (Right)	Prehension Score (Left)
1	31	M	C3	D	NT	2	28	27
2	52	M	C4	D	T	160	30	30
3	28	M	C6	B	T	68	15	12
4	64	F	C3	D	NT	21	29	25
5	49	M	C4	B	NT	52	26	11
6	59	F	C4	D	NT	76	30	19
7	39	M	C4	C	T	48	27	18
8	54	M	C4	C	NT	35	28	14
9	56	M	C3	D	NT	56	30	20
10	61	M	C4	A	NT	29	8	4
11	38	M	C5	C	T	173	5	10
12	52	F	C6	B	T	36	15	12
Mean (SD)	49 (12)					63 (52)	23 (9)	17 (7)

Augmented Reality – Functional Electrical Stimulation (AR-FES) System Development

The AR-FES system had two main components: 1) a custom AR application running on a Microsoft HoloLens 2™ HMD (Microsoft, Redmond, WA, USA) and 2) a MyndSearch™ FES unit (MyndTech Inc., Mississauga, ON, CA). The AR application was built in Unity (Unity Technologies, San Francisco, CA, USA) and used version 2 of the Mixed Reality Toolkit for hand joint tracking, voice recognition, and to display holographic elements at a sampling rate of 60 Hz. The application leverages common elements of a previously described standalone AR rehabilitation application (i.e., grasping guidance[15]) and accuracy of the hand tracking has also been previously validated with the same individuals in addition to a group of uninjured controls[20]. The goal of the current system was to 1) provide guidance for object-specific grasping postures and 2) guide closed-loop FES based on posture differences between actual

hand and target postures. Specifically, on a given trial, participants chose to interact with a marble, block or credit card, which had associated target postures (i.e., tip-to-tip, cylindrical, and lateral key pinch, respectively) presented to them to help guide grasping. After starting stimulation with a voice command, grasping errors were determined by comparing actual hand joint angles to target posture joint angles and the alignment between the thumb and index finger. Errors were continuously calculated and were used to modulate stimulation amplitude in a closed-loop fashion with large errors leading to high stimulation amplitudes and low errors leading to low stimulation amplitudes (see Figure 1). Each participant had a custom range of stimulation amplitudes for finger flexors, thumb flexors, and finger extensors, and amplitudes could fluctuate between a minimum (i.e., amplitude which produced a contraction through the full range of the desired movement when no resistance was applied and no object held) and maximum amplitude (i.e., amplitude that produced a maximum tolerable contraction). Thus, even if participants were grasping objects with minimal error, stimulation was still present. Details of the closed-loop system, error calculations, stimulation parameters, and communication between the HMD and FES unit can be found in the Supplementary Materials.

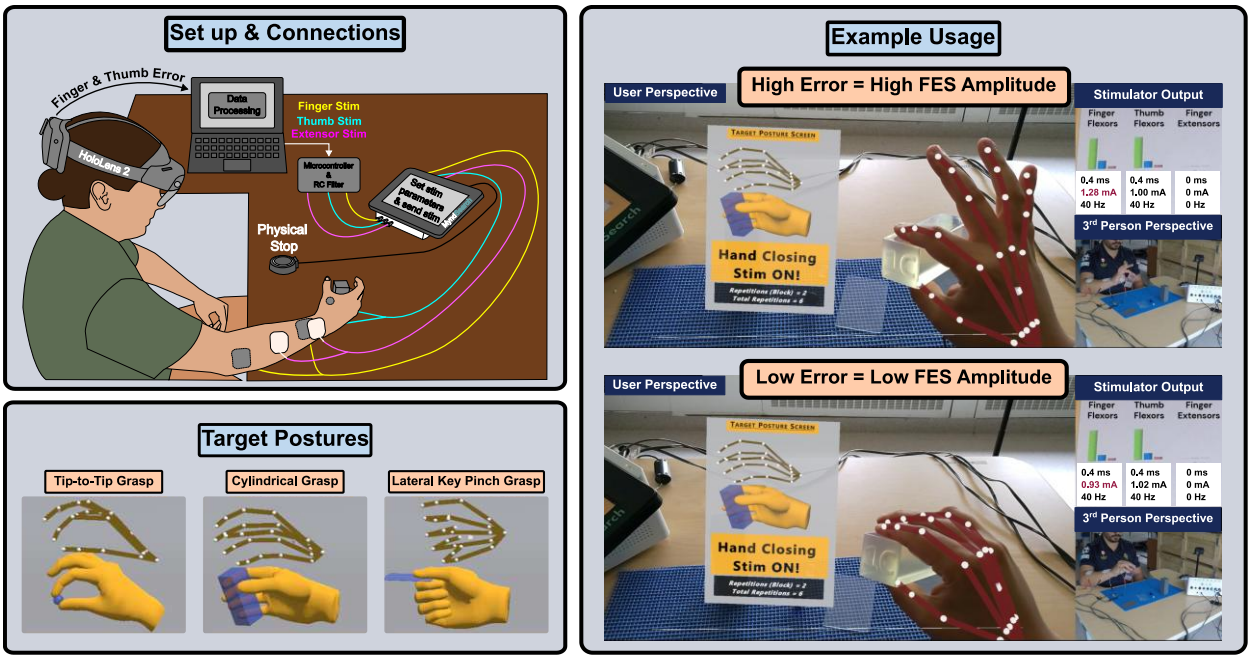


Figure 1. System overview. **Set up & Connections.** Depiction of a participant using the AR-FES system. Finger and thumb errors are sent to a companion computer which are then transformed into stimulation amplitudes and sent to participants' finger flexors, thumb flexors, or finger extensors. **Target Postures.** Depiction of the three potential target postures presented to participants and specific to the object they were interacting with. **Example Usage.** Depiction of an individual using the AR-FES system with a view from the user's perspective where participants could see their real hand and object in addition to augmented virtual elements, a view of the screen of the stimulator, and a view from a 3rd person perspective. The top panel shows an example of grasping the object with a large error (i.e., tip-to-tip grasp instead of cylindrical grasp) which results in a relatively large finger flexor stimulation amplitude (i.e., 1.28 mA). The bottom panel shows an example of grasping the object with a small error which results in a relatively smaller finger flexor amplitude (i.e., 0.93 mA).

Procedure

Individuals participated at a Canadian SCI rehabilitation centre. Participants were first oriented to the application using a brief presentation including video demonstrations for about 10 minutes. Then, the experimenter placed electrodes on their finger flexors, thumb flexors, and finger extensors and their location was adjusted to ensure the correct hand response (e.g., hand closing when finger flexors were stimulated). Participants donned the HMD themselves or with assistance from the experimenter, and

the application was started remotely. Participants were encouraged to try the application independently for around 30 minutes, but the experimenter intervened when necessary (e.g., troubleshooting, participant unsure of how to progress application, etc.). The limb that received stimulation was the more impaired arm, but if that limb did not respond to FES (i.e., stimulation not leading to finger movements) the other limb was used. Participants attempted grasping all objects multiple times, but repetitions were not recorded because the main purpose of the study was to obtain participant perspectives on the system.

Questionnaires & Semi-Structured Interview

At the end of the session, participants completed one custom questionnaire, one standardized questionnaire (i.e., the System Usability Scale[21]), and one audio-recorded semi-structured interview with DMM which lasted ~30 minutes (see Supplemental Materials for all questions and the interview guide). The custom questionnaire and semi-structured interview were designed to capture perceptions of perceived feasibility and usability of the AR-FES system in the context of potential home use, the AR-FES system's perceived meaningfulness and usefulness towards rehabilitation goals and recovery, perceptions of sensations and movements produced by the stimulation, and recommendations for system improvement. The context of potential home use was used to assess perceptions on a situation that requires complete or almost complete independence with the system.

Data Analyses

Likert scale responses to both questionnaires were summarized descriptively. A hybrid inductive-deductive thematic analysis was applied to the semi-structured

interview responses[22]. Interview responses were transcribed verbatim by DMM (Postdoctoral Researcher with qualitative research experience) and then coded inductively by authors DMM and HS (Assistant Professor with occupational therapy training and qualitative research experience). After independent initial coding, the researchers met to compare their coding, which was used to create a refined inductive codebook and generate themes. During subsequent meetings, DMM and HS independently mapped the inductive codes and themes onto the Technology Acceptance Model to analyze findings deductively (TAM[23]; see Table 2). For example, the theme “Perceived Therapeutic Value” was mapped onto Perceived Usefulness of the TAM. Their deductive coding was compared and discrepancies resolved through discussion. Final refinement of themes and subthemes occurred when writing and reviewing the final manuscript.

Table 2. Technology Acceptance Model domains[23] adapted to the context of the current study.

TAM Category	**Definition**
Perceived Ease of Use (PEOU)	Any comments reported by the participants regarding the ease or complexity of using the AR-FES system.
Perceived Usefulness (PU)	Any comments reported by participants regarding the usefulness of the AR-FES system towards their recovery.
Behavioural Intention to Use (BI)	Any comments reported by participants regarding their intention to use AR-FES system in the future and the ways in which they intend to use it.

Results

Questionnaires

Summaries of custom questionnaire and SUS responses can be found in Figure 2. Approximately 87% of the responses were Agree or Strongly Agree to positive statements about using the AR-FES system, or Disagree or Strongly Disagree to negative statements about using the AR-FES system. From the SUS, the mean score across all participants was 75.4 (SD = 12.4; 95% CI [67.5, 83.3]), placing the application in 70-79th percentile with a grade of B[21]. Thus, participants found the AR-FES system easy to use (83% of participants based on question 2 of the SUS; supporting theme 1) and that multiple aspects of the application were helpful (83% of participants based on questions 6-8 of the custom questionnaire), including the potential to improve recovery and relearning of movements (92% of participants based on questions 4 and 5 of the custom questionnaire; supporting theme 2).

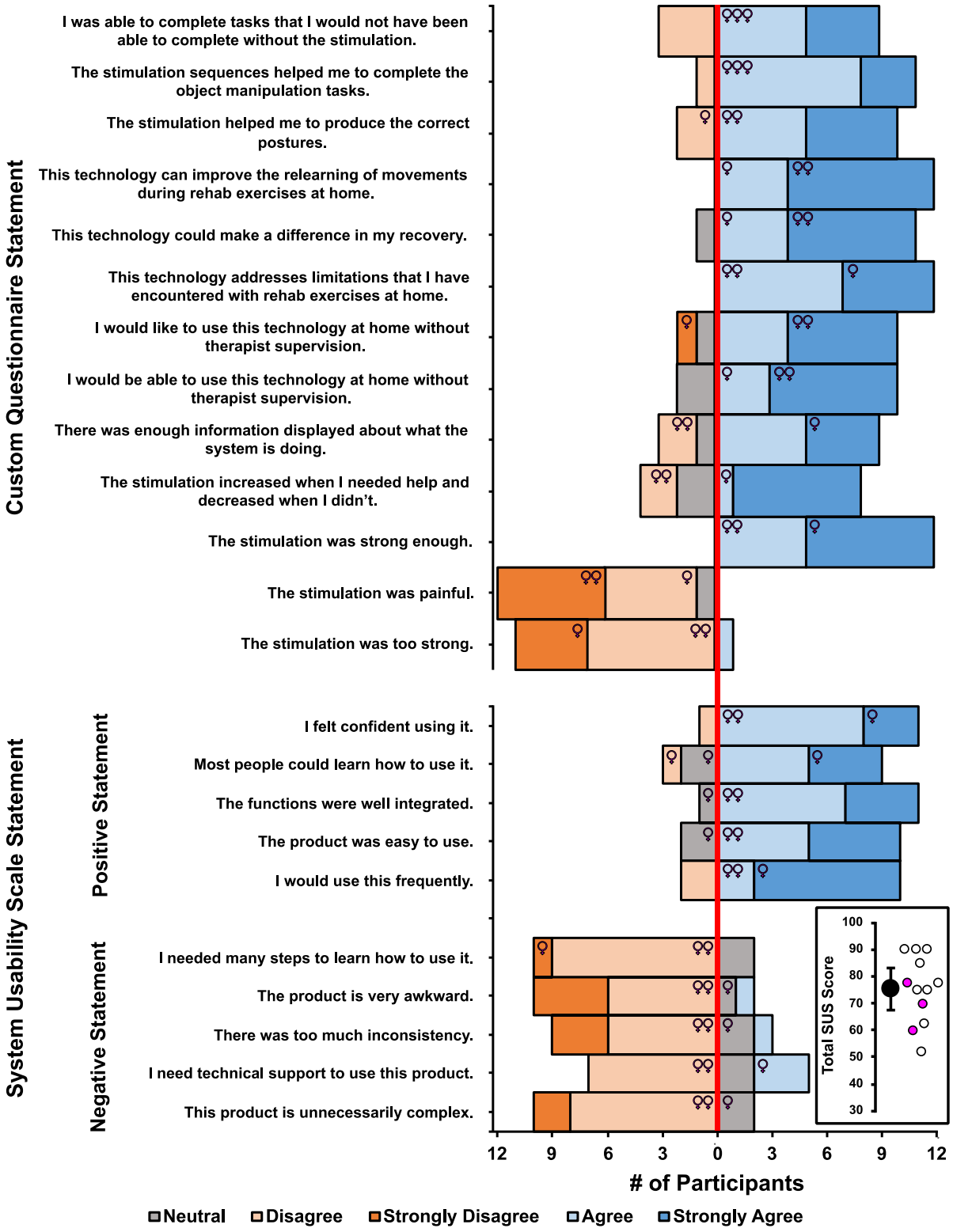

Custom Questionnaire Statement
I was able to complete tasks that I would not have been able to complete without the stimulation.
The stimulation sequences helped me to complete the object manipulation tasks.
The stimulation helped me to produce the correct postures.
This technology can improve the relearning of movements during rehab exercises at home.
This technology could make a difference in my recovery.
This technology addresses limitations that I have encountered with rehab exercises at home.
I would like to use this technology at home without therapist supervision.
I would be able to use this technology at home without therapist supervision.
There was enough information displayed about what the system is doing.
The stimulation increased when I needed help and decreased when I didn't.
The stimulation was strong enough.
The stimulation was painful.
The stimulation was too strong.
System Usability Scale Statement
Positive Statement
I felt confident using it.
Most people could learn how to use it.
The functions were well integrated.
The product was easy to use.
I would use this frequently.
Negative Statement
I needed many steps to learn how to use it.
The product is very awkward.
There was too much inconsistency.
I need technical support to use this product.
This product is unnecessarily complex.
Total SUS Score
100
90
80
70
60
50
40
30
12
9
6
3
0
3
6
9
12
# of Participants
Neutral
Disagree
Strongly Disagree
Agree
Strongly Agree

Figure 2. Participant responses to the custom questionnaire (top) and System Usability Scale (bottom). Questions for the System Usability Scale are separated into positive and negative tones. Agreeing or strongly agreeing to positive statements and disagreeing or strongly disagreeing with negative statements contribute to a higher total score (see inset plot in bottom right). Data on the left of the central red line shows the proportion of participants that responded negatively to the statement, whereas data on the right of the line shows the proportion of participants that responded positively to the statement. The number of female participants that contributed to each response is represented by the female biological sign within the appropriate bars. The inset plot represents the mean total SUS score and the error bars represent the 95% confidence intervals. Female participants are represented by filled in circles and male participants are represented by empty circles.

Thematic Analysis

Three themes were constructed and presented according to the categories of the TAM: 1) Perceived Ease of Use, 2) Perceived Usefulness, and 3) Behavioural Intention to Use. Figure 3 presents an overview of the themes, including relationships between specific subthemes, and Table 3 provides an overview of participant quotes supporting themes and subthemes, as well as their relationships.

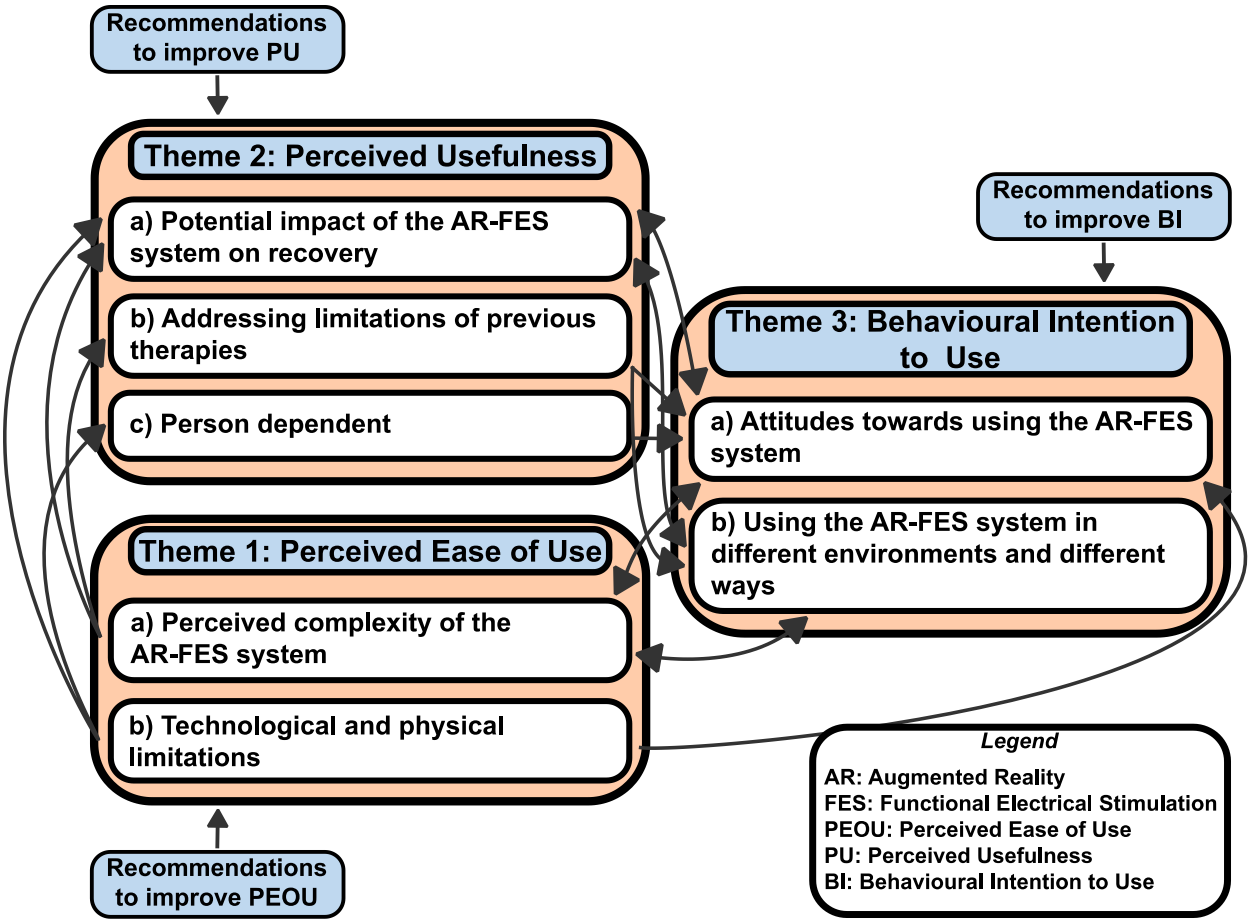


Figure 3. Themes arranged according to the categories of the TAM[23]. Arrows are displayed if there was evidence that subthemes influenced each other in unidirectional (single arrow) or bidirectional ways (double arrow). Quotes that provide evidence for specific connections can be found in Table 3.

Theme 1: Perceived Ease of Use

Subtheme 1a: Perceived complexity of the AR-FES system

Discussions related to the complexity of the AR-FES system centred around how the system was easy to use, with participants describing that the AR application providing clear instructions and one user suggesting that it provided more structure compared to previous FES therapy sessions (Table 3, quote 1). However, participants also noted that the system may be more complex for some individuals, such as older adults with low technology comfort (Table 3, quote 2), as they may not feel comfortable

using the system but those with previous experience using stimulation may find it easier to use (Table 3, quote 3). Proper electrode placement was discussed as the main challenge, but participants clarified that they were willing and able to learn with practice through “trial and error” (P4) and “testing all the positions with a therapist” (P3) prior to independent use. Only one participant noted that for complex therapies that include FES they would rather rely on a physical therapist, suggesting “if I want more advanced [therapies], I would rather go to a physical therapist instead” (P1).

Subtheme 1b: Technological and physical limitations

Technical limitations were discussed by some participants in instances where the hand tracking system was “not mapping my hand correctly” (P3) when they grasped certain objects. In some cases, participants reported that they could be deterred from using the system if technical challenges arose with no means for periodic check-ins that could influence the system’s usefulness (Table 3, quote 4). Participants also discussed that some physical limitations, such as reduced hand function or neck strength, could reduce a person’s ability to independently don/doff the headset (Table 3, quote 5) or place the electrodes. The physical limitations could lead to barriers ranging from long setup times to not being able to use the system at all if they had no access to support. However, participants noted that if support was available (e.g., via a caregiver or support staff), that the system would be easy to use “if you were not by yourself” (P4) or with “staff helping me a bit” (P11).

Theme 2: Perceived Usefulness

Subtheme 2a: Potential impact of the AR-FES system on recovery

Discussions related to the system's potential impact on recovery included increasing grip strength or "moving parts of my body that I couldn't move, and then eventually through repetition, I could do certain things" (P6) which could lead to more independence (Table 3, quote 6) and "improving quality of life" (P12). The availability of the system was also discussed as contributing to relearning movements with a participant suggesting that "if I have this machine on a daily basis, the more [repetitions] I [can] do" (P5). Participants also reported they could use the system to test their grip strength with the stimulation on (Table 3, quote 7) and improve their hand posture to help grasp properly (Table 3, quote 8). One participant also noted an immediate aftereffect of the stimulation suggesting that "after doing [the] experiment, I can move my hands more" (P5). Lastly, some participants also took note of the closed-loop modulation of stimulation amplitude (Table 3, quote 9) as being a helpful feature (Table 3, quote 10), although some mentioned that "they didn't notice a difference [in amplitude]" (P4).

Subtheme 2b: Addressing limitations of previous therapies

In this subtheme, participants compared therapy using the AR-FES system to previously completed therapies. For example, participants mentioned not having FES or AR technology at home (see Table 3, quote 11). In terms of movements produced by the stimulation, participants noted that it "made what I already have stronger" and "I was able to do more with it than without it" (P12). Several participants also noted that the system would prevent them from having to travel for therapy, contributing to being self-sufficient and cost-efficient (Table 3, quote 12), and more engaging or interactive than previous therapies (Table 3, quote 13), which could contribute to them being "more

motivated to use some technology" (P12) than other tools "like a Theraband" (P12). Participants also noted that using the system would prevent them from relying on other's schedules (Table 3, quote 14) or having limited time with a stimulator if a clinic had limited supply with "maybe two stimulation machines, [but] lots of patients" (P6).

Subtheme 2c: Person Dependent

Two participants noted that the usefulness of the system may be dependent on the characteristic of the user. For example, these participants perceived that "if somebody didn't have any function, that would be more helpful to them" (P5) or "some of the low functioning [individuals], it might me more effective that some people like me" (P1). Further, a participant expressed concern that individuals with lower function may be more sensitive to stimulation or having their postures overcorrected (Table 3, quote 15). Lastly, the specific objects used might also be person dependent with a participant suggesting "the blocks and credit card might not be useful for me" (P1).

Theme 3: Behavioural Intention to Use

Subtheme 3a: Attitudes towards using the AR-FES system

Participants expressed positive attitudes towards using the system including expressions of excitement (Table 3, quote 19) and motivation from achieving grasping patterns which acts "like a reward of sorts" (P8). Further, participants expressed their desire to use the system independently including the additional challenge that provides (Table 3, quote 16) and how availability of this could have improved confidence and reduced fear when leaving inpatient rehabilitation (Table 3, quote 17). However, one participant discussed their hesitation towards using the system preferring to rely on a

physical therapist (Table 3, quote 18), and another suggesting that "after a while, it becomes very boring" (P5).

Subtheme 3b: Using the AR-FES system in different environments and different ways

In this subtheme, participants discussed the feasibility of using the system both in their home (Table 3, quote 23) and retrospectively in clinical settings suggesting "I could have done this when I was an inpatient [and] have sessions everyday" (P6). Further, participants described the flexibility and ease of trying different stimulation timings which can influence the system's usefulness (Table 3, quote 20), preferring specific strategies to help achieve the correct posture (Table 3, quote 21), and using the system to help with specific tasks beyond a therapy session (Table 3, quote 22). Interestingly, a participant also suggested that individuals can use the system without stimulation to assess whether they can still achieve the appropriate grasps (Table 3, quote 24).

Recommendations to improve PEOU, PU, and BI

Participants provided recommendations that would improve all aspects related to the TAM. Recommendations included additional training, tutorials, and instruction manuals (PEOU), a means to track scores, additional gamified elements, and integrating additional objects (PU), and having a therapist in the loop to check progress (BI). A full list of suggestions, ranked by how many participants shared the suggestion, can be found in the Supplemental Material.

Discussion

The current study sought to assess perceptions of a prototype AR-FES system which provided grasping guidance, closed-loop FES based on grasping performance, and tracked exercise repetitions while individuals with cSCI completed exercises with real objects. Participants tried the system during a single supervised session in a clinical environment, with the goal of assessing perceptions of feasibility, ease of use, and usefulness in the context of future independent use of the system (e.g., in a home setting) via structured questionnaires and interviews. Overall, responses suggested that participants perceived that the AR-FES system was easy to use, that it was useful towards recovery compared to previous therapies, and that they intended to use the technology if it was available to them in a home setting, although additional training would be necessary prior to independent use. Further, interviews afforded the opportunity for individuals with cSCI to identify barriers to future independent use and provided recommendations to mitigate those barriers, which will be incorporated into future iterations of the system.

In relation to previous work investigating the combination of mixed reality and FES for upper limb rehabilitation, this is the first study to: 1) describe a mixed reality system that provides closed-loop FES while participants interacted with real objects and 2) assess perceptions related to feasibility, ease of use, and usefulness using quantitative and qualitative methods. For example, previously described systems relied on non-immersive virtual reality and used either muscle activity or movement kinematics to trigger but not control FES during arm and hand movements[16,17]. Specifically, the benefit of real object interactions relates to increased task specificity and additional

sensory feedback compared to interacting with virtual objects (e.g., popping a virtual bubble[16])[3,4]. This notion was supported by participants describing the potential to use the system with more meaningful objects specific to their goals. Further, the closed-loop modulation of the FES amplitude prevents constant maximum stimulations for the duration of every repetition. Although some participants did not notice the difference in stimulation amplitudes during a repetition, some noted that graded responses from the stimulator were helpful and could be used as feedback. Thus, the system ranged from triggering FES at the very least, to providing more useful stimulation patterns. Further, participants mentioned using different strategies when triggering the stimulation to make it more useful for grasping exercises. Assessing end-user perceptions of the system using quantitative and qualitative methods also extends previous work which only ascertained clinicians' perspectives for AR rehabilitation applications[24,25] and supports work which specifically sought perspectives from individuals with SCI for various mixed reality rehabilitation applications[15,26,27]. Specifically, attitudes of increased motivation and engagement when completing exercise with augmented cues and motivation from seeing the grasping response with FES are consistent with previous work when individuals with cSCI tried an AR rehabilitation application[15] or provided recommendations for virtual reality-based rehabilitation application design[26].

Leveraging the TAM model to analyse participant perspectives is consistent with its recent use and adaptation when assessing adoption of healthcare applications[28,29] and contributes to a staged manner of rehabilitation technology development for individuals with SCI[18]. In the current study, this approach allowed for the identification of factors that may influence the end user's BI for the AR-FES system, including PEOU

and PU. The data also suggest that while unidirectional relationships were found between PEOU and PU (e.g., perceived complexity influenced perceived impact on recovery), bidirectional relationships were found between BI and both PU and PEOU (see Figure 3). For example, the potential to use the system for more personally meaningful tasks or objects (i.e., related to eating or meal preparation) increased the system's PU (BI influencing PU). Further, attitudes related to wanting independent use could motivate participants to overcome the complexities of the AR-FES system or setup (BI influencing PEOU). Although participants perceived that the AR-FES system was easy to use, interview responses clarified that additional training with the system, including specific initial training with a therapist to aid individualized electrode placement would be necessary for independent use, and that previous experience with stimulation reduced perceived complexity. Thus, analysing participant perceptions using the TAM will directly inform future development and refinement of the AR-FES system, with the goal of improving BI and future actual usage behaviour.

The current study design also afforded participants the opportunity to provide specific recommendations that can directly influence all components of the TAM (see Supplementary Material). The recommendations centred around means to promote independent use (e.g., additional training, tutorials, and instruction manuals) and means to more flexibly use the system (e.g., including more objects in the system and manually adjusting stimulation levels). Thus, while most of the recommendations can be readily integrated into future versions of the system, recommendations related to telerehabilitation (e.g., a therapist checking progress remotely) warrant further investigation related to additional technological demands[30] and understanding

perceptions of clinicians. Further, recommendations which required interactions with a therapist may also suggest that independent use in clinical settings would provide access to therapists while still allowing for independent FES therapy.

The current study also included a diverse set of individuals with cSCI (i.e., age range: 28-64, AIS grade range: A-D, GRASSP Prehension Score range: 4-30; see Table 1). This allowed for diverse perspectives related to current and potential future barriers of using the AR-FES technology. For example, the only participant who was an inpatient discussed a preference for outpatient therapy with a therapist over complete independent use with the AR-FES system. Further, participants that could more accurately achieve target postures perceived that the system increased the strength of their grip as opposed to allowing them to complete tasks they could not previously. Lastly, participants with limited upper limb function discussed barriers to donning/ doffing the HMD or placing the electrodes independently. Thus, this system may not be suitable for individuals with severe hand impairment unless assistance is available, which is consistent with previous work assessing HMD applications[15]. The need for physical assistance for some individuals also suggests that the system may be best suited to clinical environments where a therapist could assist an individual or individuals in the set up phase before allowing them to carry on independently.

Limitations

A key limitation of the work is that individuals with cSCI assessed the AR-FES system during a single supervised session in a clinical environment. Thus, the current study could not assess efficacy related to therapeutic outcomes or actual usage behaviour (i.e., a construct of the TAM) over multiple sessions[23]. Specifically, the study

was limited to assessing perceived barriers to future independent use instead of actual barriers to using the system independently. Considering the positive perceptions of participants about the system identified in this study, actual usage should be explored in future research. Questions were framed around future home use to assess perceptions of using the system in a completely independent or almost completely independent environment. Assessing participants perceptions of the system allows for user-informed iterative refinement and follows recommendations of a staged approach to rehabilitation technology for individuals with SCI[18]. That is, it would not be appropriate to send users home with the technology prior to understanding if they do not find the system meaningful or useful towards recovery or if they can use the system independently. Future work must continue along a staged approach to assess perceptions after prolonged use, measure participants ability to use the system independently and safely, and whether the AR-FES system can increase the dosage of neuromodulation-based therapy and promote recovery.

A potential limitation also relates to the sample of the current study. That is, the current set of participants participated in a previous study in which they tried a different AR application while wearing the same HMD[15]. Although the studies were conducted during separate sessions and the applications had different purposes, experience using the previous AR application could have contributed to PEOU and perceived limitations when using the HMD and AR portions of the current system.

Conclusions

The current study assessed perceptions of a novel prototype AR-FES system that allowed individuals with cSCI to receive closed-loop FES while interacting with real

objects. Participants reported high behavioural intention to use the system independently aided by its perceived ease of use and perceived usefulness. Although the study was conducted in a supervised clinical setting, participants perceptions along with specific achievable recommended changes provide a foundation for future development along a staged approach with the potential to increase the dosage of independent neuromodulation-based therapy for individuals with cSCI.

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Author Contributions

Study conceptualization and design – HS, CM, JZ. System conceptualization and design – DMM, OT, JHY. Data collection – DMM. Data Analyses – DMM, HS. Interpretation of results – DMM, HS, JZ. Manuscript preparation – DMM. Critical review of manuscript – all authors. Supervision – HS, CM, JZ.

Statements and declarations

Ethical Considerations

All protocols were approved by the Research Ethics Board of the University Health Network (#23-5249).

Consent to participate

All participants provided written informed consent prior to participating.

Consent for publication

Not applicable.

Declaration of conflicting interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data availability

The data analysed during the current study are available upon reasonable request to the authors and completion of a data sharing agreement.

Table 3: Themes, subthemes, descriptions, and supporting quotes. If quotes from a specific subtheme connect with a different subtheme, the specific arrow/ connection can be found in Figure 3.

Theme and Subthemes	Description	Supporting Quotes & Connections to other Subthemes
Theme 1: Perceived Ease of Use		
Subtheme 1a) Perceived Complexity of the AR-FES system	Discussions related to the complexity of any aspect of the system	**1.** "I feel like with the therapist, when I used FES in the past, it just felt like, not structured and like, oh, we're seeing where things kind of go. Like what would be like the optimal thing. Whereas here it's like a pretty obvious goal, like what to do. And like, it's just like a scoring mechanism that like, is easy to understand" (P3) **Connection: 1a → 2b** **2.** "I didn't have any issues. But if you're afraid of, you know, what if I touch the wrong button? Because a lot of people are afraid, elderly, more so than younger people. And so if you're afraid, you know, if I put it in the wrong place, I'll hurt myself, or, you have to be confident in your abilities and yourself" (P4) **Connection: 1a → 3a** **3.** "I'd be more comfortable because it's something I've done before and during the experiment we also tried to move stuff around, right. Like my right hand could help me move the pads around you know. I'll be more comfortable experimenting to see what works and what doesn't work" (P5) **Connection: 1a → 3b**
Subtheme 1b) Technological and Physical Limitations	Discussions related to technological limitations of any aspect of the system or physical limitation of the person	**4.** "I could see that if it didn't work for one reason or another, it might deter people from doing it at all. So, I don't know if there's a way to check whether people are doing it and then to have sort of a call because it could just sit in the corner as well, unused" (P12) **Connection: 1b → 2a & 3a** **5.** "As long as I was able to get it set up properly and physically able to put the headset on my head, which this one seems easy enough, but some of them might be difficult with somebody with my impairments" (P4) **Connection: 1b → 2c**
Theme 2: Perceived Usefulness		
Subtheme 2a) Potential impact of the AR-FES system on recovery	Discussions related to potential improvements to recovery from using the system	**6.** "I think this would be extremely helpful again, because of the shock therapy. Like maybe it doesn't work for other people, but I find it really works for me. […] Like if I couldn't really grasp or grip an object, then the electrode would help the fingers grip it tighter. […] That would be probably the most important thing about this would be the ability that it's helping me. And over time doing it often, I'd be able to do it by myself. That would be the goal, right? To get to that independence" (P7) **Connection: 2a → 3a** **7.** "I was testing it to see the grasp that it gave me. So, it's definitely stronger, right? Because I have actually very limited strength. I have more movement than strength in my fingers. So, I'm not able to hold on to things" (P12) **Connection: 2a → 3b** **8.** "Yes, it did help me pick up the objects [and] even hold it properly like I was trying to mimic the exact position when I had the headset on" (P5) **Connection: 2a → 3b** **9.** "I was far from the target, yes, it did increase its tension, if I'm going closer to the proper posture it did [decrease] the tension" (P2) **10.** "So, when I needed it to help me, like for instance holding the block, my hand not being in the proper position and it sensed that. So, then it kind of like

		shocked me to say, “Hey, okay. He needs more help with this”. I appreciated that. I found [that] to be extremely helpful” (P7) **Connection: 2a → 3a**
Subtheme 2b) Addressing limitations of previous therapies	Discussions relating the current system to previously completed therapies	**11.** “I don't have stim[ulation] like that at home. I don't have the augmented reality at home. […]. I have TENS at home but it’s not the same as what you guys have” (P8) **Connection: 2b → 3a** **12.** “Getting people walking gets them out of wheelchairs that don't need to be maintained. Don't need to be replaced every five years. Don't need to be repaired. You know what I mean? But the whole thing in general, less workers need to support them. […] Same with what you were talking about with this. To not have to travel and to be at home is more self-sufficient. It's a win. It's a plus. And it costs less in the long run” (P8) **Connection: 2b → 3a** **13.** “I feel like it's more interactive. I'm getting feedback, there's a lot more stuff going on, which, like, keeps me more engaged.” (P3) **Connection: 2b → 3a** **14.** “And just maybe also, giving that again, other human beings can have its own limitation of time. Where this one you can sort of use it according to your time available that doesn't have to rely on another person's schedule” (P2) **Connection: 2b → 3b**
Subtheme 2c) Person dependent	Discussions related to characteristics of the individual that may influence perceived usefulness	**15.** “I think for me, I don't mind [the stimulation on] the whole time because [of the] weak intensity. Even like strong [stimulation], it's not that much for me. But I think you need to be alert for some of those people with like very sensitive for the intensity because when they have like weak arms and fingers […] it might be affecting or correcting, or over correcting the posture. So, it depends” (P1) **Connection: 2c → 3a**
Theme 3: Behavioural Intention to Use		
Subtheme 3a) Attitudes towards using the AR-FES system	Discussions related to emotions or feelings towards using the system	**16.** “Well, if I tried it on my own, I'd be able to figure it out, right. I think that's the key thing instead of relying on someone else to do it. That's the point of kind of bringing it home is the independence of it, right? So that's what drives me to be able to just challenge myself to do it myself. So, if I was struggling at first, I believe over a matter of time, I would find a way” (P7) **Connection: 3a → 1a & 2a** **17.** “If I would have been sent home from here with something like that, I think I would have felt a lot more confident. Going home terrified me” (P4) **Connection: 3a → 1a** **18.** “Theoretically I think using TENS and a headset seems like it's simple but, from my point of view I would rather to go to the physical therapist and let them do the job for me rather than just using some tools and you might hurt yourself [if] the amplitude [is] too high” (P1) **Connection: 3a → 2a** **19.** “100%, 100%. I would be excited for this type of technology. I feel like it should have been on the market a long time ago, to be honest” (P7)
Subtheme 3b) Using the AR-FES system in different environments and different ways	Discussions related to how the individual intends to use the system	**20.** “No, I like that I can try different things. Because movement is fluid […] it's not rigid. And it's good to, you know, say ‘ready’, feel the stim, and do the act. And then the other way, which is to grasp the object, and then say ready. And then you feel the stim” (P6) **Connection: 3b → 1a** **21.** “Let me see what I preferred. I think almost having my hand around the object and then allowing the stim to help me grasp. […] Sometimes I was already grasping the object, but although it wasn't in the right position, I was still grasping it and then it just kept getting stronger, but then it wasn't really changing my hand positioning. It was just making the grasp stronger” (P12) **Connection: 3b → 1a**

		22. “Or like while I'm in the kitchen I could pick up like […] a spoon or fork you know what I mean, or if I'm prepping some stuff” (P5) **Connection: 3b → 2a** **23.** “I think this could easily be used on a kitchen table. So, I can't really see an obstacle” (P6) **Connection: 3b → 2a** **24.** “After using the machine, like when you're not using the machine, can you actually use your hands or your fingers to mimic the posture or pick up the objects type of thing” (P5)

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Supplementary Material

Stimulation Parameters

One square electrode (i.e., anode; 5 cm x 5 cm) was placed over the finger flexors (i.e., flexor digitorum profundus and superficialis) on the ventral side of the forearm, one square electrode (i.e., anode) was placed over the finger extensors (i.e., extensor digitorum and extensor digiti minimi) on the dorsal side of the forearm, and one circle electrode (i.e., anode; 3.2 cm diameter) was placed on the thenar muscles of the thumb (i.e., adductor pollicis). Further, the finger flexor and thenar muscle anodes shared a common square cathode located proximal to the wrist joint on the ventral side of the forearm, while the cathode for finger extensors was similarly placed on the dorsal side of the forearm (see Figure 1). The specific electrode placements were determined through stimulation testing with each participant to determine whether each electrode location produced the desired response (e.g., finger flexion). Electrodes were only placed on one limb to reduce the complexity of the system at this stage. The lead wires were connected to a MyndSearch™ functional electrical stimulation unit (MyndTech Inc., Mississauga, ON, Canada), which delivered stimulation with a pulse frequency of 40 Hz, a pulse width of 400 μs, and with individualized amplitudes for each participant and dependent on grasping performance. The maximum stimulation amplitude was set as the stimulation amplitude that produced a maximal tolerable contraction. Additionally, a minimum stimulation amplitude was recorded for the thumb and finger flexors which was defined as the minimum amplitude which produced a contraction through the full range of the desired movement when no resistance was applied and no object held.

Closed-Loop Stimulation

Pre-defined target postures

The system included three target postures (i.e., tip-to-tip pinch grasp, cylindrical grasp, and lateral key pinch grasp) which were pre-defined by having DMM pick up three different objects using their corresponding grasp types while wearing the AR headset (see Figure 1; Manzone et al., 2026). The relative joint positions were then saved in Unity, incorporated into the application, and used for posture guidance and to calculate grasping errors. The objects included a marble, a block and credit card. The block and credit card were 3D printed from the Toronto Rehabilitation-Hand Function Test (Kapadia et al., 2021a & b). The specific objects were chosen because they require three distinct grasp types that are typically used in functional assessments for individuals with cervical spinal cord injury (i.e., GRASSP; Kalsi-Ryan et al., 2012; see Figure 1).

Posture guidance

After choosing what object they wanted to interact with verbally, participants were presented with a target posture screen. This included two depictions of the target posture (see Figure 1), and text information regarding cues to advance the application, posture cues, within object and total session repetitions. The screen was always visible to participants, and they could change its position using voice commands. As long as the hand was in the field of view, it was tracked with a red skeleton overlaid onto participants' real hand (see Figure 1). Once participants grasped or attempted to grasp the object, they could verbally ask the system to start the electrical stimulation. Participants had control over stimulation timing and could also ask for stimulation prior to attempting their grasp (e.g., with an open hand around the object; see Results for different strategies used by participants). The amplitude of the stimulation was linearly

related to differences between the participant's actual posture and the target posture based on finger and thumb error metrics (see below).

Finger Flexor Error Metrics

Errors for the finger flexors were computed by comparing the angles from the metacarpophalangeal (MCP) joints between the target and actual grasps. Further, the difference was normalized to a pre-defined maximum error ($E_{upper,flexion}$) based on approximate angle differences when the fingers were in full extension (i.e., marble max error = 40º, credit card max error = 40º, block max error = 25º). Lastly, for the marble and credit card, only the index finger MCP was used in the calculation, but for the block, the average of all four fingers was used to calculate error. This was expressed as $E_{finger_flexion}$ (Eq.1):

$$E_{finger_flexion} = \frac{\Sigma_{j=1}^{J}(a_{target,j} - a_{actual,j}}{J \cdot E_{upper,flexion}} \qquad (1)$$

where J is the number of MCP joints, and a is the MCP joint angle for each joint (j).

Thumb Flexor Error Metrics

For the thumb flexors, the error was based on the alignment of the thumb and index finger (see Figure S1). The alignment ($E_{thumb_alignment}$) was measured as the perpendicular distance between the tip of the thumb (P_{thumb_tip}) and a plane that passes through the origin of the index finger MCP joint aligned with the flexion-extension axis (i.e., oriented perpendicular to the plane of the palm; Eq.2):

$$E_{thumb_alignment} = \frac{n_{plane} \cdot (P_{thumb_tip} - P_{index_MCP})}{E_{upper,thumb_alignment}} \qquad (2)$$

where n_{plane} is the vector representing the normal of the plane, P_{index_MCP} is the position of the index finger MCP joint, and $E_{upper,thumb_alignment}$ is the maximum alignment error (i.e., 6 cm based on approximate differences when the thumb is fully extended).

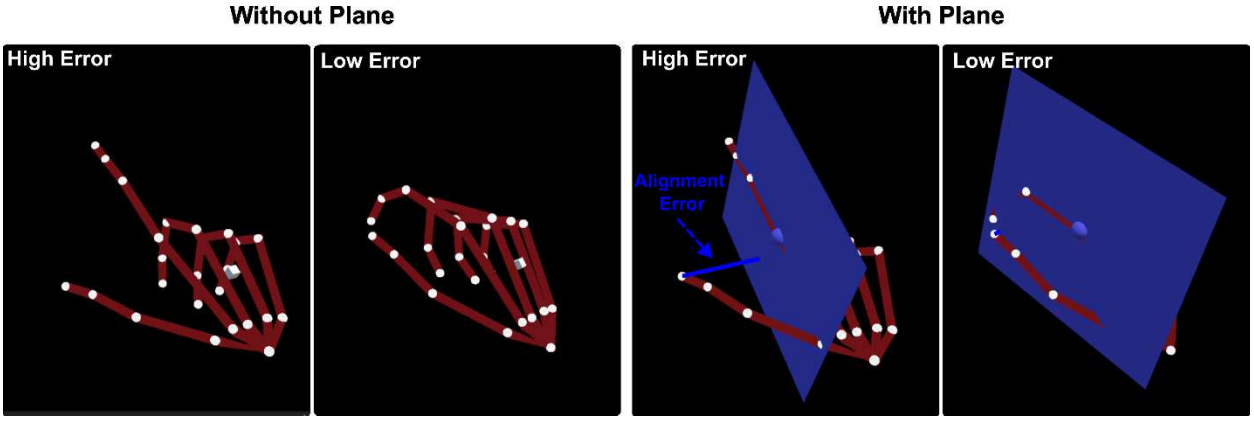


Figure S1. Depiction of the thumb alignment error. Note that the image was taken from Unity for simplicity and clarity. These images depict an example of the tracked skeleton with high and low error relative to the tip-to-tip pinch grasp (real hand not shown). The plane in blue runs through the index MCP joint (represented by a blue sphere), and the blue line labeled Alignment Error represents the shortest perpendicular distance from the thumb tip to the plane. With low error the blue line is less visible because the thumb tip is aligned to the plane. Note that the blue plane was never visible to the participants.

Determining and updating stimulation amplitudes

Once the participants asked for stimulation, the stimulation amplitude was modulated in real-time, in a closed-loop fashion and based on finger and thumb error metrics. The errors were linearly related to the amplitude of the stimulation (i.e., higher error leads to higher amplitude). To avoid situations where low errors led to stimulation amplitudes that could not produce muscle contractions, the amplitudes ranged from the minimum and maximum amplitudes defined at the beginning of the experiment (see Figure S2). The minimum (A_{min}) and maximum (A_{max}) amplitudes were used to calculate the error threshold for each channel ($E_{threshold}$; Eq.3):

$$E_{threshold} = \frac{A_{min}}{A_{max}} \qquad (3)$$

and the normalized error (E, see details above) related to the final stimulation amplitude ($A_{stimulation}$) accordingly (Eq.4):

$$A_{stimulation} = \begin{cases} A_{min} & \text{if } E \leq E_{threshold} \\ A_{max} \cdot E & \text{if } E_{threshold} < E \leq 1 \\ A_{max} & \text{if } E > 1 \end{cases} \quad (4)$$

Thus, errors below the error threshold would result in the pre-defined minimum stimulation amplitude which was strong enough to produce a contraction through the full range of the desired movement. At any point during the stimulation, participants could decide to stop the stimulation and try the grasping trial again, or switch to grasping another object.

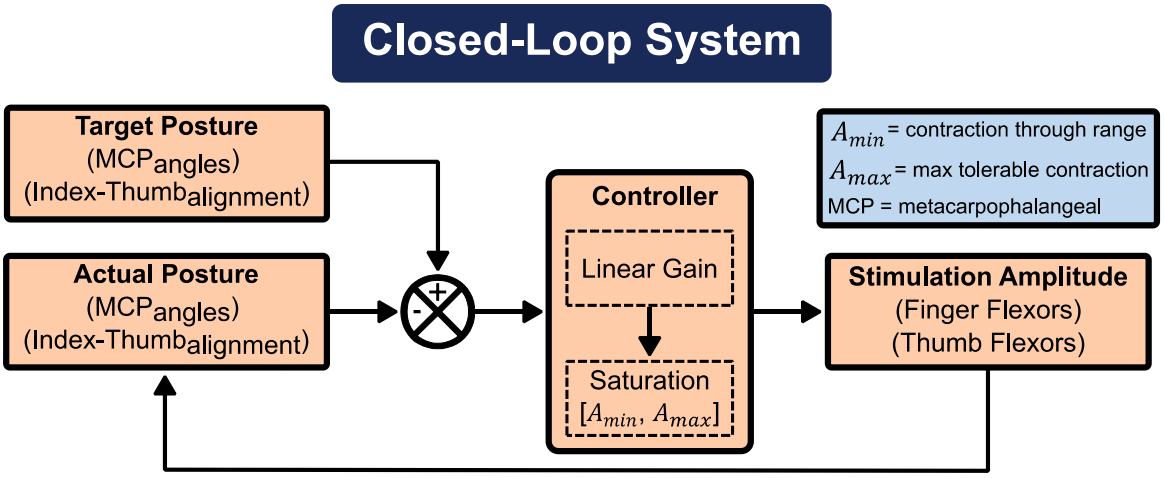


Figure S2: Depiction of the closed-loop system used to calculate the ongoing stimulation amplitude sent to the finger and thumb flexors. The error between the target and actual posture (see Eq.1 and Eq.2 for details) linearly relates to the stimulation amplitude (i.e., higher error = higher stimulation), but the stimulation amplitude ranges from the pre-defined participant and channel specific minimum and maximum amplitudes. For example, the minimum stimulation amplitude was sent if the error was

below a participant and channel specific error threshold (see Eq.4). MCP = metacarpophalangeal.

Relative Stimulation Timing

For both the marble and block, the stimulation of the thumb and index flexors both occurred simultaneously (see Figure S2). However, for the credit card, a lateral key pinch grasp requires the thumb to be placed atop of the side of the index finger (cf. tip-to-tip pinch grasp). To avoid a situation in which the thumb is flexed beyond the index finger, the stimulation for the thumb only turned if the error in finger flexion ($E_{finger_flexion}$; see Eq.1) was below 0.5 (i.e., halfway between full extension and the target angle). Thus, this attempted to ensure that index finger was close to the target angle prior to guiding the thumb. Also note that participants could ask for stimulation to help open their hand (i.e., finger extension) which delivered the maximum set amplitude to the finger extensors and was not part of the closed-loop system. The flexor and extensor stimulation patterns were never on simultaneously.

Connection between AR and FES systems

Error scores produced by comparing actual and target grasping postures were sent from the headset to a companion laptop via a UDP connection. A custom python script processed the error scores and sent digital signals to an Arduino Mega 2560 microcontroller via USB serial communication. These digital signals were used to control the microcontroller's Pulse Width Modulation (PWM) output pins, which were then passed through a two-stage, second order RC low-pass filter (cutoff frequency = 31.85 Hz) to generate a continuous analog voltage. Different analog channels of the MyndSearch™ received the signals and controlled the stimulation amplitudes corresponding to the different muscle groups. Note that turning the stimulation on and

off was primarily controlled by voice commands, but stimulation could also be stopped via a physical button connected to the MyndSearch™ or directly via the MyndSearch™ interface.

Recommendations to improve PEOU, PU, and BI

Participants provided several suggestions to improve the AR-FES system during the semi-structured interviews. The suggestions were organized into categories according to the TAM (i.e., perceived ease of use, perceived usefulness, and behavioural intention to use) and ranked based on the number of participants who shared the same or similar suggestion (Table S1).

Table S1. Suggestions organized according to the TAM and ranked based on the number of participants who mentioned each suggestion at least once during the semi-structured interview.

Perceived Ease of Use	
# of Participants	**Suggestion**
10	Additional training with the system
5	Step by step tutorials
5	Improve electrode placement procedures
3	Instructions manual with the system
3	Remove stimulation countdown
2	Other ways to progress application (i.e., without voice commands)
1	Train caregiver to use system
1	Increase the number of words the system recognizes
1	Make the system portable
1	Provide the option to remove virtual screen during tasks
1	Find the most common words across cultures for voice recognition

Perceived Usefulness	
# of Participants	**Suggestion**
6	Specific training with a therapist prior to use
5	Include more tasks or objects to use with the system
4	Track progress and repetitions across sessions
3	Show a matching score during stimulation
3	Show the stimulation levels in the virtual space
3	Adjust stimulation levels manually using voice commands
2	Create a schedule or exercise program to increase accountability
2	Have different stimulation intensities for different objects
1	Be able to check matching scores with and without stimulation
1	Increase gamification elements
1	Provide goals other than grasping posture
1	Adjust timing of stimulation
1	Include goal setting in the application
1	Increase stimulation levels for good postures
1	Adjust application based on skill or impairment level
1	Adjust how quickly the stimulation ramps up to the final amplitude
1	Trigger the stimulation in different ways (e.g., proximity to object during reaching)

Behavioural Intention to Use	
# of Participants	**Suggestion**
1	Have a therapist check on your progress remotely
1	Having a therapist available as a backup if there are any questions or concerns when using the system
1	Have intermittent sessions with a therapist to check progress

Custom Questionnaire

All of the structured questions will use 5-point Likert scales (1 – “Strongly disagree” to 5 – “Strongly Agree”).

1. I would be able to use this technology at home without therapist supervision.
2. I would like to use this technology at home without therapist supervision.
3. This technology addresses limitations that I have encountered with rehab exercises at home.
4. This technology could make a difference in my recovery.
5. This technology can improve the relearning of movements during rehab exercises at home.
6. The stimulation helped me to produce the correct postures.
7. The stimulation sequences helped me to complete the object manipulation tasks.
8. I was able to complete tasks that I would not have been able to complete without the stimulation.
9. The stimulation was strong enough.
10. The stimulation was too strong.
11. The stimulation was painful.
12. The stimulation increased when I needed help and decreased when I didn’t.
13. There was enough information displayed about what the system is doing.

Semi-structured Interview Guide

1. Do you think you would be able to use this type of technology at home if it was available to you? Why or why not?
    a. What obstacles would you anticipate, and would these be small or big problems?
    b. In what ways is this most different from rehab you have done at home in the past?
    c. What are you most unsure about in terms of using this at home without therapist supervision?

2. How helpful do you think this type of technology would be to your rehabilitation goals?
    a. Does this address any of the problems or limitations that you have encountered with rehab exercisers at home in the past?
    b. How could this make a difference in your recovery?
    c. To what extent do you think this type of technology can improve the relearning of movements during rehab exercises at home?

3. What did you think of the movements that were produced by the FES system?
    a. Did the stimulation help you to produce the correct postures?
    b. Did the sequence of movement patterns produced help you to complete the object manipulation tasks?
    c. Do you think you were able to compete tasks that you would not have been able to complete without the stimulation?

4. Did you feel that the intensity of stimulation was regulated appropriately?

    a. Was the stimulation strong enough?
    b. Was it too strong or painful?
    c. Did you feel that it increased when you needed help and decreased when you didn't?

5. Are there any changes to the system that would make it easier to use or more helpful?
    a. Should the movement patterns be adjusted? How so?
    b. Should the stimulation intensities be adjusted differently?
    c. Should there be more information displayed about what the system is doing?

References

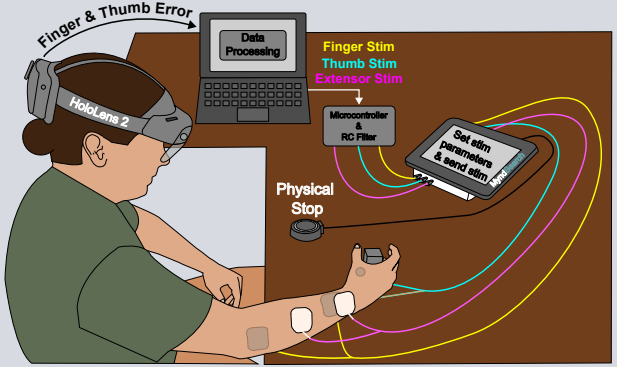
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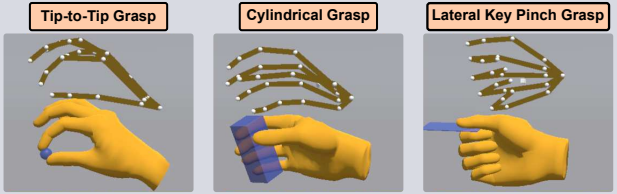
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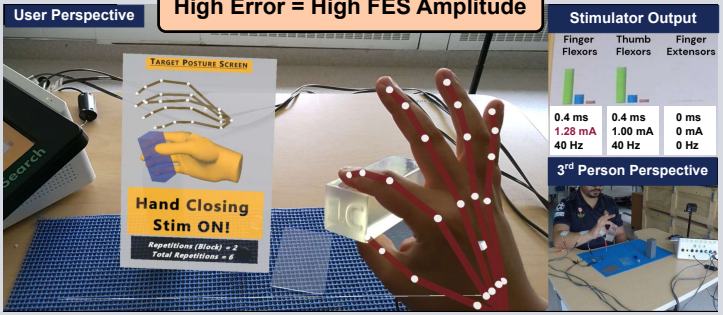
Set up & Connections

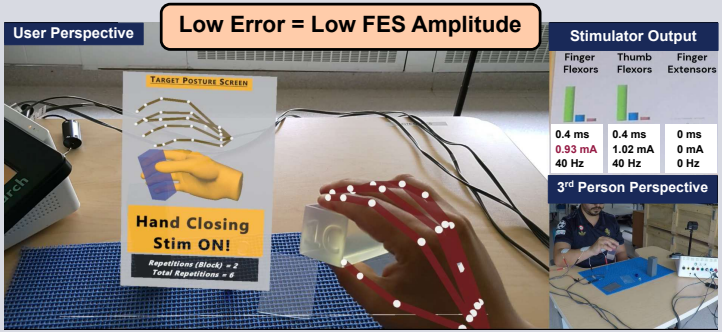


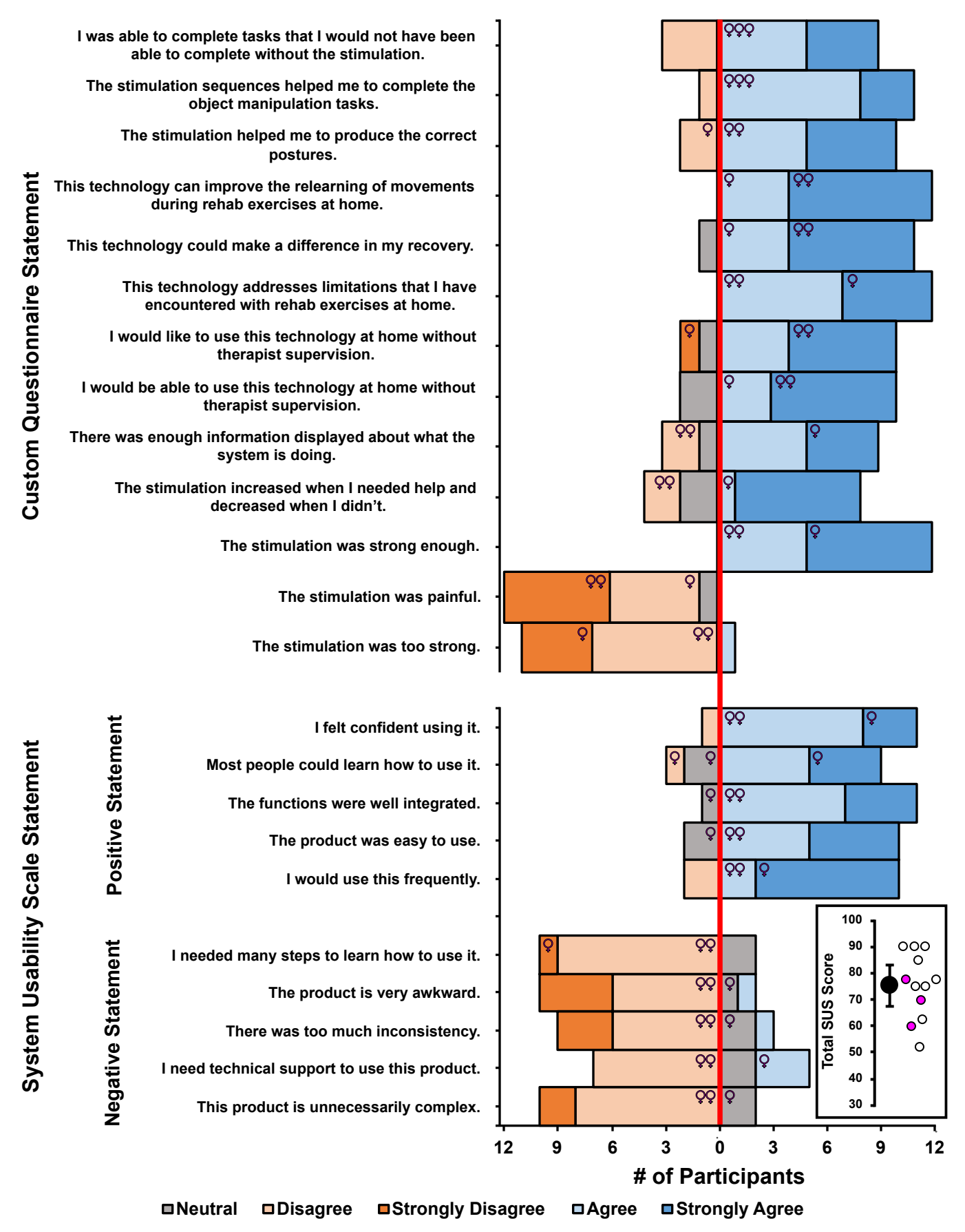
Target Postures

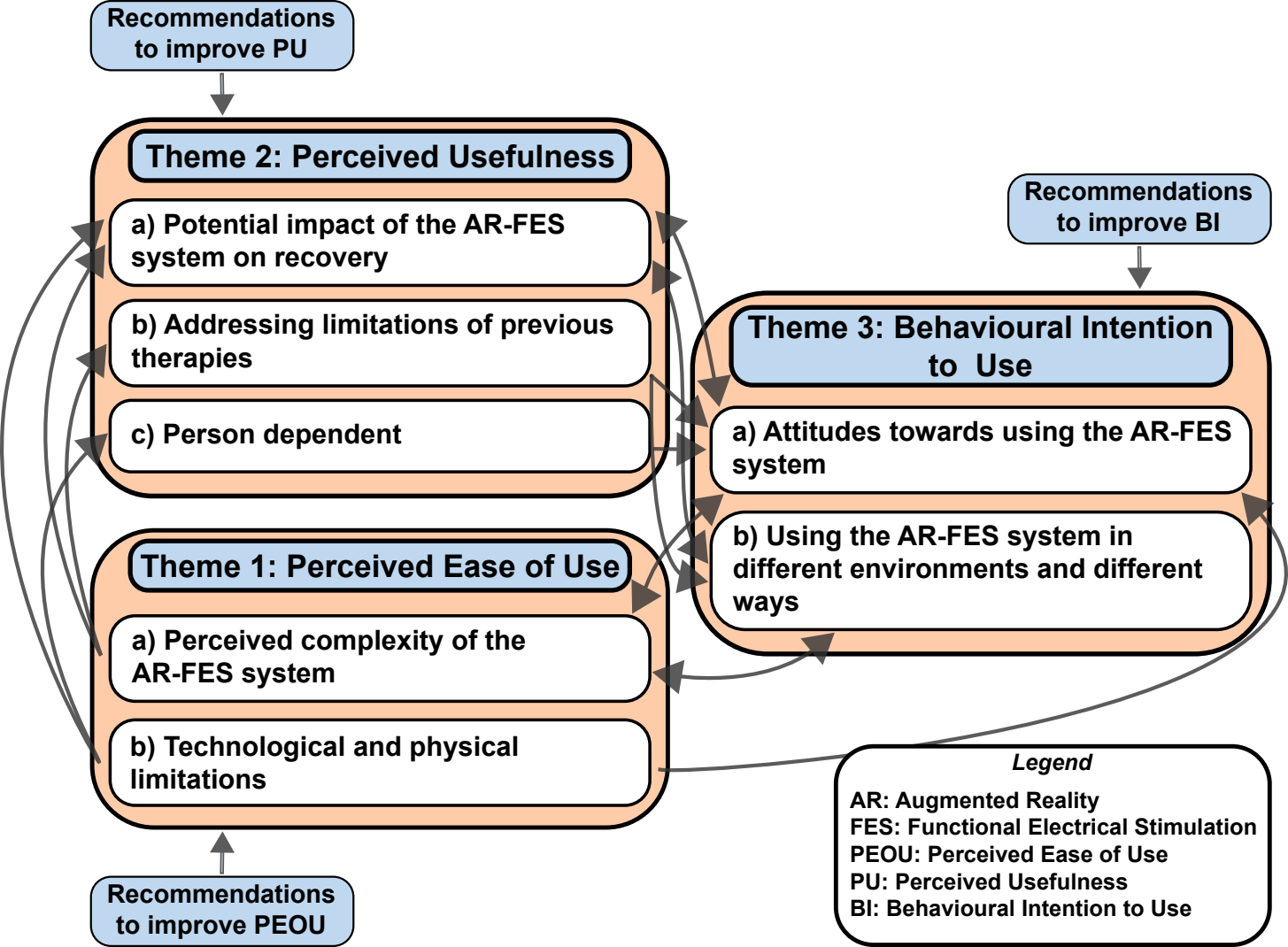


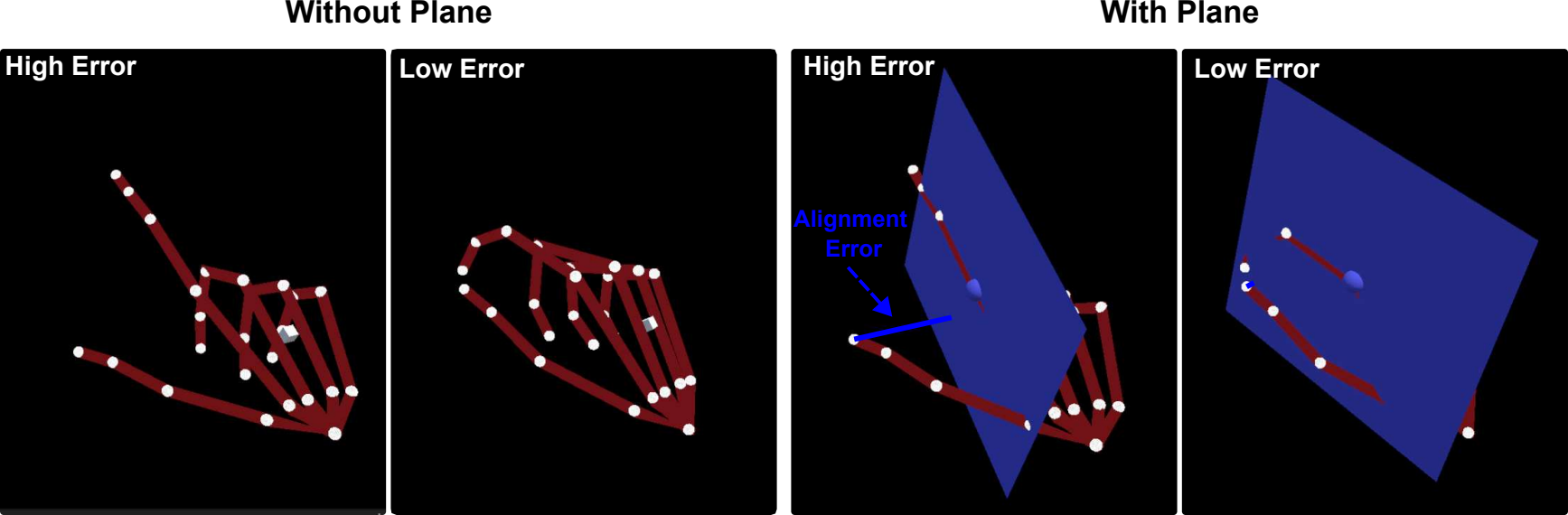
Example Usage

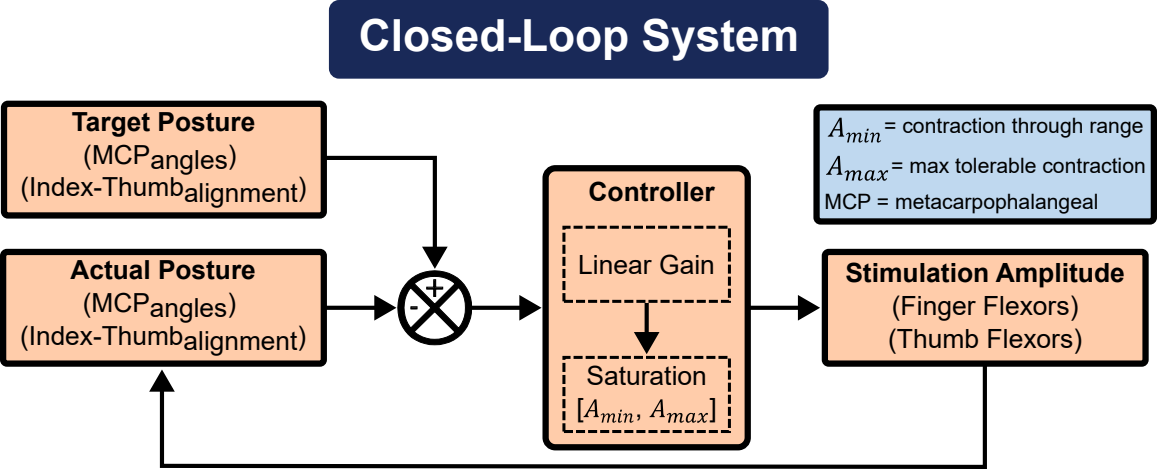





Custom Questionnaire Statement
I was able to complete tasks that I would not have been able to complete without the stimulation.
The stimulation sequences helped me to complete the object manipulation tasks.
The stimulation helped me to produce the correct postures.
This technology can improve the relearning of movements during rehab exercises at home.
This technology could make a difference in my recovery.
This technology addresses limitations that I have encountered with rehab exercises at home.
I would like to use this technology at home without therapist supervision.
I would be able to use this technology at home without therapist supervision.
There was enough information displayed about what the system is doing.
The stimulation increased when I needed help and decreased when I didn't.
The stimulation was strong enough.
The stimulation was painful.
The stimulation was too strong.
System Usability Scale Statement
Positive Statement
I felt confident using it.
Most people could learn how to use it.
The functions were well integrated.
The product was easy to use.
I would use this frequently.
Negative Statement
I needed many steps to learn how to use it.
The product is very awkward.
There was too much inconsistency.
I need technical support to use this product.
This product is unnecessarily complex.
Total SUS Score
100
90
80
70
60
50
40
30
12
9
6
3
0
3
6
9
12
# of Participants
Neutral
Disagree
Strongly Disagree
Agree
Strongly Agree


Recommendations to improve PU
Theme 2: Perceived Usefulness
a) Potential impact of the AR-FES system on recovery
b) Addressing limitations of previous therapies
c) Person dependent
Recommendations to improve BI
Theme 3: Behavioural Intention to Use
a) Attitudes towards using the AR-FES system
b) Using the AR-FES system in different environments and different ways
Theme 1: Perceived Ease of Use
a) Perceived complexity of the AR-FES system
b) Technological and physical limitations
Recommendations to improve PEOU
Legend
AR: Augmented Reality
FES: Functional Electrical Stimulation
PEOU: Perceived Ease of Use
PU: Perceived Usefulness
BI: Behavioural Intention to Use


Without Plane
With Plane
High Error
Low Error
High Error
Alignment
Error
Low Error


Closed-Loop System
Target Posture
(MCPangles)
(Index-Thumbalignment)
Actual Posture
(MCPangles)
(Index-Thumbalignment)
+
-
Controller
Linear Gain
Saturation
[Amin, Amax]
Stimulation Amplitude
(Finger Flexors)
(Thumb Flexors)
Amin = contraction through range
Amax = max tolerable contraction
MCP = metacarpophalangeal