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Original Article

PROJECT HEAVEN: Preoperative Training in Virtual Reality

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Abstract

A cephalosomatic anastomosis (CSA; also called HEAVEN: head anastomosis venture) has been proposed as an option for patients with neurological impairments, such as spinal cord injury (SCI), and terminal medical illnesses, for which medicine is currently powerless. Protocols to prepare a patient for life after CSA do not currently exist. However, methods used in conventional neurorehabilitation can be used as a reference for developing preparatory training. Studies on virtual reality (VR) technologies have documented VR's ability to enhance rehabilitation and improve the quality of recovery in patients with neurological disabilities. VR-augmented rehabilitation resulted in increased motivation towards performing functional training and improved the biopsychosocial state of patients. In addition, VR experiences coupled with haptic feedback promote neuroplasticity, resulting in the recovery of motor functions in neurologically-impaired individuals. To prepare the recipient psychologically for life after CSA, the development of VR experiences paired with haptic feedback is proposed. This proposal aims to innovate techniques in conventional neurorehabilitation to implement preoperative psychological training for the recipient of HEAVEN. Recipient's familiarity to body movements will prevent unexpected psychological reactions from occurring after the HEAVEN procedure.

Key Words: GEMINI, haptic feedback, HEAVEN, neurorehabilitation, virtual reality

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INTRODUCTION

Neurological impairments, such as spinal cord injuries (SCI), resulting in the deterioration of an individual's motor and sensory functions, are currently incurable. Terminal illnesses, in which patient survival is unlikely, have no means of remediation. A cephalosomatic anastomosis (also known as CSA, HEAVEN, head anastomosis venture) is proposed as a last-resort solution to these complications.[11,13,14,43]

One possible complication to consider in the context of a CSA is the psychological state of the recipient while acclimating to the transplanted body. Because the recipient of HEAVEN is an individual who has complications with motor controls, complete bodily freedom, especially in a foreign, transplanted body, will be an unfamiliar sensation. It is imperative to prevent psychological reactions, e.g., hypomania, stemming from the ability to move normally in a new body. To prepare the recipient for this new normalcy, development of

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virtual reality (VR) experiences supplemented with haptic feedback is proposed. This method will allow the recipient to experience the sensations of normal bodily movements and reduce the possibility of being psychologically and emotionally overwhelmed after transferring into the new body.

The concepts involved in VR training with haptic feedback are beneficial for rehabilitating patients with neurological impairments. However, the goal of this proposal is specifically for preparation before the HEAVEN procedure. The objective is to utilize and evolve contemporary methods in neurorehabilitation for familiarizing the recipient of HEAVEN to the sensations of performing bodily functions. Familiarity to bodily movement will lower the possibility of the recipient expressing unexpected psychological reactions after the HEAVEN procedure.

PREOPERATIVE VIRTUAL REALITY TRAINING TO PREVENT UNEXPECTED PSYCHOLOGICAL REACTIONS

Once the recipient is able to perform movements in the transplanted body, there is the possibility of being psychologically overwhelmed by the sense of bodily freedom. This might trigger, for instance, hypomania, a dysfunctional condition that can transition into depression, mania, and psychosis.[5-7] Another possibility is the onset of depersonalization-derealization syndrome, a disorder characterized by symptoms such as detachment from one's sense of self and experiencing objects, people, and/or surroundings as unreal.[37,42,44] These psychological conditions can potentially influence the recipient into making decisions that are harmful to their well-being.

This proposal aims to prepare the recipient for the sensations of performing bodily functions and prevent triggering the behaviors mentioned above. Replicating natural body movements through VR experiences will serve as training against unexpected psychological reactions. We speculate that VR training with haptic feedback prior to CSA will sufficiently prepare the recipient for handling the new body and prevent risk-taking behavior caused by psychotic episodes. This approach will require the creation of training that realistically replicates the sensations involved in performing voluntary motor functions. The development of appropriate activities for this approach can be accomplished by referring to the techniques used in conventional neurological rehabilitation.

Overview of virtual reality in neurorehabilitation therapy

Although a standard protocol to prepare the recipient of HEAVEN for life after CSA does not currently exist, conventional approaches to rehabilitation for neurological injuries, such as SCI and stroke, can be used as a reference for developing VR experiences that will assist the recipient in becoming physically, mentally, and emotionally prepared for the unfamiliar normality.

For SCI and stroke rehabilitation, functional training is the most effective approach in promoting neuroplasticity for recovering motor functions. Functional training is a classification of exercises that are used to practice activities of daily living (ADL). This training is used in rehabilitation for the purpose of restoring motor functions such as walking, reaching, and grasping movements.[1,21] Functional training consists of phases with passive and active exercises in which the intensity of the exercises in each phase is dependent on the severity of the patient's motor impairment.[28,35]

Advancements in VR technologies have opened new frontiers for patient care, in particular, enhancing the rehabilitation therapy experience and improving the results of motor recovery in patients with neurological disabilities. There exists several types of VR environments, such as non-immersive, semi-immersive, and immersive VR.[34] This proposal focuses only on immersive VR due to its effectiveness in providing the most realistic experience to the user. Commercially available immersive VR hardware such as HTC's Vive®[26] and Oculus' Rift®[40] facilitate interactivity by immersing the user in a three-dimensional, computer-generated world enabling them to naturally interact with virtual objects. These technologies allow the user to experience the virtual world through the first-person viewpoint of the avatar that represents them in VR. Interaction with objects in VR is a multisensory experience in which augmented feedback (visual, auditory, proprioceptive, etc.) is experienced by the user enabling a sense of realism.[49] Users undergo experiential learning by immersing in life-like virtual environments where physical interaction can be identical to the manner a person would interact with objects naturally in the real world.

Rehabilitation supplemented by immersive VR is an approach that has recently been explored in clinical settings, and studies have shown its advantages in improving the quality of recovery in SCI and stroke patients. VR is used as an enhancement to conventional therapy for patients with conditions ranging from musculoskeletal problems and stroke-induced paralysis to cognitive deficits.[9] It enables the possibility to train ADL in immersive virtual environments, as well as tasks that are unsafe to practice in the real world, such as overcoming obstacles, crossing streets,[45] and controlling vehicles. VR experiences are designed to enhance conventional rehabilitation therapy by providing a tool that delivers specific, intensive, and enjoyable activities for patients while providing feedback of performance.[31]

Recent studies on SCI and stroke rehabilitation have noted the benefits that VR and haptic feedback have provided in assisting neurorehabilitation.[49] Benefits include increase in motivation, improvements in the biopsychosocial status of patients, and encouraging neuroplasticity. These benefits will assist the recipient in realistically experiencing the sensations of being able to freely perform bodily functions.

Overview of motivation and biopsychosocial status of patients during virtual reality-augmented rehabilitation

Because VR experiences are generated using computer software (3D rendering software and game engines, etc.), an infinite number of scenarios, activities, and environments can be imagined and created. This advantage allows the creation of customized VR experiences that are suitable for the different learning styles of patients. When designing VR exercises for motor rehabilitation, the major points to consider are the preferences and expectations of the patients.[54] Providing experiences that will captivate the patient's attention is pivotal for retaining participation and increasing time spent on exercises, thus improving the overall quality of recovery.

Studies on VR-augmented rehabilitation in the clinical setting have shown that patient motivation and time spent performing exercises increased as a result of engaging with VR experiences. When compared to conventional rehabilitation, VR-augmented rehabilitation yields higher motivation during execution of assigned tasks due to the entertaining aspects of VR.[22] The motivating and enjoyable attributes of VR have been shown to increase the frequency of exercise activities performed by the patient, leading to improved function and optimal results from rehabilitation.[47]

In addition to improving patient motivation, VR-augmented rehabilitation has been noted to have effects on the biopsychosocial status of patients.[38] Patients undergoing rehabilitation exhibit symptoms such as stress, anxiety, pain, and boredom.[25,36] These symptoms have been shown to be reduced once patients were exposed to VR, resulting in improved rehabilitation outcome. According to patients, the immersive and interactive aspects of VR, the ability to perform activities beyond their means, and the novelty of the VR experiences eased anxiety, reduced pain through distraction, provided an "escape" from the boredom of residing in a hospital,[38] and led to improvements in neuropathic pain.[50] For the recipient of HEAVEN, VR is an essential tool for improving motivation, alleviating stress, and distracting from pain. These effects will result in more time spent performing rehabilitation activities, which would increase the preparedness of the recipient for life in a new body.

Overview of the effects of virtual reality and haptic feedback on neuroplasticity

In addition to psychological benefits, VR offers improvements in motor functions as well. Several studies have documented the impact of VR-augmented rehabilitation in improving motor functions of neurologically-impaired individuals. Corbetta *et al.* conducted a systematic review comparing the effects of VR-augmented rehabilitation on gait, mobility, and balance versus conventional rehabilitation therapy. The review investigated the results from 15 trials involving 341 participants who were clinically diagnosed with stroke. The review reported that VR training provided greater benefits in walking speed, balance, and mobility compared to non-VR rehabilitation.[18] Luque-Moreno *et al.* conducted a systematic review on comparing the effects of VR interventions on lower extremity rehabilitation of stroke patients. Although the 11 (n = 231) trials evaluated in this review reported heterogeneity in terms of study design and assessment tools, most studies found positive results on gait speed, balance, and motor function due to VR intervention.[34]

VR by itself offers the aforementioned benefits for patients during the rehabilitation process; however, when supplemented with haptic feedback (kinesthetic or tactile), it becomes capable of promoting neuroplasticity in addition to restoring motor functions. Neuroplasticity is defined as the ability of the nervous system to reorganize its structure, function, and connections in response to intrinsic or extrinsic stimuli,[19] and demonstrates the brain's ability to repair and learn after injuries.[4] Promoting neuroplasticity is beneficial for realistically replicating the feeling of normal voluntary motor functions. The extent of neuroplasticity development depends on the level of injury, postinjury care, and rehabilitative interventions. The occurrence of neuroplasticity can range from a few days to many years, depending on the abovementioned factors,[15] and occurs at several anatomical and physiological levels of the central nervous system (CNS).[10,27,41] The concept underlying VR-augmented rehabilitation as a treatment for neural dysfunctions is the stimulation of neuroplasticity by engaging the patient in multisensory training.[49] The multisensory aspect of VR-augmented rehabilitation activates the prefrontal, parietal cortical areas, and motor cortical networks, resulting in the reconstruction of neurons in the cerebral cortex.[53]

Providing multisensory training requires the use of VR and haptic feedback. Effectiveness of these two technologies in promoting neuroplasticity has been documented in the study by Donati *et al.* This study combined immersive VR training, visual-tactile feedback, and walking with EEG-controlled robotic actuators, including a custom-designed lower limb exoskeleton capable of delivering tactile feedback to patients. Chronic

SCI paraplegics (n = 8) participated in a 12-month long multistage BMI-based gait neurorehabilitation for the purpose of restoring locomotion. The training resulted in all patients experiencing improvements in somatic sensation, voluntary motor control, walking index, and half of the patients (n = 4) upgraded to an incomplete paraplegia classification. This study suggested that the implementation of tactile feedback played a key role in patient recovery and enhanced the ability of patients to exhibit plasticity during training.[24]

VR experiences with haptic feedback enables significant and relevant stimulation to the patient's CNS and promotes neuroplasticity. Combining VR experiences with haptic feedback realistically replicates the sensations involved in bodily movement and promotes neuroplastic recovery. Haptic feedback provides stimulation that facilitates the physiological activation of areas in the brain devoted to motor relearning.[29] With haptic feedback, interaction within the VR environment can be made to feel lifelike when coupled with different vibrations. When specific tasks are completed correctly, vibrations in the controller will accompany audiovisual feedback. For example, playing a game of baseball in VR using controllers with vibration feedback can replicate the feeling of playing baseball in reality. The controllers will serve the functions of a baseball bat, and when the user swings and hits a thrown ball in the VR experience, the controllers will vibrate to replicate the feedback of the bat making contact with the ball.

The combination of VR and haptic feedback will provide the best method for promoting neuroplasticity. In preparation for life after HEAVEN, having the recipient train with the combination of these technologies will provide the most realistic imitation of the sensations associated with normal body movement. Although the aim of this proposal is not for the purpose of rehabilitation, but rather preparation, promoting neuroplasticity will serve as a guideline and benchmark for successfully replicating natural body movements.

PROPOSED METHODOLOGY

Preoperative VR training for the recipient will take place several months before the HEAVEN procedure commences. The methodology for the training was formulated in response to the following points:

- Referring to exercises in conventional neurorehabilitation, what VR technologies and experiences will be useful for functional training?
- To provide the most realistic experience, which technologies will provide the most natural feedback in VR in response to an action performed by the user?
- Sufficiently familiarizing the user with bodily movement is crucial. Will the user remain engaged enough to spend an adequate amount of time training repetitive tasks in VR for three months?
- How will the user, a neurologically impaired individual, perform activities comfortably without causing pain or overstressing the body?
- How will progress be measured to ensure that the user is prepared for a new body?

The following solutions are proposed for resolving the points stated above:

Virtual reality technologies and experiences

The computer equipment required for this training will be a VR capable computer, computer peripherals, VR head-mounted display, position tracking sensors, and vibration feedback controllers. The VR experiences will be a combination of commercially available games as well as the creation of customized VR experiences that will include activities that emphasize functional training. Physical intensity of activities in the VR experiences will depend on the level of injury of the user. The following phases will be used as a guideline for training various functional skills:

Phase 1: Basic
- Flexion and extension
- Abduction and adduction
- Medial and lateral rotation
- Elevation and depression
- Pronation and supination
- Dorsiflexion and plantarflexion
- Opposition and reposition
- Walking.

Phase 2: Intermediate
- Increase walking speed, jogging, or running
- Interaction with objects (swinging motion, grabbing motion, throwing motion, etc.).

Phase 3: Intensive
- Action games (flight, vehicle racing, first-person shooter, etc.)
- Sports games (baseball, basketball, tennis, etc.)
- Reproductive function training.

Virtual reality capable computer and peripherals

It is essential to use a computer that is VR capable, i.e., the computer is capable of running VR experiences smoothly without causing a framerate lag, which can lead to disorientation and motion sickness. Guidelines for building a VR-Ready computer are widely available online.[16] The type of computer monitor, mouse, and keyboard are of no importance because they will only be used for initiating VR programs and experiences.

Virtual reality head-mounted display

Immersive VR hardware such as HTC Vive® and Oculus Rift® will be used for this proposal. Immersive VR offers the most realistic visualization of the VR environment

and will be ideal for providing the user with the most lifelike experience.

Technologies for performing actions in virtual reality

There are several commercial technologies that the user can use to interact with objects and to enable navigation within a virtual environment. The following products are suggested for use in the VR training – HTC's Vive® vibration feedback controllers or Oculus' Touch® can be used for hand movement tracking. Both of these controllers include triggers and buttons that enable interaction with the features of the VR experience. Using these controllers, the user will be able to interact with objects and interfaces in VR by performing natural hand and arm movements. The Virtuix Omni™ can be used for navigating VR using natural leg movements.[51] This technology is an omnidirectional movement platform that serves as a locomotion simulator. It is designed to allow a user to walk, run, and jump while remaining in one place. It functions as a controller and allows the user to navigate within the VR environment.

Maintaining user engagement

VR experiences are interactive and entertaining; however, repetition of the same tasks for a long period of time can lead to disengagement.[23,33,48] The addition of a scoring system and enabling online multiplayer will be beneficial for retaining user engagement. These features will motivate the user through competition and result in more time spent in training to improve upon skills. Having a scoring system will allow the user to compete with himself/herself and become more effective at performing a particular task. As the duration of the training progresses and the user continuously trains in VR, he/she will see improvements in scores over time, consequently increasing motivation to keep training. Online multiplayer has a similar effect in that it facilitates a competitive environment. Competition induces an increase in motivation and the user may want to improve his/her performance on a task.[17] The user will be motivated to outcompete other competitors in the online experience, and will therefore train more in VR to achieve that goal.

Progress tracking

The recipient will train in VR for 3 months before the CSA takes place. In addition, the intensity of the activities will be increased over time depending on progress results and readiness of the recipient. Progress can be tracked through improvements in game scores, surface electromyography (EMG) recordings, and observing and surveying the user. Improvements in scores will serve as an indicator of the user becoming more proficient at the tasks when scores are consistently rising. Surface EMG electrodes will be attached to the user's arms and legs for measurements on muscle electrical activity. Improvements in electrical potential generated by movements can translate to effective training. Observing the user and recording improvements such as increased time spent training and user movement appearing more natural can be indicators of effective training. The use of a survey or questionnaire regarding the user's comfort level, motivation level, and opinion on difficulty of the different experiences can also serve as a method for progress tracking.

Physical therapy gait frame

The neurologically impaired user will need assistance in maintaining a standing position while training. The IH-GAIT Frame Model provided by LL Corpus Cogere, Inc.[32] will safely support the user in a standing position and allow VR training. With the assistance of another individual, the user will be strapped into the body harness of the gait frame. The strap can be elevated or lowered depending on the specific needs of the user. The body harness of this gait frame will enable the user to maintain balance in a standing position and comfortably engage in VR training.

Reproductive function training

The fundamental purposes of HEAVEN are the extension and propagation of life.[12] Sexual reproduction is necessary for the creation of life and is a crucial subject to address with the recipient of HEAVEN. For the purpose of empowering and preparing the recipient for performing sexual intercourse in a new body, a sexually stimulating experience in a VR environment is proposed. This proposal's purpose is to achieve realistic preparatory training, therefore, it is critical to simulate scenarios for educating the recipient on sexual functioning and sexual health. Exposing the recipient to this experience will prepare him/her for future sexual encounters and prevent unpredictable psychological reactions.

To provide the recipient with a truly immersive experience of intercourse, the VR experience will be supplemented with artificial stimulation. Artificial stimulators will be used in tandem with the VR experience and provide the recipient with stimulation, which is in sync with the experience. Administering artificial stimulation will be achieved by electrostimulation. Several studies have noted the safe use of electrostimulation, via electrodes and probes, for sex rehabilitation in both male and female patients.[20,39,46] In males, electrically stimulating the parasympathetic efferents, afferent nerves, and nerves near the seminal vesicles can induce prolonged erections and seminal ejaculation.[20] For females, electrically stimulating the clitoris or internal areas surrounding the vagina can achieve orgasm.[3,52] The proper equipment for electrostimulation will need to be tested based on the preference and comfort of the user.

PROPOSED SCENARIO FOR PREOPERATIVE VIRTUAL REALITY TRAINING

The following serves as a possible scenario to give the reader a feel for the VR training [Figure 1].

HEAVEN recipient will be the user of the preoperative VR training. The setup for this method is presented in Figures 2, 3 and the demonstration video [Video 1]. The recipient will use the VR training for three months before the HEAVEN procedure begins. The user is encouraged to use VR training every day to maximize readiness for the new body. User's progress, such as improvement in scores, EMG recordings, and surveying the user's perspective on the experience, should be noted after each activity. An assistant will aid the patient in becoming accustomed to the body harness of the IH-GAIT Frame Model. The VR training routine will consist of three phases in which the difficulty of exercises increases. User will ease into the three-phase routine by beginning with experiences for training basic body movements in Phase 1. In this stage, the user will immerse in VR experiences where they will interact with objects and train basic motor functions. This phase should take approximately 3 weeks to complete. However, the user should only progress to the next phase once the exercises are completed without causing pain or discomfort. Activities in Phase 2 will build upon the foundational motor skills developed from the previous phase. The user will perform more advanced movements such as different speeds of walking, strength training movements, and more active interaction with objects in the VR environment. VR experiences in this phase will consist of navigation and exploration-based experiences, requiring more locomotive-based actions from the user. This stage of the routine should take 3 weeks to complete,

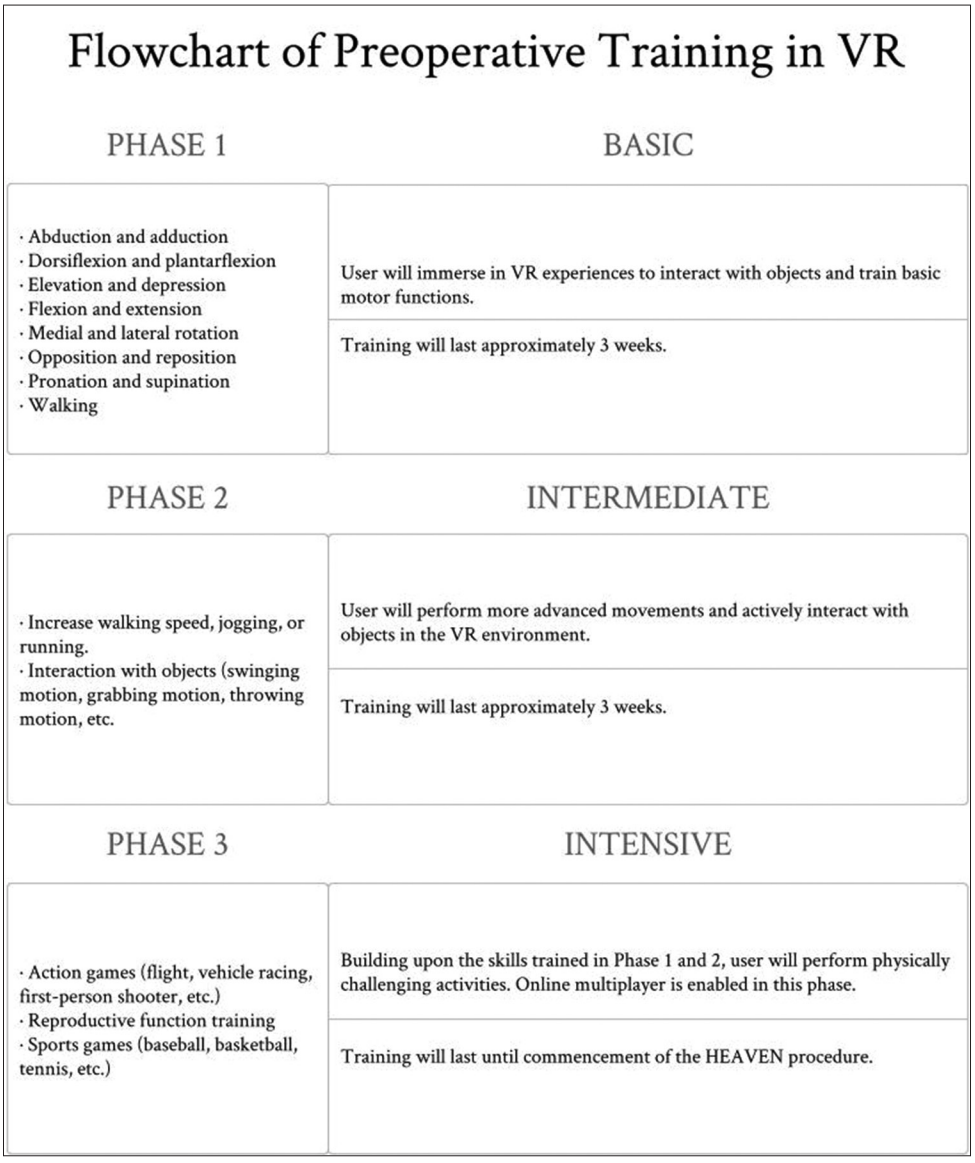

Figure 1: Flowchart illustrating the proposed schedule for the recipient to train in VR before the HEAVEN procedure begins

Figure 2: User will be strapped into the body harness of the IH-GAIT Frame Model to maintain a standing position. The user will wear either the Vive® or Rift® head-mounted displays. This setup allows upper-body interaction with the VR environment using either the Vive® vibration feedback controllers or Touch®

Figure 3: The user will be using either the Vive® or Rift® head-mounted display while strapped into the body harness of the IH-GAIT Frame Model. This setup allows both upper and lower-body interaction with the VR environment using either the Vive® vibration feedback controllers or Oculus Touch®, and the Virtuix Omni™ locomotion simulator

and progression to Phase 3 will be appropriate once the exercises of Phase 2 have been sufficiently practiced. Phase 3 includes intense activities such as action games, sports games, and a sexually stimulating experience. This phase will utilize the skills that were trained in Phases 1 and 2. Action and sports games will be the most physically challenging activities and online multiplayer will be enabled to encourage competition. For a sexually stimulating experience in VR, the user should participate in the experience as many times as they feel comfortable, but at least one time per week to be adequately prepared for future sexual encounters. Phase 3 will continue until the commencement of the HEAVEN procedure.

CONCLUSION

Immersive VR experiences supplemented with haptic feedback provide a new approach in neurorehabilitation; thus, different combinations of VR technologies, haptic feedback technologies, and other rehabilitation assisting-tools need to be tested. Further examination is needed to determine which combination of VR and haptic feedback technologies will be optimal for preoperative training for CSA due to the lack of literature that is currently available on this subject. It will be necessary to experiment with different technologies to determine the ideal combination for providing the most realistic imitation of natural movements and stimulations. Nonetheless, the methodology proposed in this literature should be sufficient in realistically replicating the sensations associated with bodily movement and appropriately preparing the recipient of HEAVEN.

The underlying concepts in this proposed methodology are beneficial for neurorehabilitation due to VR's ability to increase motivation, improve biopsychosocial status, and encourage neuroplasticity in SCI and stroke patients. However, it is important to recognize that rehabilitation is not the main goal of this proposal. The objective is to train the recipient of HEAVEN prior to cephalic exchange for the purpose of psychological preparation. Because motor memory and neuroplasticity is consolidated primarily within the CNS,[2,8,30] the memory of activities from the preparatory VR training will be retained after CSA is complete. The HEAVEN procedure transplants the head of the recipient onto the body of the brain dead organ donor (BDOD), hence the recipient's CNS and memory of VR training is maintained. The recipient will be capable of recalling the stored memory of performing the functional training exercises in VR, and will not be overwhelmed by the ability to move freely in the new body after CSA.

To conclude, the HEAVEN procedure is an endeavor that requires the readiness of not only the medical specialists, but also the recipient. It is absolutely necessary for the recipient to be prepared emotionally and psychologically. Properly preparing the recipient prior to CSA requires VR experiences accompanied with haptic feedback. The combination of these technologies will serve as protection against unexpected psychological reactions and successfully prepare the recipient for life after HEAVEN.

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