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Journal Title: Critical reviews in biomedical engineering

Volume: 44 **Issue:** 1
Month/Year: 2016 **Pages:** 1-32

Article Author: Piggott, L.

Article Title: Haptic Neurorehabilitation and Virtual Reality for Upper Limb Paralysis: A Review

Imprint:

ILLiad TN: 362683

ILL: -21027355

Call #: R856.A1 C5

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Critical Reviews™ in Biomedical Engineering, 44(1–2): 1–32 (2016)

Haptic Neurorehabilitation and Virtual Reality for Upper Limb Paralysis: A Review

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ABSTRACT: Motor and sensory loss or dysfunction affects the quality of life for thousands of individuals daily. The upper limb, and especially the hand, are important for a person's ability to complete activities of daily living. Traditional therapy methods focus on motor recovery, but future methods should include sensory recovery and should promote the use of the affected limb(s) at home. In this review, we highlight the current state-of-art robotic devices for the upper limb, and we discuss benefits of including haptic feedback and virtual reality environments during neurorehabilitation. Robotic devices, such as end-effector devices, grounded and ungrounded exoskeletons, have been developed to assist with various functions including individual finger, whole hand, and shoulder movements. Many robots highlighted in this paper are inexpensive and are small enough to be in a patient's home, or allow for telerehabilitation. Virtual reality creates safe environments for patients to practice motor movements and interactive games improve enjoyment of therapy. Haptic feedback creates more immersive virtual reality, and contributes to the recovery of sensory function. Physiological studies conducted after brain trauma and with robotic devices contribute to the understanding of brain plasticity, and illustrate the efficacy of these technologies. We conclude by addressing the future direction of neurorehabilitation research.

KEY WORDS: brain injury, haptic devices, exoskeleton devices, neurorehabilitation, robotics, virtual reality

ABBREVIATIONS: ACT, arm coordination training; **ADL**, activities of daily living; **ADLER**, activities of daily life robot; **AR**, augmented reality; **BCI**, brain-computer interface; **BiAS**, bilateral assessment system; **BPO**, body-powered orthosis; **CAHAI**, Chedoke Arm and Hand Activity; **DOF**, degrees of freedom; **EEG**, electroencephalogram; **EMG**, electromyogram; **FC**, functional connectivity; **FMA**, Fugl-Meyer Assessment; **fMRI**, functional magnetic resonance; **HEnRiE**, haptic environment for reaching and grasping exercises; **HWARD**, hand–wrist-assisting robotic device; **JHFT**, Jebsen Hand Function Test; **MRI**, magnetic resonance imaging; **MIME**, mirror-image motion enabler; **PET**, positron emission tomography; **PPD**, pneumatically powered device; **RGS**, rehabilitation gaming system; **RMII-ND**, Rutgers Master II-ND; **ROM**, range of motion; **TBI**, traumatic brain injury; **VR**, virtual reality; **WMFT**, Wolf Motor Function Test; **WREX**, Wilmington Robotic Exoskeleton

I. INTRODUCTION

According to the Christopher and Dana Reeve Foundation, roughly 6 million Americans are currently affected by motor dysfunction or paralysis.[1] Conventional rehabilitation includes drug prescriptions, occupational therapy, physical therapy, and massage therapy. However, there are limitations to these therapies, such as when and where they can be performed. Neurorehabilitation thus far has focused on the overall ability of performing activities of daily living (ADLs), which permit a patient to use the unaffected limb to complete a specific task and therefore, do not accurately reflect motor recovery of the affected limb.[2] Current research in neurorehabilitation is at an individual's level of motor and sensory recovery in the affected limb and incorporates assistive robotic devices. Taken together, novel technologies combined with traditional therapy will improve the efficacy of rehabilitation and patient quality of life; they are contributing to our understanding of how humans interact with their environment.[3] The scope of the present review is to elucidate the role of robotic devices, haptic feedback, and virtual reality for treating upper-limb paralysis. Previous reviews have focused on hand physiology and psychophysical properties for the usage of haptic devices[3] or have considered devices that only target the lower extremity.[4]

To understand how current research is improving neurorehabilitation efforts, we focus on upper-limb neurorehabilitation, which covers the upper arm, forearm, wrist, and fingers. Presented first are the causes of motor dysfunction and paralysis, motor and cognitive assessments used in research, and the most commonly studied patient groups. Discussed next are current and different types of robotic devices used in neurorehabilitation of the upper limb. Furthermore, the incorporation of virtual environments and tactile feedback is evaluated, and the paper concludes with suggested future directions in research.

A. Causes of Motor Dysfunction and Paralysis Related to the Nervous System

The leading cause of long-term disability in adults is stroke, which affects nearly 800,000 Americans per year.[5] Roughly 65% of stroke survivors experience hemiparesis and up to 85% of stroke patients experience somatosensory loss in their affected limb, which contributes to poor motor functioning.[2,3] Spinal cord injury, multiple sclerosis, cerebral palsy,[6] traumatic brain injury (TBI), post-polio syndrome,[7] and neurofibromatosis[8] comprise the next set of leading causes of motor paralysis. In addition, neurological conditions such as amyotrophic lateral sclerosis (ALS)[9] and focal dystonia[10] affect motor neurons and sensorimotor cortex, resulting in motor dysfunction. Due to the complexity of the nervous system, every individual is affected differently by these conditions, and damage to different regions within the brain contributes to a range of motor, sensory, and cognitive dysfunctions: uncoordinated movements, grip forces that are too weak or strong, problems with motor learning, and less than optimal recovery, among others.[2,11]

B. Motor and Cognitive Assessments Used in Neurorehabilitation Research

Motor, sensory, and cognitive assessments used to determine the best treatment for a patient in therapy are used in neurorehabilitation research.[12] These assessment tools are also used in conjunction with robotic devices to quantify limb function. The best set of tools for neurorehabilitation research focus on individual's functional recovery in the affected limb(s), including a motor and sensory assessment. Neurorehabilitation research uses cognitive assessments as an exclusion tool to reduce cognitive dysfunction as a confounding variable.

The most commonly used assessment of motor recovery is the Fugl-Meyer Assessment (FMA), which was designed for stroke patients.[12] With high reliability and validity, the FMA assesses both upper and lower limb recovery in these five areas: motor function, sensory function, balance, joint range of motion, and joint pain. Trained therapists are able to assess a patient in 30 minutes, resulting in a score between 0 (hemiplegic) and 100 (normal functioning). Another assessment tool of motor function in upper-limb paralysis is the Wolf Motor Function Test (WMFT), which was designed for stroke and TBI patients.[13] The WMFT uses a test with 17 items to assess performance time, functional ability, and strength. Scoring for each task ranges from 0 (participant is not attempting to move their arm) to 5 (arm movement appears to be normal).[14] To demonstrate motor recovery leading to competence in ADLs, the Barthel Index was developed. To target the performance of 10 ADLs in patients with motor disability, the Barthel Index assesses: feeding, bathing, grooming, dressing, bowel control, bladder control, toileting, chair transfers, ambulation, and stair climbing. These tasks are scored together on a scale from 0 to 100: a score of 0 indicates the inability to complete tasks without assistance, while a score of 100 indicates total independence.[15]

Functional recovery of hands is an important consideration for the ability to complete ADLs. The Block and Box Test (BBT) evaluates manual dexterity of upper-limb motor function.[14] A rectangular box is divided into two compartments, and the goal is to move as many blocks as possible from one compartment to the other within 1 minute. The number of moved blocks determines the level of manual dexterity. The Chedoke Arm and Hand Activity Inventory (CAHAI) identifies tasks needed for completing ADLs in patients following stroke.[16] It uses a 7-point scale to evaluate bilateral functional recovery; for example, a person who opened a jar without assistance receives a score of 7 and a score of 1 is given if the person required assistance. Similarly, Jebsen Hand Function Test (JHFT) assesses hand functions required for ADLs by having participants turn cards, pick up physical objects, write, and simulate feeding.[14] A researcher or clinician observes the completion time of each task up to a 120-second time limit; a lower score denotes a higher level of motor functioning.

Because virtual reality is most often implemented with a visual component, the Benton Visual Retention Test (BVRT) is used to assess visual perception and memory.[17] The BVRT uses four different forms of visual stimuli to determine a patient's visual abilities, and scoring is based on errors of omission, misplacements, and the number of correct

Reason for using haptic devices, it can analyse someone kinesthetic perception

responses. Unfortunately, effective tests of other senses, such as kinesthetic or tactile, have yet to be developed, which may prove to be essential for effective application of haptic technology.

Several tests of cognitive impairment are used to determine the level of brain function. For example, the Cognistat instrument (formally, the Neurobehavioral Cognitive Status Exam) measures major areas of cognitive function: orientation, attention, language, spatial skills, memory, constructions, and reasoning.[18] To determine the level of cognitive impairment, an index between 0 (no impairment) and 6 (strong dementia) is assigned. The Mini-Mental State Examination (MMSE) is used in clinical settings to evaluate mental deterioration in those suffering from Alzheimer's and dementia.[19] Test scores range from 0 to 7. A score of 1 classifies the patient as subjectively and objectively normal (i.e., stage 1), which indicates that the patient is capable of performing activities independently; stage 7 represents severe dementia where the individual requires complex forms of care to function every day. The Galveston Orientation and Amnesia Test (GOAT) is very similar to the MMSE.[20] The main difference between these two tests is that GOAT can be administered daily. When an individual scores 78 or more for 3 days, they are believed to not have amnesia. Language disturbance is measured by the Boston Naming Test (BNT), which requires the patient to name 60 items.[21] The Wechsler Adult Intelligence Scale-Revised (WAIS-R) measures six verbal and five performance tests related to memory, picture arrangement, vocabulary, and the assembly of objects.[22]

These tests are essential for quantifying patient recovery. Without assessments of motor recovery, it would not be possible to assess whether or not rehabilitation is effective. Furthermore, these tests allow for comparisons of different forms of therapy and help identify therapies that are better for certain types of motor dysfunctions.

C. Study Populations

Stroke is the leading cause of disability; thus, the majority of research populations consist of stroke patients. Table 1 summarizes the diverse group of patients with upper-limb dysfunction studied in neurorehabilitation research, nature of their upper-limb paralysis, type of tasks, and robotic device used. Many of the devices were tested on healthy individuals, which established a baseline of non-deficient functioning, to be compared with individuals with motor deficiencies.[23–32] Only eight studies[33–40] have included a healthy control group in addition to patients with upper-limb dysfunction. Additional population categories need to be included in the future to determine whether robotic rehabilitation is an effective therapy for a broader range of motor and sensory dysfunctions.

II. ROBOTIC DEVICES AND NEUROREHABILITATION

Robotic devices used for rehabilitation range from simple gloves to full-scale exoskeletons. They are usually divided into two categories: end-effector and exoskeleton devices. Exoskeletons can be further subdivided into ungrounded or grounded devices.[41] Although these categories are described separately in the following sections, they can be combined, i.e., gloves can be combined with an exoskeleton. Choosing the proper device and an appropriate task level is dependent on an individual's motor and sensory deficiencies. Table 2 summarizes various devices discussed in this review paper.

Progression of physiological changes starting with hyperactive reflexes (stronger and more responsive involuntary reactions), followed by increased muscle tone (greater tension in resting muscles), and ultimately leading to spasticity (increased muscle stiffness and involuntary contractions

A. Developing Rehabilitation Devices Based on Physiological Recovery

It is important to consider the physiology of recovery to attempt to restore proper functioning of the affected limb(s). Recovery begins with hyperactive reflexes followed by increased muscle tone and spasticity. Voluntary movement reemerging in stereotyped patterns of flexor/extensor synergies, and voluntary movement occurs before the normalization of muscle tone and reflexes.[12] The period of time which offers the greatest flexibility in neuroplasticity is the initial first 3 months after the loss of motor or sensory function.[6] Spontaneous recovery can occur within the initial 30 days, and by 6 months, the patient recovery plateaus (although it may occur at any stage of recovery).[42] While treatments should be given as soon as possible, it is suggested that study populations be taken from stroke patients who are 6 months post-recovery. The individuals who have shown the worst prognosis at this point may need further rehabilitation, and they may show the greatest effects of novel treatments.[1]

The most commonly affected limb is the hand, likely due to its numerous connections to the sen-

TABLE 1: Review of upper-limb neurorehabilitation studies, the haptic device and the type of assessment used when available

Reference	Population	Hemisphere Affected	Motor/Cognitive Deficiency	Task	Device Used	Assessments
Boian et al.[2]	Stroke	Right	Hand	ROM, Speed, Strength, & Fractionation	CyberGlove, RMII-ND	JHFT
Broeren et al.[4,7]	Contralateral Stroke	Left, Right	Wrist	Ball & Block	PHANToM	Purdue Pegboard, Dynamometer Hand Grip Strength, Upper Extremity Test, BBT, AMPS
Cameirao et al.[12]	Stroke	Left, Right	Upper Limb	Sphere grasping	RGS/GRAB/ARMEO	Barthel Index, Motricity Index, Modified Ashworth Scale, FMA, BBT, CAHAI
Dvorkin et al.[9]	TBI, Healthy		Upper Limb/Attention	Locationing spheres	PHANToM 3.0	
Finley et al.[5]	Stroke	Left, Right	Upper Limb	Reaching	MIT-Manus	WMFT, FMA, Motor Power Assessment
Frisoli et al.[9]	Stroke		Upper Limb	Grasp, Path fol-low-ing, & Reach	L-Exos	
Frisoli et al.[11]	Healthy		Arm	Object identification	PURE-FORM	
Guidali et al.[11]	Stroke, Healthy		Fingers	Grasp & Reach	ARMin	FMA
Hioki et al.[11]	Healthy		Upper Limb/Attention & Vision	Open Hand & Pinch Fingers	HIRO-III	
Jack et al.[1]	Stroke	Left	Hand	ROM, Speed, Strength, & Fractionation	CyberGolve, RMIII	Jebsen Test of Hand Function, FMA
Jarilla-Silva et al.[10]	Stroke	Left	Upper Limb/Attention	Maze Completion	PHANToM 1.0	
Johnson et al.[8]	Healthy		Upper Limb	Reaching and Grasping	Adler, Gentle/S, HapticMaster	
Krebs et al.[4]	Stroke		Upper Limb	Shoulder and Elbow Planar Therapy	MIT-Manus	
Larson et al.[11]	TBI		Upper Limb/Attention	Locating spheres	PHANToM	
Lonconsole et al.[13]	Healthy		Hand and Finger	Bilateral Grasping	BRAVO	

TABLE 1: (*continuted*)

Reference	Population	Hemisphere Affected	Motor/Cognitive Deficiency	Task	Device Used	Assessments
Loueriro et al.[1]	Hemiplegic	Left, Right	Upper Limb/Attention	Grasping and Reaching real and virtual objects	Gentle/S, Haptic-Master	
Loueriro et al.[9]	Stroke		Arm and Hand	Reach and Grasp	Gentle/G, Haptic-Master	FMA
Lum et al.[2]	Stroke		Arm	Reaching	MIME	FMA, Barthel Index, FIM
Luo et al.[5]	Stroke		Upper Limb	Grasp & Release	BPO, PPD	BBT, Rancho
Merians et al.[2]	Stroke	Left	Hand	ROM, Speed, Strength, & Fractionation	CyberGlove, RMII-ND	JHFT, FMA
Mihelj et al.[8]	Healthy		Upper Limb	Reach and Grasp	HenRiE, Haptic-Master	
Nagaraj, Constantinescu[9]	Healthy		Upper Limb	Pushing Cubes	Novint Falcon	
O'Malley et al.[6]	Stroke		Upper Limb	Reach	RiceWrist, MIME	
Podobnik et al.[9]	Stroke	Left	Right Limb	Pick and Place	HenRiE, Haptic-Master	
Reiner et al.[4]	Healthy			Ball and Block	PHANToM	
Rozario et al.[9]	Stroke		Upper Limb/Attention, Vision	Path Following	PHANToM, WREX	FMA, WMFT, Box and Blocks Test, Functional Ability Scale
Shadmehr et al.[97]	Healthy		Arm	Reaching	Manipulandum	
Stienen et al.[11]	Stroke		Arm	Reaching	ACT-4D	
Takahashi et al.[5,8]	Stroke	Left	Hand	Grasp and Release	HWARD	FMA, Box and Blocks Test, Action Research Arm Test
Viau et al., 04	Healthy, Unilateral Hemiparesis	Left	Right Arm	Grasp and Release	CyberGrasp	CAHAI
Volpe et al., 00	Stroke		Upper Limb	Drawing Targets	MIT-Manus	FMA, Muscle Power, Motor Status Scale

TABLE 2: Characteristics of haptic devices described in this review

Type of Device	Device Name	Targeted Limb	Haptic Sense	Force Feedback Workspace (mm)	DOF (Joints)	# of Sensors	N	Static / Dynamic Friction (Inertia (kg.m2)
End-Effector	Force Dimension Omega 7	Hand, Upper Limb	Kinesthetic	160 × 110	7			
End-Effector	PHANToM OMNI	Hand: Pivot at the Wrist	Kinesthetic	160W × 120H × 70D	6 (N/A)		3.3	0 to1 / 0 to 1
End-Effector	PHANToM Desktop	Hand: Pivot at the Wrist	Kinesthetic	160W × 120H × 120D	6 (N/A)		7.9	0 to1 / 0 to 1
End-Effector	PHANToM Premium 1.0	Hand: Pivot at the Wrist	Kinesthetic	254W × 187H × 127D	3 or 6 (N/A)		8.5	0 to1 / 0 to 1
End-Effector	PHANToM Premium 1.5	Lower Arm	Kinesthetic	381W × 267H × 191D	3 or 6 (N/A)		8.5/37.5	0 to1 / 0 to 1
End-Effector	PHANToM Premium 3.0	Full Arm	Kinesthetic	838W × 584H × 406D	3 or 6 (N/A)		22	0 to1 / 0 to 1
End-Effector	MIT-Manus	Full Arm	Kinesthetic		2-3 (N/A)	5	45-65	.02 to .29/.02 to 1.24 (nm) (.0031 to .0058)
End-Effector	Hopkins Manipulandum	Full Arm	Kinesthetic		2 (N/A)			.15 +/- .08 N/ 08 to .14 N
End-Effector	MIME	Full Arm	Kinesthetic		6 (N/A)	6		
End-Effector	GRAB	Fingers	Tactile/ Kinesthetic	300W × 400H × 600D	6 (N/A)			coefficient: .42 to 1.67
End-Effector	Novint Falcon	Lower Arm	Kinesthetic	101.6W × 101.6H × 101.6D	3 (N/A)			
End-Effector	HapticMaster	Arm	Kinesthetic	400W × 400H × 400D	3 (N/A)		100/250	0 (N/A)
Ungrounded Exoskeleton	CyberGlove II	Hand and Fingers	Kinesthetic	1 m spherical radius from actuator	6	18/22	1.2	
Ungrounded Exoskeleton	CyberGlove III	Hand and Fingers	Kinesthetic	1 m spherical radius from actuator	6	18/22	1.2	
Ungrounded Exoskeleton	CyberGrasp	Hand and Fingers	Kinesthetic	1 m spherical radius from actuator	6		1.2	
Ungrounded Exoskeleton	CyberForce	Hand and Fingers	Kinesthetic	304.8 × 304.8	6		8.8	
Ungrounded Exoskeleton	CyberTouch	Fingers	Tactile	76.2 × 115.57 × 26.42	6	2	1.2	

TABLE 2: (*continued*)

Type of Device	Device Name	Targeted Limb	Haptic Sense	Force Feedback Workspace (mm)	DOF (Joints)	# of Sensors	N	Static / Dynamic Friction (Inertia (kg.m2)
Ungrounded Exoskeleton	HenRiE Glove	Hand	Kinesthetic		3 (N/A)		90/100	
Ungrounded Exoskeleton	Rugters Master II-ND Glove	Hand	Kinesthetic	2 m radius hemisphere	5 (3)	4	16	
Ungrounded Exoskeleton	BPO/PPD	Hand	Kinesthetic		N/A (2)			
Ungrounded Exoskeleton	BRAVO	Hand	Kinesthetic		6 (5)	5		
Grounded Exoskeleton	PURE-FORM	Fingers	Kinesthetic / Tactile		6 (N/A)			
Grounded Exoskeleton	HIRO-III	Fingers	Kinesthetic	705 cm^3 (thumb), 587 cm^3 (other)	21 (21)	5	3.6	
Grounded Exoskeleton	HWARD	Wrist and Hand	Kinesthetic		3 (N/A)			
Grounded Exoskeleton	RiceWrist	Forearm and Wrist	Kinesthetic		4 (N/A)			.198 to .221 (.0048 to .0258)
Grounded Exoskeleton	MAHI Exo II	Wrist	Kinesthetic		5			.109 to .9491 (.002 to .2713)

sorimotor cortex.[43] The hand is responsible for the majority of haptic and tactile perceptions, and its complexity leads to fine motor movements.[3] The human hand has 21 degrees of freedom (DOF), 15 joints, and 29 skeletal muscles. The complexity of the hand also allows for a wide range of behaviors adapted to help with ADLs, which makes rehabilitation more difficult but essential for a fully functional lifestyle.[43] In fact, research finds that rehabilitation focusing on the distal portion of the limb leads to functional gains in the proximal limb, but not the other way around. Such an observation indicates that upper-limb rehabilitation necessarily should focus on functional recovery of the hand.

Rehabilitation should begin within the initial 3 months following a stroke to take advantage of critical periods of neuroplasticity.[6] In an fMRI study conducted by Ward et al.[44] on stroke patients, results showed an increase in motor area activation during the first couple of days after stroke. Intense widespread activation slowly decreased over the following months, suggesting that the best functional outcomes can be obtained the earlier therapy begins. Adamovich et al.,[6] state that recovery relies on learning new motor skills, and outcomes can be affected by the duration, intensity, and amount of therapy. Conceptually, neural plasticity and reorganization within the brain are dependent on use, and intensive practice promotes increased and speedy recovery. Therefore, constraint-induced therapy forces the patient to use their affected limb, potentially increasing motor function.[45] Repetitive task practice (RTP) is another therapeutically effective technique that is difficult to implement due to time and labor constraints.[43] Learned non-use (LNU) of the affected limb is a common problem in rehabilitation. When a patient returns home, there is often not enough support for continued use of the affected limb, and the patient then relies heavily on the unaffected limb. LNU is a problem when considering long-term functional recovery of the affected limb. Developing inexpensive robotic devices for in-home use that motivate a patient to comply with therapy may lead to better functional outcomes. Additionally, support for telerehabilitation may reduce costs of therapy by allowing a therapist to collect data, monitor a patient, and make adjustments without the expense of multiple visits in person.[46]

Shadmehr and Brashers-Krug[47] showed that learning and/or practicing one task before learning another produces an inhibitory effect on performance during the second task. When an individual had learned a first task, performance of the second task was better following an interval of 4–5 hours as opposed to no interval. Interval training of tasks may result in improved muscle memory and long-term
Can create and design a variety of tasks in VR using haptics
retention. However, Krakauer[42] reports that variable practice is more effective, leads to better retention than massed practice of one task (with no intervals or short intervals between successive tasks) and promotes generalization, even though performance is decreased. For example, in a reaching task, a cup is grabbed by participants and placed down in a different spot at varying speeds. The concept of interval training can still be applied when increasing or changing the task complexity. Following the earlier example, after training with the cup, an interval of at least 4 hours would be used before the patient begins training to pick up a spoon.

A number of technical requirements should be addressed when developing a robotic device for rehabilitation. Loureiro et al.[46] suggested a device that is reactive to the user's motions, provides support for a patient's full range of motion (ROM), and encourages motivation and compliance through positive feedback. Additionally, these devices should allow for the objective assessment of patient performance and progress. There is also a need to develop ambidextrous devices, or as suggested by Talvas et al.,[48] using two devices to allow bimanual exploration (i.e., with both hands). This would provide for a more natural interaction with the environment, and a larger working space for manipulating objects. Another consideration is how many DOF should be used in rehabilitation. More degrees of freedom lead to more complex and expensive devices, but evidence shows that therapies focusing on ADLs with increased degrees of freedom are more effective than single joint movement tasks.[34]

Passive, active, and interactive robotic systems respectively restrict movements to a specific path, actively move the patient's arm, or are adaptive to a patient's inputs for optimal assistance.[46] These different systems can be used to vary the task complexity, allowing the robot to first move the patient's arm and advancing in therapy to the point where a robot is providing force feedback to increase task difficulty and to promote muscle strength. By adapting how the robot works with the individual, natural recovery of motor function can be emulated. It is necessary to create devices that are easy to modify in order to fit individual arm lengths.[34] Furthermore, every individual has different capabilities and progresses through therapy at different rates; a more individualized therapy can result in device and training task choices that meet a patient's needs.[49] Participants can also be discouraged by failures in rehabilitation, and by creating error-free devices, or devices that incorporate force-feedback for constrained tasks, participants can learn more efficient strategies.[50–52]

B. End-Effector Devices

End-effector devices are usually grounded and afford a variety of interactions with a virtual or physical environment.[43] These devices vary from having two to six DOF, and they are usually used for grasping or strength tasks. Most end-effector devices are ambidextrous and require little adjustment between users. These devices can be paired with specific tools or ungrounded exoskeletons to increase the number of tasks that can be performed.

One of the most popular end-effector devices is the PHANToM manufactured by SensAble (currently Geomagic).[53] Using an impedance control paradigm, the user moves the device, and the device provides force feedback when an object is encountered.[54] The PHANToM Omni (Geomagic Touch), the most affordable of the series (see Fig. 1), is a six-DOF portable device that provides a force feedback workspace of 160 mm width × 120 mm height × 70 mm depth.[53] Similarly, the PHANToM Desktop (Geomagic Touch X) has six DOF with a larger workspace and provides higher continuous force (Fig. 1). Both PHANToMs target hand movements pivoting at the wrist. The premium versions 1.0, 1.5, and 3.0 have three DOF or six DOF of force feedback (Fig. 1). Premium 1.0 targets the hand and wrist with a workspace of 254 mm width × 178 mm height x 127 mm depth. Premium 1.5 provides a user with workspace of 381 mm width × 267 mm height × 191 mm depth that targets elbow and lower arm movements. Finally, Premium 3.0 can potentially rehabilitate upper-limb deficiencies by encompassing the entire arm in a workspace of 838 mm width × 584 mm height × 406 mm depth. The PHANToM has been used in several tasks such as the 3D Bricks game,[55,56] the block and ball task in TBI patients,[32] pursuit tasks designed to increase attention,[32,36,37,51] and maze navigation.[57] Jarilla-Silva et al.[57] presented a plausible method to measure learning performances related to kinesthetic memory in healthy subjects using PHANToM 1.0 in a maze navigation task. Rozario et al.[51] used a PHANToM 3.0 and WREX (grounded exoskeleton) gravity-balanced rest during a study task with two phases. Participants began phase one with or without error augmentation; the second phase did not have error augmentation. Participants who had error augmentation during phase one improved ROM faster than the other group, and they produced fewer errors during the second phase.

Another popular device is the Novint Falcon.[58] The design allows the incorporation of different removable grips such as a pistol or pen holder. The Novint Falcon is a three-DOF haptic device that was originally designed by Clavel[59] for the gaming industry (Fig. 2). With a 3D touch workspace of 101.6 × 101.6 × 101.6 mm, the arm of this device can extend, retract, and fold to measure displacement in space. The device also provides force feedback and vibrations. This is useful for multiple tasks commonly used in neurorehabilitation research.[23,24,58,59] Chortis et al.[60] are currently evaluating whether the Novint Falcon is safe for use in home therapy set-

FIG. 1: Geomagic haptic devices. Courtesy of 3D Systems, North Carolina.

Look at the references to the novint falcon

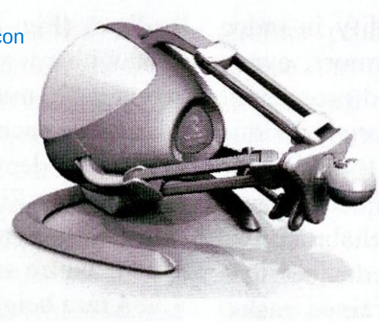

FIG. 2: Novint Falcon. Courtesy of Novint Technologies, New York.

tings. Participants are expected to complete pulling, pushing, reaching, and grasping exercises. Nagaraj et al.[23] used the Novint Falcon and vibration feedback in a virtual environment to record changes in muscular activity for healthy participants.

Similar in design and kinematics to the Novint Falcon, the Force Dimension Omega.7 is a seven-DOF haptic device that offers a three-dimensional (3D) active force feedback system for grasping through a bimanual workspace of 160 mm × 110 mm (Fig. 3). Omega.7 is commonly used in the medical and aerospace fields and has great potential for research pertaining to upper-limb paralysis.[61]

The PERCRO GRAB has two arms; the user places his or her fingers in a thimble.[62] The thimbles provide force feedback to the thumb and index finger, allowing for multiple points of contact in haptic exploration (Fig. 4). Each of the two arms has six DOF; they can be positioned in front of each other, allowing participants to interact and manipulate virtual objects in a large workspace (300 mm × 400 mm × 600 mm) with three DOF for position tracking and three DOF for finger orientation. This device was tested to ensure that there were comparable grip forces when interacting with real versus virtual objects. Frisoli et al.,[63] developed an algorithm for two-point-contact haptic devices that accounts for linear and rotational friction. They then tested this algorithm with the GRAB system. This device was tested with the rehabilitation gaming system (RGS) and compared alongside RGS alone as well as RGS with an exoskeleton.[64]

By imitating the movement of the non-affected limb, the mirror-image motion enabler (MIME) is used for the rehabilitation of the upper extremity.[46] The MIME provides the operator with six DOF, a unilateral or bimanual mode and three levels of resistance (passive, active-assisted, or constrained).[65] During the bilateral mode, mirror-image movements of the non-affected arm are sent to the ro-

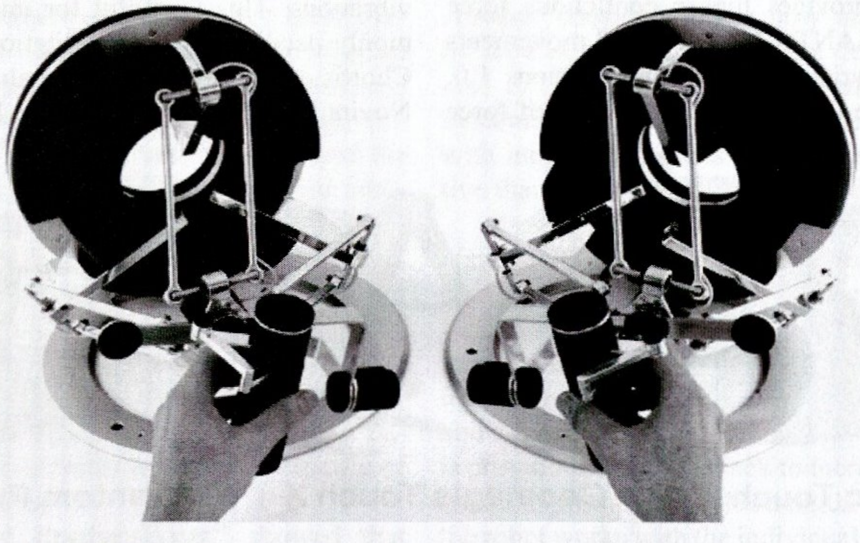

FIG. 3: Omega.7. Courtesy of Force Dimension, Switzerland.

FIG. 4: PERCRO GRAB. Courtesy of PERCRO LAB, Pisa, Italy.

bot to guide the movements of the affected forearm (Fig. 5). Tasks that involved MIME had participants engaged in reaching exercises by themselves (active), feeling the feedback of the movement they produced (constrained), and initiating the movement with help of the device (passive) in a physical environment. Another study by Lum et al.[66] placed participants in different groups to assess whether the bimanual, unilateral, or combination mode showed the most improvement. They found that the group with combined unilateral and bimanual tasks showed greater improvements than either unilateral or bimanual alone.

MIT-Manus was designed for safe and portable applications in clinical neurology.[68] It provides the user with kinesthetic information and, due to reduced friction and low near-isotropic inertia, the arm of the device can easily be moved (Fig. 6). The device encompasses four modules: the first is a planar module that targets the elbow and forearm of the affected limb with two DOF. The second planar module is found within the handle of the device, which provides three DOF for active wrist movements. Additionally, there is an active 1 DOF vertical module and a passive 1 DOF grasp module.[69] Several studies have used the MIT-Manus to research the benefits of robotic reha-

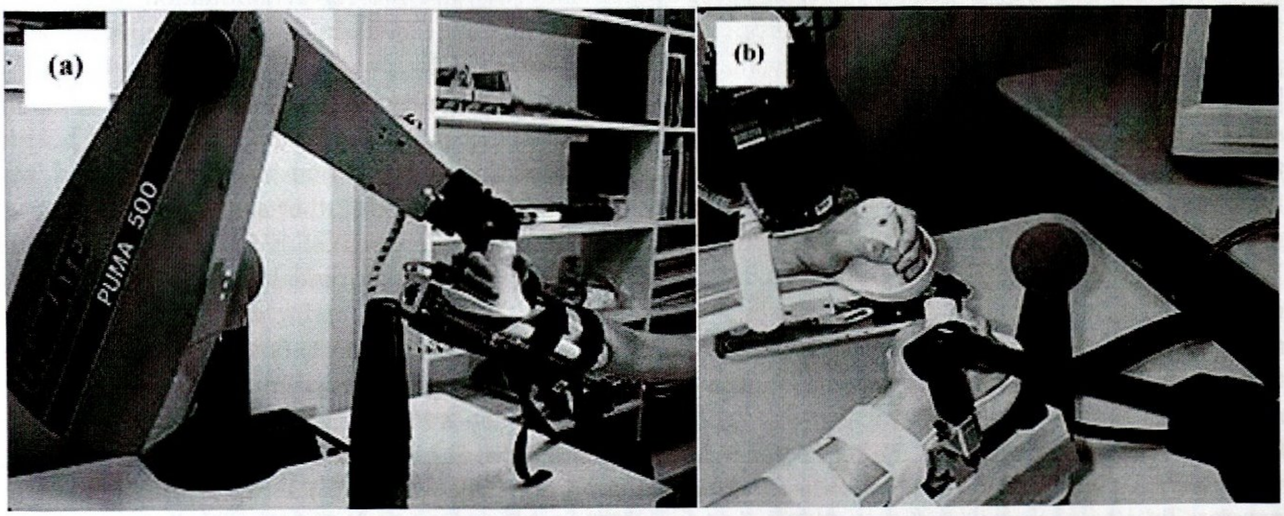

FIG. 5: MIME participant in (a) unilateral and (b) bilateral conditions. With permission from Jarillo Silva et al.[57]

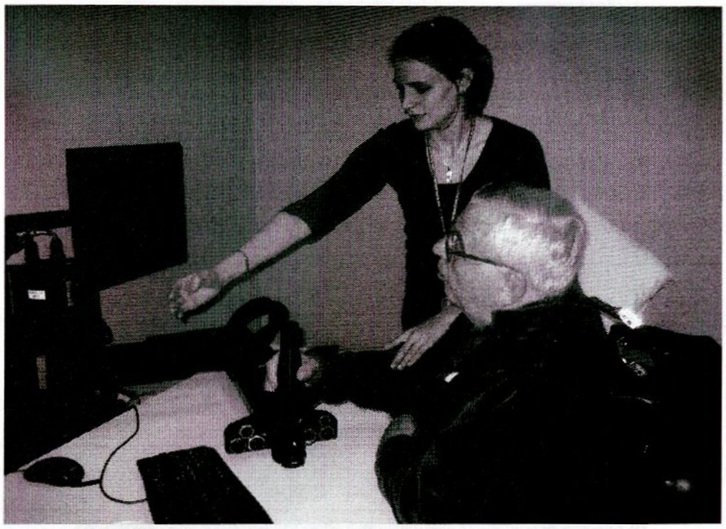

FIG. 6: MIT-Manus. Courtesy of Hermano Igo Krebs, MIT.

bilitation and the efficacy of the Mit-Manus.[70,71] In a study by Krebs et al.,[69] 250 stroke patients demonstrated improved scores with horizontal training that did not generalize to other muscle groups; this led to the development of vertical training for patients. The 9 patients tested reported no adverse effects or shoulder pain during the vertical training, and Krebs et al. plan to test this device on more patients. A device that is similar to the MIT-Manus is the Hopkins Manipulandum, a portable device with two DOF, designed for the rehabilitation of the shoulder and elbow joints.[72]

In contrast to impedance-controlled devices, the HapticMaster uses an admittance control paradigm.[73] This paradigm consists of the user applying force to the device and the device reacting with proper displacement. Admittance control has the advantage of being lightweight and backlash free, allowing for smooth natural movements. The HapticMaster has three DOF, making it possible to measure joint velocities of the hand within a vertical range of .40 m and a pivot of 1 full radian (Fig. 7). However, Verschuren et al.[54] suggested that a major limitation of this device is its generated friction, which creates a non-realistic environment, especially in a task that requires motion with changes in direction. To address this limitation, several friction-free models have been proposed to reduce the bump-feeling effect felt by the user. When the HapticMaster is compared with other commercially available devices, it excels in the areas of force, force depth, position resolution, haptic resolution, and stiffness. These traits make this device beneficial for applications in virtual reality, haptic research, and rehabilitation.[73] HapticMaster can be enhanced with a number of accessories for different rehabilitation applications.

One of the devices combined with HapticMaster is the activities of daily life robot (ADLER). In ADLER environments, functional hand movement tasks were designed to allow the patient to manipulate real and virtual objects.[26] A bilateral assessment system (BiAS) measures left and right arm movements before, during, and after ADLER tasks.[74] BiAS has the advantage of being low cost, making it a viable option for in-home therapies. The efficacy of ADLER for rehabilitation was tested in two studies; however, only healthy participants were used.[25,26] BiAS was tested with both healthy and stroke participants, which revealed the system's ability to measure wrist kinematics.[74] It also helped with functional recovery in 4 stroke patients. Johnson et al.[74] suggested further studies with more participants and an average of ≥36 hours of therapy.

The HapticMaster and a biodex experimental chair were combined to create the arm coordination training 3D (ACT-3D) device.[75] Together, these devices have six DOF and can measure specific impairments by manipulating gravitational forces, all within a workspace of 400 × 400 × 400 mm. The second-generation ACT-4D adds an elbow rotation mechanism with 4 DOF to the ACT-3D.[76] The ACT-4D system affords horizontal movement, and combining it with HapticMaster allows the arm to move vertically. This enables reaching tasks involving shoulder abduction and stretching of the elbow. ACT-4D can provide performance feedback through a 16-channel electromyelogram (EMG), which records muscle activity. HapticMaster uses an admittance control paradigm, and ACT-4D allows one to select between admittance or direct controls. In this way, the position and speed are defined by predefined profiles or by user output (admittance control).

HapticMaster was also used to create the Gentle/S and Gentle/G haptic devices.[77] The Gentle/S has three DOF and was developed for reaching tasks in therapy by combining virtual reality, haptics, and repetitive rehabilitation. It can be used in a variety of tasks aimed at error-free learning, increasing attention and motivation while providing visual and force feedback.[78] In comparison, Gentle/G has an added robotic exoskeleton for grasp and nine DOF, allowing a greater range of arm and hand movements. The device is capable of adjusting to different hand sizes and can be easily attached and detached.[79] The device has been designed with different modes (passive, active assisted, and active) and can be used in a variety of exercises. Loureiro et al.[78,80] have conducted studies with Gentle/G and Gentle/S to test their efficacy in rehabilitation. Their results indicate that robot-mediated therapy produced higher patient motivation to participate in therapy and greater functional recovery over conventional therapy.

C. Ungrounded Exoskeleton Devices

Devices that are not attached to an external frame of reference are described as ungrounded; exoskeletons are usually full-scale robotic devices that can support the entire arm and hand. The ungrounded exoskeleton devices discussed in this section focus on specific functions of the hand. They can be combined with grounded end effectors to target the entire arm and increase the ranges of motion available for rehabilitation. They have the advantage of encompassing fingers and are not limited to the wrist, like many end-effector devices. However, they only focus on motor functions relating to the hand and do not target the entire upper limb, and they are unable to emulate the mass and weight of virtual objects.[79]

Two popular devices for interacting with virtual objects using haptic glove technologies are the CyberGlove II and III.[81] Both gloves encompass the entire hand and have the option of 18 or 22 sensors capable of capturing full motion data at 90, 100, or 120 records per second (Fig. 7). CyberGlove III has the added advantage of Wifi connections up to 100 ft, which offers a larger workspace and increased maneuverability. While both CyberGloves can be integrated in virtual environments, they do not provide tactile feedback necessary for object manipulation. The CyberTouch attachment for the CyberGlove has 6 vibrotactile stimulators on the palm and fingers that are fully programmable for strength up to 1.2N and can create pulse or sustained vibration sensations to emulate different textures. To create realistic interactions with virtual objects, the exoskeleton attachment CyberGrasp was developed. Cybergrasp provides force feedback with five adjustable actuators that produce a force of up to 12N to each finger (Fig. 7). The device has a usable workspace of 1 meter within a circular radius and can be made portable by placing the actuator module in a GraspPack backpack. Finally, a grounded force-feedback armature called Cyberforce was designed to work with the CyberGlove Systems. CyberForce supports the entire arm, has the option of a left-, right-, or dual-handed version and a workspace of 304.8 mm × 304.8 mm (Fig. 8). It provides six DOF, and a force of up to 8.8N, allowing the user to fully interact with virtual objects by resting their hand on an object, picking it up with a feeling of weight, and feeling resistance when meeting a virtual wall. Subramanian et al.[38] investigated the kinematics of arm movements in stroke patients and healthy controls completing a virtual elevator task with a 22-sensor CyberGlove. In another study, Viau et al.[39] used the CyberGlove and CyberGrasp to compare how individuals pick up and grasp objects in a real versus a virtual setting. Both studies found that participants made similar movements in virtual reality and the physical environment.

An exoskeleton glove, Rutgers Master II-ND (RMII-ND), has been compared to and used in conjunction with CyberGlove and CyberGrasp. Even though the RMII-ND and CyberGrasp systems are fairly similar in terms of their capabilities, their designs are quite different.[82] For instance, the actuators of the RMII-ND are placed on the palmar side of the fingers and produce up to 16N; this hinders full closing of the hand, but in return, RMII-ND can produce opposing forces during training tasks.[83] RMII-

FIG. 7: HapticMaster. Courtesy of Moog Inc, Rochester, New York.

ND has five DOF, reduced friction, and is lighter than the CyberGrasp, which helps to create realistic interactions in virtual reality.[82] The infrared sensors that are a part of the RMII-ND actuators update at 435 records per second and measure fingertip displacement for flexion and abduction/adduction. Jack et al.,[83] Boian et al.,[84] and Merians et al.,[85] tested a combination of RMII-ND and CyberGrasp for their efficacy in grip strength training, measurements of ROM, and finger fractionation. A majority of participants studied demonstrated improved function as measured by the Jebsen Hand Function Test (JHFT).

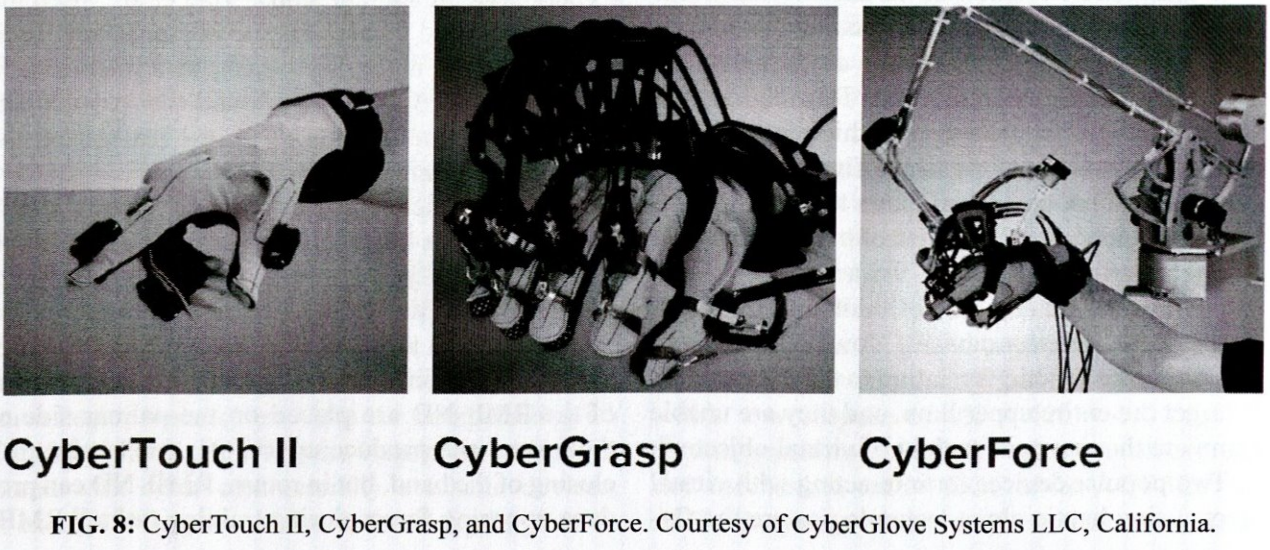

FIG. 8: CyberTouch II, CyberGrasp, and CyberForce. Courtesy of CyberGlove Systems LLC, California.

A prototype glove device that is making its way into the realm of neurorehabilitation and haptic research is HEnRiE (haptic environment for reaching and grasping exercises).[33] The device is composed of multiple parts including a HapticMaster grounded end-effector device, a grasping device, and a mechanism for gravity compensation and wrist connection (Fig. 9). Another benefit for rehabilitation is the device's 3D visualization system for immersive virtual reality. The device also incorporates virtual therapist software capable of providing guidance that is traditionally given by a therapist.[86] The device has three DOF and was designed for grasping tasks and training both proximal and distal arm movements.[33] There are two single axis cells positioned at each finger that measure finger force up to 90N during extension and flexion. HEnRiE was tested with 3 patients[33,86] to evaluate its efficacy. Subjects picked up a virtual apple, moved it, and dropped it at a new location while the device recorded grasp strength and arm trajectory. All 3 patients were able to significantly improve maximum grasp force from the first session to the last; deviations in arm trajectory based on a predefined path decreased and became stable after therapy.

Luo et al.[87] aimed to create a device that addressed the limitations of the RMII-ND and CyberGrasp. The CyberGrasp system can be both heavy and expensive, making it inaccessible to some individuals and for use in therapy; RMII-ND uses a non-stereo screen that creates a fish-tank virtual reality, whereas the Cybergrasp system uses augmented reality (AR), allowing the user to see his or her hand in a panoramic space. Two devices for finger extension, the body-powered orthosis (BPO), and the pneumatic-powered device (PPD), were created to be lightweight, compatible with AR, and reactive to the user, while the therapist is able to monitor and control the visual, audio, and haptic feedback. The BPO is affixed to the shoulder and is connected to the dorsal side of the hand by cables, and the user is able to modify the amount of assistance in finger extension with their upper-arm movements. The PPD uses an air balloon located on the palmar side of the hand that inflates and deflates to assist finger extension. A preliminary study compared the use of AR-PPD, AR-BPO, and ARonly for subjects recovering from stroke. When comparing participant's improvements on the block-and-box test, they found that AR-BPO participants had the greatest improvements.

D. Grounded Exoskeleton Devices

Robotic devices that have an external mechanism attaching them to a surface are referred to as grounded.

FIG. 9: HEnRiE. Courtesy of Matjaz Mihelj.

They have the advantage of being adaptable in terms of fit, length, and comfort.[88] The customization of grounded robotic devices facilitates task completion, a feature often missing in end-effector devices and ungrounded exoskeletons. Grounded exoskeletons are highly effective in the rehabilitation of upper-limb paralysis because they target and support the whole arm including the hand, and they can be applied to multiple joints. This flexibility allows researchers to investigate the rehabilitation of gross and fine motor control, as well as a larger ROM. These devices produce more force, and they have higher DOFs and larger workspaces than ungrounded exoskeletons. However, their cost, size, and maintenance prevent their use in an in-home setting requiring the patient to travel for therapy sessions.

The hand–wrist-assisting robotic device, HWARD, is a three-DOF robotic device capable of a wide ROM for flexion and extension of the fingers, thumb, and wrist.[89] The device can be adjusted for different hand sizes and is attached to the dorsal side, freeing the palmer side for tactile sensations of real objects. Another advantage of this device for therapy is being back drivable, which means it can be moved in a passive state with minimal friction. The user's hand motions are not restricted, and the device can be used to measure the kinematics of arm movement. HWARD is capable of producing a force up to 122.8N; however, this force is regulated to 4–15N. In addition to the regulation of air pressure for safety, the device also prevents hyperextension, and there are emergency shutdown features. When using HWARD, stroke patients increased the range of grasp and pinching motions in their affected hand and wrist.[90]

PERCRO L-Exos, light exoskeleton, affords a full ROM for healthy patients, and multiple joint configurations allow for compensatory patterns in stroke patients.[49] It has a total of five DOF, four of which are actuated and provide information regarding arm location; the fifth passive DOF allows free wrist movements (Fig. 10). While the device can be easily removed and adjusted for different users, it was developed only for the right hand. The L-Exos system is integrated with a flat VR display and three different virtual scenarios (for additional details see Frisoli et al.).[91] To demonstrate the effectiveness of L-Exos and its potential use in a clinical rehabilitation setting, participants completed virtual reaching, object manipulation, or path following tasks[49,91] and were able to increase reaching motions while decreasing completion times by 50–70%.[49]

Loconsole et al.[92] combined an ungrounded exoskeleton orthotic glove with the L-Exos to create the BRAVO system. The BRAVO system was then tested with EMG placed on the unaffected and affected limbs for bilateral training of grasp (Fig. 11). Task instructions were to grip an object with the non-affected

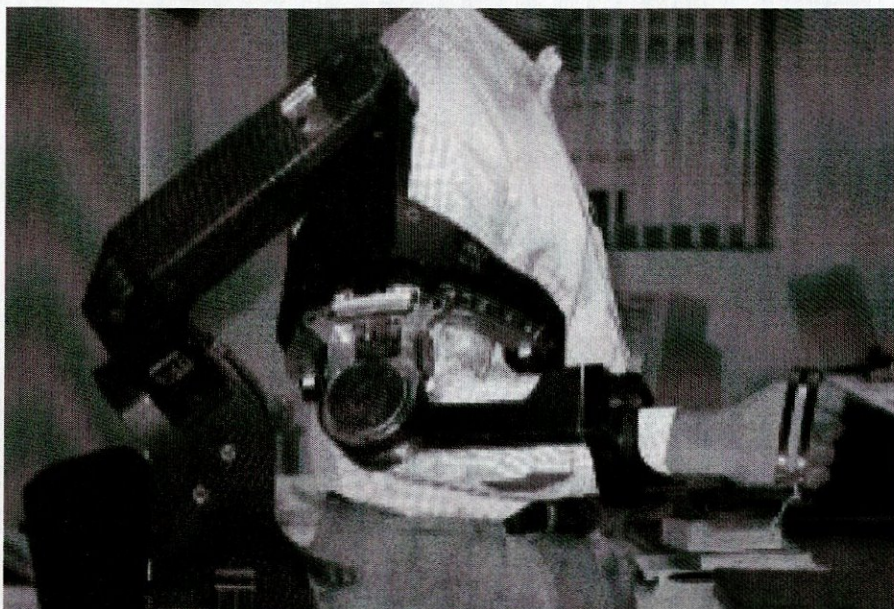

FIG. 10: L-Exos. Courtesy of PERCRO LAB, Pisa, Italy.

limb; the force produced would then be transferred to the affected limb to generate a similar grasp. In another experiment by Loconsole et al.,[93] the L-Exos was combined with an eye-tracking device. They found that eye tracking could be useful for rehabilitation. Future research could include manipulating real objects, and a device that affords grasping.

ARMin is a six-DOF (four active, two passive) grounded semi-exoskeleton that targets the rehabilitation of the entire arm.[35] Placed in an orthotic shell, ARMin can be used interchangeably between the right and left limbs, allowing for the rehabilitation of either limb (Fig. 12). It can also be custom fitted to individual users by adjusting the arm length and available ROM. Moreover, a person can voluntarily move their arm to a specific target without any assistance or can be guided by ARMin when movement is not detected. ARMin

FIG. 11: BRAVO. Courtesy of PERCRO LAB, Pisa, Italy.

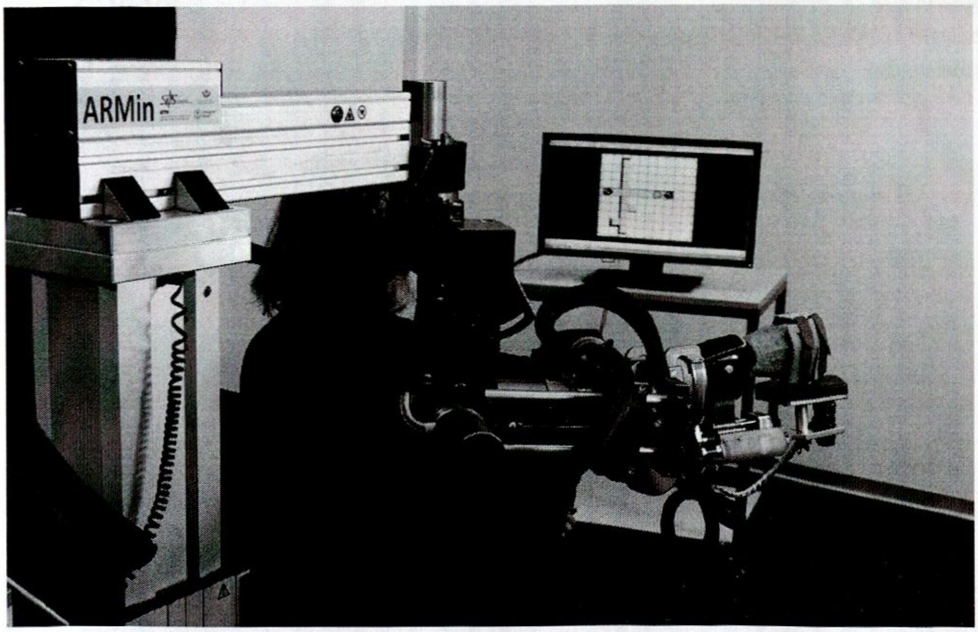

FIG. 12: ARMin. Courtesy of Dietmer Heinz.

has been used in multiple studies with virtual ADL tasks.[34,35]

The second-generation exoskeleton, MAHI Exo II, developed by Rice University, has five joints (five DOF), one for the forearm, the elbow, and three at the wrist.[94] Its workspace is almost identical to an average healthy person's full ROM due to the revolute joints and a 3 revolute-prismatic-spherical (RPS) platform for the wrist.[95] The MAHI Exo II includes design changes that allow the device to be worn on the left or right arm. It also accommodates varying hand sizes and disability with two attachment options, as well as adjustable straps to fit bicep size.[27] Three therapeutic modes passive, triggered, and active-constrained contribute to further individualized therapy. With the incorporation of haptic feedback a more immersive VR experience is created.[94] The MAHI Exo II was tested in a case study with one stroke patient to test levels of pain, fatigue, and subsequent improvement in muscle function. No increases in pain or discomfort were reported, and increased fatigue did not result in missed sessions. Furthermore, the participant showed improvements in hand function based on the JHFT, the Action Research Arm Test (ARAT), and the American Spinal Cord Injury Association (ASIA) motor score.

When the wrist structure of MAHI Exo II is combined with MIME (end-effector device) it forms the RiceWrist, a grounded haptic exoskeleton.[88] Designed to improve hand function by targeting the wrist, forearm, and elbow joint angles, the RPS platform and forearm joints, along with the inverse kinematics, allow the user to reproduce natural movements.[28] It is possible to control the force feedback provided by RiceWrist, and it can be integrated with VR environments to enhance rehabilitation. Research aimed at enhancing the efficacy of RiceWrist, studying motor learning, and developing better therapy techniques is still in progress.[88]

A six-DOF haptic exoskeleton device designed to deliver force feedback to thumb and index fingers is the PURE-FORM.[96] This device is similar to GRAB, also developed by PERCRO, because it has two points of contact for haptic feedback (Fig. 13). However, PURE-FORM is connected to the forearm, and an external grounding device helps to reduce weight, provide force for haptic feedback, and record data on the position of the arm. PURE-FORM has been used in tasks to explore objects, shapes, and their orientation.[29,30] Interestingly, this device is being used in a virtual museum project to explore 3D art and sculptures using haptic feedback.[97]

In contrast to GRAB and PURE-FORM's two points of contact, the HIRO-III, is a five-fingered haptic device.[98] The device is also placed on a table in front of the hand and connects to the fingers through passive magnetic joints, as opposed to being behind the hand (Fig. 14). The passive magnetic

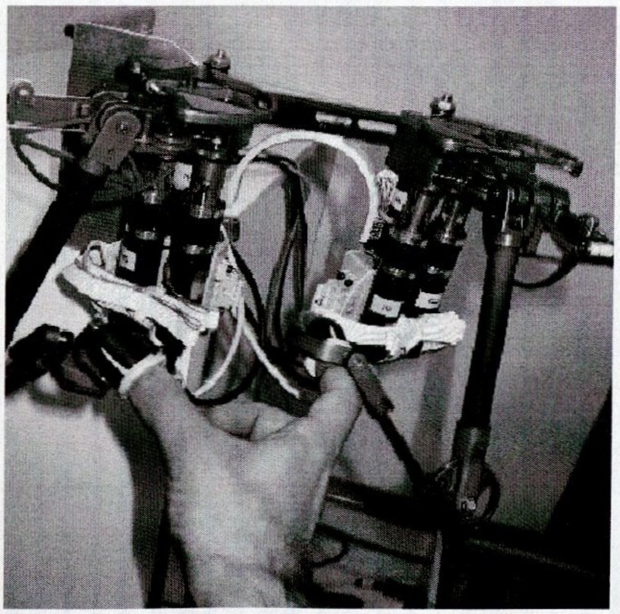

FIG. 13: PURE-FORM. Courtesy of PERCRO LAB, Pisa, Italy.

joints allow the fingers to be oriented in a number of ways without losing connection to the device. Each finger has three actuated motors and three DOF for a total of 1five DOF, which allows three-directional force up to 3.6N for all fingers, as well as finger flexion/extension and adduction/abduction.[31] HIRO-III has an arm interface with six DOF, and motors to provide force over 56N (non-continuously).[98] The arm interface provides additional working space and the ability to train shoulder adduction/abduction, internal/external rotation, and flexion/extension. Both the fingers and hand motors provide force feedback for resistive training. Sensors in the fingers record hand position and force produced. Research by Endo et al. evaluated HIRO-III's performance capabilities in the realms of force application, motion, and manipulation in virtual reality environments. Another study using HIRO-III evaluated the use of biofeedback with sEMG where the patient's intent helped in hand-opening and finger-pinching tasks.[31]

A unique non-robotic device called WREX (Wilmington Robotic Exoskeleton) is a passive antigravity arm orthosis.[99] It has five DOF, supports natural movements throughout a majority of a normal ROM, and can be moved while turned off. Its initial design was to help children with weakened arms to perform ADLs. However, the device cannot provide grip training or haptic feedback. Rozario et al.[51] combined the device with the PHANToM (end-effector device) to study rehabilitation of arm function and found that a majority of participants had improved ROM. Sanchez et al.[99] modified the device to create the T-WREX for adult patients, giving it the ability to sense arm position. They also developed a grip sensor and virtual reality software for therapy to be used in conjunction with T-WREX. With adjustments, the device can be used on either the left or right arm. A study with T-WREX was able to improve arm motions in stroke populations because of the added anti-gravity support.

III. VIRTUAL REALITY AND HAPTIC FEEDBACK IN NEUROREHABILITATION

A. Virtual Reality

Virtual reality (VR) environments allow for individualized settings that can create adaptive, intensive, and repetitive training.[6] There are different ways to present visual information through VR, such as non-immersive 2D representations, semi-immersive 3D stereoscopic displays with a fixed perspective, or fully immersive VR environments. These displayes change perspective with head movements. VR rehabilitation is capable of creating quantifiable measures of improvement that are more efficient and accurate than human measurements.[100] VR is also capable of creating a safer and enriched environment for practicing ADLs.[101] For example, if a patient has an attention deficit for sounds or objects in their periphery, VR can create a scenario to strengthen these deficits without the risk of falling or other harm.[102] Due to these advantages, VR training can be beneficial not only to stroke patients but also to individuals suffering from motor dysfunction

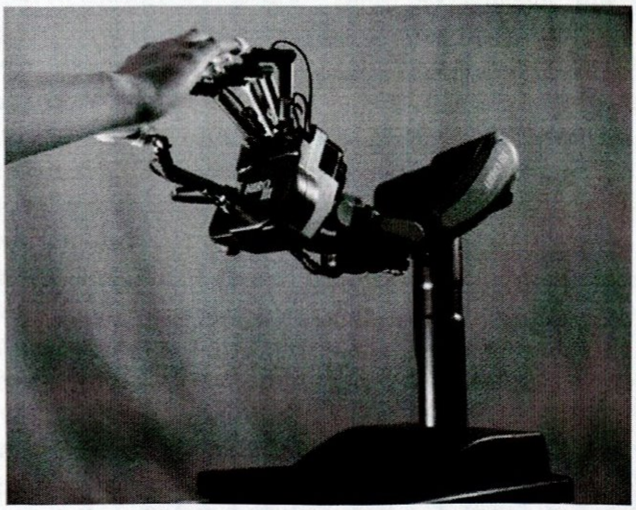

FIG. 14: HIRO-III. Courtesy of Kawasaki & Mouri Laboratory, Gifu University.

due to Parkinson's disease,[102] cerebral palsy, spinal cord injury,[103] or multiple sclerosis.

Adamovich et al.[6] compared traditional therapy to one that includes VR and found that participants in the VR conditions performed better, retained effects of therapy longer, showed higher compliance rates, and reported greater enjoyment of therapy. The use of interactive games in VR that provide performance feedback is especially beneficial for children with musculoskeletal disorders. In one study, children with cerebral palsy were required to perform a number of ankle exercises; the children in the VR condition held stretched poses for longer with greater ROM than those receiving conventional therapy. Participants also preferred virtual environments that were more realistic but not so cluttered that they inhibit task performance.[78]

A VR training system was created by Adamovich et al.[100] for improving hand function. Four simple videogames were developed to practice ROM, movement speed, finger fractionation, and finger strength. All provided frequent feedback on user performance and stored these data for later analysis. A target-setting algorithm was used to increase task difficulty based on a patient's previous performance. Another benefit of this system is its implications for objective telerehabilitation. A therapist can monitor multiple patients, their performance, and obtain a 3D representation of each patient's hand through a web-based therapy program. Every patient tested with this system had improved performance on all four videogames; however, it is necessary to test whether improvement generalizes to ADLs. Notably, Adamovich et al.,[6,100] did find that VR training generalized to improved performance of ADLs based on the Jebsen Hand Function Test (JHFT). Increased performance was also seen in measures of spatial neglect through improved spatial navigation and attention.[6]

Debate continues over whether or not brain activation while watching a virtual task is comparable to watching it performed in real life.[6] August et al.[104] found in a pilot case study that their participant showed increased brain activity performing hand movements while watching a realistic hand versus a similarly sized shape in a virtual environment. While watching a virtual hand perform a task may not produce much brain activation, participating in the same task does seem to produce greater activation.[6] Improved VR technology may allow for more immersive environments and replicate real-life settings for improved neural activation.[105] Thus, one can surmise that the art of implementing a VR environment is just as important as the science behind it.

Although VR is gaining acceptance in neurorehabilitation, participants may perform differently in VR settings versus real-life. However, there is strong evidence that the kinematics of movement in VR are similar to those made in real life.[6] Both healthy patients and those with stroke were found to make similar movements with regard to time taken to complete a movement, path trajectory during task completion, peak velocity, and maximum grip. Some studies comparing healthy and disabled participants found that movements were similar in both physical and virtual environments.[38,39] However, both groups of participants did not perform as well during a VR paradigm, likely due to the lack of haptic feedback.

B. Haptic Feedback

The objective of including haptic feedback during neurorehabilitation is to allow participants to train kinesthetic, proprioceptive, and cutaneous senses. The kinesthetic/proprioceptive senses include knowing how one is physically positioned and where one might be moving.[3] The cutaneous (or tactile) sense provides information regarding pressure, vibration, friction, and temperature. These different aspects of haptic feedback are used in grasping an object, determining grip strength, texture discrimination, identification of sticky or slippery objects, and sensations of warmth or cold.[106] Stereognosis is the active process of haptic exploration, combining the senses for fine motor control, and the ability to determine the properties of an object.[3] To incorporate and utilize stereognosis in VR, there must be a minimum number of contact points for certain sensations. One point of contact works for the perception of material hardness, but at least two points of contact are necessary for the manipulation of virtual objects;[62] the performance of temperature perception is greatly improved with three fingers.[107] However, some participants still had difficulty identifying virtual objects due to missing haptic feedback on their other fingers.[28] Indeed, haptic senses are important for engaging with and manipulating one's environment, and it follows that complete rehabilitation should include sensory restoration as a goal. Ziat and Bensmaia[108] have recently reviewed current neuroprosthetics designed to provide sensory stimulation or that use brain signals to control external devices.

Haptic feedback is necessary for interacting with physical objects, and inclusion of haptics in VR environments improves one's feeling of agency in the virtual environment.[6] When pressure is provided to the volar pad of the thumb and index finger, participants reported the perception of holding an object.[3] Such perception can be exploited for rehabilitation in VR environments by allowing a patient to practice reaching, grasping, and lifting an object.[6] Haptic feedback can also be used to provide the sensation of colliding with physical objects in VR environments, such as the table upon which a cup is placed. By incorporating haptic feedback into a virtual reality environment, participants performed faster and with more precision. Another way to use haptic feedback to improve rehabilitation is through active constraint.[109] When participants used the mirror-image motion enabler (MIME) in an active constraint mode, they had greater improvements in ROM over the participants whose movements were not constrained.

Using PURE-FORM, Frisoli et al.[30] compared the use of kinesthetic feedback, cutaneous feedback, and combined kinesthetic-cutaneous feedback. Their results showed that an improved performance was obtained during the kinesthetic-cutaneous condition when discriminating object orientation. Kinesthetic trials were affected by the size of the explored object, and participants in the cutaneous trial required more time. For the best integration of haptic feedback, and exploration of virtual or physical objects, both kinesthetic and cutaneous feedback need to be intact. Rehabilitation devices should include both for optimal performance and recovery of sensory function.[110–113]

Tactile displays allow for investigations into temperature, texture, and/or vibration.[106,112–117] For instance, Konyo and Tadokoro[113] developed a tactile display for the fingertip using an ionic polymer-metal composite (IPMC). It is able to vary the perceived friction and displays a rough or smooth surface based on a quantitative measure. Users were able to differentiate between a towel, boa, fleece, or leather. Unfortunately, textures became harder to identify when they were homogenous or if the perceived stiffness of a virtual object was inconsistent with its physical properties.[114] A tactile feedback device has been developed by Wagner et al.[115] that would allow participants to accurately determine the differences in how stiff an object is. In addition to stiffness and texture, temperature was also used for object discrimination.

A theoretical model of heat exchange for incorporating thermal feedback was designed by Guiatni and Kheddar using PHANToM OMNI and a heat pump.[118] Participants were asked to explore five different virtual materials (aluminum, Plexiglas, rubber, wood, and steel) with distinct thermal properties. They report that materials with larger thermal conductivity, such as steel and aluminum, were easier to distinguish from materials with low thermal conductivity. Kron et al.[114] and Guiatni et al.[118] found that it was difficult for participants to make a clear distinction between materials with similar heat conductivity. Ho and Jones[119] developed a contact coefficient based on the thermal properties of an object, including the density, specific heat, and thermal conductivity to further quantify material discrimination. They demonstrated that real and simulated materials with a high contact coefficient ratio are easier to discriminate between than those with a low contact coefficient ratio.[107,119] In a study with a multi-finger thermal display, virtual thermal objects were used to provide realistic sensations of temperature similar to interactions with physical thermal objects.[120] It was also reported that thermal sensations of simulated materials were similar to those of their real counterparts.[119] Research by Ziat et al.[121–123] has indicated that the color of an object influences the perceived temperature, e.g., red is associated with warm and blue is associated with cold. Careful use of color may be important when designing a VR environment with temperature. According to this evidence, it seems possible that temperature can efficiently be coupled with a force feedback device to differentiate materials. However, further research is required when materials that possess similar properties are perceived.

Another aspect of thermal perception is the radiant heat produced by objects such as a fire, or stove. Gaudina et al.[124] developed an algorithm that can be used in virtual environments to express the temperature properties of objects when approached. Gaudina et al.[124] tested their algorithm by instructing participants to move their finger toward a virtual object and stop when they felt the radiant thermal information. Their results indicate that the minimal distance between the finger and the center of the object was inversely proportional to the temperature of the item. In addition, all individuals stopped before touching the object and were able to identify the heat source. These observations suggest that thermal feedback of radiant heat could be used in virtual environments to increase real-life immersion.

Kim et al.[106] developed a novel haptic device for amputee patients to restore sensory function in the following modalities: pressure, vibration, shear (friction), temperature, and fine object discrimination. For such a device to work, the amputee patients had to undergo targeted reinnervation surgery, which reconnects remaining nerves to the existing muscle and skin tissues allowing for somatotopic matching of sensory modalities, i.e., the patient is able to feel a rough texture on the fingertips of their robotic hand. Both patients studied by Kim et al., had accuracy rates higher than 90% when asked to discriminate between different textures. Currently, the device only works with amputee patients, but it is anticipated that technology may be extended to help sensory restoration in other disorders.

C. Neurophysiological Changes

Brain plasticity helps to explain how the brain may recover from stroke or other traumatic brain injuries, as well as to learn new motor movement strategies. Neurophysiological research targets the brain areas and neurotransmitters implicated in motor learning and memory. Studying physiological changes following a pathological event enables the creation of effective techniques, and demonstrates how haptic feedback and virtual reality benefit therapy.

Due to the incompatibility of many robotic devices with a magnetic field, MRI/fMRI studies are rare; most studies compare brain scans from pre- and post-therapy training to assess brain volume changes, or functional connectivity (FC). FMRI data acquired with HWARD indicated higher activation in the left primary sensorimotor cortex (right-hand training) increasing from 176 mm^3 to 9520 mm^3 after grasp training.[90] Brain activation volumes did not change for untrained arm tasks, and EMG recordings did not change during grasp, suggesting that brain changes are a part of cortical reorganization and are not performance related.

Few fMRI compatible devices have been developed specifically for wrist rehabilitation,[125–127] finger rehabilitation,[128] and grasping tasks.[129] Using a two-DOF MRI-compatible device targeting wrist movements, Sergi et al.[125] researched FC in two patients with hemiparesis (Fig. 15). They found that after 12 weeks of training, FC in stroke patients decreased, suggesting that the brain used less overall recruitment to perform better and that robotic rehabilitation affects brain physiology. A one-DOF variable resistance hand device (VRHD) was developed by Weinberg et al.[129] for grasping exercises to be used by neurologically damaged patients. VRHD is a small force feedback device that uses electro-rheological fluids to dampen resistance when squeezing

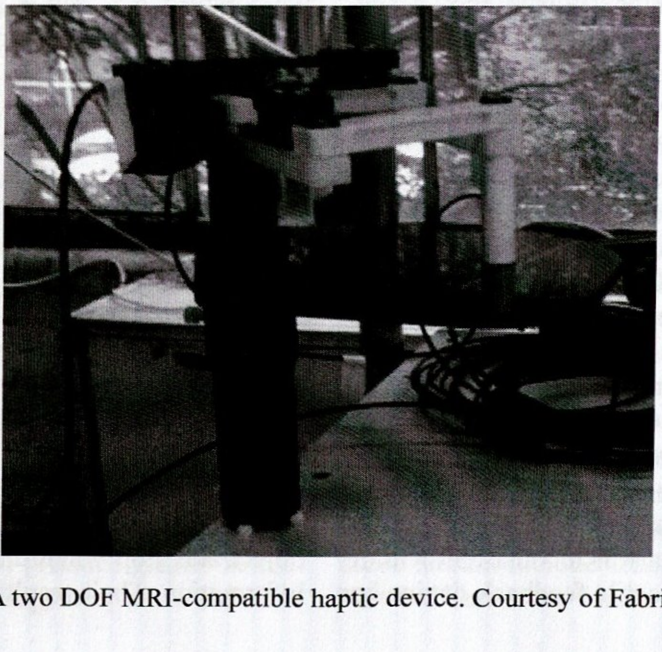

FIG. 15: A two DOF MRI-compatible haptic device. Courtesy of Fabrizio Sergi.

a movable handle. Preliminary studies with VRHD showed that it is compatible with MRI, capable of measuring grip strength, and it can be comfortably used by stroke patients.

Another challenge with the use of fMRI is the fact that a participant cannot move his or her head without compromising the quality of the scan.[127] An alternative to the creation of a compatible device is the use of motor imagery in which an individual imagines a motor movement. A case study by August et al.[104] found that their patient showed increased activation of the somatosensory and motor cortices while watching a virtual hand as opposed to a similarly sized shape during fMRI recording; the patient was instructed to perform the same movements as the virtual hand during both conditions. Similar increases were observed in the postcentral gyrus, the middle temporal gyrus, and both visual and motor cortices during real (moving the hand) and imaginary (observing the hand) movements.[130] These results suggest that motor imagery can be used in experiments and studies related to rehabilitation.

Positron emission tomography (PET) is often used to measure changes in blood flow.[109] Reinkensmeyer et al.[109] found that the cerebellum, striatum, and sensorimotor cortex, had increased activation during motor learning. As patients became more adept with learned motor behavior, the activation within these areas decreased, perhaps suggesting that the brain requires fewer recruitment of resources as performance improves. Furthermore, damage to the striatum or cerebellum is linked to poor motor learning. Research suggests when the activation of brain areas shifts, without a change in the patient's quality of performance, motor skills have been consolidated into motor memory. When individuals performed a reaching task with the Hopkins manipulandum, PET scan recordings showed that the movement became smoother.[131] Such observations suggest the creation of new connections in an internal brain model, quantified by the increase in regional cerebral blood flow (rCBF) to the cerebellar cortex.

Research involving an electroencephalography (EEG)-based brain–computer interface (BCI) was conducted with a force feedback device during a task in which participants imagined a motor movement.[132] Using a force feedback haptic device activates the somatosensory cortex and increases μ-wave and β-wave modulation of event-related desynchronization (ERD) and event-related synchronization (ERS). Haptic feedback during training improved participant performance, even when it was not used during testing. Because these results were obtained from healthy participants, future studies could involve a population with motor dysfunction to test its generalizability. In a recent study, BCI was coupled with transcranial magnetic stimulation (TMS) and a haptic prosthesis to test a healthy participant and a stroke patient.[133] Using the motor imagery paradigm, ERDs were identified as a trigger for both TMS pulses and robotic orthosis movements. The objective was to use haptic rehabilitation along with brain stimulation to facilitate movements and to induce long term neural reorganization. Results showed a higher motor cortex activity when both TMS and haptic feedback were used as opposed to the haptic feedback alone. Using repetitive TMS (rTMS) along with motor training had an increase in motor cortex excitability during upper-limb rehabilitation.[134]

Dopamine and the striatum are involved during motor learning and are a part of the brain reward pathway; dopamine is also implicated during neuroplasticity.[109,135] Therapies that include more rewards to promote brain activation and plasticity could be pursued. Furthermore, research into the effects of a GABA-receptor agonist and NMDA-receptor antagonist found that both inhibited motor learning.[109] However, if an individual had learned a skill previously, these agents did not affect motor recall, which suggests that different mechanisms for motor learning and memory may exist in the brain.

The exact mechanisms of neural reorganization after TBI are still unclear, although it has been hypothesized that a better understanding of remodeling within neural structures following TBI could result in optimal neurorehabilitation programs with the help of robotic devices.[101] Additional research with fMRI compatible devices, EEG, and PET to study and record brain changes will add to the current body of knowledge on neuroplasticity and enhance the field of neurorehabilitation.

IV. DISCUSSION

Most studies were able to show that participants' performance improved based on the evaluation of quantitative measures of motor function after training. When including robotic devices for rehabilitation, they were comparable to or better than conventional therapy. Balasubramanian et. al.[43] reviewed six clinical studies that researched how robotic technology can improve rehabilitation. Four of the six studies compared a group of patients trained with robotic assistance to a group without, or with a different form of therapy. Patients in all conditions improved their scores, indicating that inclusion of robotics is comparable to other forms of rehabilitation. In the study that compared treating patients with only VR to one that included a robotic glove, patients with the robotic glove showed greater improvement in motor function. Other studies corroborate their evidence by noting that robotic rehabilitation was comparable to or produced improvements faster than conventional therapy.[65,66,68,80,136–138] Notably, improvements gained during robotic training lasted longer after therapy concluded than improvements due to conventional therapy.

The rehabilitation gaming system (RGS) was developed to facilitate functional reorganization of the brain following stroke by taking advantage of mirror neurons, which are activated when someone views another person in an activity.[64] Participants view a virtual representation of the body and perform goal-oriented tasks that could lead to improved motor functions. In an initial study with the RGS, stroke patients performed better and recovered faster than patients enrolled in conventional therapy. Cameirao et al.[64] investigated whether or not the type of device was significant for therapy. Forty-four stroke patients were recruited and placed in either the RGS-only, the RGS-E (exoskeleton), or the RGS-H (Haptics) study group. Their results showed that all participants had significant enhancements on their scores for the FMA, CAHAI, and Barthel Index. Those who trained in the RGS-H group preserved their functional gains for all scores at 16 weeks post training and reported the highest scores for enjoyment, entertainment, and the desire to continue therapy. In many ways, RGS-only was more effective than RGS-E, but the study did not compare different exoskeletons, indicating that the results could be due to the specific device used. The inclusion of VR and haptic feedback benefits rehabilitation and is more effective than conventional therapy.[55,56]

Furthermore, haptic feedback improves attention during tasks associated with therapy, especially for TBI patients demonstrating cognitive difficulties. While using the PHANToM, TBI patients increased their attention when presented with different haptic sensations in a virtual scenario.[36] Sensations included being repelled or attracted to a target,[37] nudging or popping a balloon,[36] and judging haptically and visually the presence or absence of an object.[32] Research found that nudging an individual toward the goal was a more effective cue to remain on task than a repelling motion.[36] Dvorkin et al.[37] found that patients with TBI had slower completion times when compared to healthy controls, although their attention to the task was similar.

It must be stated that many studies reported in this paper had ten or fewer participants. Some studies lacked a control group, making it difficult if not impossible to conclude that the device was any more effective than conventional therapy.[83] Some studies had participants who did not improve,[84,85] which could be due to a number of variables such as an improper device, types of tasks, the level of assistance in task completion, the amount of therapy, or the nature of motor dysfunction. These limitations suggest a need for larger sample sizes, more rigorous experimentation, quantification of motor dysfunction, comparisons between devices, and the amount of intensive therapy provided by the investigative team.

V. FUTURE RESEARCH DIRECTIONS

Due to the high cost of rehabilitation technologies, it is much more difficult to study their benefits over conventional therapies.[46] However, an inclusion of haptic devices and VR have demonstrated not only their benefits but also far more sensitivity to the wide range of individual differences. When it comes to the brain, lesion type, and/or specific motor and sensory dysfunction, individual differences affect the prognosis of the patient, subsequent plan for rehabilitation, choice of robotic device, and the training regimen. Quantifying lesion location and specific deficits during research may lead to better individualized therapy.[42] All forms of motor dysfunction should be studied for the efficacy and generalization of robotic, haptic, and virtual reality therapies. Finally, neurorehabilitation research can be improved by including a control group or by directly comparing the use of one device to another.[3]

More precise behavioral measures are needed to generalize results of neurorehabilitation therapies applicable to different upper-limb paralysis populations.[89] Such complex metrics would be able to properly analyze the rate and quality of an individual's performance in the long term.[12,49] The creation of an assessment tool specifically for the use of robotic rehabilitation would be beneficial for comparing different devices and could lead to a more precise measurement of individual performance and functional recovery. It would also be beneficial to include a quantified measurement of sensory function that is capable of selectively stimulating different mechanoreceptors.[106]

Researchers should take into account how in-home treatment sessions may increase the likelihood of a better outcome. Loueriro et al.[46] highlighted various challenges that home treatments face, such as therapist availability, cost, exercise completion, and the use of medication. A possible solution is telerehabilitation. Initial research into the efficacy of telerehabilitation has been promising, but the small population sizes suggest further studies are required.[6] Another concern for telerehabilitation is whether or not the patient prefers having a therapist present in the same room, and how this impacts therapy.[100] Loureiro et al.[46] explored how cooperative rehabilitation with two patients affects motivation and engagement. The most interesting finding was that the participants who initially reported low motivation, increased their engagement with games while playing with individuals who had high levels of motivation. These results were also found while using ADLER in collaborative telerehabilitation.[25] It is a good idea to include a variety of games and vary the task difficulty to keep patients motivated to continue playing and match their personal rehabilitation needs.[60] Current evidence shows positive effects of telerehabilitation, indicating that further research is beneficial.

A promising rehabilitation technique is the use of brain–computer interfaces (BCIs) with robotic devices through surface EMG (sEMG), EEG, or eye-gaze tracking.[108] This modality allows the user to control a robotic device in real time through brain activity/mental imagery, muscle contractions, or eye movements. The intent to perform an action or other brain activity is transmitted and captured by the BCI and then transduced into a command to control a robotic arm.[132,139,140] Christiansen et al.[139] attached EMG electrodes and a vibrotactile device to arms of participants to control a virtual prosthetic with brain activity. During the task, each participant received visual and tactile feedback. They found that vibrotactile feedback could be used as a means of informing the participant about the virtual prosthetic. Escolano et al.[140] demonstrated the feasibility of using BCI for navigation and bidirectional communication with ALS patients. However, synchronization between the BCI and the controlled system remains the main issue, and more research on BCI timing is required. Frisoli et al.[141] showed a promising technique that uses eye gaze and BCI as a means of interacting with physical objects by controlling a robotic arm with brain activity in stroke patients as well as healthy individuals. Microsoft Kinect and an eye tracker were used to assist object localization. Interestingly, there was no difference between performances of stroke patients and healthy controls while locating targets, indicating that the new multimodal BCI method using gaze can be beneficial to stroke patients. Loconsole et al. demonstrated that the L-Exos can be controlled by a participant with sEMG[92] and eye tracking.[93]

The use of sEMG is also beneficial for measuring muscular contraction as a source of biofeedback.[31] Measuring the amount of muscle contraction during rehabilitation would be another way to quantify recovery and may indicate where the muscular weakness occurs. Using sEMG would allow a device to switch between active or passive assistance, based on the needs of the user. The researchers suggest a minimum and maximum threshold level of participant performance to improve errors when switching between active or passive modes. In stroke patients, biofeedback with EMG was used to stimulate weakened muscles to facilitate voluntary motor movements.[103] It has been recommend that when designing grasping and reaching tasks for stroke patients, the movement should be broken down into different phases, such as the grasp, trajectory movement, and finally, the release.[40] Subsequently, different phases could be used to identify where the patient is having difficulties, leading to individualized therapies.

Research into thermal perception has recently begun, and Benali-Khoudjia et al.[142,143] suggest a better understanding of how heat and electric properties are transferred, and convection of the blood (thermoregulation) before including it in VR environments. Another reason thermal cues are omitted is technological. Current thermoelectric modules are fragile, flat, and may not conform properly to a person's finger. Their large size adds weight to the device, thereby limiting their use. The real-time inaccuracy of temperature displays makes it difficult to implement, because thermal plates require time to cool down or warm up.[144] Solutions to such problems must be resolved before thermal perception can be properly and fully integrated with VR environments.

When combined, thermal and tactile displays affect the perceived magnitude of vibrotactile stimuli based on the temperature variation at HF (> 150 Hz). Further investigations into the relationship between temperature and tactile perception are needed to obtain a realistic virtual thermal rendering. However, tactile displays have been combined with robotic devices for rehabilitation.[30,114–117,145] Additional studies are needed to better understand cutaneous-kinesthetic integration and how such multisensory binding contributes to and/or enhances the neurorehabilitation process of upper extremities.

Using CyberGlove and CyberGrasp, researchers demonstrated that both healthy and stroke participants had a tendency to decrease their wrist extension and increase their elbow extension.[39] This could be due to the missing depth cues in a 2D environment, which could be resolved using a head-mounted display (HMD). The researchers also believe that altered kinematics were due to missing haptic feedback when colliding with a surface. These virtual problems indicate that current virtual technologies are not fully immersive. Reiner et al.[32] examined reasons as to what causes a break in presence (BIP) while using virtual reality, which essentially refers to participants feeling as though the virtual environment is fake or non-immersive. They discovered that BIP occurs for some participants when discrepancies between VR and physical reality are observed, such as when a person meets a physical boundary that is not present in the VR. However, instances of unexpected haptic feedback, or discrepancies between VR and haptic sensation lead to the feeling of surprise, instead of a BIP; further research is intended to explore BIPs. In an experiment with ARMin, participants reported that it felt unnatural to be sitting while performing a cooking task in a virtual environment.[34] Weinberg et al.[129] tested patients in both seated and supine positions and found that grip strength and speed were slightly better while seated. Thus, fully immersive VR environments need to take into account depth cues and the type of haptic feedback, provide haptic cues for object collision, and emulate how a task is performed in a natural environment.

Finally, another method for advancing neurorehabilitation is using blended interactions that combine tangible and intangible objects.[146] Humans interact with physical objects on a daily basis, and having participants interact with real objects could contribute to successful rehabilitation of lost function following stroke. Research into how physical and virtual objects interact could be beneficial for neurorehabilitation, with the potential to promote and enhance neuronal connectivity in the brain.

VI. CONCLUSION

The research reviewed in this paper indicates that the uses of robotic devices are comparable to conventional therapies; the inclusion of virtual reality (VR) improves patient enjoyment of therapy and creates a variety of scenarios for motor learning; haptic feedback helps to restore parts of sensory function, and creates a more immersive VR experience. Together, these technologies can create a more effective rehabilitation therapy for improving upper-limb motor and sensory functions. End-effector devices, grounded and ungrounded exoskeletons, all have specific advantages and disadvantages. These differences are beneficial when considering individual needs of patients, such as whether they were born with a motor dysfunction or later suffered brain trauma. While initial costs of these technologies may be high, therapists need not be present during the entirety of therapy, due to the passive support robotics provide and its application for therapies that can be deployed at home.[147] A majority of studies used the Fugl-Meyer Assessment (FMA) to quantify training progress and the Jebsen Hand Function Test (JHFT) to evaluate whether therapy improves the performance of ADLs. Some studies have used fMRI, EEG, or EMG recordings to document brain changes and how the brain recovers following trauma. Results of various studies presented in this paper indicate a wide variety of benefits for the use of robotic devices, virtual reality, and haptic feedback. However, many questions remain for research in the realm of haptic neurorehabilitation.

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