Home-based rehabilitation: enabling frequent and effective training

Kyle B. Reed, Ismet Handzić, & Samuel McAmis

Abstract Rehabilitation studies have recently demonstrated that the amount of time spent training is one of the most important factors in one s ability to regain motor control. The methods employed need to be effective, but individuals need to spend significant amounts of time retraining. One of the most effective ways to enable more training time is for rehabilitation to occur in one s home so individuals have adequate access to it and there is no cost associated with traveling to the clinic. There are several challenges that need to be overcome to make home rehabilitation more common; for example adapting the methods from the clinical setting to the home setting, ensuring safety, and providing motivation. This chapter outlines existing technologies for upper and lower limb rehabilitation and how they could be adapted for use in one s home. Although many types of disabilities would benefit from home-based rehabilitation, this discussion will focus on traumatic brain injuries, specifically stroke related. Many of the methods that could be used at home for stroke would also have application for helping in other circumstances.

Keywords Home-based rehabilitation, low-cost therapy, stroke rehabilitation, robotic therapy, upper-limb, lower-limb

1 Introduction

The saying "practice makes perfect", although a cliché, adequately describes a good rehabilitation method. The more a person with a traumatic brain injury, such as

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stroke, is able to practice, the better their motor relearning will be [1]. However, patients are dissatisfied with their options for training after they are discharged from the rehabilitation hospital/clinic [2], and 85% of patients would prefer a home-based rehabilitation solution [3]. The ability to train at home means individuals can train more often, which leads to better results in motor relearning [4] and can maintain individuals ability to perform activities of daily living [5, 6]. These studies indicate that appropriate methods need to be further developed to enable home-based rehabilitation to improve functional ability after discharge.

The fundamental idea of rehabilitation is to effect a relatively permanent change in the brain that allows continued use of the affected limb(s). Ideally, an individual would regain the full use of his/her impaired abilities following rehabilitation. However, this is not always feasible depending on the nature of the impairment. The literature suggests several holistic outcome measures that could be considered ideal for the individuals; for example, finding satisfaction with his/her life, contributing to society more than he/she is dependent on it, and being able to maintain physical and mental health [7, 8].

In the near future, rehabilitation *could* consist of a mix of home-based therapy and regular but less frequent visits to the clinic. During the clinic visits, the physical therapist would discuss any issues with the patient, and a functional assessment device would evaluate the subject s abilities, such as demonstrated by Schweighofer et al. [9] and Fluet et al. [10]. The physical therapist would prescribe the appropriate home-based therapy to be used daily. The home-based rehabilitation would include an engaging interaction, such as a game, to maintain the individual s interest. The data and video from each home-based session would be securely sent to the therapist at the clinic where it would be automatically evaluated by software, therapists, or both, as deemed appropriate. Non-compliance or non-use would be followed up with a phone call or earlier clinic visit. Due to the low-cost and availability of the rehabilitation, the therapy could continue until the individual was satisfied with their ability to independently perform activities of daily living [8]. Many of the technologies to enable this vision exist, but there is a severe shortage of effective and clinically validated home-based methods that would enable the home-based portion to take place for individuals with moderate impairment.

Specifically for stroke, many methods of rehabilitation are able to generate positive results, but there is no clear evidence for the superiority of any one specific approach [11]. A growing amount of literature suggests that the fundamental problem is not the methods employed, but the lack of adequate training for extended periods of time [1, 12, 13]. Thus, home-based rehabilitation that is widely and affordably available will benefit the many individuals looking for continued training [3].

One of the most common robotic rehabilitation systems, the MIT-Manus [14], is estimated to cost around $15,000 per patient for 36 weeks, which is slightly higher than intensive non-robotic therapy and usual care [15]. To use it, individuals must go to the clinic, which incurs additional cost and time of the individuals not explicitly measured in the study. A home-based method would only incur a one-time cost that would enable rehabilitation for an extended period of time (possibly years) with a small recurring cost for monitoring, whereas clinic-based methods will continue to incur costs throughout the treatment. Even with home-based methods, occasional clinic visits would be expected but would be significantly less frequent than a clinic-based solution.

There are many individuals that could benefit from home-based therapy. More than 795,000 Americans experience a new or recurrent stroke each year and more than 6 million individuals have survived a stroke and are living with the debilitating after-effects [16]. Most individuals with a stroke are left with limited functional ability of the upper limb; 40% have moderate functional impairment and 15%-30% have a severe disability [17]. The estimated costs associated with strokes in 2010 were $73.7 billion [16]. Annually, an estimated 1.7 million Americans suffer a Traumatic Brain Injury (TBI), with 275,000 requiring hospitalization [18]. Approximately 43% of TBIs requiring hospitalization result in long term disability [19] resulting in over 3.2 million Americans currently living with a disability as a result [20]. The lifetime costs associated with TBI in the year 2000 was $60.4 billion [21].

2 Traditional Therapy

Conventional therapies, such as the Bobath method [22] and proprioceptive neuromuscular facilitation technique [23], have been commonly used for stroke rehabilitation. Forced use [24] and the more recently developed Constraint-Induced Movement Therapy [25] binds the sound arm and forces the individual to use only the paretic limb, which aids in cortical re-mapping of neurons from damaged to functional brain cells [26]. One advantage of forced use is that the learning occurs directly during the tasks that are to be learned and can be implemented during home therapy. However, forced use is unable to provide assistance, so it works only on individuals with high motor function.

Traditional physical therapy will often retrain a patient s movements by a therapist physically holding the patient s limb and assisting the motion. The motions are imparted to the patient and the patient is able to feel some of the resulting forces. However, the dynamics of the physical therapist and patient are coupled, which results in motions that are not exactly as intended and the forces are not as expected due to the redundant dynamics of two people [27, 28]. The exact dynamics of this physical interaction between therapist and patient is an open question and studies with healthy subjects have shown the need for further study of the topic. In a study with relatively simple dynamics, Glynn et al. [29] examined how two participants cooperatively moved a cursor through a virtual maze. The participants had difficulty separating the force feedback of the device from the other member s forces. Several other studies have examined similar physical interactions: two individuals will naturally escalate their forces when told to apply the same force as was applied to them since they perceive externally and self-generated forces differently [30], but training can partially alleviate this effect [31]; individuals will unknowingly use constraints, possibly their partner, to generate a force in the desired direction since certain directions are easier to generate force in [32]; two people physically interacting will perform faster than either individual alone [33]; and two people cooperatively performing a task will subconsciously specialize their motions so each person takes on a different part of the task [34].

There are two main challenges in bringing traditional therapy home. First, it is not exactly clear what forces and motions are being conveyed by the physical therapist. The lack of a fundamental understanding of this interaction could potentially be limiting all realms of physical therapy. Second, there is no physical therapist at home to perform the rehabilitation, which raises several additional concerns. One of the proposed solutions is robotic therapy, discussed in the next section.

3 Robotic Therapy

Robotic technologies have been used to provide rehabilitation to individuals with low motor function since therapy is time-consuming and requires significant effort from physical therapists. Patients can also use robotic devices for longer and more frequent periods of time in the clinics.

One of the earliest robotic upper limb rehabilitation systems developed is the MIT-Manus [14], shown in Fig. 1. The MIT-Manus can operate in several planar reaching modes: assisting users, passively sensing motions, or by responding to the user s motions. The results of several independent clinical trials showed that robotic training with the MIT-Manus helped 372 persons with stroke to improve upper extremity motor function [35]. Similarly, the Assisted Rehabilitation and Measurement Guide is an active-assistive robotic device that also showed the benefit of robotic training for people with a stroke [36]. Force feedback devices have also been used to quantify the performance of a patient for use in measuring improvement and possibly prescribing treatments [10]. However, recent review papers have stated that it is unclear whether robotic methods have the potential to produce greater benefits than conventional techniques when practiced for the same amount of time [12, 13]. The amount of training is one of the most important factors for functional recovery after stroke [37, 38, 1].

Robot guided therapy can either use assistive or resistive methods and it is not currently clear which is more effective. In active assistance training, a therapist or robot assists the patient through the desired motion. The benefits of active assistance include stretching the muscles and connective tissues, reinforcing a normal pattern of motion, and allowing the patient to practice more complex tasks [13]. Active assistance also allows for an increase in the intensity of training, since with assistance, more motions may be completed in less time. However, the "guidance hypothesis" suggests that motor learning could actually be decreased when the individual is physically guided since the individual learns how to interact with the therapist or device and not necessarily how to generally move their arm [40, 13]. It is possible that the patient is subconsciously only performing a portion of the task and not learning the other necessary muscle activations [41].

Resistive training methods work to facilitate rehabilitation by making task completion more difficult during training by applying forces that resist or perturb the motion. Individuals moving in a force field that perturbs their motion will adapt to generate forces that counteract the field, resulting in a normal motion within the field [1]. The adaptation will persist for a short time after the field is removed. This after-effect has led to error enhancement training, in which the errors that an individual makes during a motion are exaggerated. Once the disturbance is removed, the after-effect results in a more correct motion, however the corrected motion typically only persists for a short amount of time [42].

One reason the after-effects only last a short amount of time is the dual-rate learning process [43, 44]. The motor output is the summation of a fast learning process, which adapts quickly to new patterns and also forgets quickly, and a slow learning process which adapts over many repeated interactions, but shows prolonged after-effects. The after-effects generated as a result of resistive training are largely due to the slow learning process, but the quick fall off of the effects is the fast learning process adapting quickly. To modify the generated motions permanently, the slow learning process must be involved repeatedly. However, simply making the training sessions longer on each day does not increase the effectiveness since time is needed between sessions to allow for motor consolidation [45, 46]. Longer sessions several times a week are unlikely to make a significant difference, but shorter sessions practiced everyday are likely to be most effective. However, this has not been confirmed since most of the rehabilitation studies train for only three days a week. It is costly and time consuming to bring a person in everyday for the study and for long-term rehabilitation. Thirty minutes performed in the home each day would not be so difficult to perform and would involve less overall time spent training each week, particularly if transportation time is included.

There are several challenges that need to be overcome before these robotic methods can be used in the home. Cost is a significant issue that will be helped partially by economies of scale and decreasing cost of parts, but these costs will only come down so far. The methods need to be reevaluated to determine the most fundamental type of rehabilitation that can be used to generate the result. As opposed to developing more complicated and expensive robots that only incrementally improve

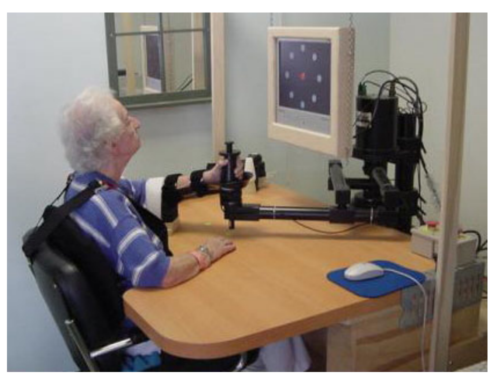

Fig. 1 MIT Manus, one of the earliest robotic upper limb rehabilitation systems. Figure reproduced from [39] under the Creative Commons Attribution License.

the rehabilitation, some of the effort should focus on finding the methods that provide 90% of the benefit at 10% of the cost. The less complicated devices could also use less powerful motors, which would inherently provide a safer environment for rehabilitation; safety is critical to a home-based solution.

4 Visual and Haptic Feedback

One major problem of many rehabilitation programs is the transference of learning between tasks, specifically from the rehabilitation therapy to activities of daily living. The use of visual and haptic feedback has been studied to overcome this problem. One study examined the effects of displaying patient motion collected from an electromagnetic motion capture system during training sessions and showed significant gains after 15 one-hour sessions [47], however no control subjects were used for comparison. In video capture virtual reality, the mirror images of patients motions have been displayed interacting in a virtual environment. These systems have been tested in a large number of studies, but have focused on presence and enjoyment rather than rehabilitation outcomes [48]. One example is shown in Fig. 2. The enjoyment is an important aspect of home-based rehabilitation as it directly relates to motivation and the likelihood that an individual will continue with the training. Virtual and augmented reality for use in rehabilitation has been a popular subject of recent research, however further study is needed to determine the long-term efficacy of virtual reality in rehabilitation [49, 50].

Haptic force feedback through a Phantom Omni [51] and a Rutgers Master II glove [52] have also been shown to help transfer stroke patient rehabilitation improvements to activities of daily living. The use of exoskeletons for force feedback providing a control force to the palm of the user s hand [53] as well as gravity support exoskeletons [54] have shown significant improvements in clinical measures of stroke patients. Haptic guidance using vibration motors on the arms have recently been shown to be as effective as visual feedback for correcting motions [55]. In another study looking at targeted force-based movement, haptic feedback was

Fig. 2 An example of a rehabilitation game to encourage movements that are appropriate for motor relearning. Figure reproduced from [48] under the Creative Commons Attribution License.

shown to lead to improved ease of use and success in accurately completing the virtual finger-pointing task, but the task with haptic feedback was slower [56].

Methods based on simple haptic and visual methods are ideal for home use since they are cheap and easy to use. The downside of them is that they are unable to provide any significant force assistance, so they are not going to be effective for moderate to severely impaired individuals. However, it is unlikely that home-based rehabilitation would ever be appropriate for individuals with severe impairment as they will likely need additional supervision and care.

5 Upper Limb Rehabilitation

This section will look specifically at methods for upper-limb rehabilitation and discuss prospects for expanding the effectiveness of home-based methods.

5.1 Home Based Rehabilitation Methods

As discussed earlier, the ability to train more often leads to better results in motor relearning [4]. Home-based methods have been shown to help maintain individuals ability to perform activities of daily living [5, 6]. There are several methods that have been adapted for home use, but they are limited to individuals with mild impairments. Ideally, moderately impaired individuals would also be able to benefit from home-based rehabilitation.

The SMART system [57] incorporates a motion tracking system to monitor performance of daily tasks and rehabilitation exercises, an online database that allows therapists to monitor patient performance, and a visual feedback system that therapists may use to provide instruction. Java Therapy [58] uses a commercially available force feedback joystick and a suite of online games to provide therapy and evaluation. Another home computer based method is UniTherapy, which uses a force feedback joystick and steering wheel [59, 60] and has been validated in clinical trials [61, 62]. These home-based methods, however, use a home computer with limited accessories that can only provide limited assistance forces and have a limited workspace. These methods are able to provide some benefit, but the rehabilitation effect is limited to people who have relatively high motor function. The challenge is to develop safe and affordable rehabilitation for individuals with moderate impairment.

The commercially available MOTOmed arm cycling training device (Fig. 3) targeted towards stroke, multiple sclerosis, hypertension, cerebral paresis and Parkinson s disease, offers a home-based rehabilitation option. For a relatively low price, patients can perform daily rehabilitative cycling exercises within the comfort of their home. MOTOmed can be customized to be used passively, motor-assisted, or active resistively. Rhythmic Arm cycling has shown to increase upper limb performance [63] and reduces arm spasticity[64, 65].

Fig. 3 The MOTOmed® is a arm cycling device with passive, motor-assisted, or active resistive options. Figure reproduced with permission.

5.2 Bimanual Rehabilitation

Self-rehabilitation using bimanual rehabilitation is ideal for home-based stroke therapy since much of the required force could be provided by the person s sound limb and minimal, or no, external assistance would be required from a caregiver or a motor. The idea behind bimanual rehabilitation is that an individual assists his own paretic arm with his sound arm through an external physical coupling. Neither a physical therapist nor a robot can determine the exact path a person wants his arm to move as well as the person can. When an individual moves both the paretic and sound arms at the same time, the same signal is sent from the brain to the arms and, since the arms are constrained to move together, the proprioceptive feedback will be similar between the two sides of the brain. Burgar et al. hypothesize that bimanual symmetric exercise will enhance recovery by stimulating the ipsilateralcorticospinal pathways [66], which is similar to the hypothesis by Wolf et al. [67] that bimanual therapies could target the ventromedial brain stem pathways. The fundamental idea is that duplicating the efferent and afferent signals will retrain the motor pathways on the paretic side.

Many devices have implemented bimanual motions in a subset of the coupling modes shown in Figure 4. In Joint Space Symmetry, the joint angles for the left and right arms are identical, resulting in hand motions that are mirrored about the sagital plane. In Visual Symmetry, both hands move in the same absolute direction in the visual reference frame. VS occurs in many daily activities, such as moving a large object with both hands. In Point Mirror Symmetry, the hand motions are mirrored about a point in space, much like turning a steering wheel.

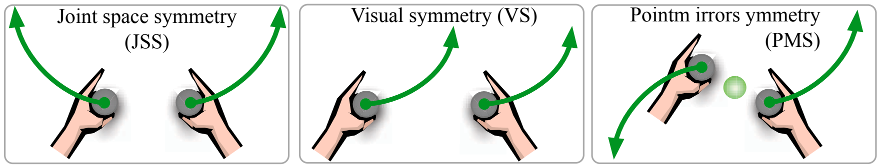

Fig. 4 There are three common symmetric motions in which bimanual rehabilitation is typically performed: Joint-Space Symmetry (JSS) where the joint angles are mirrored; Visual Symmetry (VS) where the hands move through the same visual path; and Point Mirror Symmetry (PMS) where the hand motions are mirrored about a point in space.

5.2.1 Robotic Bimanual Rehabilitation

Robotic bimanual rehabilitation uses a robotic device to assist an individual in making bimanual motions, some of which are shown in Fig. 5. The Mirror Image Movement Enabler (MIME) mirrors the position of the sound arm to the paretic arm using a large industrial robot, the PUMA 500 [66], but the study did not clearly identify the effectiveness of bimanual rehabilitation since subjects used a combination of unimanual and bimanual training [1]. Whereas the MIME focuses on mirroring the overall position of the hands, the BiManuTrack mirrors the flexion of the forearm and wrist and has shown positive results similar to the MIME [68] and to unimanual therapy [69].

Although these devices have been shown to be effective, they are limited to hospital and clinical settings. In recent years simpler passive devices have been developed that are well-suited for home-use rehabilitation.

5.2.2 Passive Bimanual Rehabilitation

Passive bimanual rehabilitation devices rely solely on the patient to generate motions, and do not provide assistive forces. Some of these devices have no physical

(a) MIME (b) Reha-Slide (c) BATRAC (now Tailwind)

Fig. 5 Several of the devices that have been used for bimanual rehabilitation. The general idea of bimanual rehabilitation is that an individual assists his own paretic arm with his sound arm through an external physical coupling. Subfigure (a) reproduced from [48] under the Creative Commons Attribution License. Subfigures (b) and (c) reproduced with permission.

coupling and rely entirely on the impaired arm to generate motions, while others physically link the hands, allowing one arm to assist the other.

BATRAC incorporates one such device where individuals independently move their hands along a linear track with in-phase and out-of-phase motions [70]. BATRAC has shown results similar to dose-matched therapeutic exercises [71]. A commercially available version of the BATRAC device, called Tailwind, is available and may be suited to home-use, although home use trials have not been conducted.

The Reha-Slide [72] implements bimanual motions only in the visual reference frame. The hands are linked by a rigid mechanism that allows an adjustable amount of friction. The entire effort to move the handles, including friction, is controlled by the sound side, The Reha-Slide is simple and demonstrated some improvement, but was not as effective as the BiManuTrack.

The ImAble system includes two devices that couple motions in a visually symmetric frame [73]. The Able-B supports the impaired arm against gravity while allowing the unimpaired arm to assist in making horizontal motions. The Able-X consists simply of a rigid handlebar with a motion sensitive game controller. The devices are used to interact with a suite of virtual reality computer games and have shown positive improvements in a pilot study [73]. The Able-X is commercially available for home use, however its home use efficacy has not been studied.

5.2.3 Compliant Bimanual Rehabilitation

The preceding devices have shown bimanual rehabilitation to be effective, but each only used one symmetry mode and either a rigid coupling or no coupling. However, for healthy individuals, certain motion types are easier to duplicate in one symmetry mode than another [74, 75]. These results indicate that the coupling symmetry mode and stiffness could affect the effectiveness of bimanual rehabilitation. Healthy individuals could recreate bimanual motions more easily in VS if the task was a rapid, unpredictable motion, but could recreate rhythmic motions more easily in JSS [76].

For bimanual rehabilitation, a completely rigid coupling may cause the individual to entirely rely upon their sound arm for all motions [40, 13] whereas a coupling that is too soft would completely eliminate the effect of the coupling, which would prevent individuals with low motor function from benefitting from this training method. With a flexible coupling, the paretic limb will have some assistance, but will apply at least a minimal amount of force, and the assistance force can gradually decrease throughout training. As discussed in Section 3, allowing the individual to gradually adapt will likely train the individual better than an all-or-nothing approach.

To directly compare the rehabilitation efficacy of different bimanual symmetry modes and coupling stiffnesses, a Compliant Bimanual Rehabilitation Device (CBRD) has been developed. This device allows the hands to be coupled in JSS, VS, or PMS, with a wide range of coupling stiffnesses, from 100 N/m to 2000 N/m. Preliminary results have shown that the CBRD can couple the motions of two healthy individuals in a task that simulates hemiparesis [77]. This study also showed that the CBRD may improve bimanual task performance of healthy individuals.

6 Lower Limb Rehabilitation

Most survivors of stroke, persons suffering from traumatic brain injury, paraplegia, tetraplegia, multiple sclerosis, cerebral palsy, or hydrocephalus are known to suffer from motor deficits, including hemiparesis. Hemiparesis in the lower limb leads to hemiparetic gait, which is characterized by an asymmetric walking pattern [78, 79]. Hemiparetic gait typically includes asymmetries in walking coordination measures, such as step length and double support. In other words, the placement and timing of each foot are not equal on the two sides. The rehabilitation techniques used for this target population can be categorized as one of the following:

- Classic gait Rehabilitation (Neurophysiological and Motor Learning)
- Robotic Devices
- Functional Electrical Stimulation

There are generally not as many methods available for home-based lower-limb rehabilitation as there are for upper-limb due to the added complications related to balance and stability when standing/walking. Below is a description of existing methods and how they could be adapted for the home.

6.1 Classic Gait Rehabilitation for Hemiparesis

Currently, the most common gait rehabilitation techniques are classic methods, but robotic devices are gaining acceptance [80]. Classic gait rehabilitation mainly includes preparatory exercises, such as calisthenics, mild stretching, range of motion exercises [81, 82], and guidance/assistance of the limb position while walking over even ground in conjunction with a physical therapist. Classic gait rehabilitation has two subcategories: neurophysiological techniques and motor learning techniques. In the neurophysiological rehabilitation approach, such as Bobath [22] and the Brunnstrom method [83], the patient is the passive recipient of the physiotherapist s corrective and assistive movements [84]. Motor learning approaches, such as the Perfetti method [85], are quite the opposite in that they emphasize active patient participation [86]. Although these are two distinct approaches to hemiparetic gait rehabilitation, in practice each method is customized for each specific situation and patient. For these two categories, no method has been explicitly developed for gait rehabilitation [87]. While overground gait training still persists to be the most commonly used method for patients who are unable to walk independently [88], States et al. [89] indicate that there seems to be no distinct benefits caused by this method. It is suggested that a combination of methods, such as the use of body weight supported treadmill training [90], is a more effective approach [91]. An example of a body weight supported training in combination with guided therapy is shown in Fig. 6.

Home-based motor imagery exercises for gait rehabilitation can also be an effective tool to improve walking performance in patients. Motor imagery is a cognitive operation that increases brain activity in neuronal cortical networks [92], or in other words, motor imagery is a meditation technique that focuses on the visualization of proper limb movement. Dunsky et al. [93] studied the effects of motor imagery exercises on 17 hemiparesis patients over a period of three months. As a result, walking speed increased by 40% with gains retained at the 3-week follow up. Also, a significant increase in stride length, cadence, and single-support time of the affected limb was reported along with a significant decrease in double-support time. A comprehensive review of imagery exercises for gait rehabilitation [94] reveals similar positive effects, however further clinical studies with strong designs and larger groups are needed for confirmation of these positive findings. If validated, motor imagery would be suitable for home-based therapy that could include a large range of individuals.

6.2 Robotic Devices for Hemiparesis Rehabilitation

Classic gait rehabilitation methods alone are unable to restore a normal walking pattern in many stroke patients [95] and are progressively used in conjunction with robotic devices. There are several advantages in the use of robotic devices for gait rehabilitation: reduction of physical assistance and therapy cost, data acquisition, measurement and assessment, and repeatability [3]. Studies indicate that introducing robotic devices into gait rehabilitation results in improved endurance, lower-limb balance, functional balance, gait symmetry, double stance support, and stride length [96, 97, 98].

Exoskeleton type robotic devices are commonly used with body weight support systems with an assist-as-needed control law. The Lokmat [99, 100], shown in Fig. 6, is an electromechanical exoskeleton that employs a zero-impedance control

Fig. 6 The Lokomat® is a gait-assistive device with a built-in body weight support system. Picture: Hocoma, Switzerland.

mode, or path control [101], which allows patients to freely move their limbs while walking. The concept of virtual tunneling, which guides the patient s motion through a force field, is applied in the lower extremity exoskeleton ALEX [102]. The Lokomat and ALEX both are used with a treadmill, body weight support system, visual feedback, and goal oriented training. However, due to their large size, exoskeletons are not likely candidates for home use.

The robotic platform by Monaco et al. [103, 104] offers an automated lower limb rehabilitation device, named NEUROBike, to patients during the initial acute phase when individuals are not yet able to keep an upright walking posture. The NEUROBike system essentially guides the position and orientation of the individual s feet in the sagittal plane to mimic normal gait. Although still in its developmental stage, this rehabilitation device can potentially offer a simple home-based system, but more study is necessary.

At a relatively lower cost, a simpler, yet effective approach is presented in the commercially available lower and upper limb rehabilitation device named MOTOmed by Reck, shown in Fig. 7. The MOTOmed is a lower (or upper) limb cycling device that can be used in a sitting position, in supine position, or with Functional Electrical Simulation (FES). It is designed to be used in a home environment on a daily basis. Passive, motor-assisted, or active resistive training make the MOTOmed customized to an individual s rehabilitation needs. Lower limb rehabilitation studies which utilized the MOTOmed five times a week have shown improvement in patient balance, walking distance (or gait), step length, increased muscle tone, and reduction in spasticity [105, 106, 107]. Such leg cycling rehabilitation in conjunction with electrical stimulation has also been shown to reduce hypertonia in patients with stroke [107].

Fig. 7 The MOTOmed® is a passive, motor-assisted, or active resistive cycling training device. Figure reproduced with permission.

Balance control is a concern for individuals with stroke and, for severely impaired individuals, shifting weight so they can take a step is challenging. A recent study examined the effects of robot-assisted balance training in which an external perturbation force field was applied to individuals while leaning only and also when taking a step [108]. The results showed that the stepping group had a larger change in the asymmetry of their gait patterns, which indicates that training needs to occur in a dynamic environment.

Once a hemiparasis patient is able to stand up and walk with appropriate supports, similar corrective forces in the sagittal plane can be applied to the patient s knee joint through Series Elastic Remote Knee Actuator (SERKA) [109] to achieve correct walking movements. SERKA compensates for the patient s lack of strength and endurance during knee flexion by applying corrective torques at key instances during the gait cycle.

While treadmills are not generally categorized as robots from an engineering standpoint, in gait rehabilitation they are classified as robotic devices. Lower-limb rehabilitation commonly includes split-belt treadmills [110, 111]. Such systems enable independent control of the two treads that each leg walks on, forcing one leg to move faster through stance than the other. Healthy participants with typical gait will walk symmetrically on the treadmill when the belts are running at the same speed (i.e., speed ratio is 1:1). When the speed ratio is changed to 2:1, these participants develop an asymmetric gait since their feet are moving at different speeds when in contact with the treadmill. After 10-15 minutes of walking at a 2:1 ratio, these participants adapt the spatial and temporal relationships between their legs to reestablish a symmetric walking pattern. When the belt speeds are returned to normal (1:1 ratio), the modifications made to gait during split-belt walking are temporarily remembered. The modifications result in an asymmetric gait that is opposite to the asymmetry induced initially by the split-belt treadmill, which is an after-effect similar to that discussed in Section 3. The same method can be used to correct individuals with asymmetric gaits.

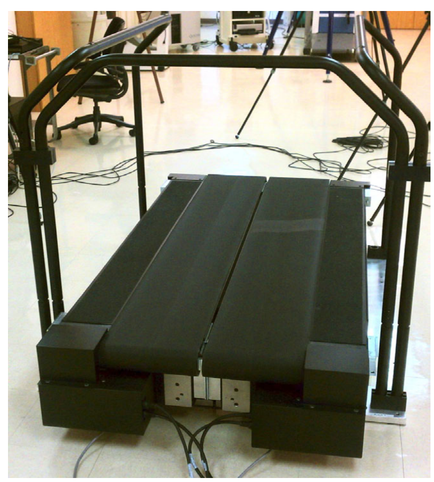

Fig. 8 A split-belt treadmill can be used to reduce an asymmetric gait. The downside is that the corrected gait does not efficiently transfer to walking over ground.

Although the split-belt treadmill can change the interlimb coordination while walking on the treadmill, the effect does not completely transfer to over-ground walking. When after-effects are assessed over ground, the magnitude is diminished to 10% of the magnitude of treadmill after-effects in control participants [112]. For individuals who have suffered a stroke, the transfer to over-ground walking is better at 30%-70%, but the effect is variable and diminishes rapidly following a single training session [113]. It has also been hypothesized that the limited transfer is due to conflicting sensory experiences between the treadmill environment and the over-ground environment [114]. On a treadmill, the scene is not moving, so there are no visual cues reinforcing the forward motion that would be present when walking over ground. Since walking is highly context dependent [112, 115, 114], these cues indicating a different context may prevent the learned patterns on the treadmill from being expressed during over-ground walking. In other words, if the participant is aware that the training conditions are different from the testing conditions, this may limit the transfer. Also, walking on a treadmill limits one s ability to change velocity whereas, when walking over ground, an individual has complete control over velocity. There are also slight differences in the passive dynamics of walking over ground and walking on a treadmill [116].

One way to counter the context-dependence of walking adaptation is to have participants learn a new walking pattern in the same context in which they typically walk. The Gait Enhancing Mobile Shoe (GEMS) [117, 118] is an alternative to the split-belt treadmill method of rehabilitation that allows one foot to move relative to the ground while walking over ground. It addresses the transference problem and it enables convenient, low cost, and potentially in-home gait rehabilitation for persons with central nervous system damage, such as stroke. The learned motions using the GEMS will generate after-effects resulting in near-symmetric gait, but because learning occurs in a real-world environment with the same dynamic and psychological effects as over-ground walking, the walking pattern transfer is increased. The shoe design and implementation is passive (i.e., has no force producing actuators). The necessary forces are converted from the wearer s own downward and horizontal forces into a backward motion through its Archimedean spiral-shaped wheels [119]. By using the weight of the wearer to generate the needed motion, the GEMS can be developed at a reasonable size, weight, and cost, which makes it applicable for home-use with adequate safety procedures in place. However, additional testing is needed.

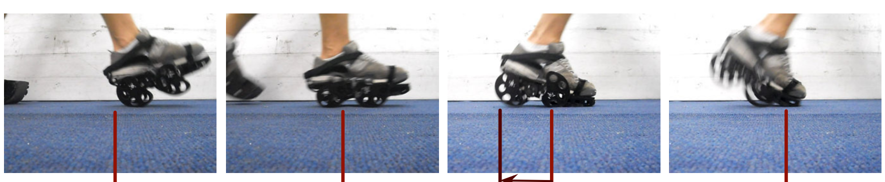

Fig. 9 The Gait Enhancing Mobile Shoe [118] mimics a split-belt treadmill, but while walking over ground to help transfer the rehabilitation effects to over-ground walking. The motion is generated passively by converting the downward motion of the wearer s weight into a backward motion.

6.3 Incorporating Natural Passive Dynamics

In some cases, there are simple solutions to correcting irregular gait. In a study by Gibson-Horn [120], individuals with ataxia wore a 2 lb. mass on their chest. The simple addition of the mass significantly decreased the unstable motions and enabled more steady and efficient walking. In this case, altering the passive dynamics helped correct the individual s gait patterns. Passive dynamics of gait have been theorized to be applicable to rehabilitation for decades and passive dynamic walkers are helping to give insight into human gait.

A passive dynamic walker (PDW) is a device that exhibits a steady and stable gait without any energy inputs except the forces due to gravity [121]. It has been proposed to use a PDW to separate the physical dynamics and the cognitive aspects of walking [122]. The PDW was initially modeled as a rimless wheel [123], was expanded by creating a five-mass system to incorporate knees [124], and then extended so that the leg masses are specified separately, thus allowing physical asymmetries within the model [125]. The gait arising from the PDW model and that of a human have been compared on a treadmill and on over-ground walking with comparable results, but the lack of ankle dorsiflexion causes a discrepancy between the results [116].

When the PDW is asymmetric, the effects of the physical changes that could be added as a means of rehabilitation or assistance can be directly studied without the added complications associated with the cognitive effects. The asymmetric version of the PDW with a heavier weight on one foot shows a similar curvature compared to a human walking with an ankle weight on one leg [126]. The PDW has be used to demonstrate how asymmetric gait can arise in individuals that are physically symmetric [127]. One example application is the design of a transfemoral prosthetic where the knee location is shifted down relative to the intact knee so that the resulting dynamics show symmetric gait [125].

6.4 Functional Electrical Simulation (FES) for Hemiparesis

Functional Electrical Simulation (FES) is the stimulation of muscle tissue by electric current delivery. FES has been a rehabilitation method since the mid-twentieth century and was most commonly used for the rehabilitation of drop-foot and control of dorsiflexion of the foot [128]. Studies have indicated that regular use of multichannel FES is a suitable treatment for hemiplegic subjects [129, 130], however it is unclear if improvements were maintained after FES was removed. Further, the combination of FES to other techniques such as treadmill walking with body weight support yields a vast improvement in gait pattern. Nevertheless, the regular use of FES combined with over-ground walking is seen to have vastly better enhancement in gait than through over-ground walking alone [131]. FES could potentially be used at home, but the placement of the electrodes is important and may require significant training, and there is high potential for damage if used improperly.

In regards to all of the classic gait rehabilitation techniques, there are not significant outcomes, but they are significantly more effective when used in combination [132]. For home use, an important area of research is to determine how they can most beneficially be combined in a cheap, safe, and easily usable package.

7 Future steps needed to bring rehabilitation home

A significant amount of research and progress has been made in the past few decades toward improving individuals quality of life and function after a stroke or other traumatic brain injury. However, there is still a long way to go to restore the motor function more effectively. Below are a summary of the key areas that need to be further enhanced to enable home-based rehabilitation so that extended amounts of training can occur.

- Continue focusing on understanding the plasticity in the brain and optimizing therapy. Some treatments that work in the clinic will be able to be adapted for use at home. A combination of intensive clinic-based therapy and home-based therapies that provide long-term training will likely be most effective.
- There is a need to fundamentally understand how physical therapists physically interact with patients. No studies have examined this interaction. Combining the knowledge of human interaction with the precision of robotics will likely lead to further advances in rehabilitation.
- Design for the home. Economies of scale will only help so much, but the fundamental methods and designs must have use-at-home in mind during the design process. Some of the therapies detailed in this chapter are not well-suited for home use (e.g., Lokomat, MIT Manus) while others are potentially effective when used at home (e.g., Reha-Slide, Tailwind, GEMS, MotoMED), but further testing is needed to determine the efficacy of the home-use devices. There is a severe shortage of studies done on home-based training.
- Safety and monitoring are critical. Devices to be used in the home must be safe and have safe failure modes. Robotic devices with large motors have potential for failure and injury, so designs that incorporate minimal actuation are desired. However, the designs should be able to adequately train individuals with moderate impairment. To facilitate interaction and support from the clinics, the devices should be able to report back to the clinic so that progress or non-use can be followed up to encourage continued improvement.
- The training needs to have a component of motivation, either extrinsically through a game or other form of entertainment, or intrinsically through a clear perception of improvement that will lead to an upward spiral in performance. Typically, in the chronic stages, the progress is not fast enough, so individuals can easily get discouraged. In this stage, providing external motivations will likely to be most effective, but further study is needed on what is most effective.

- The care should be individualized. There is no one method that is highly effective for everyone. Some therapies work for some, but not for others. Particularly as the therapy is moved into one s home, the training needs to be further personalized since the therapist will not be able to change the therapy as frequently.
- When therapy is moved home, the support of caregivers (e.g., family, friends) is even more important. Further training for the primary caregivers needs to be expanded to ensure they can encourage and provide the emotional and physical support needed during the therapy.
- And, most importantly, practice, practice, practice. Physical rehabilitation is a hard and long road that takes effort. In the end, it takes a lot of time and the methods that are developed need to recognize and support the individual through the long road ahead of them. New methods are likely to be discovered that will speed up the therapy, but these points listed above are all going to be necessary as retraining motor function is still going to be time consuming.

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