23 Passive Devices for Upper Limb Training

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Abstract

Arm and hand motor impairments are frequent after a neurological injury. Motor rehabilitation can improve hand and arm function in many cases, but in the current healthcare climate, the time and resources devoted to physical and occupational therapy after injury are inadequate. This represents an opportunity for technology to be introduced that can complement rehabilitation practices, provide motivating task training and allow remote supervision of exercise training performed in the home. Over the last decades, many research groups have been developing robotic devices for exercise therapy, as well as other methods such as electrical stimulation of muscles or vagus nerve stimulation. Robotic devices tend to be expensive and recent studies have raised some doubt as to whether assistance to movements is always preferable as it can reduce salience and engagement. This chapter reviews the evidence for spontaneous recovery, the means and mechanisms of conventional rehabilitation interventions, the advent of affordable passive devices and other treatment modalities that can be used in combination with passive devices. It is argued that task practice on passive devices, in some cases remotely supervised over the internet or augmented with functional electrical stimulation (FES), is now an affordable and important modality of occupational and physical therapy. Passive devices offer numerous opportunities in the field of neurological rehabilitation to support arm and hand motor recovery.

Keywords

Stroke · Spinal cord injury · Multiple sclerosis · Upper extremity · Tele-rehabilitation · Health technology

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23.1 Introduction

Neurological disorders are a leading cause of a disability worldwide [1]. One frequent impairment after a neurological insult is a deficit in movements of the arms and hands. This can range from paresis (weakness) to paralysis (plegia). Arm and hand paresis is characterized by muscle weakness, changed muscle tone, decreased sensation, and impaired voluntary

D. J. Reinkensmeyer et al. (eds.), *Neurorehabilitation Technology*,
https://doi.org/10.1007/978-3-031-08995-4_23

movement control resulting in slow, imprecise, and uncoordinated movement [2–4]. Among stroke survivors which are estimated to represent 7.0 million individuals in the United-States (2.5% of the population) [5], approximately 65% experience residual arm motor impairments despite intensive and prolonged rehabilitation [6]. Unilateral or bilateral arm motor impairments impact approximately 30% of individuals with traumatic brain injury [7], 60% of individuals in the first year following the diagnosis of multiple sclerosis [8], and individuals with cervical spinal cord injury, the most common site of spinal cord trauma [9, 10]. Due to the important contribution of the arm and hand to everyday activities, motor impairments often lead to activity limitations and participation restriction [11–14].

Rehabilitation interventions can help remediate arm motor impairments and regain lost function. Common interventions include task-oriented training and repetitive task practice, constraint-induced movement therapy, mental imagery, mirror therapy and virtual reality [15]. However, many health system constraints limit the delivery of neurological arm and hand rehabilitation. The decreasing rehabilitation length of stay, general lack of reimbursement for therapy, disparities in access to rehabilitation care, limited available treatment time, and competing rehabilitation priorities, such as the early focus on improving lower limb mobility and gait, are examples of frequent challenges with neurological rehabilitation [16–18]. Therefore, people with neurological disorders may not receive adequate rehabilitation interventions for arm motor recovery. Moreover, people with neurological disorders are often discharged home with limited opportunities to continue home exercises and engage in evidence-based interventions to drive recovery after therapy has ended. At home, long-term adherence to exercise programs is often low [19], due to low motivation, cognitive impairments, lack of caregiver support, frustration, pain, and musculoskeletal issues [20]. This represents an opportunity for technology to be introduced to address key challenges to neurological rehabilitation.

Passive devices offer an affordable option to continue rehabilitation outside clinical settings. Passive rehabilitation devices are defined by what they do not do. Unlike robotic rehabilitation devices, passive devices do not provide active assistance during motor rehabilitation. Although passive devices do not use actuators such as electric motors or pneumatic cylinders, some may provide postural support using energy storage devices such as springs or moving masses. Others provide no assistance, but rather simplify exercises, making them more approachable by removing degrees of freedom from the task. Still others create a motivational environment to support motor practice. The term 'passive devices' should be distinguished from the term 'passive' by rehabilitation clinicians to describe exercises or movements made without efforts from the patient. This chapter reviews the mechanisms for functional recovery, the means and mechanisms of conventional rehabilitation interventions, the rationale behind passive devices, and current evidence supporting different types of passive devices.

23.2 Mechanisms of Functional Recovery: The Significance of Compensatory Strategies

Spontaneous mechanisms of recovery at the cellular, molecular, and systems levels often follow a neurological insult. However, the degree of spontaneous recovery varies between individuals and neurological conditions, and is generally incomplete [21]. Some of the spontaneous recovery in motor function is evidently a result of the recovery of central nervous structures temporarily inactivated by the injury, or the adaptation of uninjured nervous networks to take over functions of neighboring injured networks, a process called plasticity [22–24]. Various means of early prediction of the extent of recovery have been identified [25–28]. In this regard, the concept of compensation should be distinguished from recovery [29]. Specifically, individuals with neurological disorders may adopt compensatory strategies to accomplish daily tasks, such as the use of alternative motor strategies (i.e., shoulder elevation or trunk flexion) to compensate for lost motor patterns in the elbow and shoulder [3]. At the body function and structure level of the International Classification of Functioning (ICF) [30], compensation is defined as the performance of a movement in a new manner, seen as the appearance of alternative movement patterns during the accomplishment of a task. At the activity level, compensation refers to a successful task completion using different techniques [29]. The adoption of compensatory strategies may be considered maladaptive if compensations limit recovery of independent movements of the most affected arm, contribute to secondary complications such as pain, joint contracture, and discomfort [31], and lead to a pattern of learned maladaptive behavior impeding long-term functional motor recovery [32, 33]. The use of maladaptive compensatory strategies may limit one's ability to generalize movements to a wider array of tasks [34] and contribute to incipient decline after the end of active therapy [35].

Evidence supports the effectiveness of neurological rehabilitation to remediate arm motor impairments and improve function by fostering neuroplastic changes, which often rely on mechanisms similar to those observed during spontaneous recovery [15, 21, 34, 36, 37]. An understanding of the mechanisms through which recovery is achieved after a neurological disorder is important to guide effective rehabilitation interventions. Neuronal plasticity plays a crucial role in neurologic recovery. From the work done in animal models, repetition, intensity, and salience have been identified as critical to drive experience-dependent neuroplasticity [33]. Other factors influencing plasticity include the provision of progressive and optimally adapted rehabilitation interventions tailored to one's capability and the environmental context [38, 39]. In animal stroke models, hundreds of repetitions of motor tasks are needed to induce lasting neural changes [24, 40]. In humans, the critical threshold of rehabilitation intensity needed to engage plastic mechanisms is unknown. A recent review concluded there was a positive relationship between the time scheduled for exercise therapy and the outcome with large doses of exercise therapy leading to clinically meaningful improvements [41]. The authors pointed out that time scheduled did not necessarily equate to the amount of task practice actually performed. They recommended that instead of reporting scheduled time, future studies should report active time in therapy or repetitions of an exercise. The notion that more is better was challenged in recent large, randomized control trials (RCT). Specifically, Winstein et al. [42] compared four dosages of personalized arm task-oriented training in chronic stroke survivors. Higher dosage of training led to greater gains in quality of arm use measured with the Motor Activity Log, but no changes on functional capacity measured with the Wolf Motor Function Test were noted. In another RCT, Lang et al. [43] compared four doses of task-specific training on arm and hand function (i.e., 3,200, 6,400, 9,600, or individualized maximum repetitions). The results showed no evidence of a dose–response effect of task-specific training on arm and hand functional capacity in stroke survivors. However, the number of movement repetitions provided during this trial was far superior to the amount of movement practice normally provided during conventional stroke rehabilitation [44]. Similarly, the most common dosage of home exercises prescribed for adults with neurological conditions is estimated to be 16–30 min per day with a greater focus on fine motor activities, active range of motion, active assistive range of motion, and whole or partial activity of daily living tasks [45]. Despite the lack of consensus on optimal dose, interventions for arm and hand motor impairments may not always be delivered at the most beneficial intensities and may not include enough repetitions to optimize neuroplasticity [46].

23.3 The Role of Rehabilitation to Restore Arm and Hand Function

A variety of rehabilitation interventions can be used to improve arm and hand motor recovery, but the level of evidence available varies depending on the modality and by neurological populations. The Bobath technique and proprioceptive neuromuscular facilitation, two rehabilitation approaches based on neurophysiological principles, were widely adopted in the 1970s with strong adherents in each camp. However, current evidence does not support the superiority of neurodevelopmental techniques over other types of interventions [16]. A RCT that compared these two approaches with conventional rehabilitation concluded that there were no significant between-group differences in improvement of the patients' performance of activities of daily living [47].

Looking specifically at evidence-based interventions for different neurological populations, task-oriented training, resistance and endurance training, constraint-induced movement therapy, and some types of robot-supported training may improve arm and hand function in individuals with multiple sclerosis [36]. However, the evidence for one approach over another is not clear due to large variability between studies and small sample sizes. Similarly, motor training in individuals with cervical spinal cord injury or traumatic brain injury, which can include task practice and functional electrical stimulation (FES), may reduce arm and hand motor impairments and improve function. However, there were wide differences between studies in the types of patients, training, methodology and outcome parameters [37, 48, 49]. For individuals with stroke, a meta-study concluded that sensorimotor training, motor learning training with the use of imagery, electrical stimulation, and the repetitive performance of novel tasks, could all be effective in reducing motor impairment after stroke [16]. Moderate-quality evidence suggests that constraint-induced movement therapy, mental practice, mirror therapy, interventions for sensory impairment, virtual reality and task-specific training may be effective in improving arm and hand function [15, 50].

One of the most investigated interventions to remediate arm and hand motor impairments in neurology is constraint-induced movement therapy (CIMT), a particular form of intensive and supervised task practice [51]. This approach was developed based on experiments in monkeys in which sensory input in one arm was abolished by de-afferentation. Binding of the other, non-affected arm, led to forced use of the de-afferented arm, which was associated with improvements in its motor function [52, 53] and brain reorganization [54, 55]. In humans, CIMT or the modified versions of CIMT include three key components: (1) constraint of the less affected arm for up to 90% of the waking hours to promote the use of the more affected arm, (2) delivery of intensive graded practice of the more affected arm in functionally meaningful tasks (i.e. task shaping), (3) adherence-enhancing behavioral methods designed to transfer the gains to the real-world environment (i.e., transfer package) [56–58]. CIMT and modified CIMT have been shown to have robust, clinically meaningful impacts on stroke survivors' outcomes for arm and hand motor impairment and function, making CIMT one of the most effective interventions for the paretic arm post stroke [59–61]. However, the use of CIMT in clinical practice is limited. In a survey of 92 therapists working in clinical neurorehabilitation in the USA, 75% reported that it would be difficult or very difficult to administer CIMT in their clinics [62]. Challenges with the delivery of CIMT or modified CIMT include the difficulty to achieve the recommended training intensity, stringent inclusion criteria, lack of resources and high delivery costs that may not be reimbursed by third-party payers [62–65].

23.4 Robotic Exercise Devices

Monitoring movement performance and quality is often challenging in clinical practice, as common objects used for task practice (e.g., blocks, cones, therapy putty, peg boards, resistive prehension benches, etc.) do not have sensors to quantify movement kinematics. The supervision by a therapist can prevent the use of maladaptive compensatory movements. However, the supervision by therapists is costly, and in most cases, restricted to clinics, which in turn limits access mainly to subacute patients. Robotic devices have been developed with the aim of delivering high-intensity, repetitive and adaptive training [66]. Robotic devices can be used to provide standardized exercises, take over some supervisory functions and provide quantitative outcome measures to reduce the tedium of conventional rehabilitation. The treatment paradigm for robotics is based on the provision of physical assistance to complete desired motions of the arm and hand in combination with computer games or virtual reality presented on a screen [67]. Robotic assistance is considered advantageous because it (1) allows the challenge level of the task to be adjusted to better suit the needs and abilities of the user, and (2) allows users to move through a larger range of motion—thereby providing a large afferent response that is time correlated with the user's efferent motor intent. Evidence from systematic reviews and meta-analyses support the use of robotic-based training for sensorimotor rehabilitation of stroke survivors and people with spinal cord injury and multiple sclerosis [36, 66, 68–71]. Research on robot-assisted movement therapy has rapidly increased in recent years, as the potential for robotic therapy after a neurological insult remains enormous [67].

Some of the drawbacks of robotic devices are the high cost of the devices and the lack of salience of the tasks (i.e., tasks may not be meaningful or engaging to the users). Robotic devices incorporate actuators and complex control systems, which makes them expensive. Retail prices can vary between $400USD per month for a powered wrist splint (e.g., Hand Mentor, Motus Nova, Atlanta, GA, https://motusnova.com/hand/) to tens of thousands of dollars for exoskeleton robots, such as the KINARM Exoskeleton Robot (Kinarm, Kingston, Ontario, https://kinarm.com/) or the Armeo Power (Hocoma, Volketswil, Switzerland, https://www.hocoma.com/us/solutions/armeo-power/). The high price point is a barrier to adoption in clinical practice and home use. Another criticism towards robotic devices is that the tasks may not be meaningful to the users, solicit intrinsic motivation or active participation. Ideally, robotic assistance would allow users to practice at their ideal challenge rate, allowing users to be motivated by their success and learn from their occasional failures [72]. However, over-assisting can be counterproductive [73]. Although much work has been devoted to controllers that assist only as needed, the problem of finding the ideal assistance level remains challenging. Since movements are often restricted to a 2D-plane, robotic devices are limited in the variety of movements or tasks practiced, which may not reflect the range of arm and hand movements used for everyday object interaction.

The high-cost and the lack of salience of robotic devices, along with the aforementioned challenges with the delivery of neurorehabilitation stress the need for affordable and effective solutions to harness neuroplasticity. Passive devices are more affordable than robotic devices and unlike CIMT, which has stringent inclusion criteria, they are accessible to individuals with a wide variety of impairments. They can provide motivating task practice to minimize the lack of adherence with home programs and offer the opportunity to deliver salient and intensive task practice outside clinical settings. Because passive devices are defined by what they are not, the remaining field is understandably broad and inclusive. In this chapter, we divide the field of passive devices into 5 groups: (1) passive gravity support systems, (2) tabletop therapy systems, (3) linear rail systems, (4) tone compensating orthoses, and (5) serious game controllers (Fig. 23.1).

23.5 Passive Gravity Support Systems

Mobile arm supports and balanced forearm orthoses have been a part of rehabilitation practice since at least the mid 1960s [74–77]. Although the embodiment has varied, most are either chair-mounted or desk-mounted orthotics

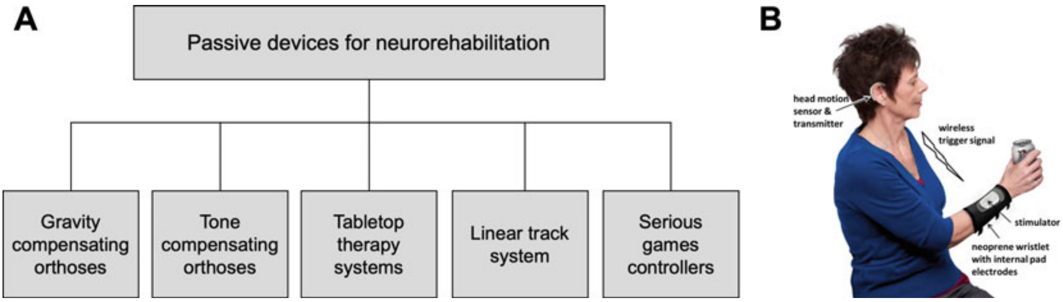

Fig. 23.1 **a** 5 types of passive devices for neurorehabilitation; **b** rehabtronics hand stimulator activated by voluntary head-nods detected by a wireless earpiece

that support the arm at the wrist using either a rigid planar linkage [78, 79], or in many cases, a spring loaded mechanism tuned to balance the weight of the arm. Initially, mobile arm supports and balanced forearm orthoses were used as assistive devices and evaluated based on whether they enabled users with motor impairments to perform activities of daily living that they could not perform otherwise [80]. Early devices were also limited in their degrees of freedom and in the range of motion that they could support [81].

Although chair- or desk-mounted mobile arm support assistive devices have continued to evolve [82], much attention has been given to a newer class of devices designed specifically for rehabilitation. The Armeo Spring (based on the T-WREX, Hocoma, Volketswil, Switzerland) [83], is a counter-balanced multi-segment arm support with six instrumented and lockable degrees of freedom and an instrumented gripper. Positional data from the joint sensor and force data from the gripper are used both to (1) control a suite of games simulating activities of daily living and (2) to quantify features of the user's motor impairment. In early testing, participants with chronic stroke that trained with T-WREX improved their motor capacity (as measured by the Fugl Meyer Assessment) significantly more than participants that trained with tabletop exercises [81]. The gains themselves were modest, but the T-WREX group also showed significantly better retention. Numerous studies have demonstrated that training in T-WREX and Armeo Spring increases the range of motion—both immediately, while in the orthosis, and to a lesser extent, persistently [81, 82, 84]. Critically, participants prefer training with gravity assistance and assign high value to the exercise [85]. The efficacy of Armeo Spring for subacute recovery is less clear. Recently, a large clinical trial in subacute participants compared therapy in Armeo Spring to dose-matched stretching and basic active exercises. The Fugl-Meyer scores of both groups increased significantly, but the differences between the groups was not significant at either the 4-week assessment or the 12-month follow-up [86].

Although the multi-segment linkage used by Armeo Spring does an impressive job of supporting the weight of the arm without placing unwanted restrictions on its range of motion, adjusting the linkages and the springs for each user can be time consuming. Freebal (sold by Hocoma under the name Armeo Boom, Fig. 23.2), by contrast, is a sling-based gravity support system that does not provide as much freedom of movement as Armeo Spring but is much simpler and requires less adjustment. Like Armeo Spring, Freebal extends the range of motion in which users are able to train [87–90]. Although the effectiveness of Freebal has not been studied as extensively as Armeo Spring, early pilot testing suggested that it had similar and lasting effects on motor capacity and range of motion [90]. The high cost of both devices remains a barrier for clinical or home use.

Fig. 23.2 The Armeo®Booom, a passive gravity support system

Armeo Spring and Armeo Boom are both stationary devices. There is also a developing class of wearable gravity support exoskeletons that offload the weight of the arm but are not constrained to a particular location [91–93]. The recently developed SpringWear system, for example, is lightweight, and increases the active workspace of its users. However, the exoskeleton did not consistently improve the wearer's ability to complete functional tasks [91, 94].

23.6 Tabletop Therapy Devices

Tabletop therapy systems are similar to passive gravity support systems in that they allow users to practice without supporting the weight of their arm. However, instead of using springs to compensate for gravity, tabletop systems rely on the surface of the table to support the weight. This simplification restricts movements to a single plane, but it makes the devices more cost effective and appropriate for home use. Normally these systems include some mechanism for reducing frictional forces between the arm and the support service such as omnidirectional wheels [95], or a 2D gantry [96]. Like the non-planar gravity support systems, most tabletop therapy systems include some mechanisms (e.g. cameras [95], encoders [97], or instrumented tracks [96]) to monitor the position of the arm and couple the movements with engaging serious games. Some systems allow users to increase the difficulty of their exercises by tilting the table [98, 99] or by introducing friction [97]. The Rutgers Arm II is noteworthy for detecting unwanted compensatory movements from the shoulder [98], and the Rapael Smart Board (Neofect, San Francisco, CA) is noteworthy for being a commercially available device.

Evidence of the effectiveness of tabletop therapy systems is somewhat limited. Most devices are validated using uncontrolled pilot studies, which indicate that the devices are safe, promising, and well received by their users [95, 98, 100]. The main exception is the Rapael Smart Board which was validated by a RCT for chronic stroke survivors. Participants that practiced with the Smart Board in addition to standard care increased their Wolf Motor Function scores significantly more than participants that practiced with a double dose of standard care [96].

23.7 Linear Track System

In much the same way that tabletop therapy devices are a simpler, more constrained alternative to systems like Armeo Spring or Armeo Boom, linear track systems are a simpler and more constrained alternative to tabletop therapy systems. Linear tracks support gravity and reduce unwanted friction, but they also resist unintentional movements caused by imbalanced motor synergies. As long as there is some forward or backward component to the forces that the user applies to the slider, it will progress along the track, making the exercise very forgiving. The three most prominent linear track systems are the BATRAC [101] which was sold for a time under the trade name “Tailwind”, the Reha-Slide [102], and the SMART Arm [103]. Both the BATRAC and the Reha-Slide promote bimanual exercises. All three devices include game-like elements, but the SMART Arm is the only device built around an actual computer gaming system. The Reha-slide has been used as an input to a gaming system with a backend for telerehabilitation, but the commercial version does not yet support these features [104]. Training with any of the three devices has been shown to significantly improve motor capacity in chronic stroke, but none of the devices have proven to be significantly better than dose-matched conventional treatment [105–110].

23.8 Tone Compensating Orthoses

In much the same way that Armeo Spring uses springs and passive mechanisms to cancel the effects of gravity, tone compensating orthoses like the Hand Spring Operated Movement Enhancer (HandSOME), SCRIPT, and EXTEND devices use springs and carefully designed mechanisms to create tunable force profiles that do an impressive job of compensating for unwanted joint torques caused by wrist and finger flexor hypertonia [111–113]. While wearing the HandSOME orthosis, stroke survivors with finger flexor hypertonia were able to both move through a significantly larger range of motion and outperform their unassisted Box and Blocks scores [111]. Similar results were observed for the EXTEND and SCRIPT Orthoses [112, 114]. The stated goal of all three devices is to enable stroke survivors to exercise more and with greater success. However, the efficacy of exercising with a tone-compensating device is far from clear. In an uncontrolled pilot study, the training with the HandSOME orthosis was shown to significantly, but not persistently improve motor capacity [115]. The EXTEND Orthosis has been tested in a controlled, at home clinical trial, but participants in the control group (who performed exercises from a book) improved more than participants that played immersive video games with assistance from the EXTEND Orthosis [116]. Saebo also sells a commercial glove called SaeboFlex, which uses springs and cables to apply forces to resist flexion contractures in the wrist and hand. Unlike the HandSOME system, the springs are not tuned to truly compensate for the unwanted flexor activity, but the device makes up for this in its practicality. It is marketed as an assistive device.

23.9 Serious Games for Home Use

Nearly all the passive devices discussed above are instrumented so that they can be used as inputs to control motivating custom and non-custom video games. The difficulty, repetitiveness, and delayed gratification of motor rehabilitation can make it very challenging for people with a neurological disorder to invest themselves. Serious games can hide the difficulty and repetition inherent to motor rehabilitation by providing a rich and motivating training environment and embedding game-playing elements. The level of difficulty of virtual tasks can often be scaled in ways that purely physical tasks cannot, allowing players to practice at higher success rates. Serious games offer the advantages of providing immediate and enhanced feedback, and can dynamically adjust task difficulty. Many systems offer the opportunity to record and monitor performance and progress, which can be very useful for patients and therapists to monitor performance and track improvements over time. Serious games also offer the opportunity to incorporate motor learning principles, such as motivation, repetitive practice, and enhanced feedback, into rehabilitation interventions [117].

However, the standard input devices (mice, keyboards, and gamepads) used to control commercial video games are poorly suited to games used for rehabilitation because they are designed to require very small, efficient movements, not the types of movements normally prescribed during motor rehabilitation. This has created an interest in unique input devices for rehabilitative serious games. Two of the earliest and most readily adopted gaming systems used for rehabilitation were the Nintendo Wii (Nintendo, Tokyo, Japan) and the Kinect System (Microsoft, Richmond, WA) [118, 119]. In a survey of 1071 practicing PTs and OTs, 41% reported having access to a Wii in a clinical setting, whereas 10% had the Xbox Kinect [118]. None of the commercial games, such as the Wii and the Kinect, were deliberately designed for rehabilitation, it is not surprising that they have shortcomings. Movement performance and quality may be diminished by the attributes of the virtual environment (e.g., viewing environment, visual, tactile, auditory, and other sensory cues, etc.), which can consequently be detrimental to motor learning [120, 121]. None of the games involve dexterous tasks requiring grasp/release, pronation/supination, pinch-grip/release or picking up and transferring objects. Nevertheless, many of the Wii or Kinect games are considered to be suitable for rehabilitation [122, 123]. Specifically, exercising with the Wii has also proven to be safe, the system is easy to use, and there is some evidence that participants in trials involving the Wii are less likely to drop out [124]. Results from a recent Cochrane review about the effectiveness of virtual rehabilitation after stroke demonstrated that virtual reality and interactive video gaming have a significant but modest effect on improving arm and hand impairments (measured by the Fugl-Meyer Assessment) when used in addition to usual care to increase overall therapy time (standardized mean difference = 0.49, 95% confidence interval 0.21 to 0.77, 210 participants) [125]. The potential benefits of virtual rehabilitation on improving function in everyday activities, quality of life, and reducing participation restrictions were also identified [125–127]. While well adopted, the use of commercially-available serious gaming systems was not found to be superior to usual care [125]. This suggests that these systems should not be viewed as alternatives to usual care, but rather as useful supplements.

More recently, a cohort of low to moderate cost input devices specifically designed for rehabilitation have become available. The most noteworthy of these being the Neofect Smart glove, the AbleX rehabilitation system (AbleX, Auckland, New Zealand), Pablo (Tyromotion, Grz, Austria), the MusicGlove and FitMI systems (Flint Rehabilitation devices, Irvine, CA), the NeuroFenix gameball (NeuroFenix, London, UK), and the Rehabilitation Joystick for Computerized Exercise (ReJoyce) workstation marketed by Saebo (Charlotte, NC).

The Neofect smart glove is an instrumented data glove designed to be easy to don, doff, and clean. It uses inertial sensors to detect movement of the wrist and hand, and resistive bend sensors to detect movement of the fingers. As such, it can facilitate distal grasp-related exercises in addition to some proximal upper limb exercises. In a RCT (N = 13), chronic stroke participants (defined in the study as >4 months post-stroke) who practiced with the smart glove for 15 30-min sessions in addition to 15 30-min sessions of conventional therapy improved significantly more, as measured by the Wolf Motor Function Test, than participants who performed 30 30-min sessions of conventional therapy [128].

The AbleX system consists of two different input devices: the first is an arm skate with a repositionable button that can be used to detect extension of any of the fingers and the second is an inertial measurement unit (IMU)-based controller that can be used both unimanually and bimanually. The AbleX system has not yet been evaluated in a RCT, but early pilot testing suggests that it is safe, motivating, and potentially effective [129].

The Pablo system by Tyromotion includes a Wii-mote-like orientation and force sensor called the "handle", an adapter that allows the handle to be used for bimanual exercises and a ball adapter that allows the handle to be held in a different orientation. The software allows therapists to adjust orientation and force thresholds [130].

The MusicGlove is a distally focused data glove for hand rehabilitation designed and priced to be appropriate for home use. The glove can detect opposition of the thumb to all 5 fingers as well as pincer grip and key pinch grip. It is coupled to a game similar to *Guitar Hero* in which players hit notes by completing the hand grips indicated by the game [131]. The MusicGlove has been evaluated for both in-clinic [132] and in-home use [131]. In both trials, therapy with the MusicGlove was compared to conventional therapy as a control. The control group performed tabletop exercises in the in-clinic study and therapy guided by a booklet of exercises for the in-home study. In both studies, both groups improved significantly and sustained their improvements (as indicated by changes in Box and Blocks scores), but the MusicGlove groups did not improve significantly more than their corresponding conventional therapy groups [132, 133]. In the in-home study, participants in the MusicGlove group improved significantly more on the Motor Activity Log scores than those of the conventional therapy group. Notably, participants in the MusicGlove group also significantly and voluntarily intensified their dose from an average of 213 ± 301 grips per week during the first week to 466 ± 641 grips per week in weeks 2 and 3 [133].

One of the main limitations of the MusicGlove is that it can only be used for distal exercises. To address this limitation, Flint Rehabilitation Devices released FitMI, a more generic serious game controller with libraries of exercises that support proximal and distal upper limb exercises in addition to lower limb exercises and core strengthening/stretching exercises. The FitMI system consists of two wireless puck-shaped controllers that can detect both forces and movement and can supply both haptic and visual feedback. The FitMI System is currently being evaluated in a RCT.

The NeuroFenix ball is a round ball that can measure movement and orientation changes. It can be strapped to one hand, used bimanually, or secured in a dock that restricts it to orientation changes only. The shape, size, and straps hold the hand in a favorable position and make the device easier to hold than many other comparable devices [134].

The Rehabilitation Joystick for Computerized Exercise (ReJoyce: Rehabtronics.com; Fig. 23.3) comprises a spring-loaded, segmented arm that presents the user with a variety of spring-loaded attachments representing activities of daily

Fig. 23.3 **a** Tele-coaching of an in-home exercise therapy session using the rehabilitation joystick for computerized exercise (ReJoyce) system; **b** participant using ReJoyce workstation to play computer games; **c** movements performed, **d** selected games

living, such as a doorknob, key, gripper, jar lid and peg. Sensors in the arm and the attachments provide signals that are used by the system's software to control serious games that exercise specific types of hand movement.

The system incorporates an automated, quantitative arm and hand function test which takes about 5 min to complete and provides an overall numerical score that correlates well with the Action Research Arm Test and the Upper Extremity Fugl-Meyer Assessment [135]. It also provides scores for specific tasks such as grasp strength, whole-arm range of motion, pronation-supination, pinch-grip and manual dexterity and can be performed in the clinic or remotely. Once a user has done the test, the system automatically suggests games and difficulty levels that match their abilities. This is achieved by an algorithm that considers the user's score on each of the components of the test. If, for example, the user has good ranges of motion but poor pinch-grip strength, games that incorporate pinch-grip are excluded from the suggestion list, and games involving range of motion and grasp-release are included, with difficulty levels corresponding to the relevant test scores.

The ReJoyce system also facilitates remote tele-coaching. A RCT was completed involving 13 tetraplegic participants who had sustained a spinal cord injury more than a year previously [136]. Participants were block-randomized into two groups, both performing exercise therapy at home with tele-coaching for 1 h/day, 5 days/week for 6 weeks. The control group played computer games played with a trackball and 20 min/day with therapeutic electrical stimulation. The treatment group played serious games on a ReJoyce workstation. Voluntary, hand grasp and release were augmented with functional electrical stimulation (FES) triggered by a wireless earpiece that detected small voluntary tooth clicks. The study demonstrated the feasibility of delivering tele-coached functional electrical stimulation-assisted exercises over the Internet. The treatment group showed clinically important improvements in arm and hand function that significantly exceeded those of the control group. Participants commencing with intermediate functional scores improved the most [137]. The ReJoyce system was designed to be affordable for clinics and, through short-term rental, by individual users who could receive tele-supervised treatment in their homes.

23.10 Therapeutic and Functional Electrical Stimulation

The simple and interactive nature of passive devices makes them a natural complement to functional electrical stimulation (FES) and non-motor specific processes like Vagus nerve stimulation (VNS). This is particularly true for passive devices that serve as an input to a computer since inputs from the devices and events from the games could both ostensibly be used to trigger stimulation.

FES refers to intentionally-triggered electrical stimulation of the motor neurons in a targeted muscle group to assist in a functional task. Although often used as a component of an assistive orthosis, it is also used therapeutically; exercising with FES in addition to standard care has been shown to improve motor capacity moderately, but significantly, more than standard care alone [138]. Although FES systems are more commonly controlled by switches [136] or electromyography (EMG) [139], they can also be triggered by passive devices designed to detect movement intent [140]. While useful, FES-enabled passive devices systems are not without their challenges. Although feedback controlled, multi-joint systems do exist [141], creating coordinated multi-joint movements vias FES is challenging, and nearly all systems rely on pre-programmed stimulation profiles targeting one or two muscle groups (e.g. elbow and forearm extensors) [138]. Furthermore, the motor unit recruitment order obtained by FES is difficult to control and leads to premature fatigue [142].

Vagus Nerve Stimulation (VNS) has been proposed as an adjunct to exercise training in neurorehabilitation. The proposed mechanism of VNS is not through muscle activation, as is the case for FES, but rather, through plastic changes in the central nervous system (CNS). Although the vagus nerve, which innervates autonomic organs such as the heart and gastrointestinal tract, might seem like an unlikely player in neurological motor recovery, it is known that vagal afferents project to neuromodulatory networks in the CNS. Neuromodulatory networks are groups of neurons that are influenced by neurotransmitters such as acetylcholine and noradrenaline and that modulate the activity of other CNS centers. It has been suggested that the cholinergic neuromodulatory network affects motor control and that the noradrenergic neuromodulatory network affects awareness and responsiveness to stimuli. There is evidence from animal studies that VNS can promote CNS neuroplasticity [143]. It has been suggested that VNS applied at the right time during motor practice will increase the neuroplastic response to that practice [144–146]. In the only human clinical trials to date, the timing of VNS was controlled manually by a physical therapist. In principle, the timing could be controlled with movement feedback from a passive rehabilitation device.

23.11 Telerehabilitation

From all the above, it is clear that the emerging technologies to deliver task practice have the potential greatly to improve arm and hand function in daily life but providing sufficient support after participants leave rehabilitation clinics is problematic. Although the users may benefit from the devices in the clinic, and initially use them daily at home, in the absence of continuing supervision, usage tends to drop off. This transition is a well-known hurdle in rehabilitation [147]. We reasoned that if participants could only perform regular supervised exercise after discharge, they would benefit much more. However, clinics are not ideal locations for outpatients to perform regular training sessions. Travel is often problematic and stressful, limiting the frequency of attendance. In recent years, telerehabilitation, a form of telemedicine, has slowly gained popularity. One of the early systems used for telerehabilitation was the ReJoyce system used for at-home tele-coaching (Fig. 23.2a). In the study mentioned above, Internet-connected ReJoyce workstations were deployed in the homes of 13 tetraplegic participants, located over a wide geographic region in western Canada. Participants were tele-coached daily by a small team of therapists and students. The logistic challenges that were overcome are detailed in a book chapter [148]. A similar study followed on chronic stroke patients in Canada and the UK [149]. Other studies have also shown that telerehabilitation can be convenient and effective for both therapists and patients [148, 150, 151]. Telerehabilitation promotes flexibility, allows greater access to care and continuity of care, and can help decrease racial and economic disparities in health care [152, 153].

With the recent health care crisis induced by the global COVID-19 pandemic, rapid technological changes have followed and telerehabilitation quickly became widely adopted by rehabilitation services across the world [154]. Key barriers that limited the adoption of telerehabilitation previously, such as reimbursement and clinicians' preference for hands-on interactions, were partly overcome in response to the global pandemic [155]. Resources and guidelines from professional associations were also developed to support clinicians in the delivery of remote rehabilitation (for example, [156, 157]).

A recent trend in stroke rehabilitation is the concept of early supported discharge. Early supported discharge is a multidisciplinary team intervention that facilitates earlier discharge from hospital with rehabilitation care provided in the community [158]. Evidence from meta-analyses supports appropriately-resourced early-supported discharge services delivered by a multidisciplinary team to reduce disability and shorten hospital stays in a selected group of stroke survivors [158, 159]. The use of passive devices is particularly well-suited for home use, early-supported discharge and remote supervision using telerehabilitation.

23.12 Clinical Adoption of Passive Devices

Healthcare professionals play a pivotal role in their patients' access to novel technologies, and they are ultimately the ones who use health technologies, such as passive devices, in their clinical practice or recommend them for home use [160]. Understanding clinicians' perspectives and the factors affecting clinical adoption is crucial to enable clinical changes and better widespread use of passive devices in neurological rehabilitation.

The clinical adoption of passive devices remains low and is not yet commonplace in clinical rehabilitation settings, which is not different from most health technologies [155, 161]. The results from a survey of 1326 healthcare professionals suggest that clinical decisions to acquire and use new technology devices are multifaceted and are based on the benefits for their patients, the technology's appropriateness for the setting and logistical practicality within the service delivery system [162]. Patient characteristics, available financial resources, technology cost, experience with technology and time demands are key factors shown to impact clinical practice patterns [161–163]. The potential benefit of technology to facilitate positive health outcomes, mainly through the provision of meaningful and objective feedback, and repetitive and independent practice, was identified as a main driver to adoption [155]. Clinicians usually have very busy schedules, with little time to deal with new technology. It is therefore vital to provide equipment that is affordable and simple to use, with highly intuitive computer interfaces that do not require procedural memorization from one session to the next [155, 164]. Since barriers to adoption are multifactorial, financial and administrative support from the leadership, and training of clinicians are essential to ensure clinical adoption and use of health technologies [165]. Future technology development should consider following the stepwise approach and conditions for successful implementation of technology in daily clinical practice, as outlined in a recent systematic review [166]. In the later stages of technology development, the incorporation of user-centered design methods and involvement of clinicians and users are important to facilitate technology adoption [167].

23.13 Perspectives and Conclusions

There is general agreement in the field that the time is ripe for physical and occupational therapy to take advantage of new technologies. It is time to move beyond simple equipment currently used in clinics worldwide, to passive devices that provide task-specific, motivating games that can also be performed in the participant's home environment, supervised remotely over the Internet. The advantages of this approach are many: increased compliance, task-specific training on a variety of customized activities, quantification of performance and perhaps most compelling, the ability to provide continuing in-home therapy after acute care in clinics, in a manner that avoids the need for participants to travel, yet retains the important component of one-on-one supervision by enabling therapists to treat participants at times that suit them all. A crucial factor is cost, especially given that costs are generally covered by patients. The cost of passive devices presented in this chapter spans from a few hundred dollars for serious games to a few thousand dollars for tabletop therapy systems, with many options offered below $1,000USD. This chapter has made the case for affordable passive exercise devices that provide entertaining exercises involving full range-of-motion and manual dexterity, with optional telecoaching and electrical stimulation (summarized in Table 23.1). Task training for arm and hand function on passive devices, with the option of FES-assistance or perhaps VNS, is now an affordable and effective modality of occupational and physical therapy. Passive devices offer numerous opportunities in the field of neurological rehabilitation to support arm and hand motor recovery. Future research could focus on the identification of who might benefit the most from the use of passive devices to guide clinical decision making and maximize the use of scarce health-care resources.

Table 23.1 Summary of passive exercise therapy devices discussed in this chapter

Device	Commercial product	Movement target(s)	Device type	Computer gaming?	Validated upper limb function test?	Integrated Telerehab/Telecoaching	Recent studies
Armeo Boom	Yes	Shoulder, arm, forearm	Gravity support	Yes	No	No	[79, 81–83, 85, 168]
Armeo Spring	Yes	Shoulder, arm, forearm, wrist, hand grasp-release (optional attachment)	Gravity support	Yes	Yes	No	[87–89]
SpringWear	No	Shoulder, arm forearm	Gravity support	Yes	No	No	[91, 94]
Rapael SmartBoard	Yes	Shoulder, arm	Tabletop	Yes	No	No	[96]
Tailwind	Previously	Shoulder, arm	Linear track	No	No	No	[101, 105, 106]
Reha-Slide	Yes	Shoulder, arm	Linear track	Research only	No	Research only	[102, 104]
SMART Arm	No	Shoulder, arm	Linear track	Yes	No	No	[103, 110]
HandSOME	No	Fingers, thumb	Tone Compensation	Yes	No	No	[111, 115]
SCRIPT	No	Wrist, fingers, thumb	Tone Compensation	Yes	No	No	[113, 169]
EXTEND	No	Fingers, thumb	Tone Compensation	Yes	No	No	[112]
SaeboFlex	Yes	Fingers, thumb extension	Tone Compensation	No	No	No	None
Wii	Yes	Shoulder, arm, forearm, wrist, thumb (pushbutton)	Input device	Yes	No	No	[122, 124]
Kinect	Yes	Whole body—software limited	Input device	Yes	No	Software dependent	[123, 170]

(continued)

Table 23.1 (continued)

Device	Commercial product	Movement target(s)	Device type	Computer gaming?	Validated upper limb function test?	Integrated Telerehab/Telecoaching	Recent studies
Neofect SmartGlove	Yes	Wrist individual fingers, thumb	Input device	Yes	No	No	[128]
AbleX	Yes	Arm, wrist, fingers, thumb	Input device/tabletop therapy	Yes	No	No	[129]
MusicGlove	Yes	Individual finger and thumb movement	Input device	Yes	No	No	[131–133]
FitMI	Yes	Ankle, core, shoulder, arm, forearm, wrist, hand, power grip, key pinch	Input device	Yes	No	Research only	[171, 172]
Pablo	Yes	Wrist flexion–extension, pronation-supination, grasp, finger-thumb pinch	Input device	Yes	No	No	None
ReJoyce	Yes	Shoulder, arm, forearm, wrist, hand grasp-release, finger-thumb pinch	Input device	Yes	Yes	Yes	[135–137, 150]

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