28 Upper-Extremity Movement Training with Mechanically Assistive Devices

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Abstract

This chapter describes the development of mechanically assistive devices to enhance upper-extremity movement training after neurologic injury. We use the term "mechanically assistive devices" to refer to non-powered devices that incorporate springs, guides, pulleys, ramps, and/or levers to assist a patient in moving his or her weakened arm primarily by reducing the effect of gravity. As a case study of this approach, we first describe the development of the T-WREX exoskeletal training device, which was then commercialized and further tested as ArmeoSpring. Next, we provide a summary of clinical evidence for the effectiveness of mechanically assistive devices. We discuss why training with mechanically assistive devices reduces arm impairment, highlighting motivational, strengthening, and proprioceptive effects. We conclude by describing our recent efforts to democratize mechanically assistive devices for arm training by incorporating them directly onto wheelchairs as armrests.

Keywords

Movement rehabilitation · Motor learning · Rehabilitation technology · Stroke · Computer games · Upper-extremity exercise

28.1 Introduction: A Case Study of the Development of a Mechanically Assistive Device

We begin this chapter by reviewing the motivation behind and development of an exemplar mechanically assisted device, T-WREX, which eventually was commercialized and became one of the most widely used devices for arm training after stroke, ArmeoSpring.

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28.1.1 From Traditional Mechanically Assistive Devices to Robotic Rehabilitation

Prior to the late 1980s, several pieces of rehabilitation equipment took a mechanically assistive approach to allow people with arm weakness to practice arm movement. These included overhead slings, mobile arm supports, or simply a towel on a tabletop. However, despite their presence in rehabilitation facilities, there was little clinical evidence on the effectiveness of these approaches in reducing arm impairment.

A key realization in the late 1980s was that such rehabilitation technology might be improved by adding powered actuators to improve adjustability/assistance and sensors to provide feedback. Out of this rationale came several new robotic devices, including the MIT-Manus [1], the MIME [2], the ARM-Guide [3], and the Bi-Manu-Trac [4]. Each device took the approach of providing powered assistance to arm movements as users played simple computer games. It was these robotic devices that laid the scientific groundwork for the observation that mechanical assistance can be beneficial for arm training after a stroke.

Specifically, thousands of persons with a stroke have now participated in randomized controlled trials (RCTs) with these devices, two of which are commercially available (MIT-Manus as InMotion ARM Interactive Therapy System and Bi-Manu-Trac). The studies indicate that people with an acute or chronic stroke can recover a modest amount of additional movement ability if they exercise for tens of hours with these assistive devices; the transfer to functional movement is typically small [5–12]. Exercise with a robotic device has also been found to be as effective or, in some cases, more effective than a matched amount of exercise performed with a therapist [8–10, 13–15], or a matched amount of exercise performed with other rehabilitation technologies, such as electromyogram-triggered functional electrical stimulation [16] or sensor-based approaches [17].

28.1.2 From Robotics Back to Mechanically Assistive Devices

Robotic rehabilitation devices are at the high end of complexity in the spectrum of therapeutic technology. While these devices have proven to be useful tools for studying rehabilitative movement training, it is still unclear whether their modest therapeutic benefit justifies their cost, and, indeed, clinical uptake of robotic therapy devices is still sporadic. In the 1990s, we asked whether it would be possible to gain the benefits of robotic assistance without powered motors—i.e. with a mechanically assistive device—but with better adjustability and feedback compared to the "old school" devices.

With National Institute of Disability and Rehabilitation Research (NIDRR) support, we began developing a new device called T-WREX (or "Therapy-Wilmington Robotic Exoskeleton") (Fig. 28.1a), which was described in the doctoral dissertation research of Dr. Robert Sanchez [18]. We used a spring orthosis as the basic platform, allowing T-WREX to be nonrobotic but still capable of assisting severely weakened patients in moving by providing gradable assistance against gravity with elastic bands. To achieve this, we collaborated with Dr. Tariq Rahman of the A.I. duPont Institute for Children, who also with NIDRR support had developed the innovative arm support called WREX to assist children with weakened arms in moving their arms [19]. We scaled up the WREX design to be large enough and strong enough to support movements by adults with a stroke.

We also designed T-WREX to support functional upper-extremity movements by integrating a grip sensor that allowed detection of even trace amounts of hand grasp, thus allowing people with weakened, essentially "useless" hands to practice using their hands in a meaningful way for simulated activities of daily living in a virtual world, in coordination with their arms. We developed a suite of computer games that were easy to learn yet engaging and which approximated the movements needed for cooking, shopping, bathing, and cleaning.

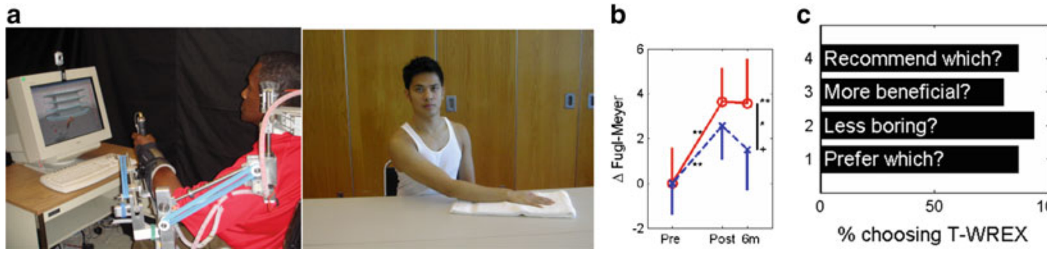

Fig. 28.1 **a** The T-WREX arm support exoskeleton was based on WREX and relieves the weight of the arm while allowing a wide range of motion of the arm. In a single-blind randomized controlled trial of T-WREX, we compared training with T-WREX to training of the arm on a tabletop with a towel. **b** Improvements in upper-extremity (UE) movement ability as measured with the UE Fugl–Meyer (FM) scale following chronic stroke with 2 months of T-WREX therapy (n = 14) and conventional tabletop exercise (n = 14) were significantly different at 6-month follow-up (p = 0.05). **c** Percentage of subjects preferring T-WREX therapy, compared to conventional, self-directed tabletop exercise, measured in our study. Subjects in both groups were given a chance to try each therapy and then select which one they preferred in ten categories, of which four are summarized here. (From Housman et al. [21] © 2009; reprinted with permission from SAGE Publications)

The first study of T-WREX quantified the effect of the gravity balance provided by T-WREX on voluntary arm movements. We measured how well volunteers with moderate-to-severe stroke (mean Fugl–Meyer upper-extremity score 25 out of 66, n = 9) could perform various arm movements while they wore the orthosis with and without arm gravity balance [18]. The most dramatic results came when the volunteers attempted to trace the outline of a large plastic disk placed in the frontal plane about 20 cm in front of their torso. The gravity balancing provided by T-WREX significantly improved the accuracy of the drawn circles for those who were able to draw a circle. Most strikingly, some participants who were unable to draw circles without support could draw them with support. Subsequent testing with T-WREX showed that the device improved the quality of movements of people with stroke, as measured by both the smoothness and timing of the movements [20].

As described next, we proceeded to test the therapeutic effects of providing assistance with T-WREX, which was eventually commercialized as ArmeoSpring by Hocoma A.G. and then further tested.

28.2 Summary of Clinical Evidence for the Effectiveness of Mechanically Assistive Devices

In this section, we discuss the evidence for the therapeutic effectiveness of training with mechanical assistance. We start with studies with T-WREX, progressing to studies with ArmeoSpring and other prominent mechanically assistive devices.

28.2.1 Effect of Movement Training Provided by T-WREX

We performed a pilot therapeutic test of T-WREX at UC Irvine [18]. Volunteers (n = 5) with moderate-to-severe arm impairment after chronic stroke (mean starting FM score 22) practiced moving with T-WREX three times per week, 45 min per session, over an 8-week period. They improved their movement ability as quantified by an average change in Fugl–Meyer score of 20% compared to baseline, hand grasp strength by 50%, as well as unsupported and supported reaching range of motion by 10%.

They achieved these improvements with approximately 6 min of direct contact with a rehabilitation therapist per 45 min of training.

Encouraged by these results, we refined T-WREX and performed a single-blind, randomized controlled trial of it at the Rehabilitation Institute of Chicago, under the supervision of the occupational therapist Sarah Housman [21]. We compared movement training with T-WREX against the standard approach for semiautonomous exercise at RIC, which was to train the weakened arm by using a tabletop to support the arm and a towel to remove the friction between the arm and the table (Fig. 28.1a). Twenty-eight chronic stroke survivors were randomly assigned to the experimental (T-WREX) or control (tabletop exercise) treatment. A blinded evaluator rated upper-extremity movement before and after 24 1-h treatment sessions and at a 6-month follow-up. The volunteers were also asked to rate their preference for T-WREX versus tabletop exercise after a single-session crossover treatment. The volunteers significantly improved upper-extremity motor control (Fugl–Meyer [22]), active reaching range of motion (ROM), and self-reported quality and amount of arm use (Motor Activity Log [23]). Improvements in the T-WREX group were better sustained at 6 months (Fugl–Meyer score improvement of 3.6 ± 3.9 versus 1.5 ± 2.7 points, mean $\pm$ SD, $p = 0.05$, Fig. 28.1b). The volunteers reported a strong preference for the T-WREX training compared to the tabletop training (Fig. 28.1c). The amount of supervision time required for both groups was about 3 min, following an initial training period of three sessions.

These results were encouraging: training with T-WREX produced detectably better results than a matched duration of the tabletop towel exercise and was substantially preferred by patients. It also required minimal direct supervision time.

28.2.2 Further Clinical Validation of the Mechanically Assistive Approach with ArmeoSpring

Hocoma AG licensed the intellectual property for T-WREX from the University of California at Irvine and then improved the mechanical, electrical, and software design of T-WREX for usability and manufacturability. The resulting ArmeoSpring device (Fig. 28.2) is as of 2021 being used in over 1000 rehabilitation facilities around the world. Multiple research studies have been conducted with ArmeoSpring measuring its therapeutic effects and expanding its use by other patient populations as we briefly review here.

Training with ArmeoSpring improved impairment and activity measures in chronic stroke patients with more mild hemiparesis than had been tested in previous studies with T-WREX (average starting Fugl–Meyer Upper-Extremity Score 45.7/66) [24]. Training with ArmeoSpring by individuals in the acute phase after stroke, as opposed to the chronic stage, was found to be about as effective as conventional one-on-one training with a therapist [25, 26]. In one of these studies, the group that trained with ArmeoSpring significantly improved shoulder range of motion and movement smoothness, while the control group did not [26]. The ArmeoSpring group also expressed higher satisfaction with the therapy [26]. ArmeoSpring was also combined with an iterative electrical stimulation system, allowing an improvement in UEFM score of almost 10 points in individuals with chronic stroke [27].

Another study used ArmeoSpring to investigate if the weight support provided by the device was in and of itself therapeutically advantageous [28]. This study compared the therapeutic effects of a single computer game, played alone, or with haptic input from a haptic robot, or with arm support from ArmeoSpring. All three groups

Fig. 28.2 ArmeoSpring, developed by Hocoma AG based on T-WREX, is designed to be more quickly adjustable than T-WREX for easier clinical use (Picture: Hocoma, Switzerland)

improved a comparable amount, although the haptic group improved more on the Box and Blocks score. The mechanical constraints inherent to ArmeoSpring (it doesn't allow shoulder internal/external rotation) appeared to prevent learning of some compensatory movements.

The largest study to date of ArmeoSpring is the REM-AVC trial, which was a multicenter RCT with a 12-month follow-up that enrolled 215 persons in the subacute phase after stroke [29]. The Exo group performed games-based exercises using ArmeoSpring. The control group performed stretching plus basic active exercises. The primary outcome was a change in upper-extremity Fugl–Meyer Assessment score at 4 weeks. The Fugl–Meyer score improved by 13.3 points in the Exo group and 11.8 in the control group ($P = 0.22$). The improvement in the primary functional measure, the ARAT, favored the Exo group (15.2 vs. 11.7 points), but only approached significance ($p = 0.07$). Participants in the Exo group rated the ease of learning and performing the self-rehabilitation significantly higher.

ArmeoSpring has also now been tested with other patient populations besides individuals with stroke. ArmeoSpring was found to increase the amount of training while reducing the amount of active therapist time required and to have a small therapeutic benefit for individuals with subacute cervical spinal cord injury, but only for individuals with partial hand function at baseline [30]. Training with ArmeoSpring benefited individuals with multiple sclerosis in a pilot study with ten individuals with a high level of disability [31], as well as individuals with proximal humeral fractures [32].

In terms of assessment, ArmeoSpring was shown to provide reliable measurement of active arm workspace for people with cervical spinal cord injury [33]. A variety of kinematic measurements obtained from ArmeoSpring during therapeutic game play accurately predicted clinical scores of upper-extremity movement ability after SCI [34].

Normative values for accuracy, speed, and smoothness for a single exercise using ArmeoSpring were recently established [35]. Analysis of kinematic data from the REM-AVC trial found that two processes are involved in the performance improvements measured when training with ArmeoSpring [36]. There is a fast process related to learning to use the exoskeleton and a slow process that reflects the reduction in upper-extremity impairment. Another analysis of REM-AVC data distinguished two clusters of persons with stroke: "Recoverers" for whom shoulder/elbow joint correlations converged toward the respective correlations for control participants, and "Compensators" for whom joint correlations diverged from that of control participants [37].

28.2.3 Other Mechanically Assistive Approaches

Other types of mechanically assistive devices have been developed and clinically tested, also demonstrating therapeutic benefits. We highlight three prominent devices here.

The FreeBal device [38–40] uses an overhead sling and cable/spring system to assist in three-dimensional movement and incorporates sensors and computer games. This device was commercialized as ArmeoBoom by Hocoma. In a multi-site study with 70 subacute stroke patients, training with ArmeoBoom produced comparable results to conventional training, although the patients rated the therapy as having higher interest and enjoyment than the conventional training [41].

The BATRAC [42] features two linear slides with hand grips positioned shoulder-width apart on a table with a joint allowing the linear slides to be raised or lowered to create an inclined plane (i.e. to allow forward motion of the hand to mechanically assist in raising the arm). This device was used to test a novel form of repetitive bilateral arm training with rhythmic auditory cueing (resulting in the acronym BATRAC). Training with BATRAC showed promise in an initial pilot study [43], with a follow-up randomized trial [44] indicating that the bilateral and/or rhythmic nature of the intervention leads to unique neural reorganizations compared to a matched dose of conventional (i.e. typically unilateral) arm training. A larger follow-up RCT (N = 111; [45]) found that training with BATRAC reduced arm impairment in chronic stroke patients by a modest amount compared with a matched dose of conventional one-on-one therapy. The BATRAC device was later commercialized as Tailwind.

Feys et al. used a rocking chair and arm splint to create a mechanically assistive arm training device [46]. They had patients with subacute stroke (N = 100) rock themselves backwards in rocking chairs by reaching forward to push against a rail for a total of 15 h (500–1000 reaches per day) with their extended elbows supported by the splint. These patients had significantly greater increases in UE Fugl–Meyer (FM) score of 17 points at a five-year follow-up [46] compared to a control group who were passively rocked. The Feys study supported the concept that early and repetitive practice of relatively simple arm movements can translate into clinically meaningful benefits, particularly if delivered early after a stroke at a high intensity.

28.3 Why is Mechanical Assistance Beneficial for Promoting Motor Recovery?

In this section, we discuss three plasticity-related mechanisms that appear to play a role in producing the therapeutic effect associated with training with mechanical assistance: motivation, neural strengthening, and proprioceptive effects.

28.3.1 The Motivational Effect

Mechanical assistance allows weakened people to practice movements that are normally impossible or difficult to practice. This has the effect of improving the motivation for training. In the words of a volunteer in a T-WREX study, "If I can't do something once, why would I do it a hundred times?" [47].

A recent study of robotic hand training rigorously tested the motivational effect of mechanical assistance [48]. Participants (n = 30) at least six months after stroke and with some residual hand movement ability (minimum Box and Blocks Test score = 3, average Box and Blocks Test score = 32 ± 18 SD, and upper-extremity Fugl–Meyer score = 46 ± 12 SD) actively moved their index and middle fingers to targets while playing the musical game similar to Guitar Hero 3 h/wk for 3 weeks, achieving about 8000 movements during the nine training sessions. The participants were randomized to receive high assistance (causing 82% success at hitting targets) or low assistance (55% success) using the FINGER robotic device [49]. Note that without assistance the participants in both groups could only achieve about 20% success on average. High assistance boosted motivation, as measured with the Intrinsic Motivation Inventory after every training session (Fig. 28.3 left). High assistance also boosted self-efficacy, measured as the self-predicted improvement in BBT each week (Fig. 28.3 middle).

Motivated patients will presumably practice with more engagement and at a greater frequency, particularly if left unsupervised. However, the effect of improved motivation may go beyond encouraging more and better practice by helping cement motor learning. In the FINGER robotic study described above, high assistance boosted the change in Upper-Extremity Fugl–Meyer score, particularly for individuals with more severe baseline motor impairment (Fig. 28.3 right). A potential explanation is that higher assistance improves success, which in turn promotes better motor retention through dopaminergic mechanisms, a known effect in motor learning studies [50].

28.3.2 The Strengthening Effect

Even if a user is more motivated when practicing with mechanical assistance, the motivation won't be of benefit unless there is a neural plasticity mechanism in play that improves sensory motor control through practice. One such mechanism relevant to rehabilitative movement training with mechanically assistive devices is neural strengthening.

Weakness is a major culprit in reducing functional ability after stroke [51–54]. Weakness following stroke primarily has a neurologic rather than muscular origin, as, for example, electrical stimulation can produce near-normal muscle forces [55]. Strength for unimpaired people also has a large neurologic component, as, for example, the initial increases in force production caused by strength training cannot be explained by muscle hypertrophy, which requires time-delayed protein synthesis [56]. Further,

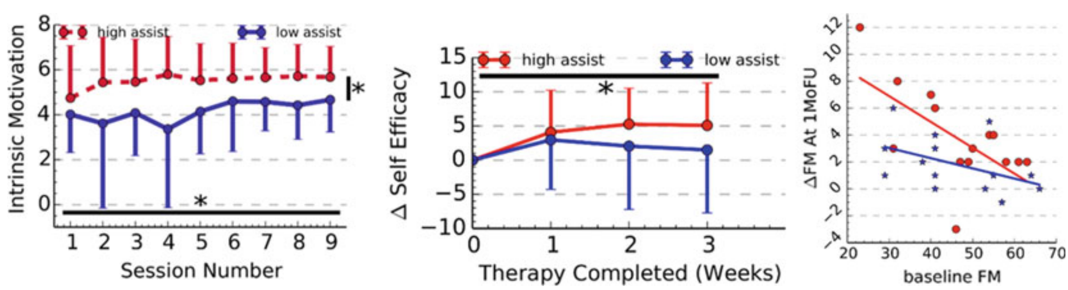

Fig. 28.3 Left: High mechanical assist provided by the FINGER robotic training device boosted self-reported motivation across the nine finger movement training sessions, judged by the Intrinsic Motivation Inventory. Middle: High assist also boosted self-efficacy across the three weeks of training. Self-efficacy was measured by asking participants to estimate how many more blocks they thought they could move in the Box and Blocks Test each week. Right: High robot assist (red) benefited Upper-Extremity Fugl–Meyer score at the one-month follow-up (1MoFU) more than low assist (blue), especially for more severely impaired participants. At the 1-month follow-up assessment, the intercept of the high-assistance group was significantly higher (Fig. 28.3E), P = 0.03, and the difference in slopes trended toward significance, P = 0.13. The figure was used with permission from [48]

imagined contractions alone can improve maximum force output [56].

Active assist movement training has been found to be beneficial for neural strengthening, almost certainly because such training requires an efferent contribution from the patient [57, 58]. Mechanically assistive devices are mechanically passive (i.e. unpowered) devices, so they will not move unless the patient initiates and drives the movement. Thus, when a patient practices with a mechanically assistive device, one should expect improvements in the neurally mediated component of strength due to repetitive efferent activation. Strength improvements, in turn, should translate into better movement ability, particularly for very weak patients, since weakness is a major culprit in reducing functional ability after stroke, as noted above.

28.3.3 The Proprioceptive Effect

A third, more speculative explanation for why movement training with mechanical assistance is therapeutic relates to proprioception. When a person moves poorly with reduced speed and range, they generate a paucity of proprioceptive input to their motor system. Mechanical assistance likely enhances the diversity of proprioceptive information delivered to the brain during training by allowing people to move with a greater variety of speeds, ranges, and directions. This may in turn promote beneficial sensory motor plasticity, through use-dependent or Hebbian-like mechanisms.

If this proprioceptive hypothesis is true, then we should expect the outcomes of movement training to depend on the integrity of proprioception at baseline. In the FINGER robotic hand training study mentioned above [48], the primary outcome was a functional measure of fine manipulation ability—the BBT score at one-month follow-up. There was no difference between groups in the primary endpoint. However, individuals with more impaired finger proprioception at baseline (measured with the FINGER Crisscross Assessment) benefited less from the training in terms of BBT ($R2 = 0.335$, $p = 0.002$) regardless of the assist mode applied. Thus, the efficacy of robotic finger therapy in promoting hand function depended on finger proprioception at baseline.

This result was mapped to a neuroanatomical basis by examining over 60 measures of clinical characteristics, sensor motor behavior, neural injury (via MRI-based analysis of both sensory and motor structures), and neural function (via activation and connectivity analysis using fMRI and resting-state EEG) to explain the observed variability in treatment response [59]. Proprioceptive ability and measures of somatosensory network injury and function best explained inter-subject differences in treatment-related hand function gains.

Impaired proprioception was also found to be one of the strongest predictors of therapeutic benefit in one of the largest, most successful upper-extremity RCTs for persons with a stroke, the EXCITE clinical trial [60]. This study reported that "Patients with impaired proprioception had a 20% probability of achieving a clinically meaningful outcome compared with those with intact proprioception". From a computational neuroscience perspective, these results make sense: proprioception likely provides the teaching signal in both supervised learning and reinforcement-learning processes that shape neural activity after stroke [61]. Further, a more diverse stimulation of proprioceptive pathways, such as occurs when gravity assistance is provided, likely stimulates plasticity of those pathways better than a more stereotyped stimulation.

28.4 Democratizing Mechanically Assistive Devices

While mechanically assistive devices such as ArmeoSpring have proven useful, access to such devices is limited because of cost. This fact was highlighted by a visit to our laboratory by Dr. Don Schoendorfer, the founder of Free Wheelchair Mission, a non-profit organization that seeks to provide low-cost wheelchairs to more than 100 million individuals in developing nations who cannot afford a wheelchair [62].

While Dr. Schoendorfer was enthusiastic about robotic rehabilitation technologies, he challenged us to develop simpler devices. We review our attempts here, which are focused on using a ubiquitous mechanically assistive device for mobility—the manual wheelchair—as a platform for a more accessible mechanically assistive arm training device.

28.4.1 Resonating Arm Exerciser (RAE)

We first developed a lever-based device that provides mechanical assistance for arm training but in a much simpler way than T-WREX or ArmeoSpring. The Resonating Arm Exerciser (RAE) is comprised of a lever and arm support that attaches to a wheelchair wheel and enables users to practice something like the stationary "rocking therapy" used in the Feys study described above while seated in their wheelchair (RAE, see [63, 64]) (Fig. 28.4 left).

In a home-based randomized controlled trial with persons with severe arm impairment after chronic stroke, we found that the use of RAE reduced UE impairment more than a conventional home exercise program [64]. We also found that individuals with subacute stroke could safely perform hundreds of reaching movements per day with RAE [64]. We also tested RAE in a rehabilitation facility in Vietnam with physical therapist collaborators from Cal State Northridge, resulting in positive clinical results [65].

However, the key feedback from patients and clinicians in these studies was that, although RAE was simple and effective, it rendered the user's wheelchair immobile, and it was too troublesome to keep attaching and removing RAE when they desired to use the wheelchair in the normal fashion.

28.4.2 Lever-Assisted Rehabilitation for the Arm (LARA)

Taking this feedback into account, we next developed a novel lever-driven wheelchair (LARA, see [66–72]) that was designed to be used as a user's primary wheelchair, thus enabling UE rehabilitation without sacrificing mobility, requiring a transfer, or requiring a separate device to be attached to the wheelchair before use (Fig. 28.4 middle). Specifically, LARA allowed people to perform stationary UE rehabilitation in their wheelchair by moving attached levers back and forth with their impaired arm or to propel their wheelchair bimanually with the levers using a hand clutching system to repeatedly engage and disengage the lever from the wheel. By timing the hand clutching with arm movement, the user can steer, ambulate, and even turn in place.

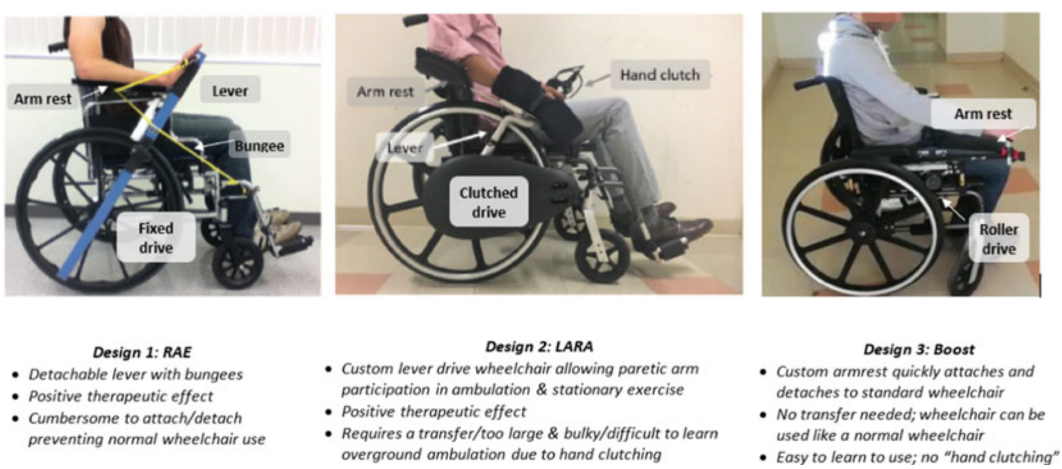

Fig. 28.4 Three design cycles toward a wheelchair-based, mechanically assistive arm training device

Using motion capture and EMG, we confirmed that persons with stroke achieved wheelchair propulsion with LARA by moving their impaired arm with normative biomechanics while activating elbow extension muscles [70]. We then tested LARA in a pilot, two-site randomized controlled trial with individuals with subacute stroke. We found that both stationary and overground exercise with LARA led to a significantly greater reduction in arm impairment than conventional treatment at a one-month follow-up [73], conforming Fey's initial observation that early, repetitive stimulation of the arm is beneficial.

However, clinicians were still resistant to the idea of using LARA in routine clinical practice because it required too much cognitive demand for patients to learn to use the hand clutching and it was too bulky to be used as a patient's primary wheelchair. Therapists also did not like the idea of having to transfer patients to another large piece of rehabilitation equipment (i.e. a standalone LARA chair) and worried about where they would physically store LARA when not in use. They stated they would use a device like LARA if it were smaller and could be quickly attached to a patient's conventional manual wheelchair without impeding normal use/mobility.

28.4.3 Boost

In a third design iteration, we synthesized the lessons learned from the experiences with RAE and LARA and invented a method to deliver in-wheelchair UE rehabilitation in a clinically and commercially viable hardware package, resulting in Boost (Fig. 28.4 right). Boost replaces a conventional manual wheelchair's existing armrest by quickly and easily "clicking in" to the existing armrest slots. Once attached, Boost safely supports the arm in an ergonomic posture while enabling individuals to practice a full range-of-motion forward reaching task in two modes: (1) against low resistance and with an adjustable range of motion to achieve a "rep", with the chair remaining stationary ("Stationary Mode"), or (2) against moderate resistance provided by the wheelchair wheel itself through an innovative one-way reel-drive that translates forward pushing into rotation of the wheel ("Overground Mode"). In Overground Mode, the user contributes to propelling their wheelchair with their impaired arm.

The reel-drive is comprised of a cable attached to the armrest that is then wrapped around a reel, which is in turn coupled to a friction disk via a one-way bearing. When the armrest is pushed forward, the cable spins the reel. When the reel is engaged with a mechanical switch for Overground Mode, it drives the wheelchair tire via the friction disk. After completing a push, a torsional spring inside the reel pulls the cable back, assisting the user in returning their arm to its initial position.

Critically, Boost's small and lightweight design does not interfere with the practice of the "good arm + good leg" propulsion technique currently taught to stroke survivors, which is essential for timely discharge from the hospital. Rather, it transforms this compensatory propulsion technique into a "good arm + good leg + impaired arm" therapeutic technique, encouraging the use of the paretic limb. That is, the patient can choose to try to incorporate their impaired arm as they ambulate in their wheelchair, thus stimulating their arm motor system.

In unpublished pilot testing of Boost with five subacute stroke patients with arm impairment, all were able to exercise the arm with Boost in stationary mode. Three ambulated overground exceeding 2 m/s after 2–5 practice trials. Two of these three were unable to push the rim to propel the wheelchair. Thus, this dynamic armrest provides a way to train arm movement, right on the wheelchair.

We recently solicited feedback on Boost from 16 physical and occupational therapists from two different hospitals. They strongly agreed that Boost was easy to set up, intuitive for patients to use, may improve their patients' motor recovery, and may improve their patients' wheelchair mobility. In addition, 100% reported that they would use Boost during one-on-one therapy sessions with moderately impaired patients, and

88% with severely impaired patients. 88% said they would allow moderately impaired patients to use Boost in the clinic between therapy sessions, and 94% would want patients to use Boost on their own at home. We are now proceeding to a randomized controlled trial to test whether we can provide early, repetitive arm stimulation with Boost and whether that stimulation is both pragmatic and therapeutic.

28.5 Conclusion

In this chapter, we traced the evolution of mechanically assistive devices for upper-extremity arm therapy after stroke, starting with a case study of T-WREX/ArmeoSpring. We briefly reviewed the large body of evidence that indicates that repetitive movement training with such devices is therapeutic, resulting in modest reductions in arm impairment that are comparable in magnitude to other forms of intense movement training. We focused mainly on arm therapy, as providing mechanical assistance for hand movement is challenging because the hand changes orientation with respect to gravity, and hand forces are often dominated by passive and spastic restraint. However, the mechanical assistance approach has been applied with success to the hand as well (see for example [74, 75]).

Importantly, mechanical assistance has also now been proven to improve motivation for training. We discussed how training with mechanical assistance also likely causes improvements in the neural component of strength, particularly for weak individuals, and may also improve the diversity of proprioceptive input to the brain, with therapeutic benefit. An important direction for future research is to precisely define the relative advantages and disadvantages of non-powered, mechanically assistive devices compared with powered ones.

Finally, we discussed a user-centric, iterative design approach that makes use of a patient's wheelchair armrest to provide mechanical assistance for arm training. We are hopeful that this approach can democratize mechanical assistance, making it accessible to a large number of people.

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