Published in final edited form as:

Phys Med Rehabil Clin N Am. 2015 November ; 26(4): 691–702. doi:10.1016/j.pmr.2015.06.003.

Robotic Therapy and The Paradox of the Diminishing Number of Degrees of Freedom

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Keywords

Robotic Therapy; Rehabilitation Robotics; Stroke; Impairment-Based Therapy; Functional-Based Therapy; Degrees-of-Freedom

Introduction

Disruptive Technology

Three years ago we discussed the concept of disruptive technology and rehabilitation robotics¹ [1]. As described then and replicated here, disruptive technology is a term coined to characterize an innovation that disrupts an existing market or way of doing things and creates a new value network. The concept was first described at Harvard Business School by Clayton M. Christensen, who described the concept in 1996 as: "Generally, disruptive innovations were technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches [2] [3]. They offered less of what customers in established markets wanted and so could rarely be initially

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Disclosures:

H. I. Krebs and N. Hogan are co-inventors of several Massachusetts Institute of Technology-held patents for the robotic technology. They hold equity positions in Interactive Motion Technologies, Watertown, MA, USA the company that manufactures this type of technology under license to MIT.

¹Parts of this review have been published elsewhere.

employed there. They offered a different package of attributes valued only in emerging markets remote from, and unimportant to, the mainstream." Eventually with improvement, borrowing from Malcolm Gladwell, the moment of critical mass, the threshold, the boiling point is reached and the old practices and existing value network is abandoned in favor of the new one, also referred to "the tipping point" [4].

Upper Extremity Robotic Therapy: The Tipping Point

Since the publication of the first controlled study with stroke inpatients[5], several studies have been completed with both stroke inpatients and outpatients demonstrating the potential of robotic therapy for the upper extremity. These results were discussed in different meta-analyses (see for example: [6-8]) and led to the 2010 American Heart Association (AHA) guidelines for stroke care which recommended that: "Robot-assisted therapy offers the amount of motor practice needed to relearn motor skills with less therapist assistance... Most trials of robot-assisted motor rehabilitation concern the upper extremity (UE), with robotics for the lower extremity (LE) still in its infancy... Robot-assisted UE therapy, however, can improve motor function during the inpatient period after stroke." AHA suggested that robot-assisted therapy for the UE has already achieved Class I, Level of Evidence A for Stroke Care in the Outpatient Setting and Care in Chronic Care Settings. It suggested that robot-assisted therapy for UE has achieved Class IIa, Level of Evidence A for stroke care in the inpatient setting. Class I is defined as: "Benefit >>> Risk. Procedure/Treatment SHOULD be performed/administered;" Class IIa is defined as: "Benefit >> Risk, IT IS REASONABLE to perform procedure/administer treatment;" Level A is defined as "Multiple populations evaluated: Data derived from multiple randomized controlled trials (RCTs) or meta-analysis" [9].

The 2010 Veterans Administration/Department of Defense guidelines for stroke care came to the same conclusion endorsing the use of rehabilitation robots for the upper extremity, but went further to recommend against the use of robotics for the lower extremity. More specifically, the VA/DOD 2010 guidelines for stroke care "Recommend robot-assisted movement therapy as an adjunct to conventional therapy in patients with deficits in arm function to improve motor skill at the joints trained." However more needs to be done particularly for the lower extremity as stated in the VA/DOD guidelines: "There is no sufficient evidence supporting use of robotic devices during gait training in patients post stroke" and "Recommendation is made against routinely providing the intervention to asymptomatic patients. At least fair evidence was found that the intervention is ineffective or that harms outweigh benefits" [10].

Presently the largest single study of upper extremity robotics confirms these endorsements for the upper extremity. The multi-site, independently run, Veterans Affairs trial CSP-558 (VA-ROBOTICS) on upper extremity rehabilitation robotics employing the commercial version of the MIT-Manus robot for shoulder-and-elbow therapy together with the corresponding anti-gravity, wrist, and hand robots [11] included 127 Veterans with chronic stroke at least 6 months post-index stroke with an impairment level characterized by very severe to moderate (Fugl-Meyer Assessment between 7 to 38 out of 66 points for the upper extremity). Veterans with multiple strokes were included in this study that lasted for 36

weeks: a 12-week intervention followed by a follow-up period lasting 6-months. Veterans were randomly assigned to either the robotic therapy group (RT, N=49), the intensity-matched comparison group (ICT, N=50), and the usual care group (UC, N=28). VA-ROBOTICS compared the efficacy of robot-mediated therapy (RT) to usual care (UC) and to intensive comparison therapy (ICT). Usual Care was not dictated or prescribed by the protocol. The treatment was allowed to vary as per therapy targeting specifically the upper extremity, which consisted of an average of 3 sessions per week from therapists delivering treatment as they deemed clinically appropriate for the upper extremity. The RT group received 3 sessions per week of robotic training for the shoulder-and-elbow, wrist, and hand that delivered 1,024 movements per session. The ICT group received 3 sessions per week of a therapy created to have a therapist deliver comparable movement intensity and repetition as the RT group during the same period. Contrary to other rehabilitation studies that employed a control intervention expected to have little effect on the primary outcome[12-14], VA-ROBOTICS was unique in that it included an active control treatment group. The study was based on the hypothesis that RT group would experience greater improvement in motor impairment at 12 weeks compared with the UC and ICT groups, as measured by the upper extremity component of the Fugl-Meyer scale. Of note, the ICT intervention is not conventional therapy. It employs manual techniques but would likely be impractical to implement as clinical therapy. It is unlikely that therapists could consistently assist the paretic arm during standard clinical care for almost 1,000 movements per session as done for the ICT group (instead of the typical 45 movements per session in usual care for chronic stroke patients [15]). We created this control treatment specifically to afford an objective cost analysis [16].

Results

The first and perhaps most understated finding of the VA-ROBOTICS was that usual care did not reduce impairment, disability, or improve quality of life in chronic stroke survivors. The usual care intervention had no measureable impact and, to conserve financial resources, it was discontinued as futile midway through the study.

The comparison between the RT and UC groups included: a) the comparison between the robot group and usual care subjects which involved roughly only the first half of the RT group while the UC was not discontinued, and b) whether the changes were robust and long lasting. On this score, robot therapy was statistically superior to usual care in Stroke Impact Scale (quality of life) at the completion of the intervention and also in the Fugl-Meyer (impairment) and Wolf Motor Function (function) 6 months following the completion of the intervention.

The results are far more impressive if we compare the whole robot therapy group with the usual care and not just the analysis that focused on the first half of the study. While the results at 12 weeks showed that the difference between the first half of the robotic treatment group and usual care was over 2 Fugl-Meyer points, the difference between the complete robotic treatment group and usual care was 5 points in the Fugl-Meyer assessment, which corresponds to a Minimum Clinically Important Difference (MCID) in chronic stroke (see Figure 1 [17-19]).

The reason(s) for the smaller clinical effects of the robotic intervention in the first stage of the study when compared with the second stage of the study have not been established. We believe this discrepancy is most likely due to the omission of a “phase-in” stage in this study [20]. When testing a new therapy, it is common practice to treat a predetermined number of subjects during the initial phase of the trial with the new therapy at each site before beginning data collection for the actual controlled trial in order to gain familiarity and expertise with the novel treatment and streamline the process. Nevertheless, even without a “phase-in” stage, VA-ROBOTICS demonstrates the robustness of the results: even when therapists are learning how to use the novel tools and cannot deliver the complete protocol in the prescribed period, the results are better than usual care.

The comparison between the RT and ICT groups did not show any difference [16]. Note also that patients in the RT group continued to improve even after the intervention was completed at 12 weeks. Thus, the continued and persistent improvement at the 6-month follow-up evaluation suggests improved robustness and perhaps an incremental advantage that prompted further improvement even without intervention. For example, an improvement of roughly 3 points in the Fugl-Meyer scale might enable a very severe patient to start to raise his/her arm and to bathe independently, or to start to stretch the formerly paralyzed arm so that independent dressing could take place. It might enable a more moderate stroke patient to start to tuck in the shirt or to hike the pants independently, or to start to reach overhead and actively grasp an object.

This continued improvement after completion of the intervention is quite remarkable as VA-ROBOTICS included patients with chronic stroke disability in the moderate to severe range and over 30% had multiple strokes. As such, the majority of this group represented a spectrum of disability burden that many studies have avoided. Moreover, 65% of the volunteers interviewed were enrolled. Taken together, these observations suggest that robotic therapy for the upper extremity offers an opportunity to a broad spectrum of stroke patients.

Cost Outcomes

In this era of cost containment, an important and unexpected result arose from the recently completed cost-benefit analysis [21]. The purchase cost of the four InMotion robotic modules (shoulder-elbow, wrist, anti-gravity, and hand – Interactive Motion Technologies, Watertown, MA – see figure 2) was \$230,750; the interest rate on borrowing to purchase these robots was estimated at 6.015% with 33% facility overhead on top of the purchase value, and a \$5,000 annual maintenance fee per robot. Yet, the additional cost of delivering RT or ICT was \$5,152 and \$7,382 respectively and the difference was statistically significant ($P<0.001$). While the active interventions (RT and ICT) added cost, when we compared total cost, which includes the clinical care needed to take care of these Veterans for the 36 weeks of the trial (12 weeks of intervention and 6 months without any active intervention), there were no differences between active intervention and usual care. The total cost for the VA was roughly the same: \$17,831 for robot therapy, \$19,746 for the intensive comparison group, and \$19,098 for the usual care. The usual care group used the rest of the health care system more often than the active intervention groups. In other words, for 36

weeks of care the robotic group cost the VA \$5,152 for robotic therapy and \$12,679 for clinical care. For 36 weeks of care the usual-care group cost the VA approximately \$19,098.

We initially speculated that perhaps the surprising decreases in healthcare cost were due to a placebo or Hawthorne effect; the active groups (RT and ICT) received extra attention during the 36 weeks' trial duration. To determine whether that was the case, the VA health economists (Palo Alto VA, Stanford University, CA) continued to collect cost data on these patients. If a placebo or Hawthorne effect accounted for a significant component of the observed cost reductions, one might expect costs to drift upward after trial completion. On the contrary, they did not for the robotic therapy group. The health care cost until the end of September 2009 (after the 36 weeks of the trial) averaged \$7,777 for the RT group and \$14,513 for the ICT group; this difference was statistically significant ($P<0.04$). In a nutshell, at least in the VA system, these results suggest better care for the same total cost.

Lower Extremity Robotic Therapy: in its infancy

The two most common lower extremity (LE) robotic rehabilitation devices are the Lokomat (Hocoma, Switzerland) and the Autoambulator (Healthsouth / Motorika, Israel). There are already over 500 Lokomats and 100 Autoambulators in clinical settings, yet the negative perception of LE robotic rehabilitation is not without merit. While the installed robotic base is reasonably large, there are few published RCTs supporting their use. In fact, some of the large studies employing the Lokomat (Hocoma, Zurich, Switzerland) showed statistically significantly inferior results when compared to those produced by usual care as practiced in the US for both chronic as well as for sub-acute stroke patients [22] [23]. Of course, the characteristics and intensity of usual care might vary according to the country and, hence, it is important to acknowledge that these results are primarily valid for the US. Nevertheless, these discouraging results demand explanation.

There are many plausible reasons for these results and the apparent immaturity of lower extremity robotic therapy. Given the success of upper extremity robotic therapy, it seems unlikely that the difficulties can be attributed to the use of technology. Instead, we believe one important factor is that we need to better understand the difference between “best practices” and tested practices. Clinicians and technologists assumed that body-weight-supported treadmill training (BWSTT) delivered by two or three therapists was an effective and superior form of therapy compared to usual care and, thus, automating BWSTT appeared to be a logical approach. However, an NIH-sponsored RCT demonstrated that, contrary to the hypothesis of its clinical proponents, BWSTT administered by 2 or 3 therapists for 20 to 30 minutes followed by 20 to 30 minutes of over ground carry-over training did not lead to superior results when compared to a home program of strength training and balance (LEAPS Study [13]). Importantly, the comparison treatment was designed to provide an equal number of sessions and time spent in therapy; to evoke a cardiovascular response similar to BWSTT; to be sufficiently credible that participants considered themselves involved in meaningful therapy; but “...expected to have little or no effect on the primary outcome, gait speed”[24]. These are landmark results that must be seriously acknowledged by both roboticists and clinicians: the goal of rehabilitation robotics is to optimize care and augment the potential of individual recovery. It is not to automate

current rehabilitation practices which for the most part lack a scientific evidential basis, primarily due to the lack of tools to properly assess the practices themselves [25].

Defining Success in Robotic Rehabilitation

We must define a benchmark to determine whether a disruptive technology has gone beyond emerging markets and passed a “tipping point” to enter the mainstream [4]. In order to satisfy all perspectives and users without generating too much controversy, we believe that the success of a therapeutic neuro-rehabilitation can be defined by positive answers to all of the following questions:

1. Does the therapy help?
2. Does the therapy help more than the “usual” standard of care?
3. Does the therapy help more than the “usual” standard of care at the same or lower cost? OR if higher cost, does it present a positive cost/benefit ratio?

Take the example of VA-ROBOTICS: the researchers compared three sets of chronic stroke patients receiving upper extremity robotic therapy, an intensity matched comparison group, and a usual care group in the VA system.

While the robotic and intensity matched therapy groups improved, the usual care group did not satisfy the first criterion: it did not lead to any measureable improvement in chronic stroke.

The robotic and intensity matched therapy groups also satisfied the second criterion: robotic group and intensity matched group improved more than usual care.

When we benchmark these groups against each other in terms of cost, robotic therapy for the upper extremity was considerably cheaper than the intensity comparison group and it led to slightly lower overall healthcare cost (intervention plus all the healthcare utilization costs) than both the usual care and the intensity matched comparison group, thereby satisfying the third benchmark at least in the VA system and we will soon learn whether the same is true in the United Kingdom (<https://research.ncl.ac.uk/ratuls/>).

In view of these three positive answers to our benchmarks, one can argue that upper extremity interactive robotic rehabilitation has reached the tipping-point [4] moving it into mainstream rehabilitation services.

Beyond the Tipping Point: Functional Rehabilitation

Despite the evidence of success, there is little doubt that further progress is sorely needed² [26]. In what follows, we review an evidence-based example that challenges a perceived best practice and argue how to move the field further. A postulated best practice to increase therapy effectiveness beyond past studies is to develop new whole-arm functionally-based approaches that better integrate robotic treatment with clinical practice to enhance the carry-over of robot trained movements into functional tasks. Two potential approaches to deliver

²Parts of this review have been published elsewhere.

such functional training are: 1) to train functional tasks with the robot or alternatively, 2) to aim at impairment reduction at the capacity level with different robotic modules, breaking these functional tasks into components and relying on the therapist to facilitate carry-over of observed impairment gains from robotic training into functional activities.

We explore these two approaches with the expectation based on the perceived best practice that a robotic treatment protocol, properly targeted to emphasize a sequence and timing of sensory and motor stimuli similar to those naturally occurring in daily life tasks, could facilitate carry-over of the observed gains in motor abilities, thereby conferring greater improvements in functional recovery. This approach is a departure from for example the VA-ROBOTICS study mentioned earlier or the RATULS study (<https://research.ncl.ac.uk/ratuls/>), which was based on a “*bottom-up*” approach and assumed that improvements in underlying capacities would enhance motor function during activities and tasks, leaving it to the therapist to concatenate the different impairment gains into a coherent set of functional gains. We envisioned, instead, that functional rehabilitation robotics might be guided by a “*top-down*” rehabilitation approach, in which a person’s identified goals for task performance are used in conjunction with our evaluation data to establish a treatment plan. Robotic technology would not only provide remediation for impairments at the capacity or body function levels (e.g. strength, isolated movement), but would also provide task specific, intensive therapy for impaired body functions (e.g. coordination of limb movement) that underlie task performance or activities. While this top-down rationale is in line with current therapy views, there is some evidence that questions this view and raises the possibility that the opposite might be correct. For example, Platz has shown that therapy aiming at impairment reduction seems to lead to better outcomes than functional/Bobath training for inpatients with severe impairment [13].

As a first step toward applying this “top down” approach to rehabilitation robotics, we wanted to investigate the effects of different robotic therapy approaches on subjects’ ability to reach, grasp, and release with the paretic arm and hand. We compared the effects of repetitive upper limb reaching training to a protocol in which integrated reach, grasp, and release training was implemented. We hypothesized that training the shoulder-elbow, wrist, and hand together (transport of the arm to the target and grasping/releasing an actual or a virtual object) should lead to better outcomes than simple training for one of the components of this functional task, namely transport of the arm (reaching or pointing to the target). Remarkably, the functionally-based approach which integrated training of limb transport with grasp/release did not outperform the impairment-based approach training of limb transport in isolation [26].

Expanding this idea further, Reinkensmeyer employed a novel a 6-DOF exoskeleton (“BONES” – see figure 3) that allows movement of the upper limb to assist in rehabilitation. His objectives were to evaluate the impact of training with BONES on function of the affected upper limb, and to assess whether multi-joint functional robotic training would translate into greater gains in arm function than single joint robotic training also conducted with BONES. He employed a crossover design and tested 20 community dwelling volunteers with mild to moderate chronic stroke. Each subject experienced three sessions per week, for four weeks, of multi-joint functional training and single joint training (eight weeks

total) with the order of presentation of the different approaches randomized [27]. Training with the robotic exoskeleton resulted in significant improvements in Box and Block Test (BBT), Fugl-Meyer Arm Motor Scale (FMA), Wolf Motor Function Test (WMFT), Motor Activity Log (MAL), and quantitative measures of strength and speed of reaching, and these improvements were sustained at the 3 month follow-up. However, comparing the effect of type of training on the gains obtained, no significant difference was noted between multi-joint functional and single joint impairment training programs. These results confirmed those reported by Krebs [26] and Platz [28]. They suggest that multi-joint functional training is not decisively superior to impairment training. This observation was further corroborated in an RCT employing the Armeo-Power and functional training, which achieved an advantage of only 0.78 points on the Fugl-Meyer Assessment over usual care as practice in Switzerland [14]. This challenges the idea that functionally-oriented games and training is a key element for improving behavioral outcomes; perhaps “breaking it down is better” [29].

The Paradox of the Diminishing Number of Degrees of Freedom

Our work on multi-joint functionally-based robotic therapy leads to an additional question: how many degrees-of-freedom should a robot provide for a particular patient? Because the evidence is yet sparse, one should take our speculations with the appropriate caveats, but we strongly believe in what one of us, Saitoh, described as the “Paradox of the Diminishing Number of Degrees of Freedom (DOF).” The paradox is that in order to reduce a person’s impairment and increase his/her motor control on a larger number of degrees of freedom, we might need to reduce the number of DOFs of the devices in which they train. The paradox can be best explained following figure 4. A patient with severe impairment should train in a rehabilitation robotic device with the smallest number of DOFs that provide challenge and some level of success. Training should be enhanced to a robotic device with additional DOFs only when a ceiling effect is observed. The Paradox also holds for assistive technology.

Conclusion

In our opinion, robotics are not a general panacea for stroke recovery; in fact, for clinically effective training there should be a mandatory number of movements per session along the lines of the 10,000 hours of practice required to attain “expert athlete” levels of physical performance. Interactive robots delivered therapy achieved 1,000 to-and-from movements per 45-minutes of therapy session, far in excess of the 45 movement attempts under standard care [15]. Furthermore, VA-ROBOTICS represents the tipping point of upper extremity robotic therapy. We contend that robotic therapy for the upper extremity that involves an interactive high intensity, intention-driven therapy based on motor learning principles and assist-as-needed leads to better outcomes than usual care in chronic stroke (and probably with even a greater impact for sub-acute strokes). Moreover, this treatment modality is now practical to implement in the clinical realm. But much remains to be answered and researched.

We still don’t know how to tailor therapy for a particular patient’s needs. One example presented here based on evidential data suggests that many of the perceived best practices

(such as delivering functionally-based rehabilitation approaches instead of impairment-based) need to be carefully examined; our results did not support this hypothesis. We speculate that until a minimum set of body functions are present, intensive robotic training might serve a patient better if it focuses on impairment—in line with the Paradox of the Diminishing Number of Degrees of Freedom—leaving the functional integration of those gains for a later phase under the supervision of a therapist.

The situation is less bright for the lower extremity. While we cannot argue with data nor with AHA or VA/DOD statements that robotic for lower extremity is still in its infancy, we believe that the field can mature and demonstrate its promise for lower extremity rehabilitation. We and other research groups are working towards such a goal of properly understanding the neuroscientific basis of gait and stroke recovery and of exploring creative solutions to move robotic therapy for the lower extremity to the same standing as upper extremity. Whether for the upper or lower extremities, therapeutic robotics is still a work in progress.

Acknowledgments

This work was supported in part by grant from NIH R01 HD069776 to H.I.Krebs and the Eric P. and Evelyn E. Newman Fund.

REFERENCES

- [1]. Krebs HI, Hogan N. Robotic therapy: the tipping point. *Am J Phys Med Rehabil.* Nov.2012 91:S290–7. [PubMed: 23080044]
- [2]. Christensen, CM.; Suárez, FF.; Utterback, JM. Strategies for survival in fast-changing industries. International Center for Research on the Management of Technology, Sloan School of Management, Massachusetts Institute of Technology; Cambridge, MA: 1996.
- [3]. Christensen, CM. The innovator's dilemma : when new technologies cause great firms to fail. Harvard Business School Press; Boston, Mass: 1997.
- [4]. Gladwell, M. The tipping point : how little things can make a big difference. 1st. Little, Brown; Boston: 2000.
- [5]. Aisen ML, Krebs HI, Hogan N, McDowell F, Volpe BT. The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. *Arch Neurol.* Apr.1997 54:443–6. [PubMed: 9109746]
- [6]. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabil Neural Repair.* Mar-Apr;2008 22:111–21. [PubMed: 17876068]
- [7]. Norouzi-Gheidari N, Archambault PS, Fung J. Effects of robot-assisted therapy on stroke rehabilitation in upper limbs: systematic review and meta-analysis of the literature. *J Rehabil Res Dev.* 2012; 49:479–96. [PubMed: 22773253]
- [8]. Mehrholz J, Hadrach A, Platz T, Kugler J, Pohl M. Electromechanical and robot-assisted arm training for improving generic activities of daily living, arm function, and arm muscle strength after stroke. *Cochrane Database Syst Rev.* 2012; 6:CD006876. [PubMed: 22696362]
- [9]. Miller EL, Murray L, Richards L, Zorowitz RD, Bakas T, Clark P, Billinger SA, N. American Heart Association Council on Cardiovascular; C. the Stroke. Comprehensive overview of nursing and interdisciplinary rehabilitation care of the stroke patient: a scientific statement from the American Heart Association. *Stroke.* Oct.2010 41:2402–48. [PubMed: 20813995]
- [10]. G. Management of Stroke Rehabilitation Working. VA/DOD Clinical practice guideline for the management of stroke rehabilitation. *J Rehabil Res Dev.* 2010; 47:1–43.

- [11]. Lo AC, Guarino PD, Richards LG, Haselkorn JK, Wittenberg GF, Federman DG, Ringer RJ, Wagner TH, Krebs HI, Volpe BT, Bever CT Jr, Bravata DM, Duncan PW, Corn BH, Maffucci AD, Nadeau SE, Conroy SS, Powell JM, Huang GD, Peduzzi P. Robot-assisted therapy for long-term upper-limb impairment after stroke. *N Engl J Med*. May 13.2010 362:1772–83. [PubMed: 20400552]
- [12]. Wolf SL, Winstein CJ, Miller JP, Taub E, Uswatte G, Morris D, Giuliani C, Light KE, Nichols-Larsen D, Investigators E. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial. *JAMA*. Nov 1.2006 296:2095–104. [PubMed: 17077374]
- [13]. Duncan PW, Sullivan KJ, Behrman AL, Azen SP, Wu SS, Nadeau SE, Dobkin BH, Rose DK, Tilson JK, Cen S, Hayden SK, Team LI. Body-weight-supported treadmill rehabilitation after stroke. *N Engl J Med*. May 26.2011 364:2026–36. [PubMed: 21612471]
- [14]. Klamroth-Marganska V, Blanco J, Campen K, Curt A, Dietz V, Ettlin T, Felder M, Fellinghauer B, Guidali M, Kollmar A, Luft A, Nef T, Schuster-Amft C, Stahel W, Riener R. Three-dimensional, task-specific robot therapy of the arm after stroke: a multicentre, parallel-group randomised trial. *Lancet Neurol*. Dec 27.2013
- [15]. Lang CE, Macdonald JR, Reisman DS, Boyd L, Jacobson Kimberley T, Schindler-Ivens SM, Hornby TG, Ross SA, Scheets PL. Observation of amounts of movement practice provided during stroke rehabilitation. *Arch Phys Med Rehabil*. Oct.2009 90:1692–8. [PubMed: 19801058]
- [16]. Volpe BT, Lynch D, Rykman-Berland A, Ferraro M, Galgano M, Hogan N, Krebs HI. Intensive sensorimotor arm training mediated by therapist or robot improves hemiparesis in patients with chronic stroke. *Neurorehabil Neural Repair*. May-Jun;2008 22:305–10. [PubMed: 18184932]
- [17]. Page SJ, Fulk GD, Boyne P. Clinically important differences for the upper-extremity Fugl-Meyer Scale in people with minimal to moderate impairment due to chronic stroke. *Phys Ther*. Jun.2012 92:791–8. [PubMed: 22282773]
- [18]. Lin JH, Hsu MJ, Sheu CF, Wu TS, Lin RT, Chen CH, Hsieh CL. Psychometric comparisons of 4 measures for assessing upper-extremity function in people with stroke. *Phys Ther*. Aug.2009 89:840–50. [PubMed: 19556333]
- [19]. Wagner JM, Rhodes JA, Patten C. Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Phys Ther*. May.2008 88:652–63. [PubMed: 18326055]
- [20]. Dobkin BH. Progressive Staging of Pilot Studies to Improve Phase III Trials for Motor Interventions. *Neurorehabil Neural Repair*. Mar-Apr;2009 23:197–206. [PubMed: 19240197]
- [21]. Wagner TH, Lo AC, Peduzzi P, Bravata DM, Huang GD, Krebs HI, Ringer RJ, Federman DG, Richards LG, Haselkorn JK, Wittenberg GF, Volpe BT, Bever CT, Duncan PW, Siroka A, Guarino PD. An economic analysis of robot-assisted therapy for long-term upper-limb impairment after stroke. *Stroke*. Sep.2011 42:2630–2. [PubMed: 21757677]
- [22]. Hornby TG, Campbell DD, Kahn JH, Demott T, Moore JL, Roth HR. Enhanced gait-related improvements after therapist-versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. *Stroke*. Jun.2008 39:1786–92. [PubMed: 18467648]
- [23]. Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH, Hornby TG. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. *Neurorehabil Neural Repair*. Jan.2009 23:5–13. [PubMed: 19109447]
- [24]. Duncan PW, Sullivan KJ, Behrman AL, Azen SP, Wu SS, Nadeau SE, Dobkin BH, Rose DK, Tilson JK, Team LI. Protocol for the Locomotor Experience Applied Post-stroke (LEAPS) trial: a randomized controlled trial. *BMC Neurol*. 2007; 7:39. [PubMed: 17996052]
- [25]. Dobkin BH, Duncan PW. Should body weight-supported treadmill training and robotic-assistive steppers for locomotor training trot back to the starting gate? *Neurorehabil Neural Repair*. May. 2012 26:308–17. [PubMed: 22412172]
- [26]. Krebs HI, Mernoff S, Fasoli SE, Hughes R, Stein J, Hogan N. A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: a pilot study. *NeuroRehabilitation*. 2008; 23:81–7. [PubMed: 18356591]
- [27]. Milot MH, Spencer SJ, Chan V, Allington JP, Klein J, Chou C, Bobrow JE, Cramer SC, Reinkensmeyer DJ. A crossover pilot study evaluating the functional outcomes of two different

types of robotic movement training in chronic stroke survivors using the arm exoskeleton BONES. J Neuroeng Rehabil. 2013; 10:112. [PubMed: 24354476]

- [28]. Platz T, Eickhof C, van Kaick S, Engel U, Pinkowski C, Kalok S, Pause M. Impairment-oriented training or Bobath therapy for severe arm paresis after stroke: a single-blind, multicentre randomized controlled trial. Clin Rehabil. Oct.2005 19:714–24. [PubMed: 16250190]
- [29]. Klein J, Spencer SJ, Reinkensmeyer DJ. Breaking it down is better: haptic decomposition of complex movements aids in robot-assisted motor learning. IEEE Trans Neural Syst Rehabil Eng. May.2012 20:268–75. [PubMed: 22531825]

Synopsis

In the last few years we have seen remarkable growth in the development and application of robotics to ameliorate or remediate impairment due to stroke, cerebral palsy, and other conditions. This growth is associated with a) the understanding that plasticity is a fundamental property of the adult human brain and might be harnessed to remap or create new neural pathways, and b) the development of robots that can safely interact with humans and assist human performance. Here we discuss whether robotic therapy has achieved a level of maturity to justify its broad adoption in the clinical realm as a rehabilitative tool. We will also discuss our view on how to improve outcomes further and on how to select the appropriate number of degrees of freedom to optimize care to a particular patient.

Key Points

- 1) Robot-assisted therapy for the upper extremity has already achieved Class I, Level of Evidence A for Stroke Care in the Outpatient Setting and Care in Chronic Care Settings.
- 2) At least in the U.S. Department of Veterans Affairs (VA) healthcare system, robot-assisted therapy for the upper extremity has not increased the total healthcare utilization cost.
- 3) Functionally-based robotic training did not demonstrate any advantage over impairment-based robotic training.
- 4) The paradox of diminishing number of degrees of freedom suggests an approach to tailor therapy to a particular patient's needs.

Figure 1.

VA-Robotics Outcomes. The left column shows the comparison of the first half of the robot training (RT) group with the usual care (UC). The right column shows the comparison of the robot and intensive comparison training (ICT) groups. Note the added arrows to the figure: they indicate the advantage of the complete RT group and the usual care which achieved the MCID threshold of 5 points in the Fugl-Meyer and the comparison between RT and the ICT group after 6 months follow-up.

Figure 2.

VA-Robotics Gym of Robots. Top row shows respectively the anti-gravity module, the shoulder-and-elbow robot, the wrist robot. Bottom row shows the hand module, the wrist module mounted at the tip of the shoulder-and-elbow robot, and the hand module mounted at the end-effector of the shoulder-and-elbow robot.

Figure 3. BONES Exoskeleton Robot and examples of each robotic training program. a) Subject training on BONES; b) examples of games played during multijoint functional robotic training, c) example of single joint robotic training (shoulder flexion/extension) (courtesy Prof. D. Reinkensmeyer, University of California, Irvine).

Figure 4.

The Paradox of Diminishing Number of Degrees-of-Freedom. The figure sketches the progression of Patient N with severe impairment, who should start training in a rehabilitation robotic device with the smallest number of DOFs that provide challenge and some level of success. Training should be enhanced to a robotic device with additional DOFs only when a ceiling effect is observed.