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Robotics: A Rehabilitation Modality

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Despite the seminal definition for a clinician to consider a novel rehabilitation technique that Krakauer and colleagues set nearly ten years ago, their attributes have remained timely and appropriate [1]. They stated that the GAINS measured for the adoption of a novel rehabilitation technique must be as good or better than those resulting from other treatments. Further, the measured gains needed to PERSIST beyond treatment and then for an undefined but “significant” period; clearly, they were suggesting strongly that the improvements should be permanent. Also the measured gains needed to be demonstrated in untrained tasks; namely, there should be evidence of GENERALIZATION of the improvements to other tasks not involving direct training. Simply training for the test, an element central to many arguments in modern teaching politics, would not qualify a novel rehabilitation technique. To those clinically important parameters, we would add that the COST of the rehabilitation technique should improve the current cost/benefit ratio of the current treatment. Knowing that most rehabilitation units operate on a daily-capped cost basis, there is a continuing drive to control costs even while delivering the most modern and effective treatment [1].

Taking advantage of Krakauer's crisp statement, we argue here that rehabilitation robotics has met the stringent requirements and should be adopted as a novel rehabilitation

Compliance with Ethics Guidelines

Conflict of Interest

Hermano Igo Krebs and Bruce T. Volpe declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent

This article does not contain any studies with human or animal subjects performed by any of the authors.

technique. Our data have demonstrated efficacy and effectiveness for the interactive-robot treatment of upper extremity (UE) weakness for patients who have experienced subacute stroke [2, 3] and also those who sustained chronic stroke (see VA-Veterans Affairs' ROBOTICS study and the employed robots in Figure 1) [4, 5]. It revealed that, in an era of cost containment, introducing upper extremity robotics in a clinic did not increase the total healthcare utilization costs. Active interventions add cost; for example, the extra cost of the robotic equipment plus an additional therapist cost the VA \$5,152 per patient. However, when we compared the total cost, which included the clinical care needed to take care of these Veterans, the robotic group cost less to the VA. The total healthcare utilization cost of the usual-care group was \$19,098 per patient, compared to \$17,831 total healthcare cost for the robotic group (including the additional cost of equipment and delivering robotic therapy). To rule out any Hawthorne type effect, we requested the VA to continue collecting healthcare utilization costs after the completion of the study. The data collected demonstrated no placebo effect. In fact, the total healthcare cost for the robotic group went down further after the completion of the study, perhaps because patients continued to improve even without intervention [5]. This suggests in the "real" therapy world away from the research environment that robotic therapy for the upper extremity offers better care for the same or lower total cost. This result led the UK National Health Service (NHS) and its Health Technology Assessment (HTA) Programme to embark in the largest ever RCT in robotic therapy; the RCT plans to enroll between 720 and 800 stroke patients to determine whether the same cost advantage can be observed in the British healthcare system (see <https://research.ncl.ac.uk/ratuls/>).

Furthermore, we have demonstrated that the gains measured by objective kinematic measures [6, 7] reproducibly generalized to untrained tasks [8, 9]. These trials and a multicenter randomized trial [4, 10] prompted the American Heart Association (AHA), the Veterans Administration (VA) and Department of Defense (DOD) to endorse the use of upper extremity robotics [11, 12].

Although we predict that robotic training devices are destined to revolutionize standard restorative neurology and physical medicine practices, robotics are not a general panacea for stroke recovery; actually, for clinically effective training there should be a mandatory number of movements per session and a number of sessions along the lines of the 10,000 hours of practice required to attain "expert athlete" levels of physical performance. Interactive robots easily reach high levels of intensity, and it remains to be shown that therapists, replicating the high intensity of robotic training, could achieve the same motor outcome goals. In fact we recently showed that intensity-matched manually delivered therapy could, in laboratory conditions, deliver 1,000 to-and-from movements per 45-minutes of therapy session and achieve similar results (not practical in the clinical setting) [13]. It allowed us to directly test whether the robot treated or therapist treated group demonstrated comparable improvement in motor behavior. These results support the effectiveness of high intensity training for the impaired limb and should banish forever the therapy in standard care that averages 45 movement attempts per session [14]. Moreover, no clinician or patient should expect a superior outcome with a low number of attempts to move an affected limb delivered during robotic or usual care [15, 16]. Missing among these clinical trials is mention of the fact that for nearly all of the patients who were 6 months or

more after their acute stroke and who then received intensive robotic training, the impairment was considered permanent and impervious to standard out-patient therapies, a fact belied by novel intensive training programs [4].

That said, much remains to be done to improve outcomes further. To highlight the variability of outcomes, notice the changes from admission to discharge in the VA-ROBOTICS study [4]:

Of notice, a third of the patients improved over 5-points in the Fugl-Meyer assessment, which corresponds to the minimal clinically important difference (MCID), a third of the patients improved somewhat, and a third did not improve. Those studies raised new questions focused on those patients who were mildly or completely resistant and the quest to determine in short order who might be a responder, quasi-responder, and non-responder and perhaps how to combine robotics with another intervention such as neuromodulation to transform a non-responder into a responder.

The accumulated evidence for the effectiveness of robotic mediated rehabilitation led the American Heart Association (AHA) to include endorsements for upper extremity (UE) robotic therapy in their guidelines for the standard of post-stroke treatment. The recommendation does not extend for the lower extremity (LE), stating that “most trials of robot-assisted motor rehabilitation concern the UE, with robotics for the LE still in its infancy...” [11]. The Veterans Administration similarly endorsed robotic therapy for UE but not for LE: “recommendation is made against routinely providing the [LE] intervention... At least fair evidence was found that the intervention is ineffective ...” [12]. The AHA and VA recommendations compared robotic outcomes with usual care as practiced in the US.

One first step to remedy this situation is to distinguish between “best practices” and tested practices. Clinicians have operated on the assumption that body-weight-supported treadmill (BSWTT) training delivered by 2 or 3 therapists per stroke patient was “best practice” and superior to the usual care. Thus, automating BWSTT appeared to be logical. However, an NIH-sponsored clinical trial, Locomotor Experience Applied Post-Stroke (LEAPS) demonstrated that BSWTT did not lead to results superior to those from a home program with only strength and balance training [17]. This result was contrary to the hypothesis of its clinical proponents. The goal of rehabilitation robotics cannot be to simply automate current rehabilitation practices as, for the most part, they lack evidential basis: a scientific basis is needed for development of effective robotic therapy. In other words, existing robotic tools that represent a robotic embodiment of BWSTT train only a subset of the required aspects for normal gait and hence, a direct comparison robotic versus usual care as practiced in the US led to negative outcomes [18, 19].

The landmark LEAPS study must be seriously considered by both roboticists and clinicians: it did not demonstrate superiority of BWSTT for either severe or moderate stroke patients. While many studies of robotic embodiments of BWSTT compared to usual care as practiced outside the US (varied levels of usual care) were more positive[20], we continue to be highly optimistic that with careful research we can improve outcomes for LE, possibly expanding the tools and training approaches to include other aspects of gait and balance.

References

1. Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol.* 2006 Feb.19:84–90. [PubMed: 16415682]
2. 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.* 1997 Apr.54:443–446. [PubMed: 9109746]
3. Volpe BT, Krebs HI, Hogan N, Edelstein OL, Diels C, Aisen M. A novel approach to stroke rehabilitation: robot-aided sensorimotor stimulation. *Neurology.* 2000 May 23.54:1938–1944. [PubMed: 10822433]
4. 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.* 2010 May 13.362:1772–1783. [PubMed: 20400552]
5. 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.* 2011 Jul 14.
6. Bosecker C, Dipietro L, Volpe B, Krebs HI. Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke. *Neurorehabil Neural Repair.* 2010 Jan.24:62–69. [PubMed: 19684304]
7. Krebs HI, Krams M, Agrafiotis DK, DiBernardo A, Chavez JC, Littman GS, Yang E, Byttebier G, Dipietro L, Rykman A, McArthur K, Hajjar K, Lees KR, Volpe BT. Robotic measurement of arm movements after stroke establishes biomarkers of motor recovery. *Stroke.* 2014 Jan.45:200–204. [PubMed: 24335224]
8. Dipietro L, Krebs HI, Fasoli SE, Volpe BT, Stein J, Bever C, Hogan N. Changing motor synergies in chronic stroke. *J Neurophysiol.* 2007 Aug.98:757–768. [PubMed: 17553941]
9. Dipietro L, Krebs HI, Fasoli SE, Volpe BT, Hogan N. Submovement changes characterize generalization of motor recovery after stroke. *Cortex.* 2009 Mar.45:318–324. [PubMed: 18640668]
10. Lo AC, Guarino P, Krebs HI, Volpe BT, Bever CT, Duncan PW, Ringer RJ, Wagner TH, Richards LG, Bravata DM, Haselkorn JK, Wittenberg GF, Federman DG, Corn BH, Maffucci AD, Peduzzi P. Multicenter randomized trial of robot-assisted rehabilitation for chronic stroke: methods and entry characteristics for VA ROBOTICS. *Neurorehabil Neural Repair.* 2009 Oct.23:775–783. [PubMed: 19541917]
11. Miller EL, Murray L, Richards L, Zorowitz RD, Bakas T, Clark P, Billinger SA. N. American Heart Association Council on Cardiovascular, and C. the Stroke. Comprehensive overview of nursing and interdisciplinary rehabilitation care of the stroke patient: a scientific statement from the American Heart Association. *Stroke.* 2010 Oct.41:2402–2448. [PubMed: 20813995]
12. 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.
13. 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.* 2008 May-Jun;22:305–310. [PubMed: 18184932]
14. 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.* 2009 Oct.90:1692–1698. [PubMed: 19801058]
15. Kahn LE, Lum PS, Rymer WZ, Reinkensmeyer DJ. Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does? *J Rehabil Res Dev.* 2006 Aug-Sep; 43:619–630. [PubMed: 17123203]
16. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabil Neural Repair.* 2008 Mar-Apr;22:111–121. [PubMed: 17876068]

17. 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*. 2011 May 26;364:2026–2036. [PubMed: 21612471]
18. 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*. 2008 Jun;39:1786–1792. [PubMed: 18467648]
19. 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*. 2009 Jan;23:5–13. [PubMed: 19109447]
20. Mehrholz J, Elsner B, Werner C, Kugler J, Pohl M. Electromechanical-assisted training for walking after stroke. *Cochrane Database Syst Rev*. 2013; 7:CD006185. [PubMed: 23888479]

Fig. 1. A Gym of Upper Extremity Robots

Top row, left shows a person with chronic stroke working with the anti-gravity shoulder-and-elbow robot. The top row, middle panel shows a person working with the planar shoulder-and-elbow robot. The top row, right panel shows the wrist robot during therapy at the Burke Rehabilitation Hospital. The lower row, left panel shows the hand module for grasp and release. The lower row, middle panel shows reconfigurable robots. The robotic therapy shoulder-and-elbow and wrist modules can operate in standalone mode or be integrated into a coordinated functional unit. The **lower row**, right panel shows the shoulder-and-elbow and hand module integrated into a coordinated functional unit.

Fig. 2. VA-ROBOTICS Multi-Site Trial: Individual Patient's Change in Score and Randomization Date

Figure shows the results of the 3 groups of chronic stroke patients: black circles = usual care (UC), blue diamond = robot training group (RT), red squares = intensive comparison training group (ICT). UC received 3 therapy sessions focused on the upper extremity, average of 45 movement attempts per session. RT and ICT received 3 therapy sessions per week focused on the upper extremity, average of 1,024 movement attempts per session. The robot and intensive care therapy group demonstrated a significant reduction in impairment and disability and significant gains in quality of life scores as compared to usual care.