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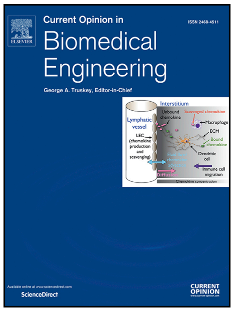

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The Road Forward for Upper Extremity Rehabilitation Robotics

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Abstract

Despite concerted efforts over the last three decades, upper-extremity robotic rehabilitation has yet to reach its full potential. We assert that assuming the goal of robotic rehabilitation is to automate conventional therapy may have led to overly narrow research directions and to mixed results from clinical studies. Recontextualizing this assumption opens promising research avenues for roboticists. Breaking the robotic device design loop and instead seeking out 'big data' opportunities has the potential to identify promising robot-mediated interventions. This will require a shift in roboticists' attitudes towards participating in neuroscience and clinical research. By expanding assessment beyond kinematics, robotic devices can provide clinicians with a more complete picture of impairment and recovery. We discuss the current assumptions in greater detail, and point towards promising research in these revised directions.

Keywords: Robotic Rehabilitation, Upper Extremity, Neuroscience, Assessment, Therapy

1. Introduction

In this manuscript, we provide a brief review of the standard viewpoint of roboticists designing devices to be used in post-stroke neurorehabilitation for the upper extremities, as well as some opinions for ways of reshaping or redirecting that perspective towards higher-impact research topics. For a more comprehensive background, we recommend review articles such as the one from Duret and Mazzoleni [1] for the context on the current state of clinical practice and the narrative review by Weber and Stein [2] for a broad introduction on robotic rehabilitation. For the readers interested in a more complete review of upper extremity devices, we recommend the review by Gull, Bai, and Bak

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[3]. For readers looking for an introduction to robotics used in neuroscience, we recommend the article by Wolpert and Flanagan [4]. Within that context, this manuscript starts with three misconceptions or overly narrow definitions which have, in our opinion, limited research and results, and then proceeds to propose new viewpoints and promising directions for upper extremity robotic rehabilitation researchers.

2. What are some shortcomings in the robotic rehabilitation community's current approach?

While the upper extremity robotic rehabilitation field has matured over the past 30 years, there have been a few guiding principles set from the beginning which have limited the scope and direction of research. The original framing of the use case for robotic rehabilitation, set in seminal works such as Krebs *et al.* [5], is that robotic devices will enable an automation of therapy tasks. As in the automation of manufacturing and assembly, the key strength of robotic devices was seen to be the ability to offload physical labor from workers to robots which could accurately and repeatedly perform predefined tasks. The end goal of automated therapy would be a reduction of the physical labor of therapists and clinicians, with the robotic device performing the requisite high intensity, long duration training [6] and the high resolution assessment. However, despite decades of active research, recent studies still find limited or no benefit to robotic rehabilitation over conventional or dose-matched conventional therapies, as seen in the RATULS study by Rodgers *et al.* [7], with similar limitations found in other large-scale studies and meta-analyses [8, 9]. This attempt has set the field on a road, depicted in Fig. 1, which has conceptual and procedural obstacles preventing rehabilitation robotics from achieving its promise.

2.1. Robotic therapy is device design

One proposed solution towards overcoming the limitations seen in these comparative studies is the development of more advanced, more capable robotic devices. The idea that there must be a new design just around the corner which will improve clinical results is alluring to a field of robotic designers. The current research approach (of which the authors are most assuredly a part) involves proposing a new device design for a particular problem and demonstrating these improvements with a few healthy and impaired study participants. Then with inconclusive or middling results, the design loop begins again, seeking out new designs, which possess more advanced kinematics or control, in the hope of discovering the gold standard. Yet, these small-scale studies are fundamentally incapable of providing statistical significance or exploring the variability and complexity of stroke impairment and neural recovery required to holistically inform design considerations.

2.2. Robotic therapy only needs pragmatic neuroscientific principles

In a broader sense, these limited experiments are a symptom of the simplified and shallow understanding of impairment and recovery. While pragmatic principles for neurorehabilitation such as those proposed by Kleim and Jones concerning repetition and dosage [6] have been accepted, roboticists have only engaged with these principles of recovery in limited ways. A principle for facilitating neural plasticity, healthy motor learning, or adaptation are assumed to stem from the same (or sufficiently similar) neurological processes, and are therefore sufficient for motivating the next design, the next controller, or the next small-scale study. Furthermore, these small scale studies are often conducted on chronic stroke participants because of their availability, which overlook the major changes which are occurring in the first six months post-stroke.

2.3. Robotic therapy assessment is a 'no-robot' condition

Finally, stemming from this simplification of impairment and recovery is the key assumption concerning assessment which has limited the field. Robotic assessment, as envisioned by Krebs *et al.* [5] and in the our own works [10] assumes that assessment occurs after a training session, and consists of minimal robotic interaction to determine kinematic properties of motion, such as spectral arc length [11], submovement analysis [5], or correlation to minimum jerk trajectories [12] at a higher resolution than is afforded in traditional clinical assessments. The strong correlation of these robotic assessments of kinematics to the movement quality assessed in clinical measures [12] suggests that the robotic devices are providing only a higher resolution, more repeatable measure of movement quality.

3. What should the robotic rehabilitation community be asking?

With these limiting assumptions, it is understandable that results from all the biggest studies with upper-extremity robots have led to similar conclusions: robot-mediated therapy results in recovery similar to conventional therapy at high dosage. This is a 'good news' and 'bad news' scenario – while robot-mediated therapy has fallen well short of promised results, robots have proven to be safe and effective in delivering complex interventions at the standard level of care. So, what is next? Should we all just close up our robotics shops? No! Tremendous need exists, and robots have successfully delivered complex therapeutic interventions. One particularly encouraging recent result discussed by Senesh, Barragan, and Reinkensmeyer [13] is the value of robotic interventions for individuals typically left behind by traditional therapies. However, we all must humbly examine the field, and ask ourselves the tough questions to boldly construct the new road in Fig. 1, unobscured by the field's previous assumptions.

3.1. How can the design loop be redesigned?

Rehabilitation roboticists have been focused on automating therapy, seeking to create a single robot therapist which can balance the sometimes competing requirements of the clinician: able to transmit high assistive or resistive loads, make high resolution measurements, and simultaneously develop models of recovery and motor learning. However, with the limited efficacy of these all-in-one

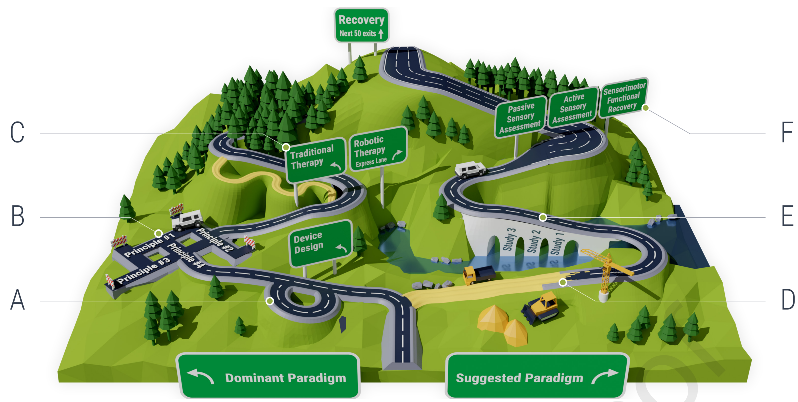

Figure 1: The field of rehabilitation robotics has been on a road towards addressing the current clinical needs much like the one shown on the left. (A) Device design has become a loop, focused on developing novel designs at the expense of progress towards the ultimate goals of the field. (B) Past this design loop, the indiscriminate use of neuroscientific principles without a guiding direction has reduced the efficacy and potential impact of robotic study designs. (C) Finally, the simplification of impairment and recovery has led to robotic assessments that are only capable of providing higher resolution and more consistent variants of existing clinical measures. We propose a new road which (D) builds off of the pioneering efforts of roboticists to engage in neuroscientific discovery and (E) uses 'big data' to bridge the gaps in the current understanding of the effects of robotic interventions. (F) Lastly, new methods for assessment promise to open new lanes for understanding and treating impairment, to bring the field closer to fulfilling its promise of helping each patient reach their desired level of recovery.

devices, it might not be fruitful to build new robots and go through the same compromised process as previous researchers. Instead of trying to serve the entire continuum of care, robots could serve as tools in three important, distinct ways: assist scientists in discovering breakthrough treatments (science); assist clinicians with real-time, quantitative, and accurate assessment of patients' disability and recovery progress (assessment); and assist clinicians to deliver customized treatment with high dosage (therapy). This new design loop might result in more involved designs to address the needs of scientific recovery and sub-acute treatment, and simpler devices to address the needs of assessment and chronic stage therapy with high dosage, in-home treatments. For example, researchers such as Dewald and Ellis [14] have taken this approach and designed a device specifically for testing neuroscientific hypotheses.

3.2. How can the connection to neuroscience be deepened?

To better design robots for neurorehabilitation, robotics investigators must re-examine their assumptions and understanding of neuroscientific principles. For instance, terms such as adaptation, recovery, and learning are often used interchangeably in the engineering circles. However, neuroscience researchers have been careful to make clear distinctions between different components of apparent improvement. Adaptation as a type of learning usually refers to modifying internal controllers to recover a prior skill, whereas *de novo* learning involves generating new controllers to complete the goal [15]. For the patient, this could mean restoration (also known as remediation) of a lost motor function or learning compensatory ways to complete the activity. Additionally, overall adaptation can be broken down into processes of fast initial learning and slow gradual retention [15, 16]. Healthy motor learning outcomes observed in the short term does not imply neurological recovery in the long term. With this in mind, rehabilitation roboticists should consider how their therapies will influence the control loops of patients at different timescales. As evidence emerges suggesting trade-offs between the efficacy and efficiency of motor practice [17], roboticists might find value in investigating how changing dosing schedules of their therapies will affect patients' performance in activities of daily living (ADL). To potentially reduce the complexity of motor control, it may be valuable to investigate how muscle synergies, or muscle activation patterns, can be targeted via robotic interaction [18]. Since motor learning does not necessarily imply recovery in all circumstances, it might also be worthwhile for roboticists to explore deeper mechanisms of recovery.

3.3. How can assessment be improved?

At present, most clinical assessments of motor function are coarse, and cannot capture the effects of these deeper mechanisms of recovery. Assessments such as the Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT), Jebsen-Tayler Hand Function Test (JHFT), and Motricity Index (MI), reviewed by Lang *et al.* [19] were implemented before the development of the accurate sensing and measurement systems available today. Even more rudimentary than motor assessments are the assessments attempting to capture sensory capabilities and, more importantly, sensory impairment. For example, sensory assessments such as the Weinstein Enhanced Sensory Test (WEST-D) [20] and the Tactile Discrimination Test (TDT) [20, 21] are only capable of measuring force detection or surface texture discrimination with limited resolution.

As has already been demonstrated with kinematic-based assessments [22], robotic devices are well-situated to provide higher resolution and individualized assessments of sensorimotor function. Given the growing evidence that suggests a need for active sensory interventions and assessments [23], it is worth considering whether these kinematic assessments alone are sufficient. Regarding assessment of sensory impairment, robotic devices are capable of increasing the resolution and variation of stimuli far beyond the limited monofilament tests in use today [24]. Furthermore, they are capable of assessing all aspects of sensory function including proprioception [25, 26] and kinesthesia [27, 28]. In combination with robots, researchers have also begun to exploit psychophysical measurement techniques in the assessment of sensory function [29, 30, 31]. While these robot-based fine-grained analyses of sensory impairment correlate well with the existing clinical assessments [32, 33], they offer unique insights into understanding neurological disorders from the perspective of sensory and motor function.

4. What are promising directions for the robotic rehabilitation community?

Even though assumptions and lack of nuanced understanding about these foundational principles have limited the perspectives of rehabilitation roboticists, the principles themselves are not incorrect. Rather, they represent central tenets from which rehabilitation roboticists must expand to fulfill the promise of robotic rehabilitation. The expanded views of the design loop, the roboticists' active role in neuroscience, and the robotic assessment of function can be redirected towards promising or even aspirational objectives.

4.1. Robots as a tool for neuroscience research

Many open questions exist in the area of neurorecovery and robots could serve as tools in this scientific endeavor. Pioneering efforts by researchers such as Shadmehr and Holcomb [34] identified promising avenues for using imaging with robotic interventions to advance neuroscience. Several groups have looked for principles to guide intervention design, such as studies to determine the impact of the dimensionality of motion and the joints included [35, 36, 37], the role of assistance, resistance, and error augmentation at facilitating recovery [38, 39, 40], and the benefits of individualized selection of practice movements [41]. Recent works by researchers such as Micera et al. [42] and Gassert and Dietz [43] have begun to lay the foundation for the next steps in these pursuits.

To build on these impactful contributions, robotics researchers must jump with both feet in the process of scientific discovery instead of being casual observers and cursory consumers to scientific knowledge. This will require gaining expertise and establishing deep collaborations. However to participate in the discovery journey, the robotics researchers must familiarize with the nitty-gritty of these fields, such as the discussions by Krakauer [15], to build the vocabulary and perspective needed. For example, robotic devices stand to improve experimental methods investigating interactions between the corticospinal tract (CST) and the corticoreticulospinal tract (CRST) [44], the CST's role in proportional recovery [13], and the potential to indicate motor improvement through imaging of the CST [45]. Beyond human studies, animal models have identified promising training modalities, such as the value of bimanual training in improving bimanual and unimanual function [46], which has broad implications for the field. With robotic devices to support rodent studies, such as the recent work from Erwin et al. [47], it may be easier to answer open questions on movement pattern characterization and optimal treatment combinations that can translate to human outcomes.

At a higher level view of therapy in practice, researchers and designers should be aware of the continuum of strategies needed across a pool of patients and help develop guidelines for scheduling and quantifying dose [48, 49]. Determining consolidation rest between sessions to ensure long-term pattern retention should be another associated research priority. Establishing multi-input models of assigning specific therapy is key to directing informed design of protocols, which could lead to more desired outcomes in ADL [50, 51]. Other competing theories of therapy including biofeedback and spontaneous recovery should be explored in greater detail [43, 52]. Additionally, the development of strategies which directly seek to train and restore muscle coordination patterns [18] may address neural outcomes better.

4.2. Robots designed for 'big data'

Even with devices designed for science, assessment, or therapy, the rapid pace at which the device development cycle unfolds limits new devices to, at most, limited validation through small-sample user studies. Given that single-site validation studies rarely generalize to the broader population, would there be some advantage to taking the existing suite of robotic devices currently deployed and leveraging them as data collection nodes in a larger big data framework? This 'big data' approach is already revolutionizing healthcare monitoring given the ubiquity of wearable sensory computing devices [53, 54, 55]. Likewise, 'big data' approaches have also been leveraged for automated skill assessment [56, 57, 58] and the development of training curricula for robot-assisted minimally invasive surgery (RAMIS), given the countless number of telerobotic surgical systems deployed in hospitals across the globe [59]. As with these approaches, this big data framework will support the development and extension of computational methods for understanding impairment and recovery [50, 51].

The issue with applying big data to rehab robotics currently is that current methodological approaches in the field tend to rely on small patient samples. Scaling up these methodologies would require deep understanding and standardization of field-specific clinimeterics applicable across studies and devices. Current devices also vary in their interaction quality such as impedance and inertia, therefore common communication of these parameters would be necessary. In the near term, workshops should be organized in-field with consultation from clinicians to discuss and finalize open datasets with agreed-upon standards regarding methodology, ID metrics, clinical measures, and robotic measures. Furthermore, it may help to advise adoption of open science registration (e.g., osf.io) for sharing research protocols and archiving databases. As a starting point, the distributed laboratory framework established through the Psychological Science Accelerator (psysciacc.org) might prove useful in catalyzing these efforts by leveraging crowd-sourced, open-sharing methodology. Additionally, it would be beneficial to agree upon providers that allow for personal small donations and transparent large sponsorships and grants to finance these services, with preservation funds as emergency backup.

In future studies, rehabilitation roboticists must work with clinicians to choose the correct target population (for example sub-acute stroke patients [60] with medium level of disability), create patient-specific therapy (tasks based on patients' preferences and at a difficulty level commensurate with their abilities, ensuring that patients are actively participating), and deliver therapy at intensity much higher than conventional methods (e.g. two orders of magnitude greater than conventional therapy). To factor out spontaneous recovery as a confounding variable between observed recovery and robotic intervention, dose-matched rehabilitation between conventional and robotic therapies in the sub-acute and chronic phases of recovery should be investigated further to quantify significant differences and to characterize distinct biomarkers with neuroanatomical and physiological imaging [61, 62].

4.3. Robots as new assessment modalities

Robots are typically endowed with a suite of sensors which open up possibilities of quantitative and reliable assessment of the motor deficits and recovery processes. However, robots can collect high resolution data beyond kinematics, which could expand and speed up the assessment process. Robotic devices stand to further expand the assessment of sensation and perception beyond the limited methods currently available, and are poised to answer questions about lower-level mechanisms of impairment and motion through assessment of biosignals such as muscle coordination patterns [63].

However, there exists an even larger opportunity for using robotic devices to assess not just function, but learning. This opportunity comes at the intersection of the three new directions for robotic rehabilitation: big data, neuroscience, and assessment. By using similar robots at multiple locations and throughout the continuum of care, there is potential to collect data at multiple locations on the longitudinal recovery process of many patients. This could lead to data-driven scientific discoveries and treatments. For example, with the widespread adoption of devices like the ArmeoSpring passive exoskeleton (Hocoma Inc.), studies examining models of motor learning and recovery can be made, such as the recent study by Schweighofer, *et al.* [16]. In this study, the authors established that learning follows dual exponential processes of different speeds, where only the slow learning process corresponded with improvements in movement quality. Due to the widespread availability of the ArmeoSpring, there exists an opportunity to investigate interesting avenues in neuroscientific inquiry, such as the use of submovement primitives in motion generation. Interesting questions in therapeutic practice could also be answered, such as the optimal timing and dosage of the ArmeoSpring intervention for post-stroke rehabilitation.

5. Conclusions

Robotic rehabilitation has grown significantly over the past three decades, and shown much promise in restoring function after a neurological injury. However, the view that robotic therapy is automated therapy led to three obstacles on the road to realizing recovery through rehabilitation robotics. First, while providing important designs capable of safely and effectively interacting with users, the design process has become an end in and of itself, and the missing focus on the robot's role within the continuum of care has prevented the field from leveraging big data opportunities. Second, rehabilitation roboticists must develop close collaborations with neuroscientists and involve ourselves in the neuroscience behind recovery to fulfill the promise of robotic rehabilitation. Lastly, the field has overly concerned itself with motor function training and assessment, without considering the importance of sensory function or lower-level biosignals. These three directions, namely big data, fundamental neuroscientific research, and expanded assessment, in our opinion, hold the most promise towards creating new roads for our community.

6. Disclosures

The authors confirm that there are no known conflicts of interest associated with this publication for authors Rose, Carducci and Brown. Co-author Deshpande has an equity in a start-up company, Harmonic Bionics, whose mission is to commercialize upper-body rehabilitation robots. The opinions expressed in this manuscript by Dr. Deshpande are based on his research experience and expertise and these have not been influenced by the goals of the start-up.

We wish to confirm that there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

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