Review

On the Role of Robotic Assistance in Upper-Limb Neurorehabilitation

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Abstract: An early hypothesis in robot-assisted stroke therapy was that sensorimotor stimulation through robotic assistance is beneficial for recovery. Despite 25 years of upper-limb rehabilitation robotics research, this hypothesis remains untested barring a few studies with small sample sizes. This review aims to provide a critical summary of the current state of this hypothesis by collating evidence from rehabilitation robotics and other related therapeutic approaches. The review starts with a causal model to expose the various direct and indirect routes through which robotic assistance can aid sensorimotor recovery. The indirect routes include the influence of robotic assistance on therapy intensity, patient motivation, and active participation. The direct route is through changes in cortical networks through Hebbian(-like) learning and changes in peripheral tissue properties. There is currently mixed evidence for the direct causal effect of robotic assistance on recovery from the upper-limb rehabilitation robotics literature. However, evidence from the neuromuscular electrical stimulation literature provides some support for this causal role. Based on the data at hand, we hypothesise that the enhanced movement-related sensory feedback from robotic assistance has a direct, possibly small, causal role in the sensorimotor recovery of the upper-limb, and this effect might be detectable with high-intensity therapy. Large, high-intensity, controlled studies are warranted to support or refute the role of robotic assistance on recovery, which is both scientifically and practically important.

Keywords: robotic assistance; Hebbian learning; sensorimotor recovery; upper-limb rehabilitation; stroke; rehabilitation robots

1. Introduction

Robots are tools for movement neurorehabilitation to sense and physically react to a user's movement or movement intention. Although human-robot physical interaction can take different forms[1], the most common form of interaction in neurorehabilitation is to assist movements that a patient cannot complete voluntarily. This assistance is provided through external forces/torques applied to a patient's limb. The ability to assist is the defining feature of rehabilitation robots, making them suitable even for patients with limited movement capacity.

In the early years of rehabilitation robotics (the late 1990s and early 2000s), robotic assistance was believed to have a direct role in recovery through sensory feedback resulting from assisted movements which help drive cortical plasticity and thus recovery[2–4]. However, the current evidence for this direct role of robotic assistance in driving recovery is unclear. Robot-assisted therapy for the upper limb (UL) following stroke reduces sensorimotor impairments slightly as measured using the Fugl-Meyer Assessment (FMA) scale[5], without significant carry-over to activities of daily living[5,6]; Veerbeek et al. reported an average increase of 2 points on FMA with robot-assisted upper limb therapy[7]. Most existing robot-assisted studies have used small sample sizes, and only a few studies have compared the effectiveness of robotic assistance with un-assisted therapy. Among these, some find differences between robot-assisted and conventional therapy groups[2,4,5,8], while others find no difference when the two groups are intensity matched[3,6,9].

Although, robotic assistance can indirectly impact recovery (through therapy intensity, motivation, etc.), but its direct role remains to be rigorously investigated. Understanding the mechanism of this direct role and its effect size can guide the appropriate design of future robotic devices to maximise recovery. There have been technical reviews on control algorithms for the physical human-robot interaction[1,10], but none have analysed the sensorimotor learning/recovery mechanisms targeted by robotic assistance. Furthermore, there has been little work integrating findings from other areas such as neuromuscular electrical stimulation (NMES) to build a comprehensive picture of the role of robotic assistance in sensorimotor recovery.

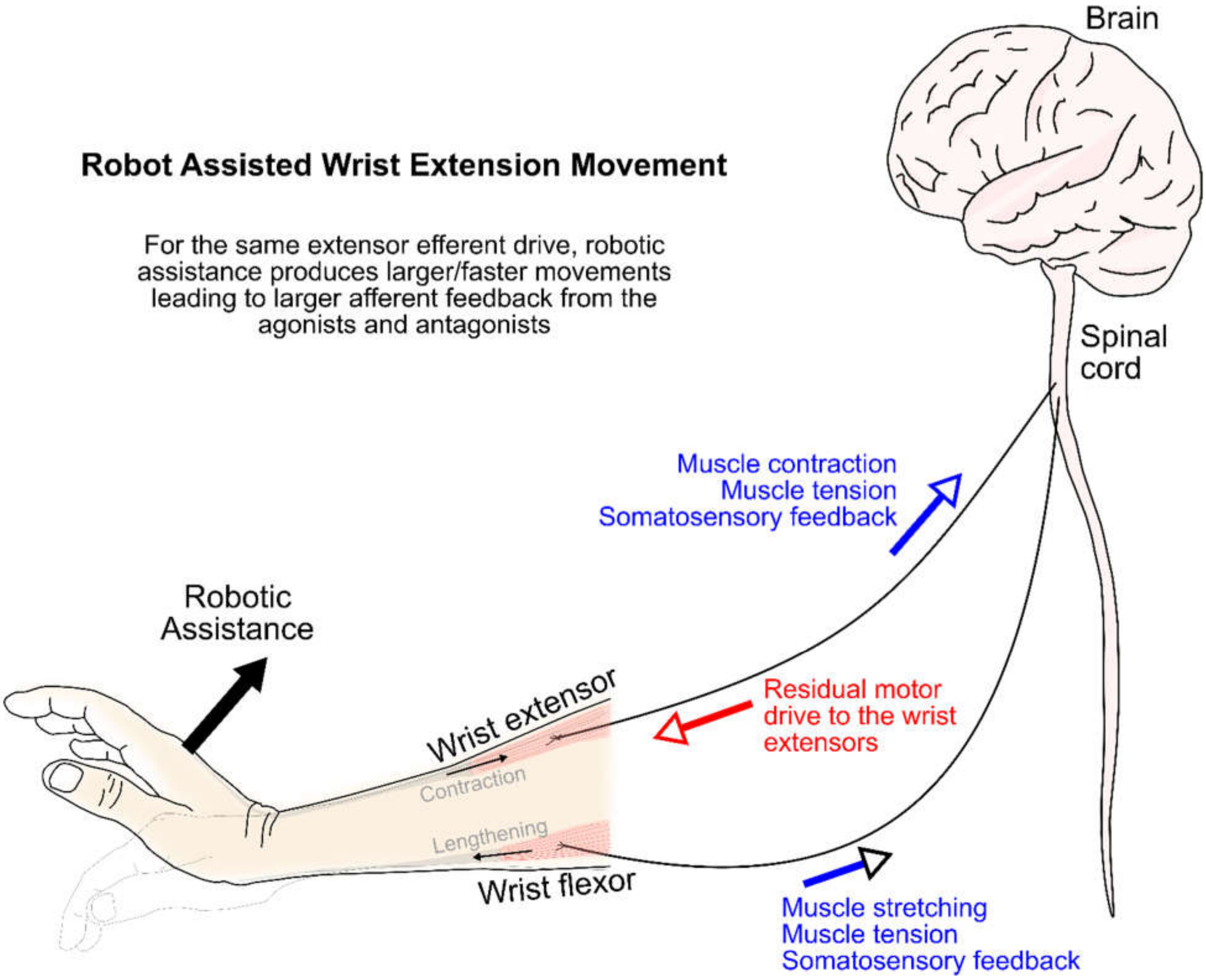

Figure 1. Depiction of the different efferent and afferent information flow for a wrist extension movement with robotic assistance. The thick black arrow indicates the external assistance force applied by the robot to assist wrist extension movement, while the subject is attempting to perform wrist extension voluntarily.

The aim of this article is to look at the current evidence for robotic assistance in UL stroke neurorehabilitation in the context of findings from other related areas in neurorehabilitation. The paper starts with a putative causal model of sensorimotor recovery and discusses the direct and indirect ways in which robotic assistance can influence recovery. Following this, evidence from the robot-assisted therapy literature is presented to evaluate the different indirect and direct effects of robotic assistance on recovery; evidence from the NMES literature is also presented to further support the potential direct role of robotic assistance.

1.1. What is robotic assistance?

There are several ways a robot can physically interact with a human limb[1]. We use the term ***robotic assistance*** to refer to an external force or torque applied on a human limb by a robot to complete the desired movement beyond one's voluntary ability. This assistance augments a subject's voluntary effort to make: (a) larger movements by moving the limb outside its active range of motion, and (b) faster movements than is possible voluntarily. Because the assistive force/torque is applied externally, robot-assisted joint movements do not produce any additional agonist muscle contraction beyond the voluntary contraction performed by a subject. Fig. 1 depicts a typical scenario in robot-assisted therapy where a wrist extension movement is performed with assistance from a robotic device; the thick black arrow indicates the force applied by the robot. When a stroke subject voluntarily attempts a wrist extension movement, residual efferent drive (red arrow in Fig. 1) from the brain activates the extensor muscles to extend the wrist, while overcoming the pull from the flexors (passive or due to co-contraction). This movement produces afferent feedback from the wrist joint, which includes the muscle spindle activity from the shortening agonists and the lengthening antagonists, the muscle tension in the agonists/antagonists sensed by the Golgi tendon organs, and feedback from other mechanoreceptors in the articular tissue[11]. However, any voluntary wrist extension movements will be larger and faster with robotic assistance, thus producing stronger afferent feedback to the brain than without assistance. There will also be tactile/somatosensory feedback from various cutaneous receptors on the skin over the wrist and the hand, where the force is applied by the robot. This enhanced movement-related sensory feedback is believed to promote recovery, as will be discussed later in the paper.

The implementation of robotic assistance during voluntary movement practice has been explored extensively in the rehabilitation robotics literature. A spectrum of control schemes exists in the current literature, such as using position control[3,12], force/torque control[13,14], impedance/admittance control[15], with continuous assistance to follow a trajectory/path[16], feedforward assistance towards discrete targets[17,18], or triggered assistance based on some movement criteria[18,19]. Adaptive assistance schemes have also been an active area of research to maximise the voluntary contribution of a subject during therapy[1,17,18,20–26].

2. A putative causal model of sensorimotor recovery in robot assisted therapy

Sensorimotor recovery is a complex, dynamic process resulting from changes in the central nervous system or the peripheral musculoskeletal system effected by therapeutic interventions or spontaneous processes. The central changes correspond to the cortical reorganisation that can improve strength and control of movements. While peripheral changes correspond to changes in the passive viscoelastic properties of soft tissue (muscles, tendons, ligaments) which can lead to increased strength, range of motion, reduced passive resistance to movements, etc. A putative graphical causal model of this recovery process in robot-assisted therapy is depicted in Fig. 2. This figure shows that sensorimotor recovery is influenced by four factors – (a) robotic assistance, (b) intensity of therapy, (c) a subject's motivation, and (d) the subject's active participation in therapy. Three of these factors – intensity, active participation, and motivation – are essential active ingredients influencing recovery in any neurorehabilitation intervention[27]; the robotic assistance factor is unique to robot-assisted therapy. Although there are a multitude of other factors that influence sensorimotor recovery, these four are the most relevant factors for the current discussion.

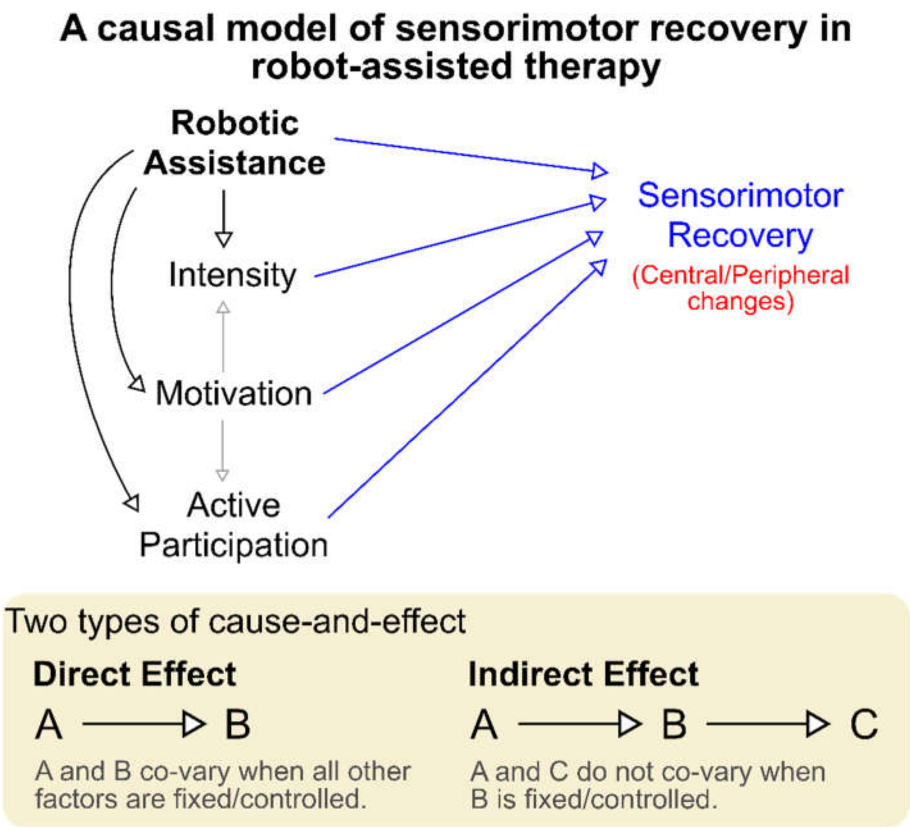

Figure 2. A putative graphical causal model of sensorimotor recovery in robot-assisted therapy. The direction of the arrows indicates the direction of causation – the variable at the arrow's tail is the cause, and the one at its head is the effect. There are two types of causal effects: direct and indirect effects, depicted at the bottom of the figure.

In Fig. 2, an arrow between two factors indicates the direction of causation; the factor at an arrow's tail is the cause, and the one at its head is the effect. For example, the intensity of therapy causes sensorimotor recovery, where higher therapy intensity leads to better recovery[28]. There are two cause-and-effect relationships between the different factors in a causal graph (depicted in the coloured box at the bottom of Fig. 2).

Direct effect[29]: A factor A has a direct effect on another factor B if they are connected by an arrow directed from A to B (Fig. 2). Here, we say that A is a direct cause of B. In Fig. 2, therapy intensity, active participation, and motivation directly affect sensorimotor recovery. One can experimentally establish the direct effect of A on B by fixing or controlling all other variables except A. Under this controlled condition, if changes in A result in changes in B, then there is a direct causal effect from A to B. In practice, a randomised controlled trial allows us to detect a direct effect of A on B by averaging out the effect of all other confounding factors through random assignment of subjects receiving different levels of the intervention A.

Indirect effect: A factor A has an indirect effect on a factor C if they are connected by a series of two or more arrows starting from A and terminating at C, with one or more intermediate factors between them (Fig. 2). In Fig. 2, A does not influence C directly, but through B; there can be multiple intermediate factors in more complex graphs. In addition to its direct effect on sensorimotor recovery (Fig. 2), motivation can also have an indirect effect through the intensity of therapy; for instance, a motivated patient is likely to train more and thus recover better. Experimentally, one can establish an indirect effect between two factors, A and C, by fixing or controlling the intermediate factors (B), which will break the coupling between A and C.

Distinguishing between these two types of cause-and-effect relationships is essential to delineate the different mechanisms through which robotic assistance can influence sensorimotor recovery.

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3. How can robotic assistance influence recovery?

Fig. 2 depicts the direct and indirect effects of robotic assistance on sensorimotor recovery. The indirect effects are mediated through its influence on the intensity of therapy, a subject's motivation, and active participation in therapy. On the other hand, the direct effect is most likely the result of the cortical and peripheral changes effected by robotic assistance. We will first discuss the indirect effects of robotic assistance, followed by its direct effects on sensorimotor recovery.

3.1. Indirect effects of robotic assistance on sensorimotor recovery

Intensity of training is commonly measured as the actual time spent or the number of movement repetitions performed in therapy[27,30]. Therapy intensity is a crucial factor driving sensorimotor recovery[28], arguably through cortical changes induced by repeated movement practice[31]. Training intensity can also lead to changes in or help maintain the integrity of the peripheral soft tissue, but its contribution is debatable[32]. Robots can increase therapy intensity through longer duration training and more repetitions per therapy session. Robots do not tire, allowing longer training time than conventional therapy. With robotic assistance, patients can perform faster movements, allowing them to perform more movement repetitions; for example, patients can train around 1000 movement repetitions during an hour-long robot-assisted therapy session[33,34]. Thus, robotic assistance can indirectly influence recovery by increasing the therapy intensity.

Motivation is defined as the energising of behaviour in pursuit of a goal[35]. It plays a vital role in the success or failure of therapeutic interventions and can directly affect the other two factors, 'intensity' and 'active participation'; a motivated patient will likely be more involved in therapy and train more (grey arrows in Fig. 2). Additionally, increased motivation could also directly affect cortical changes by impacting the learning processes in cortical circuits[36,37]. Robotic assistance can impact patients' motivation by encouraging them to attempt movements they cannot do voluntarily[38], and give them a sense of agency[33]. Rowe et al. reported that patients receiving larger robotic assistance reported higher motivation than those receiving less assistance[33]. Thus, increased motivation from robotic assistance can indirectly drive recovery.

Active (voluntary) participation during therapy is another crucial ingredient for sensorimotor recovery[27]. In task-oriented therapy, the patient is an active problem solver attempting to solve sensorimotor problems[27]. Robotic assistance can promote the active participation of patients by encouraging them to attempt movements that are not possible voluntarily[38,39]. Repeated attempts with robotic assistance can help drive cortical changes, thus promoting sensorimotor recovery. Interestingly, Rowe et al. reported that robotic assistance led to a higher perceived effort by patients receiving higher assistance[33]. This increased perceived effort could result from patients being voluntarily more involved in the training process or patients deriving a sense of agency from the robot's contribution. Furthermore, robotic assistance allows severely affected patients with no residual movements (through a brain computer interface) to voluntarily produce assisted movements, thus allowing them to actively participate in training[39,40].

We must note that robotic assistance can also negatively affect motivation and active participation. Too much assistance can lead to *slacking* – a reduction in a patient's active participation or effort during training[17]. Similarly, very high levels of assistance can also reduce the challenge of training for patients and thus, diminish motivation[41]. Robotic assistance must be designed to optimally challenge patients, which has led to an array of "assist-as-needed" controllers in the literature[1,17,18,20–26].

3.2. Direct effect of robotic assistance on sensorimotor recovery

Through cortical changes: Robotic assistance can directly affect sensorimotor recovery by inducing cortical changes through Hebbian or Hebbian-like learning mechanisms[33,42–44]. Movements of patients with neurological injury are diminished, slow, and poorly coordinated, resulting in weak afferent feedback. This feedback is stronger during

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robot-assisted movements, which are larger and faster. The temporal coupling of this strong sensory feedback with movement intention is hypothesised to strengthen cortical connections[8,33,42,43,45]. This scenario is depicted in Fig. 3, where the strong afferent feedback from robot-assisted movements arrives at the brain and spinal cord while there is ongoing movement intention, planning, and execution. The coincidence of this afferent signal with the motor planning and execution commands in the cortical and subcortical networks can modify these neural circuits[46,47]. Spike-time dependent plasticity (STDP) is often proposed as a potential mechanism for these cortical changes[43,48,49]. However, it is not clear how a synaptic-level learning mechanism like STDP operates at the circuit/system level, where there are streams of pre- and post-synaptic activity across different types of synapses across functionally diverse circuits[43,47,50].

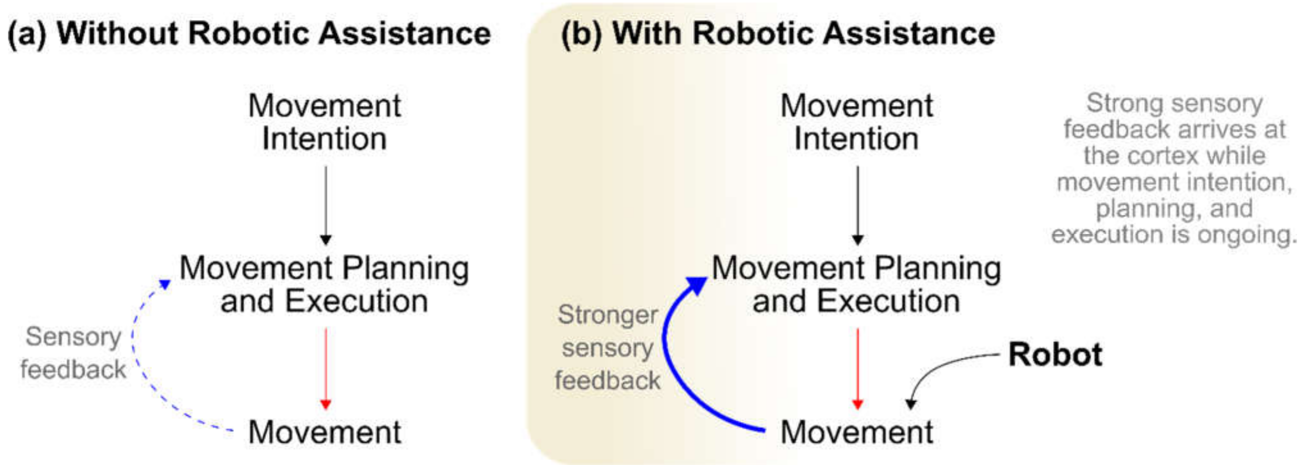

Figure 3. A flow chart of depicting the flow of information during (a) unassisted and (b) robot-assisted movements. When movements are unassisted, there is weak sensory feedback to the brain (thin, dashed blue line (a)). With robotic assistance, movements are larger/faster, thus producing a stronger sensory feedback (thick solid blue line in (b)).

Through peripheral changes: Robots can help patients move outside their active range of motion, thus stretching the antagonist muscles and other joint structures beyond that of voluntary unassisted movements. This stretching can help maintain joint soft tissue integrity and may also prevent muscle shortening and contracture. The stretching from robotic assistance may also help reduce muscle spasticity[32]. However, a recent meta-analysis reported that short (3 month long) stretching protocols do not lead to any change in joint range of motion or the viscoelastic properties of soft tissue[32]. Furthermore, the amount of stretching applied through robotic assistance is minimal compared to dedicated joint stretching exercises. Thus, robot-assisted therapy is unlikely to lead to any peripheral tissue changes.

3.3. Evidence for the direct effect of robotic assistance on recovery

There have only been a handful of controlled studies investigating the direct role of robotic assistance on upper-limb recovery. A summary of selected studies identified through a non-systematic search on PubMed and Google Scholar based on the authors' knowledge of the literature is provided in Table 1. We note that this is not an exhaustive list, but we firmly believe it to be representative of the evidence in the current literature. These studies compare groups receiving different levels/types of robotic assistance while controlling for at least the intensity (duration) of therapy and the types of movements trained by the groups; studies that did not explicitly compare the role of assistance were not included. A quick glance at the summary column in Table 1 shows mixed evidence for a direct role of robotic assistance; three studies support the beneficial role of robotic assistance on recovery[8,39,42], two do not[33,51], and one is equivocal[52]. All these studies are small n studies with significant inter-study protocol differences, preventing us from drawing any strong conclusions. Nevertheless, we make the following observations about the individual studies to form a tentative understanding of the role of robotic assistance in sensorimotor recovery:

- **Kahn et al. 2006**[51] found no difference between robot-assisted and unassisted therapy. They used a strict position control scheme that completed movements when a stroke subject made a small trajectory error of $\pm 1cm$, leaving little scope for patients in the robot-assisted group to learn appropriate movement patterns through trial and error. There could have been considerable slacking in the robot-assisted group.
- **Takahashi et al. 2008**[8] is the only study to date to show a strong dose-dependent response to robotic assistance. It has the highest concentration of therapy intensity[1] of 7.5 hours/week among the studies in Table 1, which could have amplified the effect of robotic assistance. However, this study also has the smallest sample size (7/6 in experimental/control groups) among the ones in Table 1.
- **Ramos-Murguialday et al. 2014**[45] shows that the time synchrony between movement intention and robotic assistance is essential. Patients who received assistance contingent on movement intention (detected using event-related desynchronisation in EEG) had better outcomes than those whose assistance was unrelated to movement intention. Interestingly both groups perceived BCI triggered assistance to be consistent with their intention.
- **Susanto et al. 2015**[52] found no difference between the assisted and unassisted groups in the Action Research Arm Test (ARAT). But, the experimental group had significant improvements in the Wolf Motor Function Test (both score and time). There was large intra-group variability in the study, which contributed to the non-significant result in the ARAT.
- **Rowe et al. 2017**[33] found no difference between the two levels of robotic assistance for finger training, which led to different success rates between the two groups of 80% (high assist) and 50% (low assist). Could there have been a difference between the groups if one was unassisted instead of being partially assisted? Confounding factors such as the game success rate could be controlled in the absence of assistance, e.g., through visual amplification or lowering the game difficulty. It is also currently not clear if the number of movements in therapy needs to be controlled if we have already controlled for the actual therapy duration.
- **Cordo et al. 2022**[42] found a significant difference between the experimental and control groups in Fugl-Meyer Assessment (FMA) in the subacute stroke population. We note that the inclusion of this study in this list is debatable as the control group did not actively participate in the training. However, we chose to include this study in our analysis as the intervention provided enhanced movement-related sensory feedback like robot-assisted therapy. This study had a crossover design, and the benefits seen in the experimental group were also seen in the control group once the control group received the experimental intervention. This study also had the highest sample size (38/35 in experimental/control groups) among the studies in Table 1. Nevertheless, this study does not allow us to distinguish between the contribution of active participation and enhanced sensory feedback during voluntary movements in promoting recovery. An active control group would have addressed this issue.

A recent retrospective secondary analysis by Takebayashi et al. using data from a robot-assisted therapy study on subacute stroke patients found differences in recovery depending on the amount of time patients received high or low robotic assistance[53]. Robotic assistance resulted in differential benefits for severe-to-moderate and moderate-to-mild patient groups; the severe-to-moderate group benefited from high robotic assistance, while the moderate-to-mild benefited from low robotic assistance. Although this study

[1] We define the 'concentration of intensity' as the hours of duration of therapy per week.

does not establish a causal role for robotic assistance on recovery, it does provide preliminary support for this role.

Overall, no strong claim can be made about the direct benefits of robotic assistance on recovery based on these studies; nevertheless, they do allude to this possibility. More tentative support for this beneficial role can be found from another assisted training approach through neuromuscular electrical stimulation (NMES), which provides stronger afferent feedback during training than robots.

Table 1. Summary of relevant studies comparing the effect of robotic assistance on sensorimotor recovery.

Study	Experimental & Control Groups	Upper-limb segment trained	Intervention and Outcomes	Results Summary
Kahn 2006[3]	E: Robot-assisted (10) C: Unassisted (9) Chronic stroke	Shoulder-elbow reaching movements against gravity.	24 sessions, 45min/ session for 8 weeks. CMS, RLA, free reaching kinematics, and other robot-aided biomechanical assessments.	Both groups improved, but there was no difference between the groups on any scale, except for smoothness of reaching. **No difference between the groups.**
Takahashi 2008[8]	E: Robot-assisted therapy on all 15 sessions (7) C: Unassisted for the first 7.5 sessions, and robot-assisted for the rest of 7.5 sessions (6) Chronic stroke	Fingers, thumb, and wrist to perform gross hand opening and closing and wrist flexion-extension.	15 sessions, 90min/session for 3 weeks BBT, ARAT, FMA, NHPT, SIS, MAS, and others.	Both groups improved in BBT, ARAT, and FMA. The experimental group improved more than the control group on ARAT and FMA. Improvements in the experimental group were higher only in the first half of the study when the two groups were different. **Dose-dependent difference was seen between the groups.**
Ramos-Murguialday 2014[45]	E: Robot-assisted contingent on movement intention (16) C: Robot-assisted not contingent on movement intention (14)	Shoulder-elbow reaching and gross hand opening and closing	20 sessions, 4 weeks FMA, MAL, GAS	**The experimental group showed significant improvements in FMA score, while the control group did not show significant change.**
Susanto 2015[52]	E: Robot-assisted (9) C: Unassisted (10) Chronic stroke	Gross hand opening-closing, three and two-finger pinch grasps while moving the hand across the table.	20 sessions, 60min/session, 5 weeks. ARAT, WMFT, FMA, and others.	Both groups improved in ARAT and FMA. But there was no significant difference between the groups in terms of ARAT. The Experimental group did better in the WMFT-FT score and time. **Mixed results in different clinical outcome measures.**
Rowe 2017[33]	E: High robotic assistance (15) C: Low robotic assistance (15) Chronic stroke	Index and middle finger flexion-extension movements	9 sessions, 60min/session, 3 weeks BBT, FMA, ARAT, MAL, MAS, IMI	Both groups showed modest improvement in BBT, ARAT, and FMA. The high assistance group reported higher motivation and higher perceived effort. **No significant difference between groups in terms of the clinical scales.**

Cordo 2022[42]	E: Robot-assisted movements with antagonist muscle vibration (38) C: Passive robot-assisted movements with sham vibration (35) Subacute stroke	Gross hand opening and closing, wrist flexion-extension	18 sessions, 30min/session, 6-9 weeks FMA, RLA, SIS, MAS	**Experimental groups showed significantly larger improvements in FMA than the control group.** When the Control group was offered training with muscle vibration after the end of the first phase of the study, the control group showed a comparable increase in FMA to the experimental group.

4. Evidence from the NMES literature

NMES is used in neurorehabilitation for various purposes[54], one of which is to provide assisted movement therapy. In this apprsoach, desired movements are produced through the contraction of agonist muscles elicited via external electrical stimulation. NMES-assisted movements are arguably more natural than robot-assisted movements since the latter is produced without requiring agonist contraction through external forces on body segments. NMES also recruits sensory nerves and other sensory structures during stimulation. Thus, compared to robots, NMES produces stronger afferent feedback through (a) more agonist muscle contraction, (b) activating cutaneous sensory structures underneath the stimulating electrodes, and (c) the direct stimulation of the sensory nerves. It also produces antidromic activity on the motor nerves innervating the agonists, which could play a role in strengthening local spinal cord circuits through Hebbian learning[46].

If Hebbian learning contributes to sensorimotor recovery, we should see better recovery from NMES-assisted voluntary movements than unassisted ones. A recent systematic review on upper limb electrical stimulation found that NMES during voluntary movement intent had a slightly better outcome in terms of FMA when applied early on after stroke[55]; this study did not find any significant difference due to NMES on the Box and Block Test. Another systematic review on NMES computed the standard mean difference (SMD)[56] to conclude that NMES improved upper-limb activity more than unassisted training[57]. The control groups in both these reviews received sham or no stimulation during voluntary practice. A comparison between the effectiveness of brain-computer interface (BCI) triggered assisted training with robots, or NMES found that BCI+NMES had significantly large SMD, while BCI+Robot did not[40], compared to sham BCI training or usual care. Although based on small n studies, these systematic reviews further support the tentative role of enhanced movement-related sensory feedback in promoting sensorimotor recovery.

5. Discussion

The question of the role of robotic assistance on sensorimotor recovery has been of great interest since the early days of rehabilitation robotics. Despite more than two decades of work, our understanding of this role remains poor. This paper looked at the different indirect and direct causal routes through which robotic assistance can drive recovery, along with some data supporting or refuting these causal claims. Robots can increase therapy intensity through longer training and a greater number of movement repetitions per therapy session. Optimally designed robotic assistance can increase motivation and active participation even for patients with no residual movements[1,17,19–25]. Although various assist-as-needed controllers continue to be proposed, most of them are likely to produce similar recovery. Simpler control schemes are robust, suitable for a wide range of movements, and are likely to be equally effective; e.g. Takahashi et al. used a single time-based rule to assist movements[8], which was clinically effective.

Additionally, a patient's motivation and active participation might also be determined by how s/he perceives and uses robotic assistance during training. We have anecdotal evidence from informal testing of our robots where patients reported that robotic assistance provided them with clues as to what to do and how to move. A further boost to patient motivation during robot-assisted training will also come from video games and regular feedback[33]. These indirect causal routes to recovery make a strong argument for using robots in upper limb neurorehabilitation for patients for whom robotic assistance can positively impact intensity, motivation, and active participation.

The direct effect of robotic assistance on recovery is an equally important question, both scientifically and practically. Sensory information is vital for creating and maintaining sensorimotor maps[58]. The enhanced movement-related sensory feedback provided by robotic assistance might be behaviourally beneficial, as indicated by the current, albeit limited, evidence. These benefits are likely due to cortical changes induced through Hebbian or Hebbian-like learning mechanisms[46,47]. Further support for robotic assistance comes from the NMES literature; the stronger afferent drive from NMES assisted voluntary movements appears to promote recovery better than unassisted ones. If enhanced movement-related sensory feedback has an influence on movement recovery, then the stronger and additional sensory feedback from NMES-assisted training could lead to better recovery than robot-assisted training. However, the differential effects of robot versus NMES assisted movements are currently unknown.

Limitations

The arguments and data presented in the study must be taken in light of its limitations.

1. This was not a systematic review but rather a commentary/opinion. The studies used for the arguments were based on the authors' knowledge of the literature. Thus, the paper might have presented a biased view of the role of robotic assistance.
2. The study did not look at any evidence from other human-robot interactions, such as error augmentation[59,60], which might be more beneficial than robotic assistance. Error augmentation is likely to operate through different learning mechanisms than robotic assistance, e.g., error-based learning[61].
3. The clinical benefits of paired associative stimulation (PAS), a technique similar to robot- or NMES-assisted therapy, remain unclear. PAS relies on the tight temporal coupling between cortical activity and afferent feedback to induce Hebbian learning[62,63]. The mixed results from PAS studies potentially weaken the support for enhanced movement-related sensory on recovery. However, most PAS studies have only looked at changes in corticospinal excitability, which might not be a good indicator of behavioural recovery[47]. Additionally, the strict timing requirements in PAS, like STDP, are not warranted[47].

6. Conclusion

A strong case cannot yet be made to support the direct causal role of robotic assistance in recovery through enhanced movement-related sensory feedback. However, based on the current evidence, we hypothesise that high-intensity training with robotic assistance will produce a superior behavioural outcome than training without assistance after controlling for factors such as intensity of therapy, motivation, and active participation; this superior outcome is likely to be small. Recent high-intensity training studies have shown clinically significant improvements in impairment and activity scales in chronic stroke[64,65]. Thus, higher intensity training could help better resolve the small differences between assisted and unassisted training. If future studies establish the direct role of robotic assistance on recovery, assisted movement therapy will become another valuable tool in our arsenal in the fight against sensorimotor impairments and disability.

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