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ROBOT-AIDED NEURO-RECOVERY

Robots help people recover after neurological injury.

Stroke—cerebral vascular accident, or CVA—is the leading cause of lasting disability in the developed world. It is considered a paradox of modern health care—a disorder whose widespread growth is the result of continuous medical progress and advancement. As most of us are living longer, we grow increasingly susceptible to disorders such as stroke. Although there is some degree of spontaneous, unaided recovery, about 90% of stroke survivors are left with residual disability that requires treatment. Although hundreds of pharmacological agents have been tried, no drugs exist to aid recovery. Only one has been FDA-approved for neuro-protection, helping the brain survive a stroke, but none have been FDA-approved for neuro-recovery, restoring brain function after a stroke.

Care usually involves some form of movement training, delivered by physical or occupational therapists, which creates both a challenge and an opportunity. The challenge is how the physical medicine and rehabilitation (PM&R) community can manage the rapidly growing burden of treatment. The opportunity is that physical and occupational therapy are labor-intensive, manual procedures, ripe for augmentation by technology. Properly designed robots can help people recover after neurological injury.

HOW CAN ROBOTS HELP?

There are two types of stroke: haemorrhagic, caused by bleeding in the brain; and ischemic, the more common, caused by blocking blood flow. An ischemic stroke occurs because a blood clot finds its way into the blood supply to the brain, where it impedes blood flow and starves "downstream" nerve cells of the oxygen they require to live and function. The brain consumes almost a third of the oxygenated blood supplied by the heart. Because of the way this blood is transported to the brain (i.e. the "plumbing") the parts most vulnerable to blockage tend to be those most rostral (Latin for "towards the head"). The most rostral parts of the central nervous system (CNS: brain plus spinal cord) are the cerebral hemispheres (the parts inside your head), which include areas of cerebral cortex (the wrinkled part just inside the skull) involved in sensory-motor coordination. In general, the aftermath of surviving a stroke is that some parts of your brain do not work properly, often in the upper reaches of the CNS where sensory-motor coordination is managed.

How does movement experience provided or assisted by a human therapist help to heal what is essentially a "hole in the brain"? How might a robot augment this process and alleviate an injury to the brain? The answer is found in the slowly emerging (and as yet incomplete) understanding of how the brain works. For most of the 20th century, the adult CNS was considered to be a stable, fixed entity. Only in the last few decades has evidence emerged that, in fact, the adult brain is highly plastic (i.e. susceptible to change). The basic mechanism of neural plasticity was initially proposed by neuropsychologist Donald O. Hebb and confirmed many decades later by careful experimentation. To paraphrase Hebb's law: "Nerves that fire together wire together."

FIGURE 1 **Robot-aided neuro-rehabilitation for the shoulder and elbow.**

The most successful robot-administered therapy to aid neuro-recovery is based on several principles of learning. A visual display indicates a target location to which the patient should attempt to move.

FIGURES 2 & 3
Robot-aided neuro-rehabilitation for the wrist.
***Far right:* Robot-aided neuro-rehabilitation for the hand.**

The robot sets up a virtual channel between the current location of the patient's limb and the target location. If the patient moves along that channel, no forces are experienced. However, if the patient's motion deviates to either side of that channel, those aiming errors are permitted but resisted by a programmable damped spring. If the patient moves too slowly (or does not initiate movement at all) the back wall of the channel (the end at the patient's starting location) moves smoothly towards the target location, nudging the patient to the target.

The result of all this is that: 1) the visual display evokes the intent to move; 2) that intention generates neural activity (possibly incoordinated) descending from the higher CNS through cortico-spinal pathways to the muscles; 3) that activity generates a corollary discharge or efference copy of the descending command that is routed back up to areas of the brain associated with learning and coordination; 4) a short time later, a movement occurs that roughly approximates an unimpaired, properly-coordinated response; 5) that movement generates sensory neural activity that ascends the cortico-spinal pathways back up to the cerebral hemispheres, where 6) it may be compared with the efference copy of the command. According to Hebb's law, those commands that correlate well with the appropriate movement are reinforced; those that do not are attenuated.

Repeating this process with high intensity—a typical session of robot-aided therapy involves over a thousand movements, whereas a typical session of human-administered therapy involves about eighty—provides the stimulus and statistics for the brain to re-acquire movement control and coordination. This account is confirmed by the observation that the patient's active participation is essential. Passively moving a patient's limbs may help improve joint mobility but it yields no improvement of motor function.

Other principles of learning are also built into the therapy algorithm. Visual feedback about progress, based on several measures computed by the robot, is provided to the patient, but not continuously. That is because intermittent feedback provides the greatest retention of acquired skill. In addition, the assistance provided by the robot is continually adapted based on the patient's performance. Specifically, if the patient becomes better at aiming, the stiffness of the channel sidewalls is progressively reduced; as the patient needs less help, less help is provided. Similarly, as the patient moves faster, the speed with which the back wall of the channel converges to the target is progressively increased; as the patient can move faster, faster movements are encouraged. These parameters are continuously updated to keep the patient at a "challenge point" where their success rate is about 80% ± 10%—not too successful, to maintain engagement; not too much failure, to avoid discouragement. This robot therapy algorithm is like coaching: assistance is provided, but only as needed; and "the bar is raised" but only to a level the patient can achieve.

Aside from its theoretical underpinnings, this form of robot-administered treatment works well. The American Heart Association periodically issues recommendations for rehabilitative care of stroke patients. The most recent issue gave robot-aided neuro-rehabilitation for the upper extremities its strongest recommendation based on the strongest level of evidence[1]. The U.S. Veteran's Administration similarly endorsed upper-extremity robot-aided neuro-rehabilitation[2]. Remarkably, this technology-based treatment is less expensive than usual care, at least within the Veteran's Administration health-care system[3].

HOW HARD CAN THIS BE? THE NEED FOR GENTLE ROBOTS

At first glance, administering therapy using robots might seem trivial; just move the patient's limbs. However, robot-administered treatment requires physical contact and dynamic interaction with the patient, and that's a challenge. There's the obvious requirement for 100% safety. A related but subtler challenge is coupled (in)stability. Due to physical interaction, the dynamics of an object—in this case, a patient—coupled to the robot may profoundly affect the robot controller's stability. This challenge was identified in the earliest days of research in robotics. Given a sufficiently detailed knowledge of the object's dynamics, the controller might be structured to preserve stability, but in this application, the "object" is a neurologically-impaired human. Unfortunately, we know very little about the dynamic behavior of unimpaired humans and vastly less about the dynamic behavior of neurologically-impaired humans.

One simple solution to this problem emerged from studying the interaction of dynamic physical systems. If the robot's interactive behavior is structured to approximate that of an energetically passive object (any collection of springs, dampers and masses, connected in any configuration) then connecting the robot to a passive object cannot induce instability. Almost all observations of unimpaired humans show that their interactive dynamic behavior is also energetically passive. Structuring the control system so that the robot's interactive dynamic behavior (its mechanical impedance) approximates that of a passive object is sufficient to ensure stability when coupled to unimpaired humans. To date, that has also proven sufficient to ensure stability when coupled to neurologically-impaired patients.

Beyond the obvious requirement for stability, a therapeutic robot must also be gentle. The human skeleton is often modeled as a collection of kinematic pairs, but in fact its integrity requires muscle activity. For example, the shoulder joint is held together by the activity of the shoulder muscles. Neurological disorders such as stroke weaken those muscles and compromise the skeleton's integrity. As a result, even moderate forces (that an unimpaired joint would readily withstand) may cause discomfort or injury. Joint pain and a disorder known as shoulder-hand syndrome are common side-effects of post-stroke therapy. Remarkably, their incidence appears to be lower with robot-administered therapy. The key is that the robots are highly back-drivable (they have low mechanical impedance); large displacements may evoke small forces. Maintaining low mechanical impedance ensures gentleness—the robot never generates large forces, however far the patient's motion deviates from nominal.

WHAT CHALLENGES REMAIN?

Despite the success of upper-extremity robot-aided therapy, much remains to be done. Most important is the application of robot technology to lower-extremity disorders. Some encouraging results have been reported, but robotic lower-extremity therapy has overall been less successful than its human-administered counterpart. The Veteran's Administration strongly recommended against it, while the American Heart Association described it as "still in its infancy"[1,2].

But lower-extremity robot-aided neuro-rehabilitation ought to work—the same mechanisms of neural plasticity in response to high-intensity movement experience should operate. The problem does not lie in the several robots that have been developed; many are elegant examples of mechatronic design. Instead, the challenge lies in our collective ignorance of how unimpaired human locomotion is controlled, and our even deeper ignorance of how it may be recovered after neurological injury.

Underlying the success of upper-extremity robot-aided therapy is a quantitative knowledge of how humans coordinate and control their upper extremities. Decades of study have shown that unimpaired upper-extremity movements are primarily controlled by first specifying the kinematics of hand motion. Exposure to visual distortions or perturbing forces (including Coriolis accelerations) evokes a rapid adaptation that largely restores the unperturbed hand motion, showing that joint actions and muscle forces are subordinated to the kinematic specification of hand motion. Independent of movement duration and any load carried, that kinematic specification is well-approximated as the smoothest movement subject to task constraints (i.e. acquiring a target). This is precisely the specification at the core of the successful robot-aided therapy described above.

A corresponding quantitative knowledge of unimpaired human locomotion has yet to emerge. One reason is that humans are exceptional. For excellent reasons, almost all of more than a century of neuroscience research into the control of locomotion has been based on animal studies. While that research has provided deep insight about the evolution of the nervous system, its relevance to human locomotion is unclear.

In addition to the more obvious factors that make humans exceptional (vastly more elaborated cerebral cortex, superior tool use, language, laughter) there are several factors specific to locomotion. While other mammals can walk upright on two legs, humans are the only mammals to do so preferentially. We walk plantigrade (foot flat on the ground during the stance phase) whereas other mammals walk digitigrade (on their toes). We walk with much straighter legs than our nearest cousins, chimpanzees and apes. As a result, mechanisms known to play a prominent role in mammalian locomotion may not apply to humans.

For example, neural networks capable of self-sustaining oscillation, known as central pattern generators (CPGs), contribute to the locomotion of several species, and coordinated rhythmic locomotion is preserved even after the cerebral hemispheres of the brain are surgically disconnected. However, there is very little evidence of a CPG in humans, and none so far in the context of upright walking. It may be that locomotor CPGs have been largely suppressed in humans, replaced by more direct control from the vastly-enlarged cerebral hemispheres.

This is important because most robot designs for lower-extremity therapy are based on imposing rhythmic patterns of lower-limb movement. Steady walking is clearly rhythmic but we also make discrete steps and smoothly integrate them with other actions such as throwing, at which humans are again exceptional. Recent studies of humans learning to compensate for visual distortion have shown that practice based on discrete movements leads to rapid learning that transfers well to rhythmic execution of the same movements. In contrast, rhythmic practice leads to slower learning and, more important, does not transfer to discrete execution of the same movement. Thus the emphasis on rhythmic motion in lower-extremity robot-aided neuro-rehabilitation may account for its lack of success.

PROSPECT

This is where the synergy between biology and engineering can be most productive. In the past few years, major advances in robotic locomotion have been achieved, including that of humanoid bipeds. While human locomotion may be controlled entirely differently, robotic research clearly identifies the major challenges of biped locomotion.

Those challenges—for example, rapid foot-placement—may prove to be effective targets for robot-aided locomotion therapy. Conversely, the emergence in the past few years of exoskeletal assistive technologies may provide the means to deliver this kind of treatment. At the same time, these technologies, which can interact with humans in a realistic context of upright locomotion, may enable critical experiments to establish how unimpaired human locomotion is controlled and—most important—how it may be restored after injury. ■

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ACKNOWLEDGEMENTS

The work reported here is the product of many students and colleagues supported by public funding and private foundations, all too numerous to list in detail.