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Automating activity-based interventions: The role of robotics

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Abstract—We have seen a continued growth of robotic devices being tested in neurorehabilitation settings over the last decade, with the primary goal to improve upper- and lower-motor function in individuals following stroke, spinal cord injury, and other neurological conditions. Interestingly, few studies have investigated the use of these devices in improving the overall health and well-being of these individuals despite the capability of robotic devices to deliver intensive time-unlimited therapy. In this article, we discuss the use of robotic devices in delivering intense, activity-based therapies that may have significant exercise benefits. We also present preliminary data from studies that investigated the metabolic and cardiac responses during and after 6 months of lower-limb robotic training. Finally, we speculate on the future of robotics and how these devices will affect rehabilitation interventions.

Key words: activity-based rehabilitation, cardiovascular, gait, Lokomat, metabolic response, rehabilitation, robotics, spinal cord injury, treadmill training, walking therapy.

INTRODUCTION

In the articles of this special *Journal of Rehabilitation Research and Development* (*JRRD*) issue, we have presented numerous examples of how effective activity-based therapies can improve important health qualities in individuals following stroke and spinal cord injury (SCI). For example, following long-term manual-assisted treadmill training, individuals with incomplete SCI demonstrate lower total cholesterol and low-density lipoprotein,

increased muscle mass, and a muscle fiber-type conversion to more fatigue-resistant type IIa and I fibers (see Hicks and Martin Ginis, p. 241, this issue). Similar improvements can be observed in stroke patients, where improvements in cardiovascular performance, muscle endurance, and functional gait can be realized with exercise-based interventions (Hafer-Macko et al., p. 261, this issue). What these and other studies have demonstrated is that with appropriate interventions, individuals with neurological injuries can realize important cardiovascular and metabolic benefits of exercise-based interventions beyond simply improvements in function.

While exercise is clearly important to the health and well-being of individuals after stroke, SCI, and frankly most neurological disorders, many of these individuals cannot participate in conventional exercise programs

because of significant motor impairments. Therefore, while walking on a treadmill may benefit an individual's cardiovascular performance, the safety risks to someone with balance and stability deficits outweigh the potential benefits. One possible solution is to use interventions that are safer and reduce demands on coordination and balance. For example, functional electrical stimulation (FES) has been shown to be quite beneficial in building muscle mass and slowing the progression of bone mineral loss in SCI (Dudley-Javoroski, p. 283, this issue). Studies have reported similar effects that have used FES-based bicycling in SCI, perhaps most notably the reported gains in health and well-being that Christopher Reeve experienced [1]. The limitations with such interventions are that they may not always be possible (e.g., sensate subjects may not tolerate electrical stimulation) and they do not necessarily allow for the practice of functional, coordinated movements. While pedaling a bicycle could surely be seen as a precursor to gait [2], functional walking needs to occur at some point. If an intervention could be designed that promotes intensive exercise in the context of a functional task (e.g., gait), improvements in both function and overall health may be realized. To this end, robotic devices may be one possible solution.

The original focus of robotics-based interventions was to take advantage of the fact that the central nervous system is quite plastic (Lynskey et al., p. 229, this issue) so that with intensive, task-specific movements, individuals with stroke and SCI can regain function and perhaps some level of independence. Significant evidence suggests that robotic therapy improves upper- and lower-limb function after SCI [3–4] and stroke [5]. Ironically, little has been reported on the exercise benefits individuals may experience following robotic therapy, particularly in gait. In this article, we review robotic technology, outline the potential benefits of using these devices for exercise-based interventions, and present some early evidence that suggests robotic-based interventions can have positive exercise benefits in individuals with neurological injuries.

REHABILITATION ROBOTIC DEVICES

Rehabilitation robotic devices come in many forms, none of which resembles *The Terminator* in the famous Arnold Schwarzenegger movie. While most rehabilitation robots attempt to re-create therapeutic interventions that are often used in the clinic, such as reaching movements or grasping objects, some robots offer greater capacities that would be daunting for a physical therapist to deliver. One cannot doubt that robots targeting the upper limbs may provide exercise benefits if they allow subjects to practice repetitive reaching under some level of resistance. However, one could argue that other less-sophisticated interventions could provide the same benefits for a fraction of the cost. We therefore propose that the role of upper-limb robots will likely continue to focus on improving motor function rather than exercise benefits. While this role may be true for the upper limb, for which subjects can perform interventions in a seated and therefore safe position, providing gait-training interventions poses additional challenges.

As outlined in the articles by Macko et al. (p. 323) and Hicks and Martin Ginis (p. 241) in this *JRRD* issue, treadmill training following stroke and SCI has significant cardiovascular and muscular effects. Yet providing such an intervention to individuals with poor balance and stability provides added risks, particularly if the intensity of the intervention is near the individual's limits. Robotic gait trainers provide an excellent alternative because they add a component of safety for the patient and therapist that allows individuals to train at higher intensity levels for longer durations. While we highlight the Lokomat (Hocoma AG; Volketswil, Switzerland) robotic gait-orthosis in an article by Colombo et al. [6], we need to stress that many other gait-training systems are now being developed that parallel the Lokomat [7–10].

The Lokomat was developed in the late 90s to help automate manual-assisted body weight-supported (BWS) treadmill training. The device, as shown in **Figure 1**, is an exoskeleton that attaches to the outside of the subject's legs and assists the subject as he or she ambulates on the treadmill. Small direct current (DC) motors drive the hip and knee joints while dorsiflexion is provided at the ankle with two elastic straps. The latest version of the Lokomat control software allows for variable robot assistance, ranging from full passive mode in which the device moves the subject's legs through a prescribed trajectory to a compliant mode in which the robot provides no active assistance. Recently, a pediatric Lokomat version was released to the public that allows children approximately 4 to 12 years of age to participate in gait-training programs.

The major benefits of training with the Lokomat are that patients can practice intensive gait training early
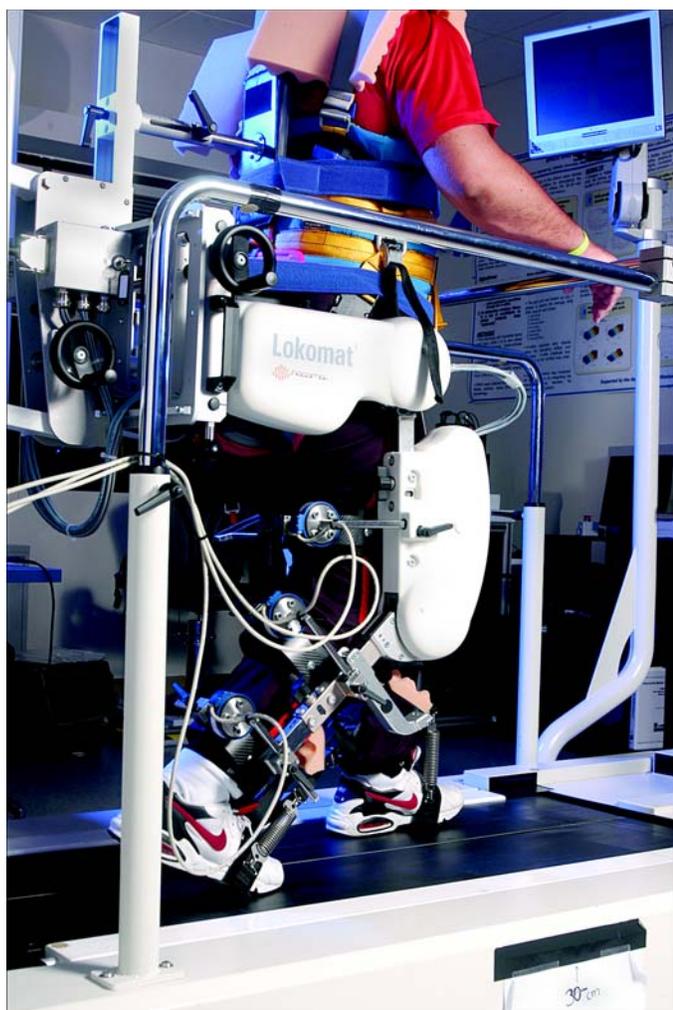
Figure 1.
Lokomat (Hocoma AG; Volketswil, Switzerland) robotic gait orthosis.

after their injuries in a safe and controlled environment. DeJong and colleagues recently published a longitudinal study that looked at factors important to stroke outcomes [11–12]. They found that early interventions (e.g., time postinjury) and intensity were factors that strongly correlated with gains in function. These two factors, early training and intensity, are supported by the Lokomat. First, because of the BWS system, subjects can practice walking much earlier in their rehabilitation program, since the risk of falling is eliminated. This added security allows individuals to begin walking as soon as they are medically stable, which is important not only for functional returns but also for prevention of secondary complications such as deep venous thrombosis (DVT),

muscle atrophy, cardiovascular deterioration, and pneumonia. One could also argue that getting subjects to walk early after their injuries can have positive psychological effects. Second, the intensity of the training can be graded by adjusting of the BWS level, changing the walking speed, and varying the amount of robot assistance. Each of these training parameters place additional cardiovascular demands on the individual and can be altered both within and across training sessions. In addition, unlike treadmill training sessions that may be limited by therapist fatigue, training sessions on robotic devices like the Lokomat are time-unlimited, since they are actuated by DC motors.

Most of the studies to date have focused on the lower-limb robotic devices as clinical training tools that improve walking ability, yet they have overlooked the added exercise benefits of the intervention. The U.S. Surgeon General recommends that "persons of all ages should include physical activity in a comprehensive program of health promotion and disease prevention and should increase their habitual physical activity to a level appropriate to their capacities, needs, and interest," and this is echoed by the National Cholesterol Education Panel, American Heart Association, Centers for Disease Control and Prevention, American Diabetes Association, American College of Sports Medicine, and others. Unfortunately, the reality is that diminished levels of fitness account for a large part of accelerated cardiovascular disorder (CVD) and increased body fat after SCI [13–20] and 25 percent of young, healthy persons with SCI have a level of fitness insufficient to perform essential activities of daily living [21]. We know that fitness and well-being are improved in persons with SCI by exercise conditioning [13,22–27] and higher levels of fitness are associated with reduced CVD risk [28–34]. Furthermore, several reports have highlighted the beneficial effect of exercise conditioning in persons with risk factors for CVD [28–29,32–34]. Here, we highlight three studies that have investigated metabolic and cardiac responses in SCI during robotic-assisted gait training, as well as some preliminary work investigating changes in cardiovascular performance after long-term robotic gait training.

METABOLIC AND CARDIAC RESPONSES DURING ROBOTIC GAIT TRAINING IN SCI

Israel et al. published a recent study that compared muscle activation patterns and metabolic responses in

individuals with incomplete SCI who walked on a treadmill with either therapist assistance or Lokomat assistance [35]. Twelve individuals classified as C or D on the American Spinal Injury Association (ASIA) Impairment Scale [ASIA, 2004] were tested on two separate sessions. In one session, two therapists assisted the subject as he or she ambulated on a treadmill under 30 to 40 percent BWS. Each therapist provided enough assistance so that the subject could clear his or her toe during swing and achieve adequate knee extension during stance. In a separate test session, each subject walked under the same levels of BWS, but the Lokomat assisted rather than the therapists. One should note that in these tests, the Lokomat was run in passive mode. In this mode, the Lokomat moves each subject's legs through a prescribed trajectory regardless of the subject's intensions (akin to a continuous passive machine). Each subject was asked to walk "with the robot" and try to match the machine's movements to the best of his or her ability. For both treadmill (therapist-assisted) and Lokomat sessions, muscle activity was collected from tibialis anterior, soleus, medial gastrocnemius, vastus lateralis, rectus femoris, and medial hamstrings. Metabolic measurements included rates of oxygen consumption (VO_2) and carbon dioxide production, while metabolic cost (or equivalent power) was calculated from these metrics.

The investigators found that during therapist-assisted treadmill walking, individuals with incomplete SCI demonstrated significantly greater VO_2 and metabolic cost than during Lokomat-assisted training. On average, subjects achieved VO_2 levels of 14.0 ± 3.9 mL/kg/min when walking on the treadmill with the therapist's assistance, but only 9.0 ± 2.4 mL/kg/min when walking with Lokomat assistance. For power measures, subjects generated approximately 3.1 ± 1.4 W/kg when walking with therapist assistance but only 1.9 ± 0.8 W/kg with Lokomat assistance. (Measurements are mean $\pm$ standard deviation unless stated otherwise.) While significant differences were observed in metabolic parameters for treadmill and Lokomat walking, in general, no significant differences were found in muscle activation patterns in six lower-limb muscles (for amplitude or timing of activity) during the gait cycle.

We should reiterate that metabolic differences were observed between therapist-assisted and Lokomat-assisted walking trials when subjects were instructed to walk as the device walked and match the kinematic trajectory prescribed by the Lokomat. However, in separate trials in which subjects were asked to maximize their effort during therapist- and Lokomat-assisted trials, no differences were found in metabolic parameters or muscle activation patterns.

The results from Israel et al.'s study indicate that similar muscle activation patterns and metabolic responses can be achieved in the Lokomat when compared with therapist-assisted training [35]. However, this finding only applies when the appropriate instructions or training conditions are given to the subject. This finding exposes a serious limitation with robotics. That is, if too much BWS or robotic assistance is provided to the subject or if the instructions are not clear, the subject may become complacent and allow the robot to assume a greater workload. As a result, the cardiovascular demands on the subject will decrease dramatically. In therapist-assisted treadmill training, this decreased effort level is not an issue, since therapists can continuously sense how much effort they are providing the subject and therefore indirectly measure the subject's effort level. This finding clearly emphasizes that therapists need to know the robot equipment, understand how to change parameters to continuously challenge the subjects, and be able to assess when the workload is inappropriate for the subject's abilities.

Nash and colleagues investigated metabolic and cardiac responses during Lokomat training in a 25-year-old female subject with a motor complete C3 to C4 (third to fourth cervical vertebrae) chronic SCI [36]. In this study, they measured VO_2, minute ventilation (V_E), and heart rate (HR) during seated resting and supported standing and while walking 40 minutes in the Lokomat. They found that the resting VO_2 of 50 mL/min increased immediately at the onset of walking to 118 mL/min, while V_E increased from 7.2 L/min in rest to 9.6 L/min during walking. HR also increased from 76 bpm during rest to 93 bpm during Lokomat walking.

The findings in this study indicate that even in motor complete SCI with lesions interrupting vagus and phrenic nerve pathways, significant cardiac responses can be elicited. While the investigators speculated that the increased metabolic response was attributed to reflex activity generated by stretching the muscles, this claim cannot be validated, since muscle activity was not recorded in this experiment. What this study does highlight is strength of robotic gait trainers. Since the robot can stabilize the lower limbs during training, individuals with no function below their injury level can be trained for extended durations. Although therapists could administer similar interventions,

whether they could maintain consistency over an extended training session is questionable. Additionally, therapists engaged in treadmill training paradigms have reported repetitive strain injuries and lower back problems. Training individuals with motor complete SCI may have additional health benefits beyond cardiovascular conditioning, such as prevention of DVT, improved circulation, slowing of bone mineral loss, and improved psychological state. Unfortunately, no studies to date have reported such effects, so these potential benefits are speculative at this point.

CHANGES IN METABOLIC AND CARDIAC RESPONSES FOLLOWING LONG-TERM ROBOTIC-ASSISTED GAIT TRAINING IN SCI

While the studies just described investigated within-session changes in metabolic and cardiac responses during robotic-assisted walking, they did not investigate whether people with SCI will experience a cardiovascular or metabolic training effect following repeated training sessions. A randomized controlled trial is currently underway at the National Rehabilitation Hospital (NRH) in Washington, DC, and the Miller School of Medicine, University of Miami, to quantify the effects of 6 months of robot-assisted BWS treadmill training on selected measures of fitness in persons with SCI. Subjects are people with ASIA C or D traumatically induced SCI between 1 and 6 months postinjury.

Subjects are randomized to either exercise training using robot-assisted BWS treadmill training or usual rehabilitative care. The experimental group participates in 72 Lokomat training sessions lasting 1 hour, three times a week for 6 months. Here, subjects walk in the Lokomat at an initial training speed of 1.9 km/h, progressing to a maximum of 3.2 km/h. During the training sessions, the levels of BWS and robot assistance are decreased as tolerated at each training session so that weight-bearing and workload can be increased. Subjects walking in the Lokomat are encouraged by the physical therapist and a computer-based biofeedback system to actively move the robotic legs. Subjects in the experimental group often begin Lokomat training while they are inpatients, where the Lokomat training supplements the standard physical therapy they receive at NRH or The University of Miami. Since these subjects often continue outpatient therapy following their discharge, the Lokomat training simply supplements their

usual care until they complete their outpatient therapy program. At that time, subjects only receive Lokomat training. The control group receives the same inpatient and outpatient therapy programs; however, they do not receive the supplemental Lokomat therapy.

Changes in metabolic responses are assessed for both groups at baseline and again at 3 and 6 months (**Figure 2**). A resting 12-lead electrocardiogram is performed and analyzed for rate, rhythm, and contraindications to exercise testing throughout the evaluation session [37]. Metabolic responses to exercise are continuously monitored by the open-circuit method on a metabolic analyzer as described by Nash et al. [36]. Resting metabolism and HR are measured for 6 minutes with the subject in the seated position, for controlling metabolic and chronotropic responses to the upright position, and after 6 minutes of BWS standing. The subject then ambulates in the Lokomat at the matched subpeak work rate of 1.8 km/h with the least BWS
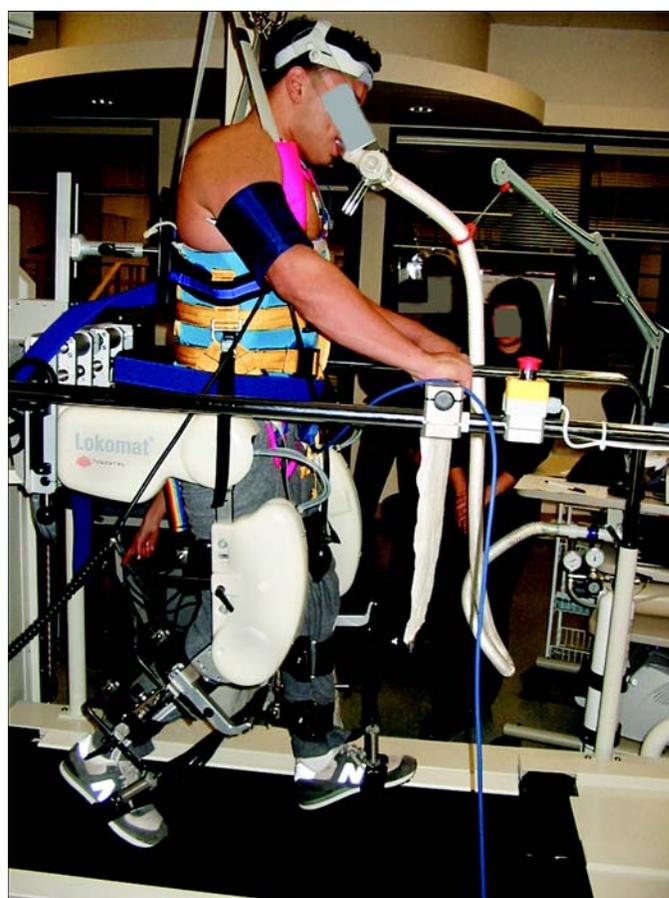

Figure 2.
Metabolic testing in Lokomat (Hocoma AG; Volketswil, Switzerland).

tolerated for 6 minutes. Both the 3- and 6-month follow-up metabolic tests are repeated at the same speed (1.8 km/h) and same percent BWS provided during the initial testing.

To date, five subjects have been trained on the Lokomat and four subjects have been assigned to the control group. The age range for the sample is 24 to 59 years, with an average age of 44.1 years. The **Table** summarizes interim trends for the subjects trained on the Lokomat.

The working hypothesis is that with the use of a standardized work rate on the Lokomat for all three tests, an exercise training effect in the intervention group would be reflected by lower resting and peak HRs, VO_2, and respiratory exchange ratio (RER) values on the 6-month test compared with the baseline test. Data from the 6-month test demonstrated a dramatic decrease in resting and peak HRs but a modest increase in VO_2 accompanied by a small decrease in RER at peak exercise. By comparison, mean values in the usual group for resting HR and peak HR decreased only 8.4 and 1.4 percent, respectively, while peak VO_2 increased 5.1 percent on the final test. While no statistical conclusions can be made from this small set of data, the trend indicates that a training effect may have been achieved after 72 sessions of Lokomat walking.

CONCLUSIONS AND FUTURE DIRECTIONS

While the future of robotics in neurorehabilitation programs is still unclear, early evidence suggests that interventions such as robotic-assisted gait training may improve gait as well as cardiovascular and metabolic performance. Some of the advantages of robotics devices in delivering intensive therapy have been outlined, such as the capability to train for longer time periods, at higher intensities, and in a well-controlled environment. However, using robotic devices has some disadvantages. These devices are very expensive, they sometimes break down and require routine service, and perhaps the biggest disadvantage, they do not have the same "feel" as therapists do. That is, for interventions such as therapist-assisted treadmill training, the therapist can continuously monitor important characteristics of the training, such as the subject's effort level, spastic contractions, and fatigue. While robots have high-resolution sensors that can also monitor such events, they currently are not programmed to do so. We hope that next-generation robots will have better monitoring capabilities and interact much more, providing "as needed" assistance. Integrating advanced concepts such as virtual reality [38] and quantifying impairments such as weakness and spasticity [39] has already begun. Adding measures of cardiac and metabolic responses would surely make these devices well-rounded additions to rehabilitation clinics.

ACKNOWLEDGMENTS

Table.
Comparison of baseline and 6-month exercise test data following Lokomat (Hocoma AG; Volketswil, Switzerland) training.[*]

Variable	Baseline	6 Months	% Change
Resting HR (bpm)	103.0	67.2	–35.8
Peak HR (bpm)	131.8	84.4	–36.0
Peak VO_2 (mL/kg/min)	7.8	8.2	+7.0
V_E (L/min)	16.5	16.9	+2.4
RER	0.96	0.94	–2.1

[*]All values are group means.
HR = heart rate, V_E = ventilation, VO_2 = oxygen consumption, RER = respiratory exchange ratio.

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