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Developing a Novel Gait Training Device Using a Minimally-Required-Assistance Principle

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ABSTRACT

The purpose of this report is to propose a new principle of minimally-required-assistance in the design of assistive devices for sensorimotor training in patients with neurological disorders. We illustrate the implementation of the principle in design and development of a novel assistive device for gait training in stroke survivors. Specific aims of this report are three folds including a brief review of literature on gait training after stroke, revision of movement specifics during gait in the context of task-specific training, and design of a novel assistive device for gait training.

BACKGROUND

The purpose of this report is to propose a new principle of minimally-required-assistance in the design of assistive devices for sensorimotor training in patients with neurological disorders. We illustrate the implementation of the principle in design and development of a novel assistive device for gait training in stroke survivors. Specific aims of this report are three folds including a brief review of literature on gait training after stroke, revision of movement specifics during gait in the context of task-specific training, and design of a novel assistive device for gait training. We focus our literature review on the progress and limitations of current technology used in gait training. Gait training is essentially a task-specific training through repeated practice of stepping movement. Task-specific training has emerged as an effective approach that is commonly utilized in motor training programs in stroke survivors.[1-4] The minimally-required-assistance principle is based on a careful analysis of movement deficiencies of the targeted patient population in performing the training task, and identifies a set of movement components that are minimally required to perform the task. Furthermore, the magnitude of assistance provided to each of those movement specifics is also minimized according to the task. A novel assistive device for gait training is designed based on such principal. The device may present with a great potential to overcome the limitations of current technology in gait training.

The ability to walk independently is a major determining factor in deciding whether a patient returns home or moves to a nursing home after stroke.[5, 6] Traditional gait training includes usually facilitating selective movement on the affected side, such as sitting balance, standing balance, weight shifting, etc., and over-ground walking on the floor and/or stairs. The over-ground gait training may utilize parallel bars, assistive devices such as walkers or canes, orthotics, and/or most often assistance from therapists. Traditional gait training is labor intensive and brings high risk of overuse bodily injuries to therapists.[7]

Partial body weight-supported treadmill training (PBWSTT) was first developed in the 1980s [8] to provide highly repetitive stepping training on a treadmill. PBWSTT provides harness-secured balance control for patients to practice numerous steps on a treadmill, and has been considered by some as the gold standard in gait training.[9] It lines up well with clinical guidelines of task-specific training, including task being meaningful, repetitive, with variability through changes in treadmill speed, and finally with real-time feedback by therapists.[10-12]

However, during PBWSTT therapists make intensive efforts to move the impaired leg/foot of the patient at every step while remaining at a nonergonomic body position.[13] Under such working condition therapists often feel fatigue within 5 minutes of gait training. It significantly limits the total number of steps practiced within a training session and reduces efficiency of training. Furthermore, a combination of high working load and twitched body posture may lead to an increased risk of chronic back pain for therapists.

In last two decades various robotic devices have been developed to reduce working load of therapists, including Lokomat,[14, 15] Lopes,[16] LokoHelp,[17] GaitTrainer,[18] Walk Trainer,[19] etc. Those training robots are similar in their configurations and use servo-motors to drive hip, knee, and ankle joints of the affected lower limb of patients. During gait training, the robot moves each joint in the sagittal plane based on normal movement patterns, while constraining other motions of the joints. The robot-assisted stepping training (RAST) can release therapists from heavy working load of moving the affected foot/leg step-by-step.

Despite promising results reported in some past studies, [20] RAST has not been proven superior to other approaches in gait training. Gait training using RAST was found to be even less effective when compared to therapist assisted PBWSTT in recent clinical trials in stroke survivors.[21-23] Given the high cost and unsatisfactory outcomes shown in recent trials, some investigators have recommended no routine use of RAST in locomotion rehabilitation.[24]

Combining opinions from field experts [21, 25] with recent findings in motor learning research, limitations of the current RAST may include the following. (1) Excessive physical control/guidance on leg/foot motions provided by a robot may limit active involvement of the patient during gait training.[25] In a mouse study, better recovery of locomotion was achieved using a training paradigm of “assist-as-needed” rather than a fixed training paradigm.[26] (2) Sensory inputs generated during gait training play an important role. For instance, the level of hindlimb loading provided to a spinally transected rat strongly influenced the quantity and quality of stepping.[27] Physical interactions between the robot and lower limb generate proprioceptive and tactile sensory inputs that are unwanted sensory disturbances for gait training when the impaired foot/leg is moved by a robot. Improper sensory inputs do not benefit motor recovery.[28] (3) Introducing variability and engaging the subjects in trial-error process is beneficial because variability in stepping training can enhance motor recovery in animals after a spinal cord injury.[29, 30] The guided foot/leg movements in RAST allow neither movement errors nor corrective action by the patient. Simple repetition of movement without active correction of errors does not lead to cortical remodeling.[31, 32] (4) The current RAST brings unnecessary movement constraints to the foot, pelvis, or upper limb that may also impair motor learning.[21]

RE-DEFINE SPECIFICS OF MOVEMENT PATTERNS IN THE TASK-SPECIFIC TRAINING

Although not explicitly stated, the movement pattern of the affected lower limb in current RAST protocols follow a normal gait pattern. The training robot moves the affected leg/foot according to a normal gait pattern when a stroke survivor is either unable to make forward steps or presenting with movement deficiencies. Movement deficiencies during walking after stroke may include limited thigh lift or hip rotation due to hip muscle weakness, diminished/limited ankle dorsiflexion (drop-foot) due to a combination of spasticity of plantar flexors and weakness of dorsiflexors, lack of hip and knee extension in the middle of stance phase, reduced ankle plantarflexion after heel strike, etc.[33] For stroke survivors who are either non-ambulatory or walking with multiple deficiencies, movement pattern of the affected leg/foot depends entirely or primarily on the type, number, and amount of assistances provided during walking. There are nine degrees of freedom in hip, knee, and ankle joints at the affected lower limb. A gait cycle can be further divided into stance and swing phases. A typical stroke survivor may show movement deficiencies in all nine degrees of freedom and during both stance and swing phases. If we define the normal movement pattern to be the movement specifics of RAST, the robot would have to provide assistances for all movement deficiencies. However, as we have already known, assistances provided by a robot for all movements at lower limb during gait training may in fact hinder the motor learning and functional recovery. The question is whether a deviation from normal gait pattern may be better for motor learning and functional recovery in gait training after stroke.

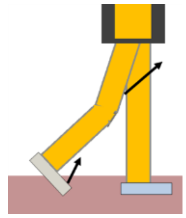
In revising movement specifics of gait training, we identify that two movements of lower limb are critical: hip flexion starting at the end of stance phase through the swing phase and ankle dorsiflexion starting at the end of stance phase for the first half of swing phase. Hip flexion during swing phase is essential for making forward step. Ankle dorsiflexion is critical for clearing off the foot from hitting the floor and preventing maladaptive circumvent walking pattern in stroke survivors with spasticity in ankle extensor muscles. We consider that other movement deficiencies in the affected lower limb are not critical for performing step movement. We believe that when assistances are provided for hip flexion and ankle dorsiflexion during swing phase, stroke survivors can practice forward stepping repeatedly on a treadmill and are given a chance to learn and improve their movement from their own errors. Furthermore, the magnitude of assistance for each of two critical movements can be minimized according to the level of movement deficiencies of the individual stroke survivor. Under such strategy, only the minimal number of assistances with minimized magnitudes for completing the forward stepping are provided. Obviously, the resultant movement pattern, when only the hip flexion and ankle dorsiflexion during swing phase are assisted, may show multiple remaining deficiencies. Those remaining movement deficiencies, and consequently movement errors may be in fact beneficial for motor learning.

Benefits of the revised movement specifics in RAST include the following. First, the patient will have to learn to control many aspects of walking without any assistance, and therefore encourage them to be actively engaged in training activities. Second, the resultant imperfect stepping motions would in fact provide an opportunity for trial-error learning throughout gait training. Patients can learn from their own errors and results of their corrections. Third, the minimized number of assistances can also minimize sensory disturbance. Finally, by using the strategy of minimally-required-assistance, there will be no unnecessary movement constraints introduced.

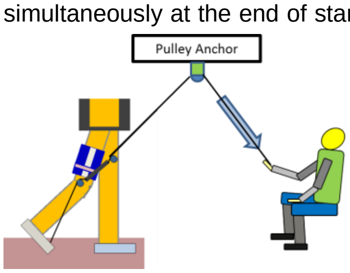
The strategy of minimally-required-assistance is similar to a training paradigm of “assist-as-needed”. Experienced rehabilitation therapists have advocated the assist-as-needed paradigm, which refers to the principle of helping a patient to perform a movement with a minimal amount of manual assistance.[34] Past studies reported positive results by implementing the assist-as-needed paradigm in various ways in animal and human studies.[26, 35-38] A study compared outcomes of lower limb movement between robot-assisted training and therapist’s assistance as needed.[23] The result showed significant improvement in the consistency of intra-limb movements of the impaired lower limb in the group received therapist assistance, but not in the group with robot assisted training. However, majority of past studies using the “assist-as-needed” paradigm have tried minimizing only the magnitude of assistive forces. It has been unclear in past studies about how to define the “need” and whether assistances needed for all movement deficiencies. Our proposal of a principle of minimally-required-assistance makes a step forward. It first requires a careful analysis of movement deficiencies of walking in stroke survivors and follows by a clear definition of movement specifics of stepping task, under which minimally required assistances are identified. The resultant motions of affected lower limb may still show multiple movement deficits. In case of gait training, for instance, assistances are provided only to hip flexion and ankle dorsiflexion during the swing phase. Other movement deficits will remain, which in fact may benefit motor leaning and functional recovery.

THE DESIGN OF A NOVEL ASSISTIVE DEVICE FOR GAIT TRAINING

To implement the principle of minimally-required-assistance, we use pulling cables in the design of an assistive device that provides assistive forces for hip flexion and ankle dorsiflexion starting at the end of stance phase for the affected leg/foot (right figure). The pulling cable is flexible, low-cost, and light weighted. More importantly, the pulling cable allows a patient to move the affected lower limb faster than the motion of the cable without encountering any movement constraint. In addition, therapists can further engage the patient in actively learning to control hip flexion and ankle dorsiflexion by slowing down the motion of the pulling cable. The training device will impose no constraints to motions of trunk, pelvis, or upper limbs. There is no sensory disturbance in using the device, only the sensation of pressure on the thigh and forefoot where the pulling cables is attached. Those pressure sensations may in fact serve as sensory cues to initiate hip rotation or ankle dorsiflexion. Wu et al (2011) designed a gait training device using pulling cables. [39] A key difference from our device is that their cables pull on the ankle/foot directly. The human natural walking is primarily driven by muscles around hip and knee joints. A direct pulling on the ankle/foot may generate unnatural motions in the lower limb. The sensory disturbance would be significant due to a direct pulling on the ankle/foot.



The two pulling cables can be further combined into one cable because hip flexion and ankle dorsiflexion occur simultaneously at the end of stance phase. A cable can pull both hip flexion and ankle dorsiflexion at the end of stance phase (left figure). Specifically, a brace that wraps around the upper leg is secured using Velcro straps. The pulling cable wraps around a wheel fixed at the front of the thigh brace, goes through a fixed pulley anchor, and connects at one end to a handle that a therapist can pull on. The other end of the cable goes through a spherical joint and connects to a foot strap. The foot strap is placed around the forefoot of the affected limb. The pulley is anchored to the treadmill. A therapist can pull the cable to assist the stroke survivor with toe-lift and hip flexion during the swing phase in a gait cycle. After initial pulling, ankle dorsiflexion will be held in place by a stop nut throughout the swing phase. We have developed a prototype of the gait training device and are currently conduct a feasibility study of the manually operated device in a clinical setting (right figure). Using the assistive device, the therapist can sit comfortably at an ergonomic body posture to pull the cable.



We have also developed a prototype of the automated gait training device using a servomotor and controller (left figure). The servomotor pulls and release the cable according to the angular movement profile of the hip joint at swing phase during gait. This will free a therapist from manually pulling the cable. A graphic user interface allows the therapist to adjust several variables including when to pull and/or release the cable, magnitude and rate of assistive forces, etc. The design of the control system is a challenge task. We plan to further improve function and performance of the automated device by implementing machine learning strategies into the control system.

SUMMARY

In this report, the recent progress in gait training after stroke, especially on the use of RAST, is briefly reviewed with a focus on a dilemma that recent randomized clinical trials did not support the use of RAST. The walking pattern after stroke depends strongly on the assistance provided for the affected leg/foot during walking. Normal walking pattern is implicitly assumed in current RAST protocol as movement specifics of stepping task. We carefully analyze movement deficiencies of the affected lower limb after stroke and re-define a set of movement specifics according to the minimally-required-assistance principle proposed here in the first time. In case of gait training for stroke survivors, the assistances are applied only to hip flexion and ankle dorsiflexion at the swing phase of a gait cycle. We have developed a novel assistive device for gait training. The same principle may be applied to the design of assistive device for other tasks or neurological diseases.

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