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Feasibility of Entrainment with Ankle Mechanical Perturbation to Treat Locomotor Deficit of Neurologically Impaired Patients

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***Abstract*—Entraining human gait with periodic torque from a robot may provide a novel approach to robot-aided walking therapy that is competent to exploit the natural oscillating dynamics of human walking. To test the feasibility of this strategy we applied a periodic ankle torque to neurologically impaired patients (one with stroke and one with multiple sclerosis). As observed in normal human walking, both patients adapted their gait periods to synchronize with the perturbation by phase-locking the robotic torque at terminal stance phase. In addition, their gait cadence became significantly faster due to the training with clear after effects when the perturbation ceased. These results support a new strategy for walking therapy that exploits an embedded neural oscillator interacting with peripheral mechanics and the resulting natural dynamics of walking, which are essential but hitherto neglected elements of walking therapy.**

I. Introduction

REHABILITATION of human motor function is an issue of the utmost significance, and the demand is increasing due to a growing elderly population and the incidence of age-related disorders. Robot-aided therapy has been developed as a promising method to meet the enormous demand for effective rehabilitation services; robots are able to support the labor-intensive tasks of therapists and provide more frequent therapy. In addition, direct interaction with a robotic device enables quantitative measure of human performance, which is essential for systematic training. However, while upper-extremity robotic therapy has been proven effective and is now recommended by the American Heart Association, lower extremity robotic therapy is much less effective and was declared "still in its infancy" [1].

One plausible reason for the immaturity of lower extremity robotic therapy is that current therapeutic robots suppress the natural rhythmic dynamics of walking. The lower-limb therapeutic robots that have been evaluated to date either constrain natural motion or impose nominal kinematics. However, numerous studies in neuroscience [2-5] and robotics [6-8] suggest that human locomotion is a limit-cycle oscillation that emerges from nonlinear dynamic interactions between neural circuits and limb mechanics. If that is so, current therapeutic robots inadvertently interfere with the natural rhythmic dynamics of the neuro-mechanical system by imposing "pre-planned" kinematics.

As an approach to support human walking while exploiting natural oscillating dynamics, entrainment with ankle mechanical perturbation was proposed and its feasibility was tested in normal human walking [9]. In this novel robotic therapy, a robot may be programmed to entrain the patient's walking frequency, and gradually "drag" it towards the normal walking frequency. In [9], entrainment with a finite basin and phase locking were reliably observed, supporting the role of a neuro-mechanical oscillator in human walking and the feasibility of the proposed strategy.

In this paper, as an extension of [9], we report experiments to test whether periodic mechanical ankle torque can change the cadence of neurologically impaired walking. Our results support dynamic entrainment with ankle mechanical perturbation as a novel approach to rehabilitate locomotor deficits of neurologically impaired patients.

II. Materials and Methods

One stroke patient (57 yrs) and one multiple sclerosis (MS) patient (48 yrs) who gave informed consent as approved by the Providence Veterans Affairs Medical Center (PVAMC) institutional review board and MIT's Committee

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on the Use of Humans as Experimental Subjects were asked to walk on a treadmill at comfortable speed while wearing Anklebot [10], a therapeutic robot designed to assist and evaluate the ankle function of patients with gait abnormality. It can deliver torque simultaneously in both dorsi- and plantar-flexion and inversion and eversion, though in this study, we focused on sagittal plane motion. The time profile of ankle torque actuation is programmable at a sampling rate of 200 Hz.

The speed of the treadmill was determined by each subject to be comfortable for walking, and this speed was maintained throughout each session. Before applying periodic mechanical perturbations, we measured the preferred stride duration (τ_0) of each subject. During this procedure, the Anklebot was programmed to act like a torsional spring and damper with constant equilibrium position, stiffness and damping. The stiffness was set as 5 N·m/rad; it was selected to approximate the stiffness necessary to compensate for the effect of Anklebot's inertia on the natural frequency of the body about the ankle. The damping was chosen to be 1 N·m·s/rad; it was sufficient to stabilize the system but not excessive to minimize possible discomfort of subjects. The equilibrium position was determined as the ankle angle when the subject stood upright.

After measuring τ_0, periodic square torque pulses of magnitude 10 N·m and duration 0.1 second were added to the torque due to the programmed spring-damper behavior. The period of perturbation (τ_P) was initiated at the estimated value of preferred stride duration, τ_0. After 20 perturbation cycles, the perturbation period gradually decreased by 50 ms over 10 cycles and then held at that period ($\tau_P = \tau_0 - 50$ ms) over 20 perturbation cycles. This procedure of gradual decrease and hold of τ_P was repeated until τ_P became noticeably faster than the cadence of the subject's gait (Fig. 1). The torque exerted by the Anklebot, and the resulting

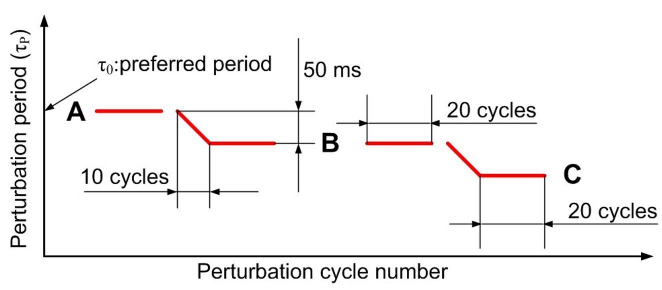

Fig. 1. Scheme of perturbation: The subject walked without periodic perturbation (A). Then, the Anklebot applied square torque pulses with period τ_0, the subject's preferred walking cadence. After 20 perturbation pulses, another sequence of perturbation pulses whose interval decreased linearly with cycle number was applied over 10 cycles until the interval became τ_0 – 50ms. This sequence was immediately followed by another set of perturbations whose period was constant over 20 cycles. No perturbation was applied for the following 20 strides (B). After that, the same program of perturbation was initiated with the last value of τ_P of the previous sequence. (For the cycles just before C, the period of the perturbation, τ_P was τ_0 – 100ms.) This program was continued until the experimenter visually observed that the subject could not keep up with the perturbation cadence.

kinematics of the ankle and knee were measured at a sampling rate of 200 Hz by sensors onboard the Anklebot. Foot contact was measured by pressure sensors at the toes and heels of both feet at a sampling rate of 1000 Hz using a wireless Myomonitor system by Delsys Inc. Heel strike of the paretic leg was defined as 0 (or 100) % of each gait cycle. Stride period and the phase of the perturbation torque pulse were analyzed to assess entrainment and phase-locking statistically.

III. Results

Though the clinical scale of the subjects was not available, the treadmill speed which was chosen by each subject was compared with comfortable walking speed of comparably aged unimpaired control. The treadmill speed was 0.34 m/s for the stroke patient, and 0.18 m/s for the MS patient, which corresponds to 24 % and 12 % of the comfortable mean speed of comparably aged unimpaired control respectively.

Both the stroke and MS patients showed entrainment to the periodic mechanical perturbation. Entrainment with phase-locking was observed when the perturbations had constant period as well as when the perturbation cadence gradually increased. Typical gaits entraining to a gradually accelerating perturbation are shown in Fig. 2.

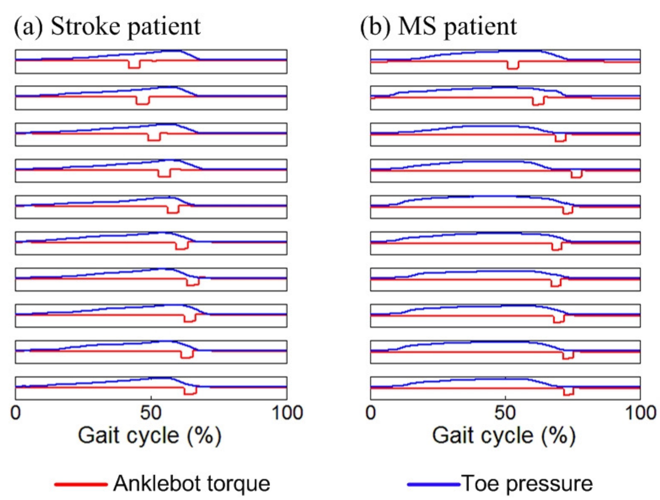

Fig. 2. Transient behavior and subsequent entrainment to an accelerating perturbation: (a) and (b) show the Anklebot torque profile (red) and toe pressure (blue) for each gait cycle of the stroke patient and the MS patient respectively. Stride number increases from top to bottom, and perturbation cadence gradually increased; the perturbation cadence is faster in the lower gait cycles. The onset of the torque pulse drifted initially but converged to a specific phase of the gait cycle. The toe pressure shows that the phase where the robotic pulse locked is close to the toe-off phase. Phase locking indicates that the subjects gradually increased stride frequency to synchronize with the gradually increased perturbation frequency.

Consistent with the entrainment of unimpaired walking [9], entrainment was always accompanied by a specific relation between the gait cycle and the robotic torque pulse; in entrained gaits, the terminal stance phase consistently coincided with the square pulses exerted by the Anklebot. This observation of *phase-locking* was reliable; Fig. 2 clearly shows that the subjects synchronized their cadence to the perturbation to maintain the specific phase relation even under the gradual change of perturbation cadence. The distribution of the gait phases where the perturbation pulses were located in entrained gaits is shown in Fig. 3. For each subject the pulses are clustered at the terminal stance phase.

Another important observation was an after effect of the perturbation. Fig. 4 shows the distribution of durations of 10 successive (unperturbed) strides immediately before the beginning of perturbation and 10 successive (unperturbed) strides immediately after the end of perturbation. An after effect was defined as a statistically significant difference ($p < 0.05$) between stride period before perturbation and after perturbation based on a balanced one-way ANOVA test. Both the stroke patient and the MS patient showed clear after effects due to the perturbation.

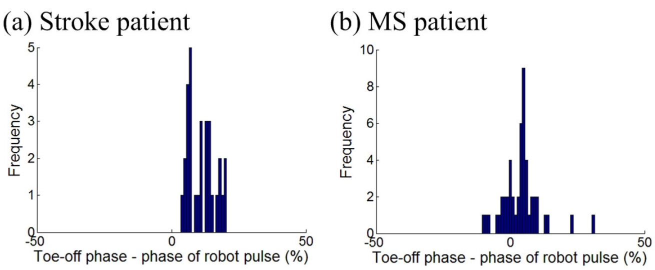

Fig. 3. Histogram of the gait phases where perturbation pulses were located in entrained gaits: (a) and (b) show the distribution of the phase difference between toe-off and perturbation pulse in entrained gaits of the stroke patient and the MS patient respectively. The highest frequency at around 5% phase difference reflects that most of the perturbation pulses were clustered at the phase slightly prior to toe-off phase, indicating phase-locking at terminal stance. The narrow distribution justified use of standard statistical tests based on a Gaussian distribution for this periodic variable (rather than circular statistics).

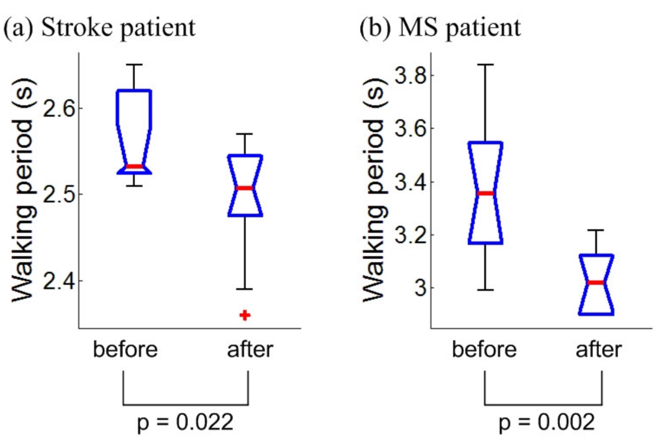

Fig. 4. Distribution of walking periods before and after perturbation: (a) and (b) show the durations of 10 successive strides immediately before the beginning of perturbation and 10 successive strides immediately after the end of perturbation for the stroke patient and the MS patient respectively. Statistical analysis concluded that walking period decreased significantly due to the perturbation for both subjects.

IV. Discussion

A. *Nonlinear oscillators in human locomotion*

Though the results of this study are based on only two subjects and therefore preliminary, the results are consistent with the observations of normal human walking [9]. Entrainment and phase-locking were reliably observed in the two impaired subjects who suffer from two distinct neurological disorders (stroke and MS) as well as unimpaired subjects. Remarkably, phase-locking occurred at the terminal stance phase for both impaired subjects, which is also consistent with the phase-locking observed in normal walking in response to the same mechanical perturbation [9].

Entrainment to an external periodic perturbation is a distinctive characteristic of nonlinear limit-cycle oscillators. The entrainment to periodic mechanical perturbation we demonstrated indicates that a nonlinear dynamic oscillator plays a role in the neuro-motor execution of human locomotion. That oscillator may be due to a neural central pattern generator (CPG), the musculo-skeletal periphery, or a combination of both, probably mediated by afferent feedback.

Other possible explanations of entrainment include supra-spinally mediated adaptation. However, the rigorous consistency of the entrainment and phase locking across the stroke patient, the MS patient and normal subjects shows that unimpaired supra-spinal control may be nonessential for the observed limit-cycle behavior of human walking. The subjects with two distinct neurological disorders and normal subjects exhibited the same consistent limit-cycle behaviors despite significant differences in their gait kinematics such as walking speed, walking cadence and joint angle trajectory. This suggests that the essential components responsible for entrainment and phase-locking are embedded in the lower levels of the central nervous system (CNS) which may be less affected by stroke or MS.

B. *A potential strategy for locomotion therapy*

Entrainment to periodic mechanical perturbations supports a new strategy for locomotor rehabilitation that may have promise: based on a patient's performance, a robot may be programmed to entrain the patient's walking frequency, and gradually "drag" it towards the normal walking frequency. If, as our results and numerous studies in neuroscience [2-5] and robotics [6-8] suggest, an embedded neural oscillator interacting with peripheral musculo-skeletal mechanics plays a role in normal human locomotion, most current robot-aided walking therapy (which is focused on controlling limb trajectories) may interfere with the normal execution of locomotor function. Instead, rehabilitation by entraining the embedded oscillator might provide an essential but hitherto neglected element of walking therapy by exploiting the natural dynamics of walking.

Another important observation is that entrainment always occurred at a specific phase of the walking cycle. Phase locking was always achieved such that the torque from the Anklebot occurred at ankle push-off, where it assisted in propulsion. Considering this phase locking, entrainment to mechanical perturbation is distinct from entrainment to auditory input: mechanical interaction may supply the additional power needed to facilitate more normal gait, especially when patients cannot produce enough propulsion. The amplitude of mechanical perturbation as well as its frequency can be adjusted based on a patient's performance, providing assistance only as needed to promote the patient's participation, which is an essential element of neuro-restoration [11], [12].

An important limitation of the current preliminary version of the training protocol is that the subjects were asked to walk on a treadmill at a constant speed; it is not obvious whether the subject can actually improve their walking speed in overground walking. One necessary future work is to modify the strategy so that the speed of treadmill is adjusted as the walking cadence of the subjects becomes faster.

V. Conclusion

Entrainment to ankle mechanical perturbation was observed in neurologically impaired subjects. Consistent with observations of entrainment in unimpaired walking, the entrainment was always associated with phase locking at the terminal stance phase; entrainment synchronized the ankle-push off phase with the external periodic torque. Gradually changing the perturbation cadence was able to "drag" the walking cadence of the subjects so that they increased stride frequency. Clear after effects of the increased walking cadence were observed. These results support our proposal that the entrainment of human gait by periodic torque from a robotic aid may provide a novel approach to walking therapy that is uniquely supportive of normal biological function, exploiting the oscillating dynamics of walking. Further assessment of the feasibility of entrainment to mechanical perturbation as a therapeutic strategy for various impaired subjects is in progress.

Acknowledgment

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Experimental work of this study was conducted at the Neuro-rehabilitation Laboratory, Providence VA Medical Center.

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