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# Feasibility of Dynamic Entrainment with Ankle Mechanical Perturbation to Treat Locomotor Deficit

Joeun Ahn and Neville Hogan

**Abstract**—Dynamically entraining human gait with periodic torque from a robot may provide an approach to walking therapy that is uniquely supportive of normal biological function. To test the feasibility of this approach we perturbed the gait of unimpaired human subjects by applying a periodic impulsive ankle torque at various frequencies. Eighteen subjects out of 19 exhibited entrained gaits: for a small range of frequencies their gait periods adapted to synchronize with the mechanical perturbation. In addition, the phase when synchronized was such that the robot perturbation assisted propulsion. 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

HUMAN-interactive robots can deliver sensory-motor treatment safely, and numerous studies have shown their value for upper-limb therapy [1]. There also have been attempts to develop effective robotic therapy for the lower extremity; with robot-assisted walking therapy, the robotic device aids the leg motion of patients, and supplements the efforts of physical therapists.

However, most gait rehabilitation strategies with robots developed to date have limitations; unlike robot-aided therapy for upper limbs, recent studies have reported that robotic walking therapy has not outperformed conventional physical therapy [2], [3]. One plausible reason for this limitation is that walking is a periodic process, a hybrid of continuous and discrete dynamics, which is essentially different from reaching and grasping movements; neural control of the limb trajectory is known to be important in reaching [4], [5], but not necessarily in walking. In fact, robotic experience teaches that much of the detailed coordination required to walk probably emerges from the passive pendular dynamics of the lower limbs rather than control of joint kinematics [6], [7]. The approach of most

therapeutic robots is tantamount to an assumption that restoration of kinematic patterns of leg motion is sufficient for restoration of functional locomotion; the robots either impose kinematic patterns or encourage patients to aim at normal kinematic patterns. However, merely mimicking or tracking the kinematic patterns of leg motion neglects the role of interaction between the neuro-muscular periphery and gravito-inertial mechanics; therefore, current therapeutic robots may inadvertently interfere with the natural dynamics of walking.

The goal of this study was to test the feasibility of a robot-aided gait training procedure that enables the natural dynamics of walking to be exploited, and may aid recovery based on patients' performance. Available evidence, though not as strong as in the case of quadrupeds, indicates that there is a rhythmic central pattern generator (CPG) in the human spinal cord [8], [9]. Several studies have shown that a nonlinear limit cycle oscillator can serve as a competent model of a CPG [10], [11]. That suggests that a suitable periodic mechanical perturbation might entrain this CPG, thereby providing a means to influence the neuro-mechanical process underlying walking without suppressing its natural dynamics. Load-related afferent inputs and cutaneous inputs from the ankle-foot complex are known to be important in regulating the walking pattern [10], which suggests that mechanical intervention at the ankle may be an effective means to rehabilitate locomotion, especially for persons with spinal cord injury (SCI).

On the other hand, the relative importance of a spinal CPG in the control of human locomotion remains unclear. Supra-spinal influences may intervene and even dominate. For example, it is known that the kinematic trajectory of the foot is precisely controlled in adult humans [12]. If so, entrainment to peripheral mechanical perturbation may not occur.

In this paper we report experiments to test whether dynamic entrainment of human locomotion with ankle mechanical perturbation is feasible. Our results support dynamic entrainment with ankle mechanical perturbation as a new approach to robotic walking therapy.

## II. MATERIALS AND METHOD

Nineteen healthy subjects (ages 23–35) who gave informed consent as approved by MIT's institutional review board were asked to walk on a treadmill at comfortable speed while wearing Anklebot [13], a therapeutic robot

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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 ( $\tau_0$ ) 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. 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  $\tau_0$ , periodic square 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 ( $\tau_p$ ) varied from lower than  $\tau_0$  to higher than  $\tau_0$  in different trials, whose order was chosen at random. To minimize any possible effect of auditory input on entrainment, six subjects wore a noise-cancelling headset

through which white noise was played at sufficient volume to mask all other auditory inputs. In addition, to minimize the likelihood of voluntary adjustment to the perturbation, four of these subjects were asked to perform a distracting task, counting backward from 100 to 1 in their second language. The torque exerted by the Anklebot, and the resulting kinematics of the ankle and knee were recorded at a sampling rate of 200 Hz. Because no sensor directly measuring foot contact was available, we alternatively defined a gait cycle by observing knee angle data, and compared stride duration before, during, and after the perturbation in each trial. Then, for each trial, a statistical analysis determined whether the gait was entrained by the perturbation.

### III. RESULTS

In 18 of 19 subjects, entrainment was observed when  $\tau_p$  was close enough to  $\tau_0$ . Conversely, when  $\tau_p$  was not close to  $\tau_0$  subjects ignored the perturbation, and did not show entrainment. This indicates a *finite basin of entrainment*, as would be expected for a limit-cycle oscillator. The range of the basin of entrainment was estimated from the highest and the lowest value of  $\tau_p$  that entrained the gait, and found to be less than approximately 15% of  $\tau_0$ . Typical results are shown in Fig. 1, and transient behavior of a subject who is plausibly in the process of becoming entrained is shown in Fig. 2.

For entrained gaits, synchrony occurred at a specific phase

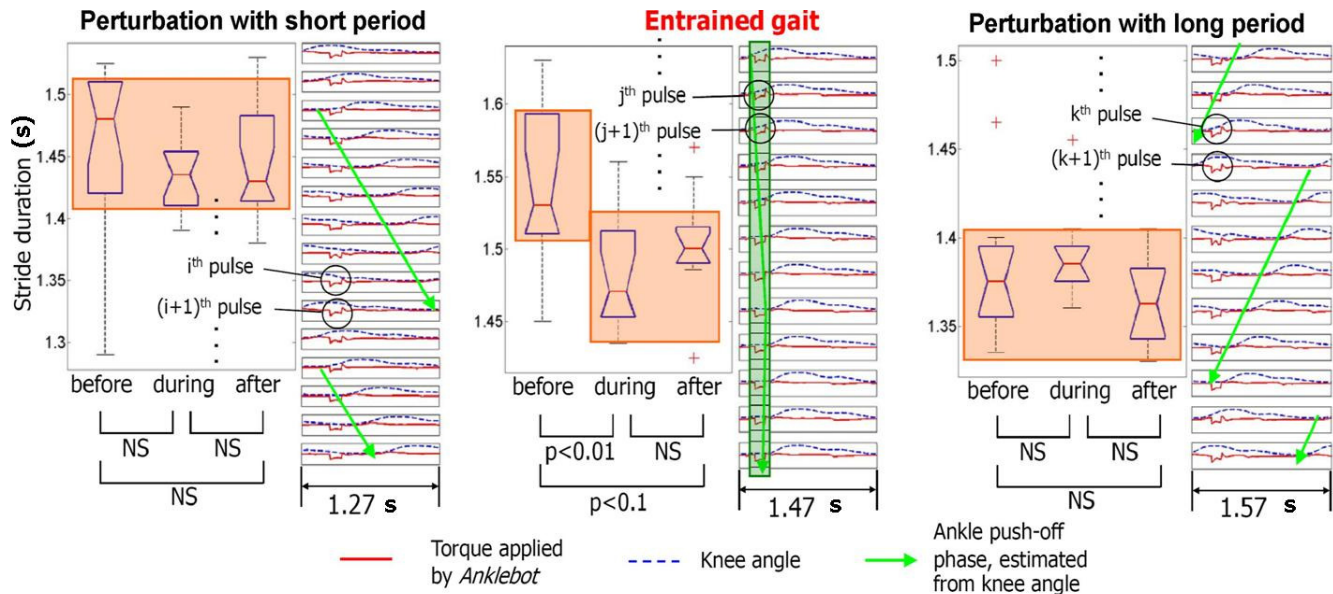


Fig. 1. Typical results of entrained (middle panel) and not entrained (left and right panels) gaits: the box plots show the distribution of stride duration before, during, and after the mechanical perturbation was applied. The knee angle and torque supplied by Anklebot during the perturbation are plotted next to each box plot; each row indicates knee angle (the dotted curve) and torque profile (the solid curve) during one perturbation cycle. For each cycle, the phase of ankle push-off (the arrow) was estimated from the knee angle data. The left and right panels show failure to entrain for  $\tau_p < \tau_0$  and  $\tau_p > \tau_0$  respectively. The ankle push-off phase drifted as step number increased, and stride duration (shown in box plots) did not change significantly due to the mechanical perturbations; the subject ignored the perturbation rather than entraining to it. The middle panel shows a case of entrainment; stride duration approximated  $\tau_p$  with a statistically significant difference from  $\tau_0$ . The subject's cadence changed from its original preference to synchronize with the periodic perturbation.

where the ankle push-off coincided with the square pulses exerted by the Anklebot (middle panel of Fig. 1 and Fig. 2). This observation is termed *phase-locking*. To test whether phase-locking was reliable, we initiated the periodic mechanical perturbation at a phase far from ankle push-off, and observed whether and how subjects became entrained. Seven subjects participated in this experiment, and all seven showed phase-locking at the same specific phase of ankle actuation. Auditory inputs were masked for six of the seven subjects, and four of those six performed the distracting task, counting backward from 100 to 1 in their second language; neither manipulation influenced the outcome. A typical result is shown in Fig. 3.

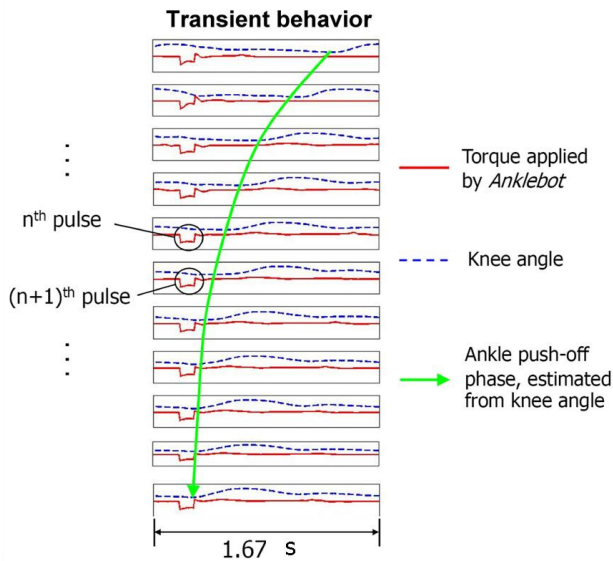


Fig. 2. Transient behavior under perturbation; the ankle push-off phase drifted initially, but converged to the Anklebot's torque pulse.

## IV. DISCUSSION

### A. Evidence for the prominent role of nonlinear oscillator in human locomotion

Entrainment to an external periodic perturbation with a finite basin of attraction is characteristic of nonlinear limit-cycle oscillators. The entrainment to periodic mechanical perturbation we demonstrated suggests that a nonlinear dynamic oscillator plays a prominent role in the neuro-motor execution of human locomotion. That oscillator may be due to a neural CPG, the musculo-skeletal periphery, or a combination of both, possibly mediated by afferent feedback.

Other possible explanations of the observation include (a) entrainment through auditory sensory inputs, which is commonly observed in human walking; (b) voluntary adaptation to avoid any discomfort caused by asynchrony; and (c) entrainment of supra-spinal central nervous system to the periodic afferent stimuli.

When applying the perturbation, Anklebot generated a small but perceptible periodic sound. For six subjects, we minimized the possible intervention from those auditory inputs using a masking sound displayed via a noise-cancelling headset. All six subjects showed entrainment to mechanical perturbation with finite basins of entrainment, suggesting that the effect of auditory input on observed entrainment to mechanical perturbation is not significant.

Though we cannot exclude the possible contribution of involuntary entrainment of the supra-spinal central nervous system to periodic afferent stimuli, voluntary adaptation to minimize discomfort due to asynchrony does not seem to be a plausible mechanism of entrainment to mechanical perturbation. If voluntary supra-spinal adaptation subserved entrainment to mechanical perturbation, most normal walking frequencies should have been entrained. On the

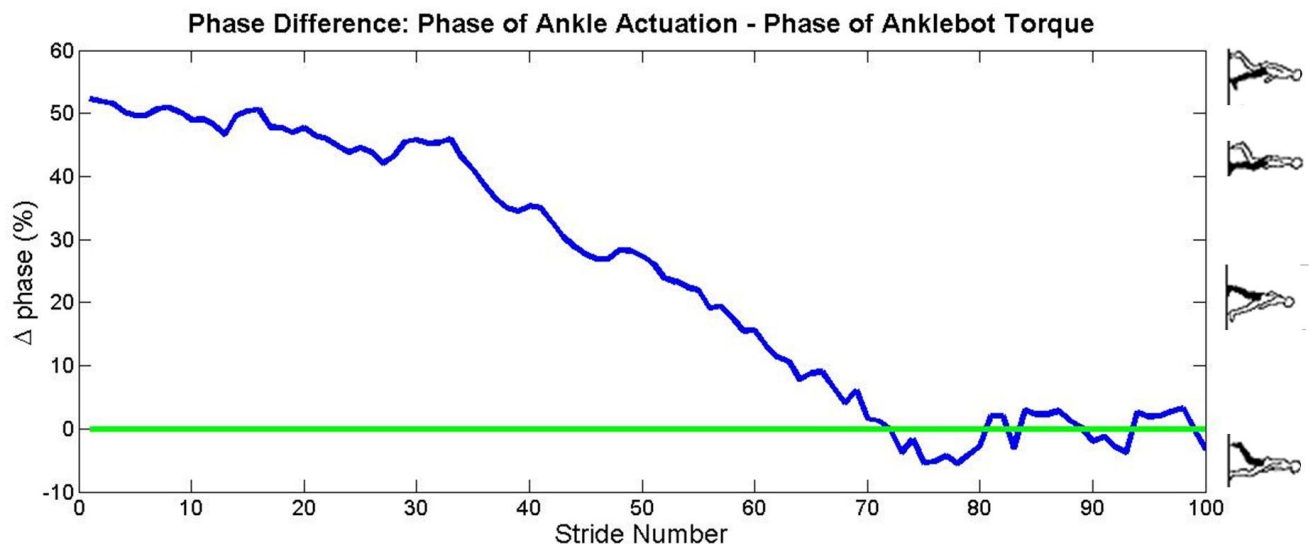


Fig. 3. Phase difference vs. stride number: zero phase difference indicates synchronization of human ankle actuation with Anklebot perturbation, and positive  $\Delta$  phase means that human ankle actuation follows perturbation torque. The initial perturbation pulse was applied at the beginning of a double stance phase (50% gait cycle later than an ankle push-off phase). Over 70 strides (140 steps) taking approximately 100 seconds, the subject gradually changed cadence to match the ankle-actuation phase with the perturbation pulse.

contrary, we observed that the basin of entrainment was narrower than the typical variability of preferred cadence. More convincing evidence is that all four subjects who performed distracting tasks also showed entrainment to mechanical perturbation with finite basins of entrainment. Furthermore, voluntary adaptation of gait would be expected to occupy a few steps, not the 140 or so steps typically required to achieve phase-locking (Fig. 3).

#### B. A potential strategy of locomotion therapy

Entrainment to periodic mechanical perturbation 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 suggest, an embedded neural oscillator interacting with peripheral musculo-skeletal mechanics plays a prominent 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 the patients cannot produce enough propulsion. By controlling not only the frequency but also the amplitude of the supplementary torque, we may also continuously adjust the robotic assistance to promote patient participation, assisting only as needed. This has proven to be an essential component of neuro-restoration [14], [15].

Even if the supra-spinal central nervous system dominates the control of unimpaired walking and our observations are ascribed to entrainment to periodic afferent stimuli due to the mechanical perturbation, the proposed approach provides a minimal-intervention strategy for locomotor therapy. However, the weight of evidence indicates that entrainment to mechanical perturbation is due to an embedded neural oscillator interacting with peripheral musculo-skeletal mechanics. If so, this approach may be able to promote recovery without a significant involvement of supra-spinal input. In particular, rehabilitation after SCI may also be feasible. Further assessment of the feasibility of entrainment to mechanical perturbation as a therapeutic strategy for various impaired subjects including persons SCI is in progress.

### V. CONCLUSION

Entrainment to ankle mechanical perturbation with a finite

basin of attraction was observed in unimpaired subjects. The entrainment was always associated with phase locking at a specific point in the gait cycle; entrainment synchronized the ankle-push off phase with the external periodic torque. The present results provide strong evidence that a limit-cycle oscillator, a plausible element of the coupled system of central nervous system and musculo-skeletal periphery, plays a significant role in the neuro-motor execution of human walking. 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.

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