Dynamic Entrainment to External Mechanical Perturbation in Human Walking: Treadmill vs. Overground Experiments

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1 Introduction

In animals, rhythmic muscle activation is sustained even in the absence of higher inputs from the brain and/or peripheral sensory feedback, demonstrating that centers in the spinal cord are important for locomotor control [1]. The role of spinal mechanisms in locomotion of humans is less clear. Competent mathematical models of rhythmic locomotion have been developed using nonlinear limit cycle oscillators [2, 3]. One characteristic of nonlinear limit cycles is dynamic entrainment to external perturbations: they adjust their period of oscillation to match the period of an applied perturbation. It is important to note that entrainment is only observed when the perturbation frequency is close to the frequency of the oscillator. Previous work conducted by Ahn and Hogan [4] demonstrated the presence of dynamic entrainment to an external mechanical perturbation in human walking. Such experiments consisted of perturbing unimpaired subjects with a moderate periodic plantar-flexion torque applied to the ankle by a robotic device as they were walking on a treadmill. The preliminary experiments presented in this paper are a continuation of the work presented in [4] to compare dynamic entrainment in human walking on a treadmill versus overground.

2 Methods

2.1 Equipment and Protocols

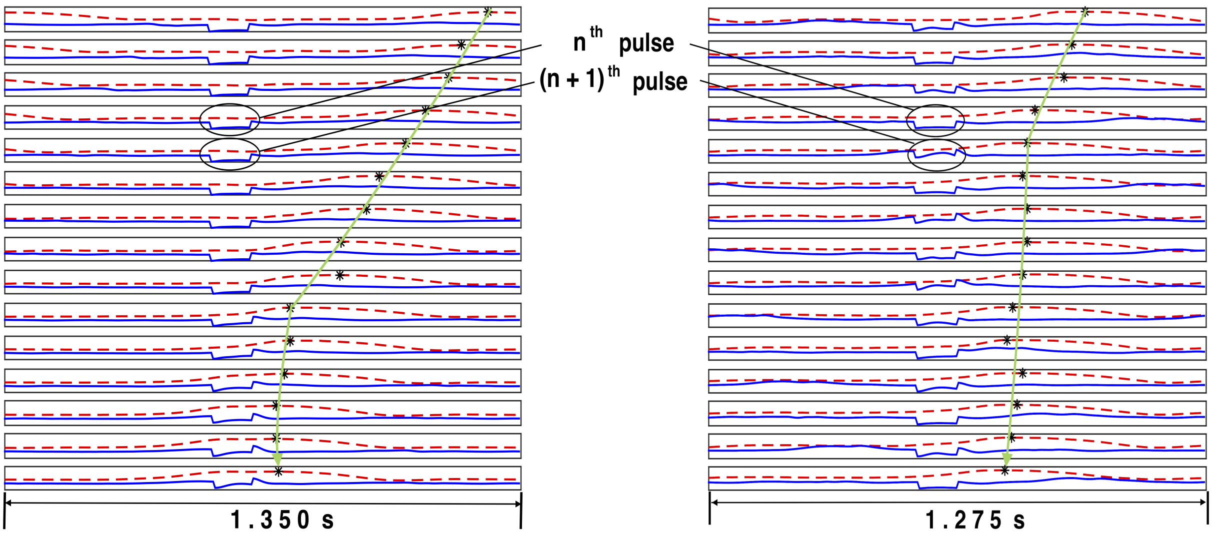
A preliminary trial was conducted with a healthy male subject who gave informed consent in accordance with the Institutional Review Board (IRB) for the Massachusetts Institute of Technology (MIT). The purpose was to compare the subject's performance on a standard treadmill versus overground. The treadmill experiment was conducted using a Sole Fitness F80 treadmill with a 0.84 m x 1.90 m deck. The overground experiment was conducted in a large corridor at MIT, only populated at the time by the subject, the experimenter, and 3 additional assistants. In both experiments the subject was asked while walking to perform a distracting task that consisted of either reading out loud and discussing a poster placed in front of him or watching a comic show on a small screen.

The robot used in these experiments was the Anklebot (Figure 1) by Interactive Motion Technologies, Inc. The Anklebot's ability to deliver dorsi/plantar flexion torque and measure knee angles was used for these experiments. The robot was preprogrammed to apply periodic square torque pulses of magnitude 10 N-m and duration 100 ms in the same fashion as previously reported by Ahn and Hogan [4]. In addition to exerting torque pulses, the robot behaved like a torsional spring and damper with a 5 N-m/rad stiffness, 1 N-m-sec/rad damping, and a constant equilibrium position measured from the subject's upright posture. A sampling rate of 200 Hz was maintained throughout the trial.

Figure 1: An unimpaired subject wearing the Anklebot overground.

2.2 Treadmill Experiment

The subject was asked to adjust the speed of the treadmill to a comfortable walking speed. The selected speed was recorded and maintained through the duration of the experiment. The perturbation period (τ_p) was selected to be 50 ms slower than the subject's preferred stride duration (τ_0), which was measured beforehand as the average duration of 15 consecutive strides. The experiment was then divided into 3 subsections: *before*, *during*, and *after*. The *before* phase consisted of 20 strides with no perturbation. The *during* phase began as the experimenter commanded the robot to initiate the perturbations at intervals τ_p. After 50 perturbations were completed, the robot stopped exerting the torque pulses but maintained its spring-damper behavior. The *after* phase comprised the first 20 strides after the torque pulses were discontinued. The subject stopped walking and the experiment terminated immediately afterwards.



(a) Treadmill. (b) Overground.

Figure 2: The subject's gait showed entrainment to perturbation in both the treadmill and the overground experiments ($\tau_p \approx \tau_0 + 50$ ms). The knee angle and the square torque pulses exerted by the Anklebot during the last consecutive 15 strides of each experiment are plotted above, with each row corresponding to one perturbation cycle. The solid blue curve represents the Anklebot's torque profile, while the dashed red curve represents the knee angle. The asterisk on each row indicates the maximum knee flexion in each gait cycle.

2.3 Overground Experiment

Instead of selecting a fixed speed for the trial as with the treadmill, the overground experiment was initiated by asking the subject to walk at his preferred walking speed. Once a comfortable walking speed was achieved, the walking period (τ_0) was measured using the subsequent 15 strides. The rest of the experiment was conducted in the same fashion as the treadmill experiment, with 20 strides for the *before* phase, 50 torque pulses for the *during* phase, and 20 strides for the *after* phase. Through the entire overground experiment the subject was followed from a very close distance by the experimenter and the assistants who moved all the computer equipment on a rolling cart (Figure 1).

3 Results and Discussion

The subject's selected treadmill speed, preferred stride duration, and the applied perturbation torque for both experiments are summarized in Table 1. Entrainment was observed in both experiments since the maximum knee flexion occurred at a near-constant phase of the gait cycle with respect to the applied perturbation. However, the overground experiment revealed signs of entrainment much sooner than the treadmill experiment (Figure 2). While entrainment becomes noticeable during the last 6-8 perturbation cycles on the treadmill, entrainment to perturbation was evident in the last 15 cycles during the overground experiment. Another important fact is that in the overground trial, the last 15 pulses seen in Figure 2 occurred near the moment of maximum ankle actuation at approximately 50% of the gait cycle[1]. This suggests that the subject's gait assumed a phase relation with the perturbation such that it assisted propulsion occurring at the terminal stance and the pre-swing phases. The subject's walking period during perturbation was significantly different from before. Remarkably, after the pulses were discontinued, the subject continued walking at the perturbation period (τ_p) with no statistical difference of stride duration between the *during* and the *after* phases. Entrainment to periodic perturbation with an after-effect for at least 20 strides occurred in both cases despite substantial differences between these contexts. As the treadmill operated at constant speed, an increase in stride duration required a concomitant increase of stride length. This constraint is not present when walking overground. The details of how subjects' overground gait responds to the perturbations is a topic for future study.

Table 1: Subject's selected treadmill speed, preferred stride duration (τ_0), and applied perturbation period (τ_p).

	Treadmill Speed	Stride Duration (τ_0)	Perturbation Period (τ_p)
Treadmill	0.715 m/s	1.300 s	1.350 s
Overground	–	1.225 s	1.275 s

References

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[1]The gait cycle was estimated from extrema of the filtered knee angle [4].