Influence of Voluntary Intervention on Gait Entrainment

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I. INTRODUCTION

Robot-aided therapy has emerged as a promising approach to meet the increasing demand for effective rehabilitation. Recent work suggests that entraining gait with periodic torque pulses from a minimally-encumbering ankle robot may provide a novel approach to robot-aided walking therapy [1]. Contrary to other rehabilitation approaches, this intervention does not constrain natural walking. Rather, it exploits the natural oscillating dynamics of human locomotion. A previous study [1] found that neurologically-impaired patients entrain to periodic torque pulses applied to the ankle in a way that maximized the assistance of the torque pulses during propulsion. This observation of impaired gait entrainment to perturbation periods shorter than preferred stride period suggested this approach could increase gait cadence in neurologically impaired patients.

Recent work with healthy subjects showed that they entrain to both shorter and longer perturbation periods in both overground and treadmill walking [2], exhibiting a moderate rate of phase convergence (~24-32 perturbation cycles). Importantly, subjects achieved gait entrainment while performing a distractor task intended to minimize or eliminate voluntary adaptation to the perturbations.

An open question remains: how does active recruitment of the higher levels of the CNS affect the natural control of human locomotion? By addressing this question, we will gain further insight into the control of locomotion, which may eventually lead to approaches for further expediting locomotor rehabilitation. The purpose of this study was to assess the influence of voluntary intervention on entrainment.

II. METHODS

A. Subjects

Four unimpaired subjects (ages 23 to 28; 2 males and 2 females) participated in this experimental study. Participants gave informed consent in accordance with procedures approved by the Institutional Review Board of the Massachusetts Institute of Technology (MIT).

B. Equipment: Anklebot

The robot used in these experiments was the Anklebot by Interactive Motion Technologies, Inc. (Figure 1). The robot's highly back-drivable linear actuators were programmed to deliver periodic square plantar-flexion torque pulses in the same fashion as in [1]. The magnitude (10 N·m) and duration (100 ms) of these torque pulses were selected to approximate 10% of maximum ankle torque and 10% of one stride duration in normal adult walking, respectively [2-4].

C. Experimental Task

Each subject performed 4 trials walking on a motorized treadmill. In the first 2 trials, subjects performed a cognitive distractor task that consisted of listing items in alphabetical order (one category at a time). They were neither informed that the torque pulses would be delivered periodically, nor asked to 'entrain' to these perturbations (*distraction* condition). In the next 2 trials, subjects did not perform the distractor task and were explicitly instructed to 'entrain' to the periodic torque pulses delivered by the robot (*instruction* condition).

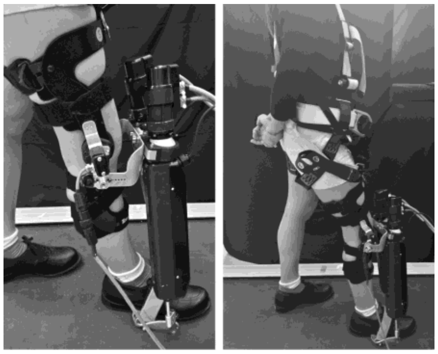

Figure 1. An unimpaired human subject wearing the Anklebot, with knee brace, custom shoes, and harness.

Trials began with subjects walking at their self-selected speed on the treadmill; this speed was maintained throughout all 4 trials for each subject. The first 15 strides were considered transitional and not included in the data analysis. Subjects' preferred stride duration (T_0) was then measured as the average duration of 15 consecutive strides. The perturbation period (T_p) was selected to be 50 ms shorter or longer than T_0. Each subject performed one trial with shorter and one with longer T_p in a randomized order. After the first 15 strides, the 50 consecutive periodic perturbations were initiated at random gait phases. After walking with the perturbations, subjects then continued to walk for another 15 strides unperturbed.

D. Data Analysis

Gait entrainment required subjects' stride period to converge to the perturbation period, i.e. each torque pulse would occur at the same phase of the gait cycle. The torque pulse phase was defined as the percentage of the gait cycle at the onset of the torque pulse. The 50 torque pulse phases were calculated in reverse order, starting from the 50th torque pulse. For each trial, a linear regression of torque pulse phase onto pulse number indicated entrainment if the 95% confidence interval of the slope (m) of this line included zero slope over segments of at least 10 consecutive pulses. If the null hypothesis was accepted (H_0: m = 0), then the gait was considered entrained.

III. RESULTS AND DISCUSSION

For the *distraction* condition, entrainment was observed in 6 out of 8 trials (Figure 2 top row). Regardless of the type of perturbation period and the gait phases at which perturbations

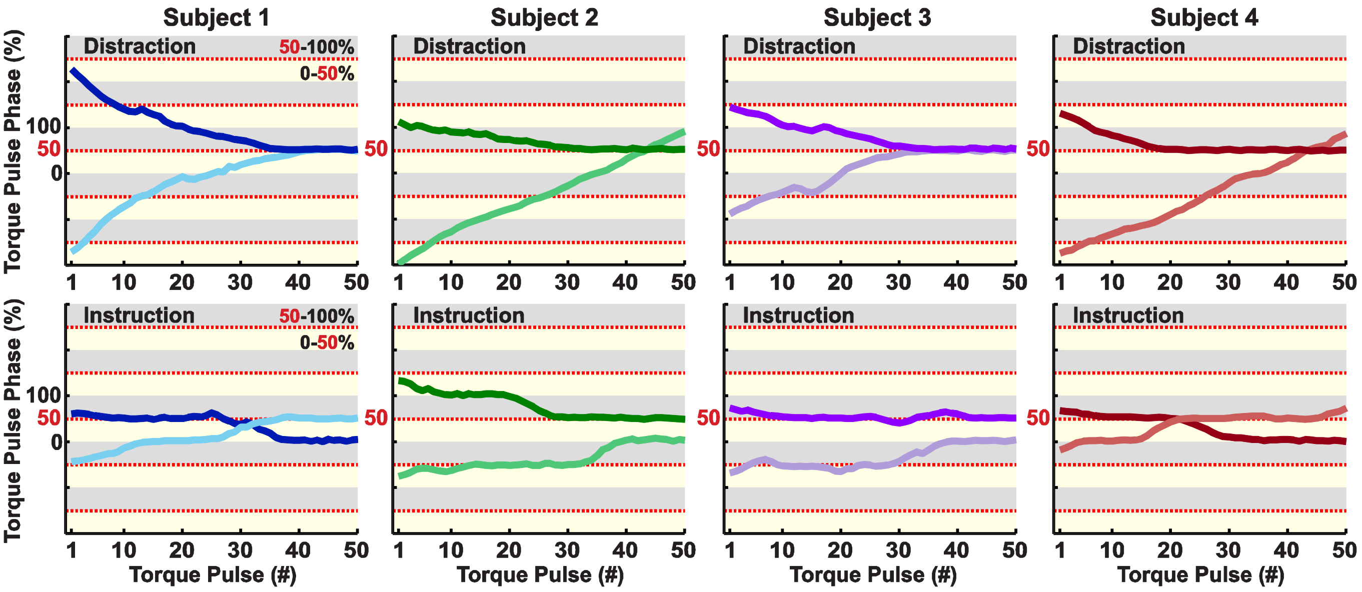

Figure 2. Torque pulse phase as a function of torque pulse number for each subject and condition. Each color represents one subject, with a dark and a light shade for the trials with shorter and longer T_p respectively. Each shaded region in light yellow corresponds to torque pulses occurring within the first half of the gait cycle (0-50%), while light gray regions correspond to the second half (50-100%). Alternating yellow-gray segments represent *wrap-arounds* in the gait cycle. **Top row**—Subject's behavior while performing a distractor task (and given no instructions to 'entrain'); if their gaits synchronized, they did so with the torque pulses at ~50% of the gait cycle (i.e. ankle 'push-off'). **Bottom row**—Subject's behavior when instructed to 'entrain' (at no specific phase) to the periodic torque pulses; their gaits synchronized with the torque pulses at the first opportunity the ankle motion was in the same direction as the torque pulses (i.e. during ankle push-off or after heel strike). In this case, synchronization was not maintained throughout the trial (as before), but instead drifted between 0 or 100% and 50%.

were initiated, subjects synchronized their gaits with the torque pulses at ~50% of the gait (ankle push-off), giving the plantar-flexion torques assistive function during forward propulsion. Interestingly, entrainment was not evidenced at the very first opportunity a torque pulse occurred at push-off. These observations were consistent with previous experiments comparing gait entrainment in treadmill vs. overground walking [1].

Despite having entrained to the same perturbation just moments before, subjects' motor behavior for the *instruction* condition was noticeably different. For this condition, entrainment was observed in all trials, yet with an 'intermittent' phase-locking pattern (Figure 2 bottom row). Subjects entrained more than once and at different phases within a single trial. The converged gait phase across all subjects for the *instruction* condition were either 51.85% ± 1.63% (ankle push-off) or 3.06% ± 1.64% (initial loading after heel strike). In contrast to the *distraction* condition, entrainment for the *instruction* condition always occurred at the first instance a torque pulse did not oppose ankle motion. This was not necessarily when it provided maximum assistance.

Previous studies reported unimpaired and impaired gait entrainment during both treadmill and overground walking under *distraction* conditions [1-2]. These observations of robust entrainment confirmed that unimpaired locomotion is competently modeled as a nonlinear limit-cycle oscillator. However, results presented here suggest active cognitive engagement may affect the expression of the previously identified limit-cycle attractor. This voluntary engagement of the higher levels of the CNS may have altered the mechanism by which subjects previously adapted their gaits to converge to the periodic perturbations. The instruction may have evoked additional neural processes that interfered with the underlying processes that control "natural" human walking. Such processes may have caused subjects to focus their attention on an aspect of their behavior that they would not otherwise attend to. For instance, they may have attempted to correct errors or minimize costs that were not previously controlled in the *distraction* condition.

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