On the interlimb coordination and synchronization during gait

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***Abstract*— Human locomotion is based on the finely tuned coordination of the two legs. For this research, we studied the contribution of interlimb pathways for coordinating and synchronizing the legs' motion in the case where body weight is externally supported and vestibular feedback is limited. The experiments were conducted using a novel device intended for gait therapy: the MIT-Skywalker. The subject's body weight was supported by an underneath saddle-like seat, and a chest harness was used to provide stabilization of the torso. Two neurologically healthy individuals were asked to walk on the MIT-Skywalker, while one side of its split belt treadmill was unexpectedly dropped during the perturbed leg stance phase. Leg kinematics are reported as well as the effect of the timing of perturbation on the unperturbed leg. Presented here are the phase-response curves (PRCs) for both legs. We found that unilateral perturbations evoked responses at the contralateral limb, while the timing of the activation played a significant role in those responses.**

I. INTRODUCTION

The mechanism of the interlimb coordination, particularly the maintenance of stability under various environmental perturbations, is a problem that has been intriguing researchers for more than one century [1]. The importance of bilateral sensorimotor information in coordination of locomotion has been demonstrated in animals but is difficult to ascertain in humans. For human locomotion, it is believed that reciprocal coordination of limbs during locomotion is closely linked to rhythmic activity of circuits that control different muscles and synergies [2]–[4]. However, the effect of unilateral perturbations on the interlimb synchronization required for stable walking is not well understood.

Several studies have investigated sensory feedback and the interlimb coordination under the effect of unilateral perturbations [5]–[10]. Most of these studies focused on the effect of unilateral perturbations at the ipsilateral leg muscles with few focusing on the bilateral response [7, 8, 11]. However, little is known whether this influence is exclusively based on the mechanisms for body stabilization and balance maintenance, or if it is also brought about from interlimb connections from central pattern generators. Here we study the mechanisms of interlimb coordination by applying unilateral mechanical perturbations and investigating the effect of those perturbations on the two legs. We experimentally define the phase-response curves (PRCs) of both the perturbed and unperturbed leg. All the perturbations are done when the body weight is supported, the position of the body center of mass is fixed, and excitation to the vestibular system is limited.

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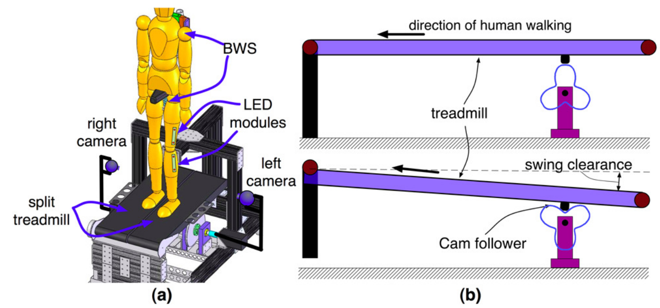

Fig. 1. (a). The MIT-Skywalker platform used for the perturbation experiments. The subject's weight is supported by the body-weight support (BWS) including a saddle-like seat and a chest harness. Two cameras and four LED modules were used for leg motion tracking. (b). Cam-based mechanism of the vertical actuation of the treadmill. As the cam rotates, the follower comes into the low dwell of the cam and a swing clearance of 8.9 cm is created.

II. MATERIALS AND METHODS

A. Subjects

Two healthy subjects [28 and 30 y.o.] were enrolled in this study. Data was collected from both legs of each participant with the dominant leg determined by asking how he/she would kick a ball. The experimental protocol was approved by the MIT Committee on the Use of the Humans as Experimental Subjects (COUHES).

B. Apparatus

The MIT-Skywalker is a unique device intended for providing robot-assisted gait therapy [12]. It consists of a split treadmill and a body weight support, which supports subject's weight from underneath in a saddle-like manner. This system can provide support ranging from zero to 100% of the patient's weight and keep the subject safe from falls, yet not interfere with the required ranges of leg motion. The body weight support system includes a chest harness providing stabilization for the torso. Each side of the split treadmill can also be vertically actuated through a cam system. In other words, each side of the treadmill can be lowered from the ground level and raised back in a controlled fashion (see Fig. 1).

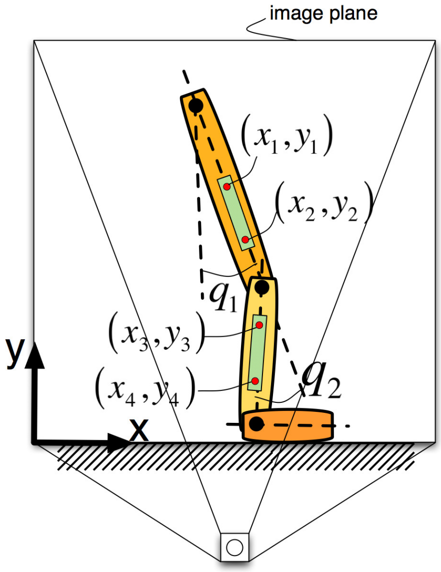

Fig. 2. The computation of hip flexion-extension (q_1) and knee flexion-extension (q_2) is done using the coordinates of each LED at the image plane reference system, included in the LED modules. Offset values of joint angles are discarded through an initial calibration procedure.

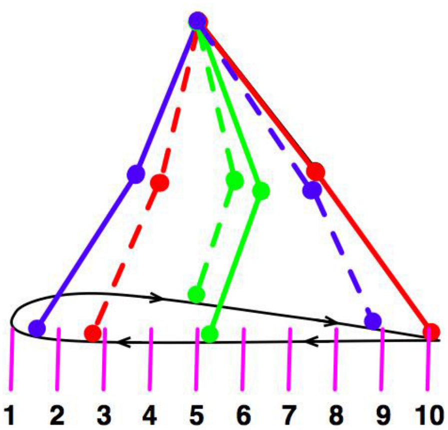

Fig. 3. The ten (10) instances where the perturbations were applied. Solid (dashed) lines represent three phases of the perturbed (unperturbed) leg during the gait cycle. Red-colored phase (perturbation 10) corresponds to heel-strike and terminal stance phase of the perturbed and unperturbed legs respectively. Green-colored phase (perturbation 5) corresponds to mid-stance and mid-swing phase of the perturbed and unperturbed legs respectively. Blue-colored phase (perturbation 1) corresponds to terminal stance and terminal swing phase of the perturbed and unperturbed legs respectively.

To measure the hip flexion-extension and knee flexion-extension of both legs in real time, we used a custom-made, camera-based motion tracking system. Two low-cost cameras (Logitech Quickcam Pro 9000, Logitech Inc.) were mounted on the sides of the platform at an appropriate distance to cover the whole range of leg movement (0.7m). Two battery-powered systems equipped with two infrared LEDs were placed on each of the subjects limbs, one on the shank and the other on the thigh. Fig. 2 depicts the configuration of the sensors. The cameras were modified in order to be able to see the infrared light filtering out the visible spectrum[1]. Standard image processing techniques were used to monitor the position of the LEDs on the sagittal plane [13, 14].

C. Experimental protocol

Subjects were fully supported with their heel barely touching the treadmill at heel-strike, i.e. fully extended knee and hip flexed at about 25 degrees with respect to the vertical axis [15]. Ankle foot orthoses were attached to both ankles to minimize ankle motion during the experiment.

The subjects were first asked to familiarize themselves with the device and walk on the Skywalker at preferred speed (1.7 MPH). Then, perturbations were introduced randomly with the interval between two successive perturbations randomly varying between 3 and 6 steps. The perturbations were randomly presented in ten (10) different instances of the perturbed leg gait cycle. These instances were selected during the stance phase of the perturbed leg, and they were uniformly distributed, as shown in Fig. 3.

III. Results

A. Leg kinematic responses

Figure 4 includes a typical set of ensemble data from a subject. The knee and the hip flexion-extension angles from both the perturbed (right) and the unperturbed (left) legs are shown for three conditions, namely toe-off, mid-stance and heel strike. As it is shown, perturbation closer to the heel-strike of the perturbed leg had a greater effect in the kinematics of the perturbed leg. Moreover, the effect on the unperturbed leg was larger when the unperturbed leg was in swing phase. The latency in the response of the unperturbed leg can also provide a significant insight into the interlimb coordination mechanism. Recent work by the authors revealed latencies in responses higher than 100 msec [13], which is consistent with the findings in this work.

B. Leg phase plots

In order to investigate interlimb coordination, we focus on the response of the contralateral (unperturbed) leg after the unilateral perturbation. We assume the leg motion as periodic and each leg as an oscillator. The oscillator assumption is valid up to 10% variability in the period of oscillation [16]. The phase-space plot provides useful insight into the periodic motion of the legs, as well as how the latter is affected by the perturbations. An example of the phase-space of the knee joint of the unperturbed leg before and after a perturbation is shown in Fig. 5. The unilateral perturbation is transferred to the unperturbed leg, having a significant impact in the kinematic space. However, the leg returns to the periodic *limit cycle* pre-perturbation. Similar observations can be made for both legs.

[1]We removed the infrared filter from the camera lens, while a photographic black thin film was placed on top of the lens to block human-visible light.

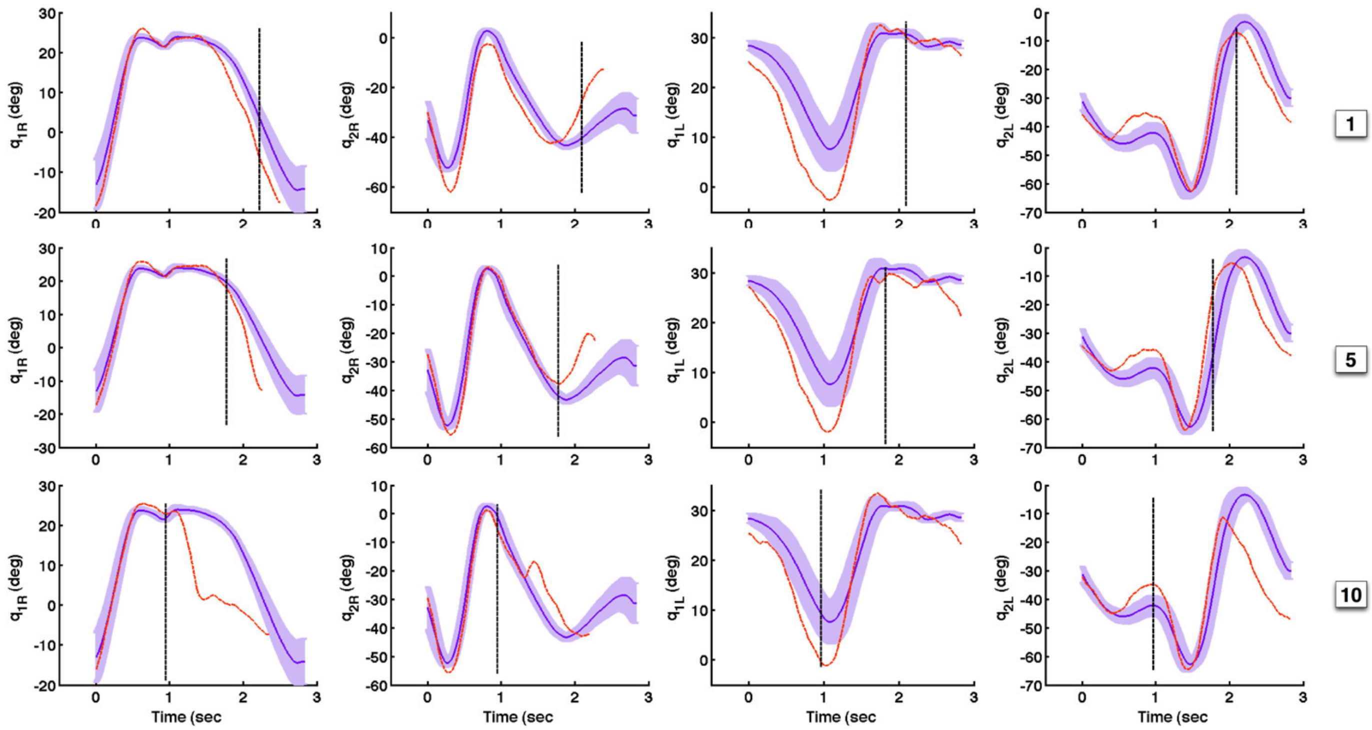

Fig. 4. Kinematic responses of the legs to the applied perturbations (perturbations 1, 5, 10 are only shown). Vertical black dashed line shows the instance when the perturbation was applied. q_{1R} , q_{2R} denote the perturbed hip and knee flexion-extension angles. q_{1L} , q_{2L} denote the unperturbed hip and knee flexion-extension angles. Blue lines represent averaged normal-unperturbed trajectories (mean and standard deviation are plotted), while red lines represent perturbed trajectories. Differences between normal and perturbed trajectories *before* the perturbation are due to kinematic data variability.

C. Phase-response curves

The assumption of a stable oscillation of both legs implies the existence of a limit cycle, which is a periodic solution to the system of differential equations describing the leg motion. Transient changes decay leaving the original oscillatory activity intact, and this was observed in our experimental data (see Fig. 5). Although the oscillatory behavior of the legs was unchanged, *a phase-shift* was induced in both legs. The relationship of this *phase-shift* with the phase at which the leg was perturbed is called a phase-response curve (PRC). For an oscillator (leg) to synchronize with periodic perturbations, which can be other oscillators in the network (e.g. the other leg), it must respond differently to perturbations at different phases of its own oscillation. Therefore, the PRC of the unperturbed leg can facilitate our understanding of the dynamics of the interlimb coordination and synchronization.

For each of the ten (10) induced perturbations, we determined the oscillation phase difference between the pre- and post-perturbation. Experimentally, this is calculated by comparing the behavior of each of the leg joints post-perturbation, with a *control* periodic profile pre-perturbation, as shown in Fig. 6a. The *control* profile is the averaged behavior of the specific joint over the last three (3) steps pre-perturbation. Fig. 6b shows a typical example of the perturbation effect in the phase of the knee joint of the unperturbed leg. The PRC for both joints of both legs is shown in Fig. 7. For each of the ten (10) phases of perturbations, the mean values of 8 steps are shown. The results suggest a non-zero PRC for both legs, with perturbations just after the heel-strike of the perturbed leg causing the larger phase shift.

IV. Conclusions

We have shown that a unilateral perturbation could affect the contralateral leg kinematics and that the timing of perturbation plays a significant role. Furthermore, the PRC analysis suggested the existence of a limit cycle, to which post-disturbance both legs converge. Our results also suggest that employing PRCs as an analytical tool is a powerful way to better understand the neural mechanisms for interlimb coordination and synchronization.

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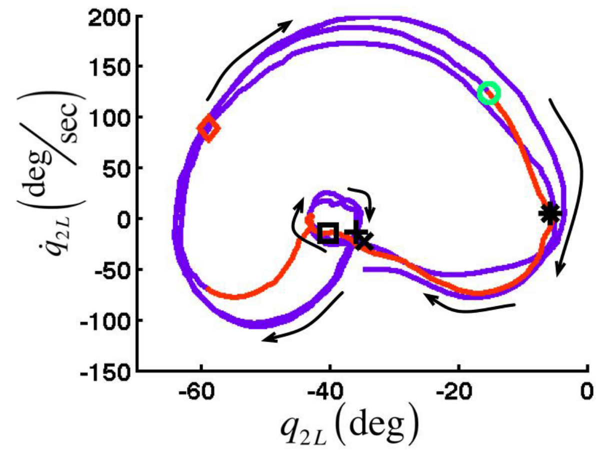

Fig. 5. Phase-space plot of the unperturbed knee motion before and after a perturbation. Three gait cycles are plotted. The start of the perturbed cycle is indicated by the **x** symbol, while the time instances every 1 sec from the start are indicated by the symbols **+**, *****, square, and diamond symbols respectively. The instance of perturbation is indicated by a green cycle, and the trajectory of the knee motion in the phase-space is colored red for the duration of 1 sec after the perturbation. Arrows show direction of plot as time progresses.

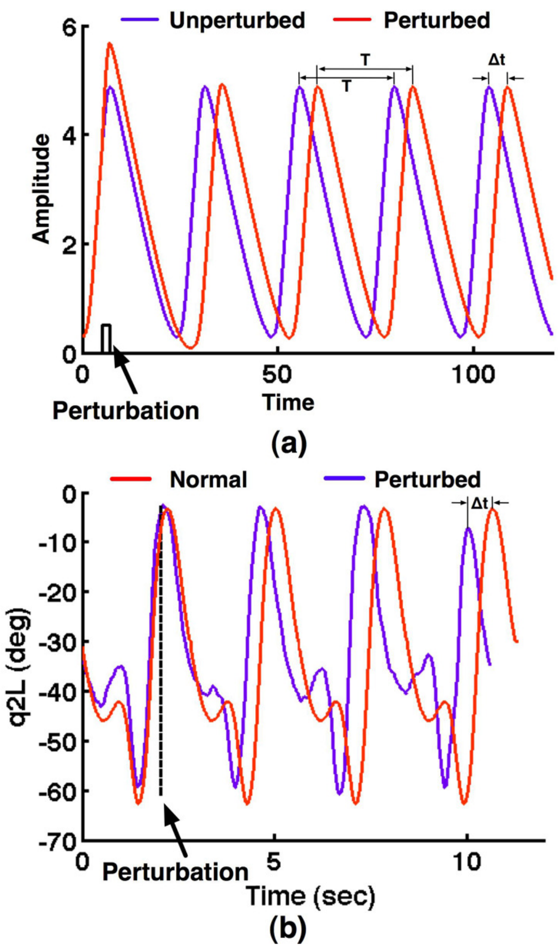

Fig. 6. a) Example for computing phase-shift in a periodic motion due to disturbance. The phase-shift is computed by $\Delta\varphi = \frac{2\pi\Delta t}{T}$. b) Indicative phase-shift caused at the left knee after a perturbation applied at the right leg.

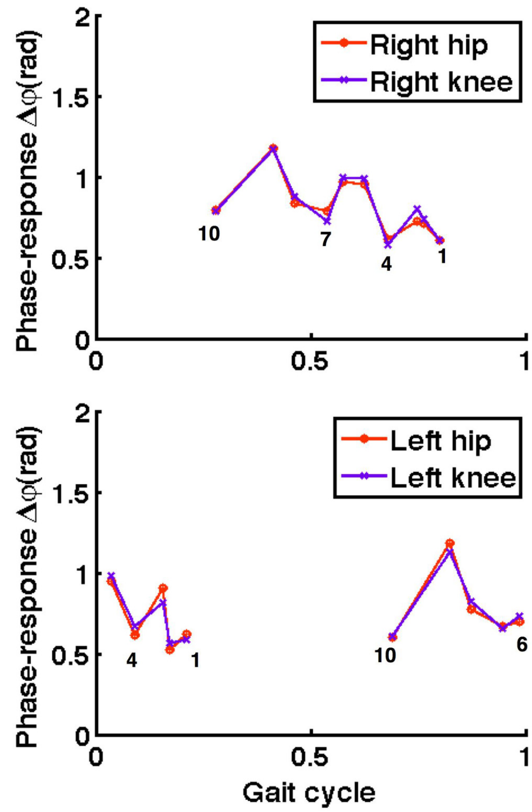

Fig. 7. PRCs for the unperturbed (left) and perturbed (right) leg joints. PRCs are drawn only for the phase regions where perturbations on the right leg were induced, i.e. for the right leg during stance phase, and for the left leg from mid-stance to terminal swing phase. Numbers on the plots indicate the type of perturbation according to Fig. 3. Positive values for phase-responses indicate phase advance. The horizontal axis indicates the gait phase for each leg, where the start (0) is toe-off for each leg and end (1) is just before toe-off of the next gait cycle.

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