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Interlimb coordination in body-weight supported locomotion: A pilot study

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ABSTRACT

Locomotion involves complex neural networks responsible for automatic and volitional actions. During locomotion, motor strategies can rapidly compensate for any obstruction or perturbation that could interfere with forward progression. In this pilot study, we examined the contribution of interlimb pathways for evoking muscle activation patterns in the contralateral limb when a unilateral perturbation was applied and in the case where body weight was externally supported. In particular, the latency of neuromuscular responses was measured, while the stimulus to afferent feedback was limited. The pilot experiment was conducted with six healthy young subjects. It employed the MIT-Skywalker (beta-prototype), a novel device intended for gait therapy. Subjects were asked to walk on the split-belt treadmill, while a fast unilateral perturbation was applied mid-stance by unexpectedly lowering one side of the split-treadmill walking surfaces. Subject's weight was externally supported via the body-weight support system consisting of an underneath bicycle seat and the torso was stabilized via a loosely fitted chest harness. Both the weight support and the chest harness limited the afferent feedback. The unilateral perturbations evoked changes in the electromyographic activity of the non-perturbed contralateral leg. The latency of all muscle responses exceeded 100 ms, which precludes the conjecture that spinal cord alone is responsible for the perturbation response. It suggests the role of supraspinal or midbrain level pathways at the inter-leg coordination during gait.

1. Introduction

Interlimb coordination, particularly the maintenance of stability under various environmental perturbations, is a problem that has been intriguing researchers for more than one century (Baker, 2007). For quadrupeds it has been proven that at slow speeds, the animals coordinate their limbs such that three feet always remain on the ground to provide stability like a tripod while the forth limb advances. Bipedal walking does not have this stability trait and requires greater effort to maintain balance while advancing (Inman and Ralston, 1981). On the other hand, it has been proven that sensory feedback not only assists the transition between the gait phases, but it also affects corrective responses to external perturbations (Nielsen and Sinkjaer, 2002). Indeed, interaction of sensory inputs with those circuits' activity can determine the coordinated pattern of agonist and antagonist muscles (Duysens et al., 2000). This sensory activity contributes to motor control in two ways. It may carry "error signals" following sudden external perturbations, and it may contribute to the pre-programmed motoneuronal activity such as the cutaneous and stretch reflex responses (Zehr and Stein, 1999; Nakazawa, 2004).

The coordination of the limbs during locomotion can be seen as a rhythmic activity of circuits that control different muscles and are specialized in repeating particular actions over and over again (Bernstein, 1967; Bizzi et al., 2000; Dietz, 2003). For locomotion, the term used is central pattern generator (CPG), which refers to a functional network of neurons within the spinal cord. This network

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is responsible for generating the rhythm and shape of the motor pattern (Grillner and Wallen, 1985). Although the CPG might receive supraspinal and afferent inputs, it is defined as being able to produce self-sustained patterns of behavior, independent of any sensory input. This understanding of the basic principle of such a CPG is mainly based on data obtained from experimental animals, primarily on experiments with cats (Brown, 1911).

Although there is some evidence that a CPG may exist in humans similar to the one in cats (Duysens and Van de Crommert, 1998), it has not yet been proven. Rhythmic activity has only rarely been observed in spinal cord injured (SCI) patients. For patients with a completely transected spinal cord, it is possible to induce, modulate and stop rhythmic contractions of the trunk and lower limb extensor muscles; however, these rhythmic contractions never occurred spontaneously and had only a one-step cycle duration (Bussel et al., 1996). On the other hand, for patients with incomplete lesions, several studies reported subjects with the presence of alternating flexor and extensor activity (Calancie et al., 1994).

In the past decades, several studies on different experimental platforms have been investigating corrective reflex mechanisms during different phases of the gait cycle with experimental protocols focusing on overground walking with a unilateral perturbation during the stance phase (Nakazawa, 2004; van der Linden et al., 2007; af Klint et al., 2009). Even though these studies mostly focused on the effect of unilateral perturbations to the ipsilateral leg muscles, the bilateral response has also been studied (Berger et al., 1984, 1987). During posture maintenance, experiments with powerful unilateral displacement of one leg produced bilateral responses both in adults (Berger et al., 1984, 1987) and in healthy human infants (Lam, 2003). 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 by interlimb connections from gait pattern generators.

Here we hypothesized that the latency of neuromuscular responses to unilateral mechanical perturbations, when the body weight is supported, will be higher than 100 ms suggesting the involvement of the supra-spinal circuitry in the responses.

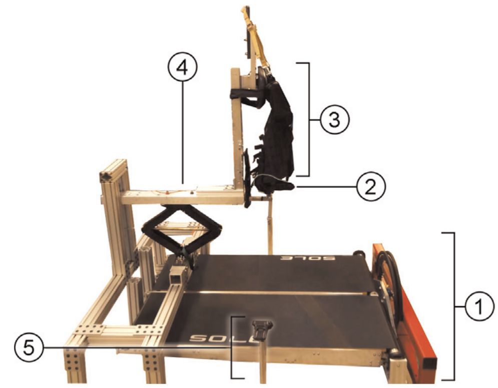

Fig. 1. The experimental setup mainly consists of (1) a split-belt treadmill (MIT Skywalker) and a body-weight support system (BWSS) composed of (2) a bicycle seat and (3) a chest harness to prevent any upper body movements. The amount of body-weight supported can be adjusted by lowering or lifting the whole BWSS with (4) a car-jack. Additionally an optical motion capture system is used which is based on (5) modified webcams installed on each side of the treadmill.

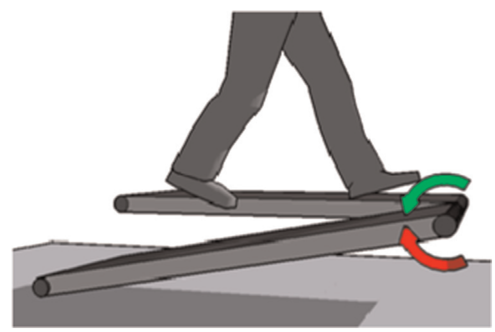

Fig. 2. One single split-belt is lowered to apply the vertical perturbation at mid-stance of the right leg. The green arrow illustrates the rotation of the split-belt downwards during the drop of the walking surface and the red arrow illustrates the return of the walking surface upwards, back to horizontal level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

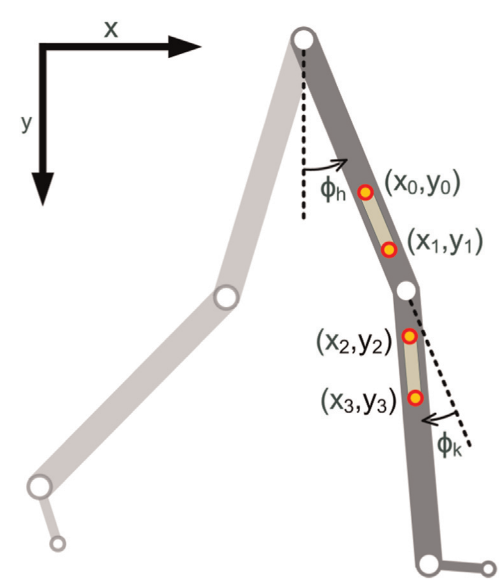

Fig. 3. Model of human leg walking with LED markers attached at thigh and shank from the view of the tracking camera. The hip and knee angle are determined out of the coordinates of the four markers. With the measured length of thigh and shank, the heel coordinates were calculated to further determine the gait phase in real-time in order to introduce the proper perturbation.

2. Methods

2.1. Apparatus

In this study we employed the beta prototype of the MIT Skywalker (Fig. 1). It is a unique, novel device intended for providing robot-assisted gait therapy (Bosecker and Krebs, 2009). The overall concept consists of a split-belt treadmill and a body weight support. This system can provide support ranging from 0% to 100% of the patients' weight and, while keeping the subject safe from falls, still not interfere with the required ranges of leg motion. The body-weight support system (BWSS) includes an underneath bicycle seat and a loosely fitted chest harness providing torso stabilization and preventing falls. Each side of the split-belt treadmill can also be vertically actuated through individual brushless motors. More specifically, each side of the treadmill can be lowered below the ground level and raised back in a controlled fashion (see Fig. 2).

To measure the flexion-extension of the hip and knee joint of both legs in real time and to control the MIT-Skywalker (i.e., determining when to lower the split treadmill panels), 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 be able to capture the whole range of leg movement. 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. 3 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. By modifying the cameras to infrared spectrum, we guaranteed that even in a non-controlled environment such as a therapy clinic, background has limited influence on the readings. Standard image processing techniques were used to monitor the position of the LEDs.

To quantify head movement in real-time and estimate the efficacy of the BWSS in reducing the afferent feedback as the walking surface drops up to 0.8 G, a 3-axis analog accelerometer (MMA7361L, Freescale Semiconductor, Austin, TX) was attached to the subjects' head, in the front and centrally located. Each of the three