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The comparison of ground reaction forces and lower limb muscles correlation and activation time delay between forward and backward walking

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ABSTRACT

This study aimed to compare the ground reaction forces (GRF) and lower limb muscles correlation and activation time delay between Forward (FW) and Backward (BW) walking. Twenty-four male students participated in this research. Electromyogram activities of gluteus medius, biceps femoris, medial gastrocnemius, soleus and anterior tibialis muscles along with GRFs were measured. Each participant performed two FW and two BW trials bare foot. Statistical parametric mapping (SPM) analysis was performed over anterior-posterior and vertical GRFs time series. The paired *t*-test was used in SPM analysis. Cross-correlation analysis compared similarity in shape and time delay of EMG pattern. SPM analysis of GRFs showed that these two walking modes have asymmetrical kinetic behavior during most parts of stance phase. Based on cross-correlation analysis, the shape of EMG activation profiles differed, where a phase shift in the muscle activation pattern of approximately 60% occurred. This shift may indicate different control mechanisms, at the spinal level, underpin FW and BW walking modalities.

1. Introduction

Forward (FW) and backward walking (BW) have been researched intensively and it has been reported that same neural mechanisms underpin control in each walking pattern [1–3]. Studies have shown that BW is, basically, FW in inverse [1–5]. Meyns et al. [3] by comparing the kinematic and interlimb coordination patterns of FW and BW between groups of healthy participants and those with supraspinal/cortical deficits, reported that FW and BW symmetry is not affected by cortical deficits. Meyns et al. subsequently concluded, that, neural control mechanisms of these walking patterns are likely to depend mostly on subcortical components (*e.g.* brain stem and spinal Central Pattern Generators (CPGs)) [3]. Grillner et al. [6] demonstrated that CPGs consist of three processes including: a) cellular, the process related to properties intrinsic of single cells; b) synaptic, governing the actions of single synapses, and; c) network, those assembling the cells and synapses into circuits. The cooperative interaction and different combinations of these processes lead to different motor pattern emergence. Therefore, it seems that FW and BW are different only in the interaction of these processes. Based on this notion, BW has been recommended as an alternative treatment strategy to improve FW. For example, in patients with hemiplegia after stroke, BW is recommended for enhancement of the motor control during FW [7]. Patients with sustained joint trauma could train BW instead of FW, because the joint stress will be minimized during BW [8]. Children with cerebral palsy (CP) could use BW for gait rehabilitation when FW is accompanied with disadvantageous consequences [3].

Raising doubts about the same neural mechanisms of FW and BW, there are several studies that have compared the electromyographic (EMG) profile of FW and BW. Based on these findings, it has been reported that there are differences in the motor control required to produce BW [4]. Indeed, activity patterns of muscles in BW are strikingly different from those of FW. Additionally, Winter et al. [9] noted that a simple reversal of the motor patterning is not evident when switching from FW to BW. However, these studies are based on subjective comparisons of FW and BW EMG profiles. To analyze the neural patterns underling motor control during FW and BW, alternative data analysis is required [10]. Cross-correlation analysis can be performed on almost any kinematic or physiological descriptor of a complex movement, and yields the directions and latencies of coordinated movements. Since this method does not involve the use of a time origin, it is suitable for studying both sustained (multiple steps) and periodic (cyclical actions)

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sensorimotor controls [11].

Another important limitation in the literature is the lack of data comparing the kinetics of BW and FW. Previous studies, having done so, have mostly focused on discrete (peak) values of ground reaction forces (GRFs) for comparing the kinetic behavior of FW and BW [1,5], ignoring the possibility of differences in other instants of the GRF time series.

The contemporary view of BW is as an instinct of human locomotion based on FW. Studies have subsequently positioned BW as having substantial potential for understanding the control of human locomotive behavior more generally. There remains the question, however, whether this symmetric behavior shown in kinematics (*i.e.*: if BW can be viewed as FW in reverse) is also evident in kinetic patterns and EMG time series of the lower limbs. We therefore, compared GRFs data between FW and BW in order to test the hypothesis that FW and BW kinematics patterns would be accompanied by corresponding symmetrical kinetic behavior. In contrast to previous studies based on discrete values of GRF, we captured features of the entire GRFs time series, and conducted a vector analysis using statistical parametric mapping (SPM) methods [12]. This statistical approach captures features of the entire time series, rather than a few discrete variables. When only discrete variables are used, this can fail to capture sufficient portions of the data and covariance among vector components [12]. SPM analysis uses random field theory to identify field regions that co-vary with the experimental protocol [14]. Indeed, analyzing the entire time series, SPM can reveal significant differences in portions of stance phase that could be of special interest, and which would not be revealed by discrete variables.

In addition, we compared the mean EMG profile between FW and BW during the stance phase. We predicted that a 50% phase shift in muscle activation can account for the differences in FW and BW. Cross-correlation analysis was used to compare lower limb muscles correlation and activation time delay between FW and BW.

2. Methods

2.1. Participants and ethics statement

Twenty-four undergraduate physical education male students (21.79 ± 2.32 years old, 65.75 ± 9.20 kg) participated in the study. The exclusion criteria were a history of lower extremity injuries/diseases that might alter walking patterns. All students were healthy, without any musculoskeletal injury or pain at the time of data collection (self-reported after a brief interview).

Prior to the experiment participants provided fully informed consent. The study had prior approval by a local university ethics committee.

2.2. Instrumentation

Two force plates (Bertec, 40 × 60, USA), embedded into a 6-m walkway and positioned with 60 cm center to center distance in anterior-posterior (AP) direction, were used to collect GRF data at a sampling rate of 200 Hz.

The EMG data were recorded at 1000 Hz using an EMG system (MT8 Model, MIE Medical Research Ltd 40 × 60, UK) and surface Ag–AgCl electrodes. The MIE pre-amplifier had a gain of 4000×, 32 kHz bandwidth, 108 dB (typical) CMRR and $10^8\ \Omega$ input impedance. The force plates were synchronized to the EMG system.

2.3. Procedures

Before the gait analysis, the participants' age and anthropometric (weight and height) data were measured. The participants were tested for their dominant side by means of the test of kicking a soccer ball [1]. All participants kicked with their right limb.

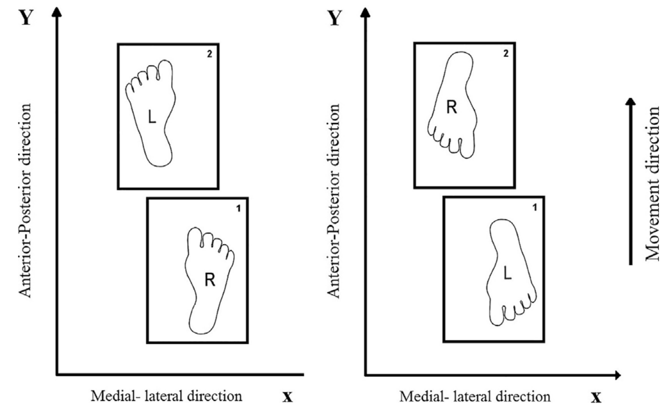

Fig. 1. Procedure of Forward (Left) and Backward (Right) walking. R: right foot, L: left foot. 1: Force plate 1, 2: Force plate 2.

After shaving and cleansing the skin, electrodes were placed, with an inter-electrode distance of 2 cm, longitudinally over the following muscles on dominant leg according to European recommendations for surface electromyography [13]: gluteus medius (GM), biceps femoris (BF), medial gastrocnemius (MG), soleus (SOL), and tibialis anterior (TA).

The participants familiarized with BW prior to the experiments for successful adaptation to the new walking pattern. Successful trials required that participants land a clean foot-strike onto the force plates while walking at a self-selected pace and without an awareness of the position of the force plates.

Each participant performed two valid FW (Fig. 1, Left) and two valid BW trials (Fig. 1, Right) on walkway in a barefoot condition. The direction of the movement was the same for both FW and BW, so that the right foot and left foot struck the force plate 1 in FW and BW, respectively (Fig. 1).

2.4. Data analysis

GRF data were processed using a zero lag, low-pass Butterworth fourth order filter with a cutoff at 15 Hz. Initially, we chose a threshold of approximately 2% of average body weight (13 N), as recommended in kinetic studies, in order to avoid transients in force acquisition at the initial contact and toe-off. Then, we reran the data using a threshold ~1% of average body weight (~6.5 N) in order to verify if there were qualitative changes on results. The chosen threshold for ground contact was defined as the time when vertical (V) GRF exceeds 10 N. Peak VGRF were calculated during the walking for each subject trial [9], and normalized to subject's body weight (%BW). The use of 10 N threshold for VGRF was proven to be a reliable value to be used in this study, since it was within the analyzed range that sustained the same qualitative results.

An estimated gait speed was calculated as the step length divided by step duration, *i.e.* distance between the center of pressure AP position at successive initial contact on each force plate (considering the 60 cm between them) divided by time interval between those successive contacts on the force plates, took as the number of force samples divided by sampling frequency.

Some peak parameters were extracted for GRF. For AP GRF, the values (as BW%) were extracted for both conditions on the minimum (first peak) and maximum (second peak) values during stance phase. For VGRFs, we extracted three peaks: the maximum of the first half (first peak), the maximum of the last half (second peak), and the minimum value between those two (valley) during stance phase. These GRF values were extracted for both left and right feet in both FW and BW conditions.

In addition, a vector analysis of the GRF time series data was conducted using the SPM method, as described elsewhere [12]. We