Gait & Posture 40 (2014) 134–139

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Interpreting lateral dynamic weight shifts using a simple inverted pendulum model

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ARTICLE INFO

Article history:
Received 15 October 2013
Received in revised form 28 January 2014
Accepted 7 March 2014

Keywords:
Balance
Lateral shifting
Inverted pendulum model
Standing
Non-minimum phase behavior

ABSTRACT

Seventy-five young, healthy adults completed a lateral weight-shifting activity in which each shifted his/her center of pressure (CoP) to visually displayed target locations with the aid of visual CoP feedback. Each subject's CoP data were modeled using a single-link inverted pendulum system with a spring-damper at the joint. This extends the simple inverted pendulum model of static balance in the sagittal plane to lateral weight-shifting balance. The model controlled pendulum angle using PD control and a ramp setpoint trajectory, and weight-shifting was characterized by both shift speed and a non-minimum phase (NMP) behavior metric. This NMP behavior metric examines the force magnitude at shift initiation and provides weight-shifting balance performance information that parallels the examination of peak ground reaction forces in gait analysis. Control parameters were optimized on a subject-by-subject basis to match balance metrics for modeled results to metric values calculated from experimental data. Overall, the model matches experimental data well (average percent error of 0.35% for shifting speed and 0.05% for NMP behavior). These results suggest that the single-link inverted pendulum model can be used effectively to capture lateral weight-shifting balance, as it has been shown to model static balance.

1. Introduction

Balance assessment is important in rehabilitation after neurotrauma such as stroke, allowing clinicians to identify balance problems (functional approach) and determine underlying causes (systems approach) [1]. Quiet standing postural control, in which subjects attempt to center their center of mass (CoM) and reduce sway, has been a major focus of research. Static balance assessment examines center of gravity (CoG), the vertical projection of the CoM onto the ground, and center of pressure (CoP), the location of the resultant ground reaction force (GRF). CoP location affects CoG motion as CoG acceleration is proportional to the difference between the two [2]. Several metrics have been shown to distinguish between static balance data for young, elderly, and balance-impaired subjects [3,4]. Many clinical studies take a functional approach [5–9], while others examine human postural control with a systems approach [2,10]. In either case, ceiling effects limit the utility of balance assessments based purely on static balance as patients grow increasingly adept at standing upright [8]. Analyzing dynamic gait is another approach [2] characterized by floor effects due to the higher difficulty of the walking task.

Lateral weight shifting is a balance task more difficult than quiet standing and less difficult than walking in which subjects laterally translate their CoM, often using visual targets and CoP feedback. Easily applied clinically, lateral weight shifting is a robust task for evaluating stroke patient balance [7] that provides information beyond that available through static balance assessment [6]. Additionally, weight-shifting balance training may reduce fall risk in hemiplegic patients [5]. While previous studies have examined its relationship with functional balance [5,6,11–14], a systems approach to weight-shifting assessment that could shed light on underlying control mechanisms and fundamental differences between healthy and pathologic weight-shifting is currently lacking. Systems approaches can enable analysis of standing balance within a dynamic controls context, generally using PID or PD control. For example, a PID static balance control model postulates that increased control stiffness and damping compensate for added noise in elderly static balance [10]. The stiffness/damping ratio from PD control in other work demonstrated the significance of body velocity in balance control [15].

This study is the first to take a systems approach to establish the validity of a simple inverted pendulum model for lateral weight shifting and to build the foundation for clinical applications.

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http://dx.doi.org/10.1016/j.gaitpost.2014.03.011

Inverted pendulum models of anterior–posterior [10,16], medio-lateral [17], and bilateral [18,19] quiet standing are common, and some more complex models, such as the parallelogram [2] and multi-link inverted pendulum models [20], have been proposed to better mimic human physiology. No such models, though, have been applied to lateral weight shifting with the focus on balance control herein. Furthermore, existing quantitative metrics for lateral weight shifting are limited to weight-shifting speed, precision of weight shifting, temporal symmetry, and force symmetry [4–6,12]. This study examines a new metric based on non-minimum phase (NMP) behavior to focus on the control of shift initiation.

2. Methods

2.1. Non-minimum phase behavior

In control theory, a non-minimum phase system is one in which the output initially moves in the direction opposite that of a new reference position [21]. For weight shifting with visual feedback, the output is the CoP, and the reference is the target CoP position to which the shift occurs. From a mechanics viewpoint, the leg opposite the shift direction generates an increased GRF with a lateral component that accelerates the CoM toward the target (assuming no other contacts and no foot adhesion to the floor). This GRF increase causes the CoP to briefly move in the direction opposite the weight shift until the CoG has shifted far enough to cancel the effects of the initial GRF increase. This NMP behavior is readily observed in the CoP trajectories of visually guided weight shifting (Fig. 1). Similar behavior has been observed during gait initiation, and GRF peaks have been used to characterize dynamic gait [9,22]. As vertical CoM movement is typically small during weight-shifting, the total vertical GRF is nearly constant. More meaningful is the difference in vertical GRF between the feet, which peaks during weight shift initiation, causing NMP behavior.

In this study, NMP behavior magnitude, the distance the CoP travels in the direction opposite the weight shift, is introduced as a characteristic property of lateral weight shifting to establish a metric for quantitative analysis. This metric parallels use of peak GRF in gait analysis since the timings of the peak NMP behavior and the peak GRF difference between the feet coincide and their magnitudes are directly related. Therefore, this NMP metric measures the strength of shift initiation as a subject prepares to move his/her CoP toward the target.

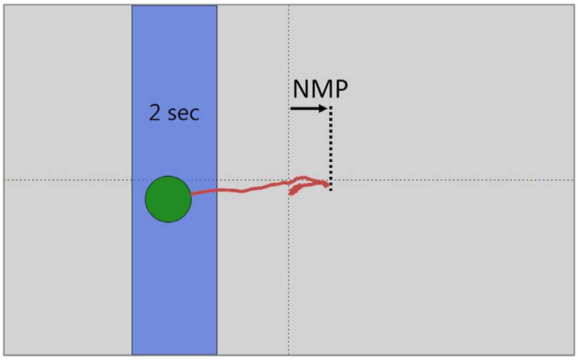

Fig. 1. Non-minimum phase behavior demonstrated by a lateral weight shift. The magnitude of the NMP behavior along the *x*-axis is illustrated by the arrow terminating at the thick dotted line. In shifting from a laterally symmetrical position to the blue target region on the left, the red CoP trace travels to the right before moving toward the target region. The subject's CoP is shown as a green circle, the target CoP region is shown as a blue rectangle, and the time that the subject's CoP has remained within the target CoP region is shown by the text inside the target region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

2.2. Weight-shifting task

Subjects were led through a lateral weight-shifting task using the WeHab system [23]. Each subject stood with one foot on either of two Nintendo Wii balance boards and shifted his/her CoP, presented as a green circle on a rectangular field, from one target region to another (Fig. 1). While both sagittal and lateral CoP information were presented, the task was based on lateral CoP information alone. Target regions were presented as blue rectangles twice the width of the CoP marker. Subjects were instructed to hit as many targets as possible within the time provided. A new target appeared once the center of the CoP marker entered and remained within the target region for 3 s. Targets alternated between central (symmetrical stance) and offset locations positioned at a 70–30% weight distribution randomly located to the left/right. To account for anticipation effects, only offset target shifts were examined.

2.3. Metrics

The reaction time (t_R) is the time required for a subject to recognize the new target location and begin shifting his/her weight. Due to the natural sway in static balance, it is difficult to determine the start of a purposeful shift. Therefore, t_R was estimated using a three-sample (≈0.05 s; see Section 2.4) moving window that iterated backward in time from the point of maximum NMP displacement ($\mathrm{NMP}_{\mathrm{max}}$). When this window no longer contained a point closer to the target location than any point previously examined, the point with the last minimum distance was taken to mark the reaction instant (Fig. 2a). The time between the target shift and the reaction instant was t_R, and the subject's CoP position at the reaction instant was the initial CoP position.

The initial time-to-target (t_S), the time required to shift the CoP to a target region, quantifies the speed of weight shifting [4,6]. This metric was calculated by subtracting t_R from the time between the target shift and the CoP entering the target region (Fig. 2a).

The NMP shift ratio (r_{NMP}) was measured as $d_{\mathrm{NMP}}/d_{shift}$, where the NMP magnitude d_{NMP} is the distance from the initial CoP position to the CoP trajectory's farthest point from the target and the shift distance d_{shift} is from the initial CoP position to the target region's center. This ratio supplements the t_S metric by characterizing shifting force at the onset of a weight shift. Fig. 2a shows d_{NMP} and d_{shift} in the context of experimental shift data, both calculated based on lateral CoP balance alone.

2.4. Data

Lateral weight-shifting data were obtained from 79 healthy subjects participating in a visual feedback study [24]. All subjects gave informed consent, and the study received approval from the appropriate Institutional Review Board. Four subjects' data were discarded, two due to missing height data and two due to an error in selecting single board instead of dual-board configuration in the software. The remaining subjects included 35 males and 40 females, 17–22 years old (body mass 66.7 ± 11.7 kg; height 173.6 ± 9.4 cm; mean ± standard deviation). Data were collected at 63.9 ± 2.0 Hz (mean ± standard deviation).

Each weight shift consisted of the CoP trajectory starting from a target location shift and ending when the CoP first enters the target region. Considering all shifts from all subjects, weight shifts with t_S or t_R values outside of three standard deviations of the mean were excluded. For r_{NMP}, shifts with values greater than 1 were excluded to account for false starts in the wrong direction. Metric values were averaged across each subject (10.7 ± 1.5 shifts per subject; mean ± standard deviation) and used to determine subject-specific control parameters.