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Short communication

Adaptive control of center of mass (global) motion and its joint (local) origin in gait

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A B S T R A C T

Dynamic gait stability can be quantified by the relationship of the motion state (i.e. the position and velocity) between the body center of mass (COM) and its base of support (BOS). Humans learn how to adaptively control stability by regulating the absolute COM motion state (i.e. its position and velocity) and/or by controlling the BOS (through stepping) in a predictable manner, or by doing both simultaneously following an external perturbation that disrupts their regular relationship. Post repeated-slip perturbation training, for instance, older adults learned to forward shift their COM position while walking with a reduced step length, hence reduced their likelihood of slip-induced falls. How and to what extent each individual joint influences such adaptive alterations is mostly unknown. A three-dimensional individualized human kinematic model was established. Based on the human model, sensitivity analysis was used to systematically quantify the influence of each lower limb joint on the COM position relative to the BOS and the step length during gait. It was found that the leading foot had the greatest effect on regulating the COM position relative to the BOS; and both hips bear the most influence on the step length. These findings could guide cost-effective but efficient fall-reduction training paradigm among older population.

1. Introduction

A vital functional plasticity of human locomotion lies in its ability to make motor adaptations in the adaptations to guarantee stability. Dynamic gait stability can be characterized and quantified by the relationship of the motion state (i.e. the position and velocity) between the body center of mass (COM) and its base of support (BOS) (Hof et al., 2005; Pai and Patton, 1997; Yang et al., 2009). After encountering perturbation that commonly occurs in everyday living, a person must maintain his/her body at a stable condition by adjusting his or her (absolute) COM motion state or altering the BOS (through modified stepping), or doing both at the same time. The BOS is the area under the stance foot while it becomes the outline area under and between both feet during double-stance phase in gait (more on this definition can be found in Supplementary materials). Post repeated-slip exposure in laboratory observations (Bhatt et al., 2006; Cham and Redfern, 2002a), for instance, older adults would adaptively shift their COM anteriorly relative to the BOS at step touchdown (TD) in walking while simultaneously shorten their step length. Such alterations make their gait pattern more robust and stable, because they can well sustain the next slip should it occur unknowingly again without falling backward – the direction of vulnerability, from anatomical and functional perspectives.

How will such (global) objectives pertaining to the COM and BOS be achieved at joint (local) level? Given the large number of mechanical degrees-of-freedom (DOF) in the human body segments, these adaptive alterations in gait pattern could theoretically be achieved by a reduction in an infinite number of options (i.e. the combinations of changes in joint angles) as eloquently addressed by Bernstein (1967). Being too flexible is not necessarily desirable, because it also increases the complexity and hence the cost in the control of these movements. Hence, it is suggested that for movements that involve multiple body segments, vast options may be reduced to a small set of variables (Sadeghi, 2003; Soechting and Lacquaniti, 1981). The question arises that should the central nervous system (CNS) simplify the adaptive control of the body degrees of freedom in accordance with physical rules?

Before such question can be addressed satisfactorily, the physical rules themselves must be clearly formulated. It was found that subjects, after perturbation training, would land foot more flat (Cham and Redfern, 2002a; Marigold and Patla, 2002) with more knee flexion (Cham and Redfern, 2002a) at TD than the pre-training gait. As mentioned above, body COM is directly related to joint angles. It is possible that these changes in lower limb joint kinematics took place because they are more suitable than others

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to affect COM position and step length in that joint configuration (posture). The impact to global changes in the COM motion state or changes in step length may vary from one joint to another. One physical rule for adaptation can be such that those joints bearing greater kinematic advantage should be more active (with greater change in motion) than the others. Before such hypothesis can be tested, however, a clear picture on how each individual joint influences on and contributes to the body COM position relative to the BOS and step length will provide us useful insights to understand each joint's (or lack of) kinematic advantage.

The purposes of this study was to develop such an approach to investigate the influence of each individual lower limb joint on COM position relative to BOS and step length during gait. It has been identified that gait stability (Bhatt et al., 2011) and foot kinematics (Cham and Redfern, 2002b) at TD may differentiate ones with high risk of falls from others. Therefore, our study would focus on the instant of TD. The findings from the present study could provide insights into the underlying mechanisms of adaptive changes in gait pattern after the perturbation training.

2. Methods

2.1. Human model and sensitivity analysis

A three-dimensional human biomechanical model comprised of eight rigid body segments was developed (Fig. 1). The segments included a lumped head, arms, and trunk (HAT) segment as well as both feet, legs, thighs, and a segment connecting both hip joints. This mass-less link segment between hips was for considering the effect of pelvic rotation on the COM position and step length (Fig. 1b). For each subject, the anthropometric parameters for every segment were computed using the gender-dependent segmental inertial parameters based on the experimental data (see below) (de Leva, 1996). The body COM position (x_{COM}) relative to the BOS (i.e. the leading heel) and the step length (s) during walking was analytically represented as the functions of the segment anthropometric parameters and joint angles (see Supplementary materials for derivation). Both feet were excluded when calculating the COM position due to their negligible mass ratio (1.4%) (Winter, 2005). The functions for the COM position relative to BOS and step length were

$$x_{COM} = x_{COM}(\theta_{1,2,3,\cdots,7}) = \frac{\begin{array}{l} l_1\ \cos(\theta_1+\alpha) \\ + m_2\big[-(h_2+l_2)\sin(\theta_1+\theta_2) - l_3\ \sin(\theta_1+\theta_2+\theta_3) \\ \quad -l_4\ \sin\ \theta_4 - l_3\ \sin(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5) \\ \quad -(l_2-h_2)\sin(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5)\big] \\ + m_3\big[-2l_2\ \sin(\theta_1+\theta_2) - (h_3+l_3)\sin(\theta_1+\theta_2+\theta_3) \\ \quad -l_4\ \sin\ \theta_4 - (l_3-h_3)\sin(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5)\big] \\ + m_4\left[\begin{array}{l} -l_2\ \sin(\theta_1+\theta_2) - l_3\ \sin(\theta_1+\theta_2+\theta_3) - \frac{1}{2}l_4\ \sin\ \theta_4 \\ -h_4\ \sin(\theta_1+\theta_2+\theta_3+\theta_5) \end{array}\right] \end{array}}{2m_2+2m_3+m_4} \quad (1)$$

$$\begin{aligned} s &= s(\theta_{1,2,3,\cdots,8}) \\ &= -l_1\ \cos(\theta_1+\alpha) + l_2\ \sin(\theta_1+\theta_2) + l_3\ \sin(\theta_1+\theta_2+\theta_3) + l_4\ \sin\ \theta_4 \\ &\quad + l_3\ \sin(\theta_6-\theta_1-\theta_2-\theta_3-\theta_5) + l_2\ \sin(\theta_6+\theta_7-\theta_1-\theta_2-\theta_3-\theta_5) \\ &\quad + l_1\ \cos(\alpha-\theta_6-\theta_7-\theta_8+\theta_1+\theta_2+\theta_3+\theta_5) \end{aligned} \quad (2)$$

where θ_i (i=1, 2, 3, …, 8) respectively specified the joint angle of the leading foot, leading ankle, leading knee, pelvic rotation, leading hip, trailing hip, trailing knee, and trailing ankle. l_1 Represented the distance between ankle and heel. l_2 and l_3 were the Segmental length of the leg and thigh, respectively. l_4 Depicted the width of the pelvis. h_i (i=2, 3, 4) Respectively indicated the distance from the distal end to the segmental COM of the leg, thigh, and HAT. m_i (i=2, 3, 4) respectively was the segmental mass of the leg, thigh, and HAT. α was the Angle formed by the line connecting ankle and heel and the sole (Fig. 1).

By taking the COM position's and step length's partial derivatives with respect to each joint angle, the sensitivity of COM position and step length to each joint angle could be obtained as Eqs. (3) and (4). The sensitivity quantifies the extent to which the COM position or step length changes in response to the increment in the

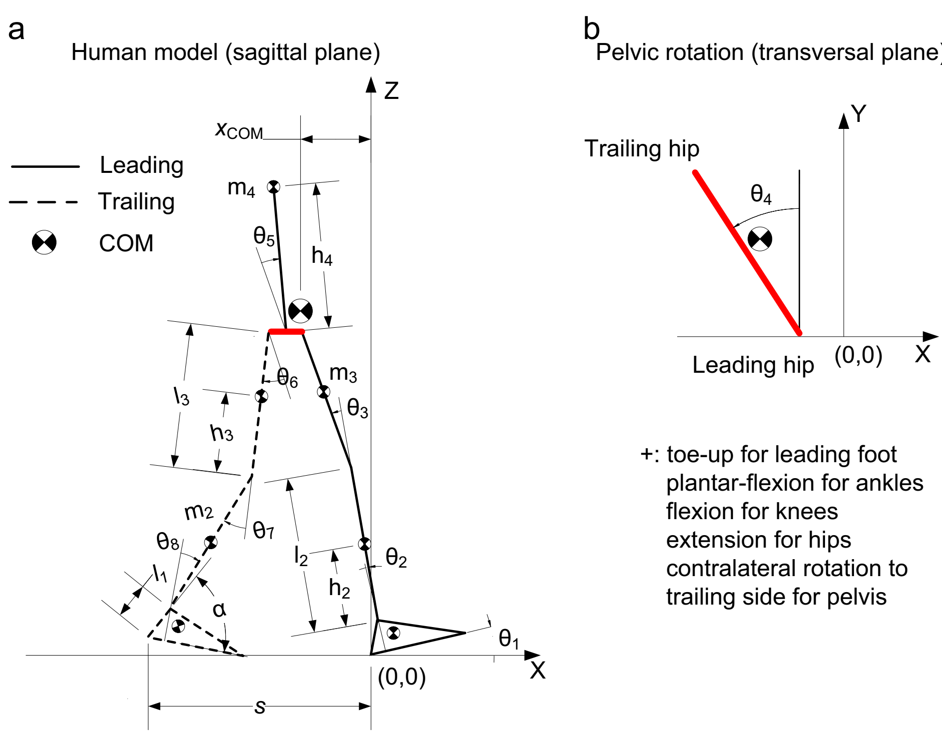

Fig. 1. (a) The sagittal plane and (b) the transverse plane of the schematic of the eight-link, three-dimensional, model of the human body with leading heel at the point of (0, 0, 0). Solid thick and dashed line respectively represents the leading and trailing sides of the body. The model includes a lumped head, arms, and trunk (HAT) segment as well as both feet, legs, thighs, and a segment connecting both hip joints. This link segment between hips, which was mass-less, was for considering the effect of pelvic rotation on the step length. α is the Angle formed by the line connecting ankle and heel and the sole. Its value is fixed for each individual subject, but may vary among subjects. The segmental length and mass and the position of each segment's center of mass (COM) were calculated for each individual subject. The COM position (x_{COM}) is represented relative to the base of support (BOS, i.e. the leading heel). The step length (s) is calculated as the distance between two heels in the anteroposterior direction at the instant of touchdown. Joint angles θ_i (i=1, 2, 3, …, 8) specify the angles of the leading foot, leading ankle, leading knee, pelvic rotation, leading hip, trailing hip, trailing knee, and trailing ankle, respectively. On the leading side, the positive direction of the rotation axes is along the negative Y-axis (laterally to the leading side), but for the trailing side of the body the joint axes were in the direction of the positive Y-axis (laterally to the trailing side). The positive direction of the pelvic rotation is along the positive Z-axis. The positive X-axis is the direction of forward progression, the positive Y-axis is leftward, and the positive Z-axis is upward.