Balance Recovery after an Unexpected Media-Lateral Gait Perturbation

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Abstract:
In this study we examined the recovery responses to sideways pushes to the right shoulder during walking. To examine a realistic situation the width of the walkway was restricted (boundary condition). Perturbations were applied randomly without previous knowledge of the subjects at either right or left single support phases of the gait. Perturbations were triggered by foot contact on a force plate mounted in the laboratory walkway. Planar displacement of the center of mass and rotational angles of the trunk in the frontal and transversal planes show that *a)* boundary conditions affected mainly the control of movement in the media-lateral direction, and *b)* gait phase influenced chiefly the rotational movement of the trunk in the transversal and frontal planes. The results indicate that foot-placement strategy was applied for balance recovery after perturbation.

Keywords: Media-lateral stability, gait perturbation, balance recovery.

Introduction

In order to walk around in the real world, we must be able to navigate through a complex environment, and recover from disturbances such as being unexpectedly pushed or tripped. The underlying challenge of locomotion is to control of the centre of mass (COM) and the base of support (BOS), which are both in motion. During gait, the BOS is not only in motion, but also in change over time [1]. During single support phase, the BOS is defined by the area of contact between one foot (stance foot) and the ground. During double support phase, the BOS is the areas of contact of the two feet with the ground plus the area between the two feet. Throughout the gait the COM is only within the BOS during the two brief double support phases (each lasting only approximately 10% of the gait cycle), and is actually outside the BOS during the remaining 80% of the gait cycle [2]. In [2] two kinds of stability for human locomotion have been stated. *Static stability* is defined as the distance of the COM from the “tipping edge” of the BOS. This definition usually applies for bipedal standing-in-place. *Dynamic stability* is often stated as a goal or

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requirement in locomotion, and rarely being quantified. Dynamic stability during gait is managed by applying anticipatory, predictive, and reactive modifications to the gait pattern, and can be summarized as the control of the COM position and velocity with respect to the changing and moving BOS [1]. Reactive strategies are, by definition, produced in response to unexpected sensory information, such as the sensations associated with being pushed. Townsend [3] demonstrated that swing foot placement control can be used to stabilize balance in gait by manipulating the redirection of the COM that occurs at the heel-contact. Winter [2] found empirically that in every step, appropriate foot placement is required in order to prevent a fall. All these findings indicate that balance control during gait is in fact an end point control task.

On the other hand, in both standing-in-place and gait, the motor control system must be able to modify its performance to address changes in demands. Studies about different perturbations applied to the upright posture have demonstrated that the central nervous system is capable of producing responses according to the nature of the perturbation, such as pushes applied in various directions to the feet [4], hands [5], and trunk [6]. In addition, it has been demonstrated that there are situation-specific 'change-of-support' reactions such as stepping or grabbing a handrail [7]. Issues such as the phase of gait dependence of reflex modulation [8] and recovery strategy recruitment [9] have demonstrated that the principles established about stability of standing-in-place cannot be applied directly to the situation of walking. Rather than being reflexive brief responses, the reactive recovery from an unexpected gait perturbation continues for at least two steps following the perturbation onset [10]. In this study we investigated the recovery responses to sideways pushes to the shoulder during walking in a situation where the walkway width was restricted, as might happen on a busy street corner. The reactive recovery from gait perturbations was examined with respect to the phase of gait at perturbation onset for the perturbed step and up to two steps after that.

Protocols and materials

Six healthy female adults (16-24 years) were participated in this study. Media-lateral trunk "push" perturbation were delivered to the left shoulder with a custom-built computer-controlled mechanical perturbation device positioned to the left of the walkway. The height of the perturbation arm was adjusted for each participant, such that the end effector of the mechanical perturbation device would be within approximately 10 to 15 cm of the superior portion of the participant arm. The participants walked on the level floor at their natural speed looking straight ahead at a target on the opposite wall. The boundaries of the walkway (its width) were restricted either by a blue mat (soft boundary condition: B) or by wood sticks on two sides of the walkway (hard boundary condition: W). Rightward perturbations were triggered by an initial foot contact on a force plate mounted in the laboratory walkway. There was an inherent delay from the time of initial foot contact until the perturbation arm was able to begin pushing on the participant. This delay was lengthened such that perturbation onset occurred during the following left single support (LSS) or right single support (RSS) phase of the gait cycle. Each subject performed 90 unperturbed gait or Walk Through (WT) trials (as control trials), 20 trials of LSS (10 trials with LSSB and 10 trials with LSSW), and 20 trials of RSS (10 trials with RSSB and 10 trials with RSSW). The sequence of trials was completely randomized.

Twenty-eight infrared light-emitting diodes (IRED's) were fixed on the following anatomical landmarks and were monitored by OPTOTRAK cameras: the lateral aspects of head (anterior to the ear), shoulder, elbow, wrist, midpoint of last rib, iliac crest, anterior superior iliac spine, the greater trochanter of the femur (hip), knee, ankle, heel, and 5th metatarsal head (all bilaterally), and also on the chin, and xyphoid.

From collected kinematics the ML velocity of the body COM (VZcom), trunk rotational velocities in the frontal and transversal planes (VRoll, VYaw, respectively) were obtained. Moments when the chosen variables attain their maximum value were also determined (TmaxVZ, TmaxVR, TmaxRoll, TmaxVY, TmaxYaw). Trajectories of the step length (Xstep), and step-width (Zstep) were also estimated. From step-length trajectory, heel-contact (HC) and foot-flat (FF) moments for the perturbed step and one step after that (1stHC, 1stFF, and 2ndFF, respectively) were identified (Figure 1). Values of chosen variables at all mentioned events were calculated.

Results and Discussion

Step width and length are two variables that characterize the foot-placement strategy. Table 1 shows the average step width and length at 1stHC after perturbation under two boundary conditions and for different gait phases at the perturbation onset. Negative sign of Zstep for RSS indicates that swing leg in response to the perturbation has crossed over (media-laterally) the stance leg. For LSS trials, in response to the perturbation a wider step was taken to stabilize the body. Therefore, based on the supporting leg at the perturbation moment (*i.e.*, gait phase), different strategies were applied to stabilize the movement.

Table 2 summarizes the average and standard deviation of the important events. Our results show that TmaxVZ has not changed based on the gait phase. Whereas, the maximum ML velocity of the COM occurred mostly after the first HC after perturbation (TmaxVZ(LSS)>1stHC(LSS), TmaxVZ(RSSW)<1stHC and TmaxVZ(RSSB)>1stHC with Pr = 0.062, DF=1, F 5.73). Therefore, after the foot touched ground, VZcom began to decrease. In general, the 1stHC of the LSS trials occurred significantly earlier than that of the RSS trials (Pr=0.023, DF=1, F=10.61). On the other hand, the 1stHC of LSSW trials happened significantly earlier than that of the LSSB (p=0.03), whereas there was no significant difference between 1stHC of the RSSB and that of the RSSW. The results indicate that the boundary conditions of the walkway have been considered in the process of controlling the 1stHC during LSS and the ML velocity of the COM in general. The second fact shows itself in the significant differences of TmaxVZ for B and W (TmaxVZ(W)< TmaxVZ(B)). In other words, for LSS trials the 1stHC and the TmaxVZ has changed from B to W. While in RSS trials only TmaxVZ has changed from B to W. For RSS gait perturbation the ML movement of the trunk was controlled more strictly, because the swing leg after perturbation has crossed over the stance leg. That is why the TmaxVZ in RSS occurred earlier than in LSS trials (when its occurrence is considered relative to the 1stHC).

The percentage of the decrease in the velocities (calculated relative to the difference between maximum and minimum values of the corresponding velocities) for VZcom, VRoll and VYaw at different time intervals was also computed (table 3, see also figure 2). These results indicate that rotational velocities of the trunk have decreased significantly before TmaxVZ (more than 75%), whereas, media-lateral velocity of the COM at the second FF (2ndFF) decreased less than 50%. Thus, recovery from perturbation in the rotational movement of the trunk accomplished more quickly than recovery in the ML direction. In fact, foot-placement strategy, which was applied to recover from rightward push perturbation, demonstrated its effect in the ML velocity of the COM. To control the rotational movement of the trunk a stiffness-control should be applied (at the L3L4 level). Increasing the stiffness of the trunk will also dampen the increased ML velocity of the COM and will help the COM to return to its normal path more easily. For LSS trials first when the swing foot touched the ground stiffness control of the trunk was applied (TmaxVZ >1stHC). For RSS trials, based on the boundary conditions the time when the stiffness control was applied has changed relative to the 1stHC.

Conclusion

The results of this study indicate that boundary conditions of the walkway affected the control of movement in ML direction (Vzcom). Whereas, gait phase (RSS/LSS) affected the rotational movement of the trunk in the transversal and frontal planes. On the other hand, AP component of the first step after perturbation was planned based on the gait phase at the perturbation moment and the boundary conditions of the walkway, and the ML component of the first step was affected only by the gait phase at the perturbation onset. We have also noticed that stabilization of the rotational movement of the trunk in the frontal and transversal planes has been accomplished more quickly than stabilization of the ML movement of the body. All these facts indicate that balance recovery after perturbation was mainly based on foot placement strategy (change in the base of support). In addition, trunk rotation in the transversal and frontal planes was an answer to the mechanical perturbation, and most probably was stabilized through stiffness control.

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Tables

Table 1: Step length and width (cm) at the 1stHC after perturbation onset and under different gait phases together with different boundary conditions. Last column shows the step length and width for walk through trials averaged over both boundary conditions. The values are averaged over all six subjects.

	RSSB	RSSW	LSSB	LSSW	WT
|Xstep|	50.85±8.32	49.55±8.61	48.28±11.12	43.55±9.97	58.26±4.23
Zstep	-2.57±5.4	-1.48±4.91	23.36±6.11	21.55±5.06	10.18±2.73

Table 2: Average and standard deviation of the important events (sec) relative to the onset of the perturbation.

	LSSB	LSSW	RSSB	RSSW
TmaxVR	0.15±0.03	0.15±0.02	0.14±0.02	0.16±0.13
TmaxVY	0.13±0.02	0.14±0.04	0.12±0.02	0.14±0.13
TmaxVZ	0.4±0.06	0.35±0.1	0.42±0.15	0.33±0.13
1stHC	0.36±0.062	0.33±0.059	0.38±0.067	0.37±0.075
2ndFF	0.57±0.11	0.58±0.1	0.59±0.1	0.59±0.1

Table 3: Decrease in the linear and rotational velocities during different time intervals. The percentage of the decrease is calculated relative to the difference between maximum and minimum values of the velocities.

	RSS	LSS
MaxVR-VR(TmaxVZ)	2.57±1.12 (83.7%)	2.31±0.81 (87.5%)
MaxVY-VY(TmaxVZ)	2.96±0.83 (85.5%)	2.45±0.65 (76.4%)
MaxVZ-VZ(2ndFF)	0.18±0.075 (49%)	0.18±0.08 (38.3%)
MaxVR-VR(2ndFF)	1.99±0.73 (66.8%)	2.15±0.74 (80.2%)
MaxVY-VY(2ndFF)	2.87±0.73 (83.4%)	2.32±0.65 (71%)

Figures

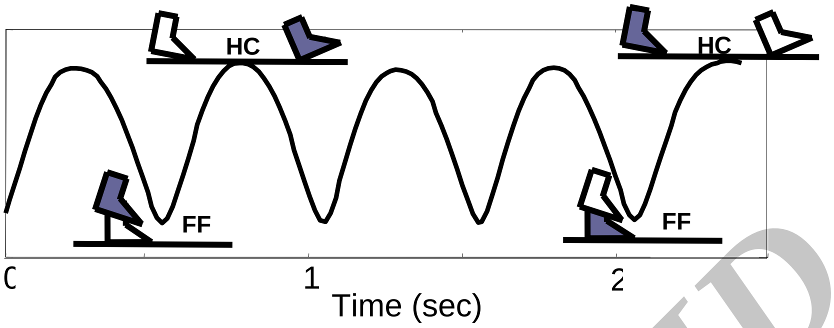

Figure 1: Estimating heel-contact and foot-flat moments from the trajectory of the step length.

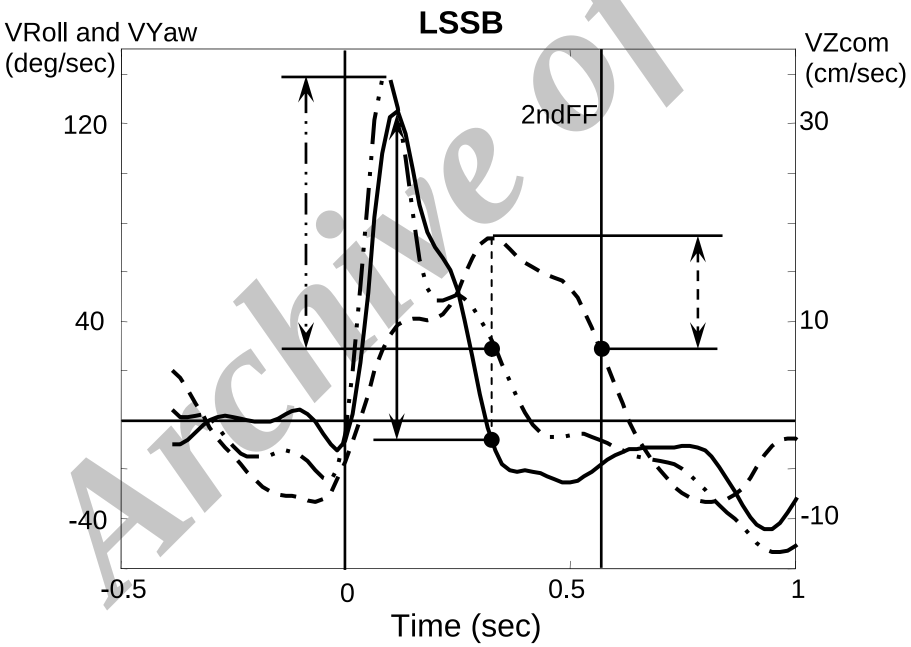

Figure 2: Roll (bold line) and Yaw (dash-dotted line) angular velocities (deg/sec), and (dashed line) Vzcom (cm/sec) for a typical LSSB trial.