The use of Centroidal Momentum Analysis for defining a Stability Index for walking with an exoskeleton

Je Hyung Jung[1], Irune Gutiérrez[2], Jan Veneman[1],
[1]Tecnalia Research and Innovation, [2]Tecnun, Universidad de Navarra, Spain

Abstract

This paper presents preliminary results of Centroidal Momentum (CM) Analysis in human walking over a customized treadmill while the walking is perturbed. CM is referred to as a vector composed of linear and angular momenta about a body´s Centre of Mass (CoM). Behaviour of CM in perturbed walking is demonstrated and compared to that in unperturbed walking. Perturbation is generated by random combination of 6 different durations and 7 different magnitudes of pushing as well as pulling force and applied laterally to the pelvis of a subject through 2 DOF serial linkages mechanism device. Moreover, contribution of segmental angular momenta to Centroidal Angular Momentum (CAM) in both perturbed and unperturbed walking is presented. The results reveal that CM and segmental contribution to CAM are significantly influenced by large perturbations while small perturbations do not cause substantial changes. The CM Analysis will be further investigated for designing a Stability Index to assess balance of a lower limb exoskeleton supporting human walking.

1 Introduction

Up to date, a variety of methods has been presented so as to well explain the dynamics of bipedal walking due to its importance not only in daily living activities of humans, but also for the development of bipedal robots. Recently, angular momentum-based analysis has been in the spotlight as it offers important clues on how humans maintain balance during walking [1]. From the biomechanical point of view, a hypothesis that angular momentum at the Centre of Mass (CoM) may be regulated directly by the central nervous was postulated and various findings supported this hypothesis [2]. Besides, in the robotics domain, specifically in humanoid robot field, the regulation of angular momentum during standing or bipedal walking has been employed as a control objective [3] although the control laws have been implemented in various forms. Findings from several simulations as well as experiments using angular momentum-based controllers suggest that the control of angular momentum behaves like a damper when a motion is perturbed, resulting in dissipation of the perturbation by reconfiguring a body pose [1].

As an extension of this context, in this paper, we present analysis results of the Centroidal Momentum (CM), which is composed of angular and linear momenta at the CoM, during human walking under perturbations, specifically lateral perturbations applied to the pelvis. Main objective of the paper is to examine whether CM could be used as a kind of Stability Index to detect the perturbations as well as an initial loss of balance. Contribution of segmental angular momenta to the Centroidal Angular Momentum (CAM) in perturbed as well as unperturbed walking is also analysed in order to investigate which segments show large variation between two cases. This study was carried out in the context of the EU FP7 project BALANCE that aims at supporting the function of maintaining postural balance directly through a leg exoskeleton. For this purpose CM-based stability index to be developed will be extended to the exoskeleton cooperating with a human and assessed on performance in this context.

2 Methods

2.1 Centroidal momentum

Centroidal momentum (CM) vector is calculated by

$$\vec{H} = \sum_{i=1}^{n}\left[\left(\vec{r}^{\,i}_{CM} - \vec{r}_{CM}\right) \times m_i\left(\vec{v}^{\,i}_{CM} - \vec{v}_{CM}\right) + \overleftrightarrow{I^i}\vec{\omega}^i\right] \quad (1)$$

$$\vec{L} = M\vec{v}_{CM} \quad (2)$$

where n is the number of body segments, $\vec{r}^{\,i}_{CM}, \vec{v}^{\,i}_{CM}$ and m_i are, respectively, the position and velocity of the CoM of each segment, and the mass of *i-th* segments and $\overleftrightarrow{I^i}$ and $\vec{\omega}^i$ are the *i-th* segment's inertia tensor and angular velocity, respectively, and $\vec{v}_{CM}$ and M are, respectively, the linear velocity at CoM and the total weight of the body [2]. In order to minimize data variance between different subjects, the angular and linear momenta are normalized by $N_H = M|\vec{v}_{CM}|H$ and $N_L = M|\vec{v}_{CM}|$, respectively, where *H* is the height of the body.

2.2 Experimental setup

One healthy subject (male, 75 kg) participated in an experiment. The experiment was performed using a customized platform which consists of two parallel and adjacent treadmills having force sensors to measure ground reaction force (Figure 1), developed at and by the BALANCE partner University of Twente. Since the main interest of the experiment is to investigate reaction of the lower limbs and upper body during perturbed walking, the subject was asked to cross both arms over the chest and keep this posture throughout the experiment. Camera-based motion analysis system using markers was used to record kinematic data of seven body segments (HAT, right/left upper legs, right/left lower legs, and right/left feet) during straight walking of 2.5 km/h on the platform. Total forty lateral perturbations, applied at the pelvis timed immediately after right toe off, were randomly decided by a force generated by combination of 6 different durations and 7 different magnitudes (12, 10, 8, 6, 4, 3, 2% of body weight (BW)) in both pushing (- sign) and pulling (+ sign) directions) through a custom-made 2 linkages mechanism actuated by a motor (Figure 1).

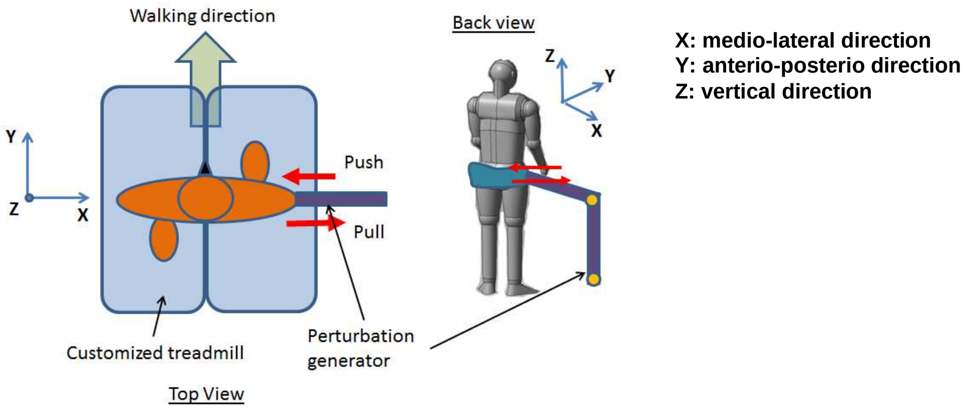

Figure 1. Perturbation platform on the customized treadmill.

3 Results

3.1 Centroidal momentum in unperturbed and perturbed walking

Using measured kinematic data and body mass and inertia information ([4]), CM during both unperturbed and perturbed walking was calculated and compared as shown in Figure 2. Plots in Figure 2(a) show means and standard deviations of centroidal momenta obtained from 40 unperturbed gait cycles and they have quite regular patterns in all directions. From Figure 2(a), (b) and (c), it can be seen that strong perturbation, which has a long duration (e.g 199 ms) and large magnitude (e.g. -12% of BW), makes large deviation from the regular pattern of CM in unperturbed walking, while a small perturbation does not. Note that the effect of the perturbation appearing in Figure 2(b) is sustained to the following gait cycle.

3.2 Contribution of segmental angular momenta to centroidal angular momentum

As expressed in Eq.(1), CAM is calculated by summing up all segmental angular momenta of a body, which implies that variations in CM observed in Figure 2 result from those in segmental angular momenta. Hence the contribution of segmental angular momenta to CAM was investigated in order to identify which segmental angular momenta significantly vary under strong perturbation. To calculate the contribution, the formula presented in [5] was utilized and results are shown in Figure 3. In unperturbed walking (in Figure 3 (a)) HAT dominantly contributes to X directional angular momentum while right and left upper legs dominantly contribute to Z directional angular momentum. In the Y direction, however, all segments show approximately equal contribution to the CAM although right and left upper legs are prime segments. Under strong perturbation, the contribution of right/left lower legs and feet to the X and Y directional angular momenta vary largely, while a variation in the Z direction is rarely observed. This observation can be anticipated as a result of the lateral pelvic perturbation.

4 Conclusion

We presented the Centroidal Momentum (CM) in straight walking with lateral pelvic perturbations. Discrepancy of CM between unperturbed and perturbed walking could be adopted to design a Stability Index for detection of perturbation as well as loss of balance in walking. In addition, combining the segmental angular momenta could simplify calculation of the stability index as it requires a lower number of sensors. As further tasks, statistical analysis with more experimental data is required to identify the influence of perturbations on CM. Formulation of a CM-based Stability Index and application of it to an actual case will be a future topic of interest. Although the study has been done with a human subject only, the Stability Index to be induced from this study can be extended to the case of a human subject walking while assisted by a lower limb exoskeleton because both have similar dynamics and kinematics, having only different inertial properties.

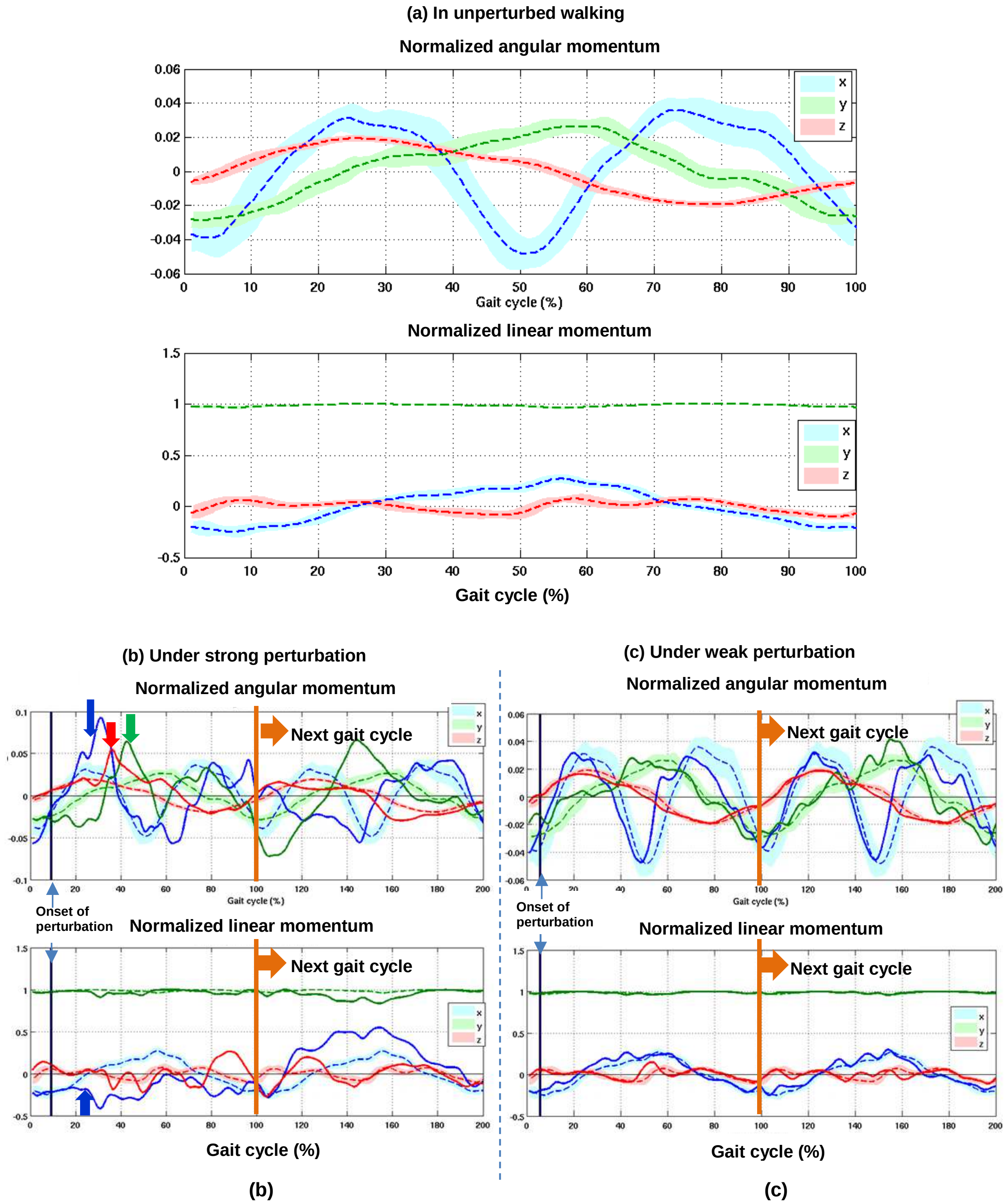

Figure 2. Centroidal momentum in unperturbed and perturbed walking: (a) in unperturbed walking (dotted lines: mean, coloured regions: standard deviation), (b) in perturbed walking with a disturbance force having a duration of 200 ms and magnitude of 12% body weight (solid lines) and (c) in perturbed walking with a disturbance force having a duration of 99 ms and magnitude of 3% body weight (solid lines).

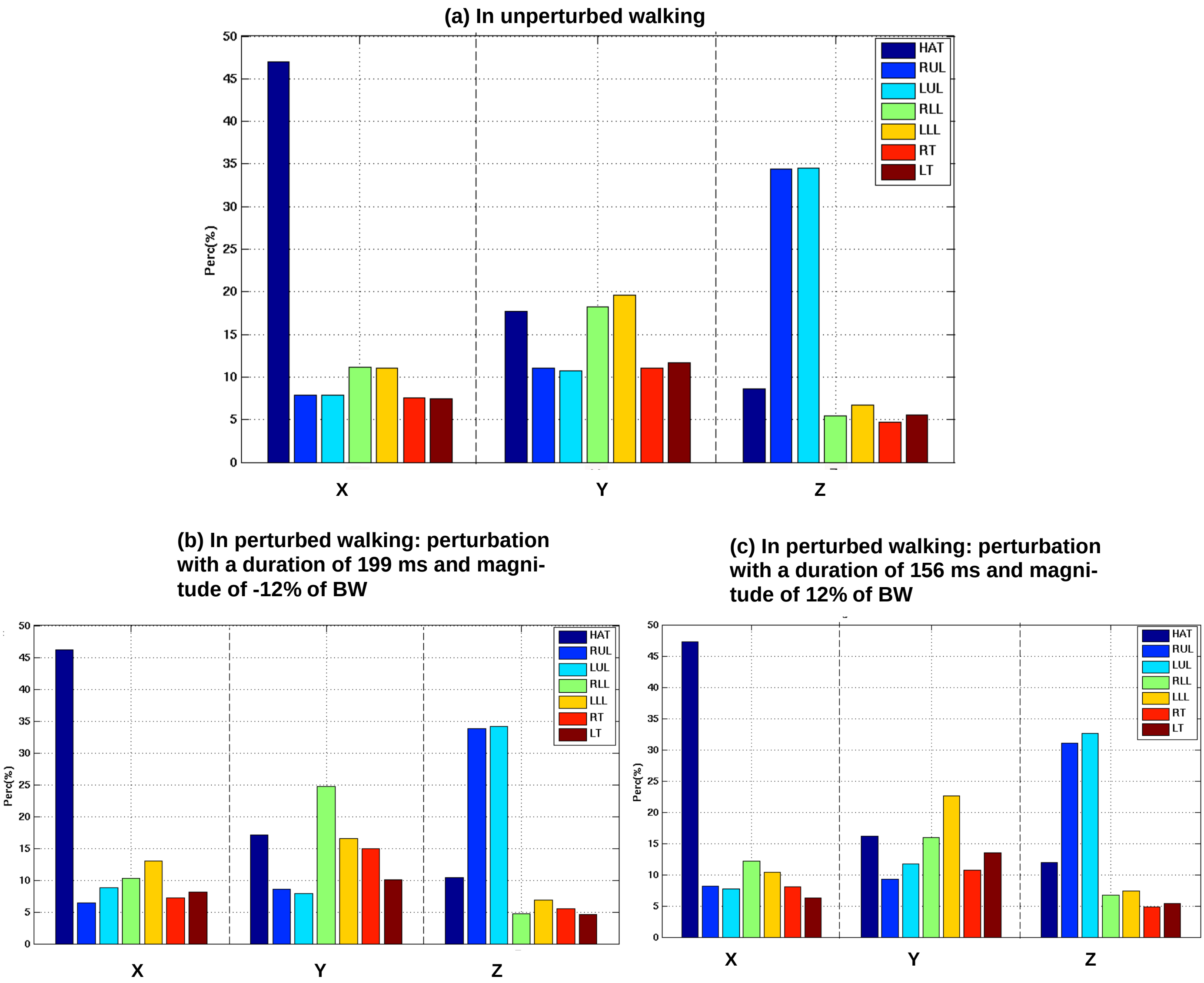

Figure 3. Contribution of segmental angular momenta to centroidal angular momentum. Note that HAT denotes head+trunk+upper limbs, RUL and LUL right and left upper leg, RLL and LLL right and left lower leg, and RT and LT right and left foot respectively.

Acknowledgments

This study has been supported by EU funded project BALANCE, FP7-ICT-2011.2.1 grant no. 601003. Authors wish to acknowledge Mark Vlutters from University of Twente for performing the experiment and providing the recorded data.

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Contact: Je Hyung Jung, jehyung.jung@tecnalia.com, (+34) 667119675