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BALANCE

Balance Augmentation in Locomotion, through Anticipative, Natural and Cooperative control of Exoskeletons

Deliverable 5.6

Evaluation of Postural Stability Observers

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1 Executive Summary

WP3 investigates and develops a sort of stability measures, referred to as Stability index (SI), aiming at monitoring and assessing actual balance of human in exoskeleton. In this context, two stability indices have been proposed, one is based on relationship between Centre of Mass (CoM) and Base of Support (BOS), and the other based on the Centroidal momentum (CM) that consists of linear and angular momenta at CoM. The former, CoM-BoS based stability index (CBSI) is considered a measure that can be used as a balance conditioner while the latter, CM based stability index (CMSI), can be employed as a balance observer due to its inherent physical meaning. In this deliverable, evaluation results of CMSI as the postural stability observer is presented. Evaluations were performed in two different experimental conditions, only human walking in the perturbation platform and human walking in the exoskeleton (LOPES II) implemented in Twente University (UTWENTE) who is a partner of BALANCE. It is noted that LOPES II is an exoskeleton type gait training robot for stroke patients.

2 Introduction

This deliverable, D5.6, relates to Task 5.4, which is 'Implementation and evaluation of the postural stability observer (M36-M42)'. Original task, as specified in the DoW, was to 1) integrate a novel sensory system including (Extended) stability index into the exoskeleton (EMY platform) to measure kinematic and kinetic data, especially ground reaction forces both hardware and software level, and 2) evaluate implemented stability index with human wearing "passive" robot in several conditions, such as: straight walking, making a turn, treadmill walking eyes open, eyes closed, walking with exoskeleton, walking with obstacles or perturbations. Sudden actions, such as sudden stops, that are known to challenge the balance, were supposed to be used to identify whether the "Extended Stability Index" produces an adequate signalling of such events. Additional task was to evaluate whether common, planned actions like turning, starting and stepping, are correctly identified by the "Extended Stability Index" as risky but not alarming situations. This task covers the following activities:

- Implementation of postural stability observer in hardware and software
- Definition of the evaluation criteria and scenario
- Evaluation of postural stability observer

Due to delay of preparation of the exoskeleton platform EMY, however, sufficient time to implementation the new sensory system and evaluation of the stability index in the Exoskeleton has not been given. As an alternative the LOPES II and perturbation platform developed by UTWEN were adopted for this task. LOPES II is a gait rehabilitation robot consisting of an exoskeleton and treadmill (with force sensors) and provides both high level transparency mode and support (or disturbance) mode with complete kinematic and kinetic sensing, so it was supposed to be the best alternative platform to evaluate of postural stability observers in an actual robot. Moreover, since the perturbation platform facilitates the evaluation of the observers in perturbed human walking, the study with the perturbation platform was also included in the task to investigate only human behavioural effect on the stability observers.

3 Evaluation of the Centroidal Momentum based Stability Index (CMSI) as Postural Stability Observer in the perturbation platform of UTWEN (Details in ANNEX I)

This section describes evaluation results of CMSI, specifically focusing on centroidal angular momentum, in only human walking in the perturbation platform, developed by UTWEN, which consists of two independent treadmills and perturbation generators that produce anteroposterior and mediolateral perturbations. *Since these contents are planned to be submitted as journal paper, details of them are described in ANNEX I which should be confidential until publication.* Here short summary is presented.

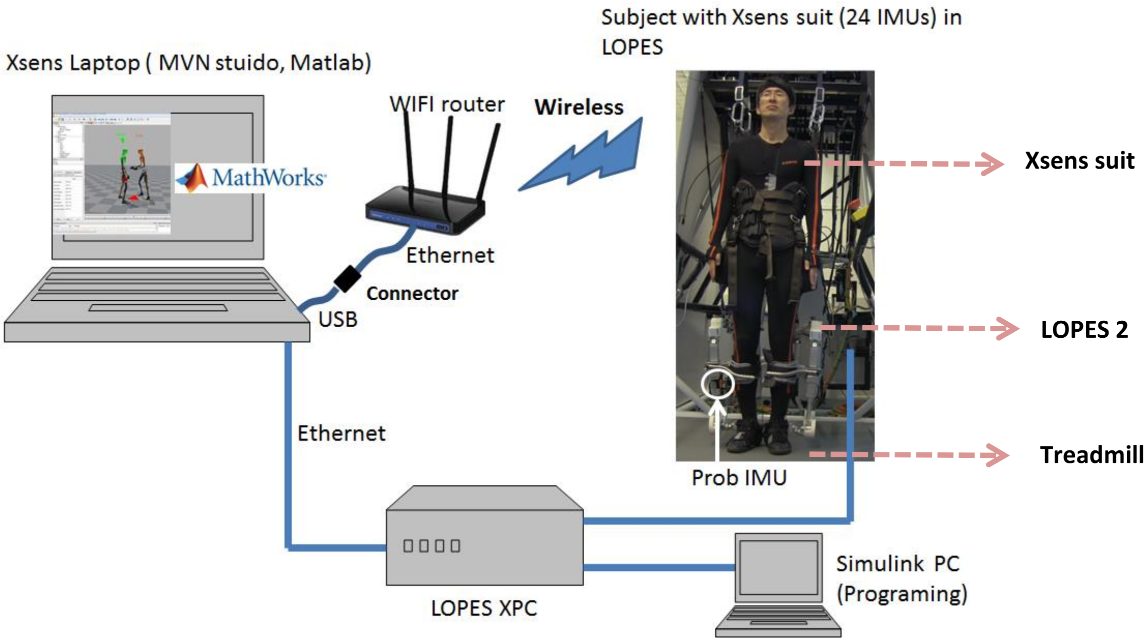
Short summary

In this study, we investigated how the moments at center of mass (CoM) are managed following mediolateral (ML) and anteroposterior (AP) perturbations delivered at CoM level (pelvis) during slow and normal walking in healthy adults. In particular, we questioned 1) whether CoM moments are modulated along all three spatial axes in response to the various perturbations, even though the perturbations are directed along only one of those axes, 2) whether CoM moments are more strongly modulated in the double support phase compared to the single support phase, given that both feet can contribute during the double support, and 3) whether this modulation increases with increasing walking speed. Experiments were conducted using an instrumented treadmill and a perturbation device. Statistical analysis ($\alpha=0.05$) was performed to investigate significant difference in CoM moments between perturbed and unperturbed walking, and to test the hypotheses. The results reveal that both ML and AP perturbations affected all components of the CoM moments, and that humans used different response strategies to ML and AP perturbations to manage the rotational dynamics and the walking speed. In addition, the CoM moments mostly changed in the double support phase, which offers a wider choice in the center of pressure and ground reaction force modulation compared to single support phase when dealing with the perturbations. The findings support that CMSI, specifically one of its elements, angular momentum can be used as a stability observer.

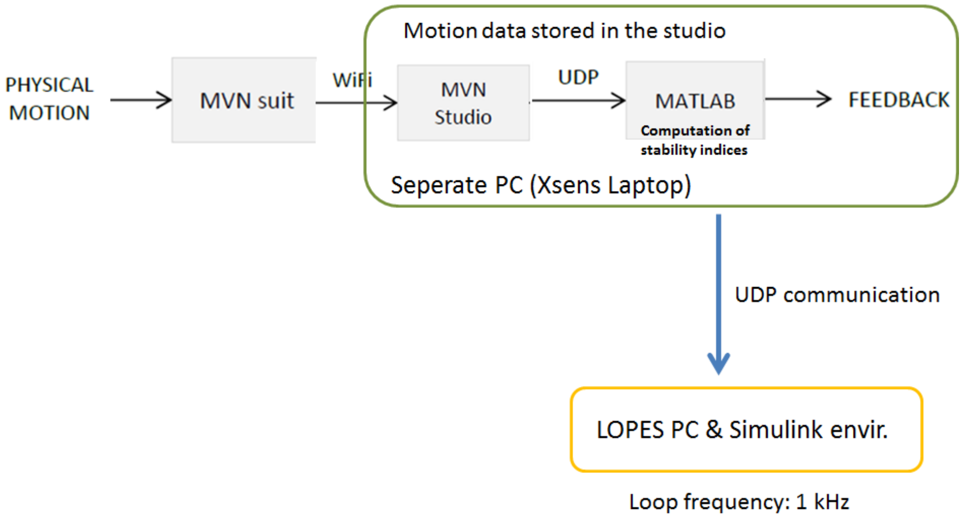
4 Evaluation of the Centroidal Momentum based Stability Index (CMSI) as Postural Stability Observer in the exoskeleton (LOPES II)

4.1 Experimental setup

In order to foresee the behaviour of the developed CMSI in an actual exoskeleton, as a preliminary test, we implemented and validated the stability indices in the LOPES2 developed by UTWENTE, which is an exoskeleton device combining a treadmill for lower limb rehabilitation. To minimize the implementation time and effort, Xsens motion capture suit was incorporated together into the implementation and SIs were calculated using kinematic data from the suit. The used experimental setup is described in Figure 1.



(a) Overall experimental setup



(b) Kinematic data flow from motion capture suit and SIs computation in the setup

Figure 1. Experimental setup used in preliminary test of SIs

In the setup, CMSI was computed in Matlab application in the laptop where the motion capture suit software (MVN studio) is installed and the calculated values were transferred to LOPES controller through UDP protocol for data synchronization. Computation times of SIs in the setup were estimated as shown in the following table.

Computation time of CMSI

Freq. in the Xsens laptop*	CMSI
Appr. frequency*	90Hz

* by tic-toc function provided in Matlab

Due to safety consideration of the LOPES device, which doesn´t allow to across legs in motion, the perturbations are onset in outer direction of stance leg as shown in Figure 2. For example, when the right leg starts stand phase, the perturbation is applied to left direction (pushing to left direction) so that the left leg makes a step in forward-leftward direction. Specifically, the perturbations were onset only at the end of double stance phase and applied to pelvis position laterally.

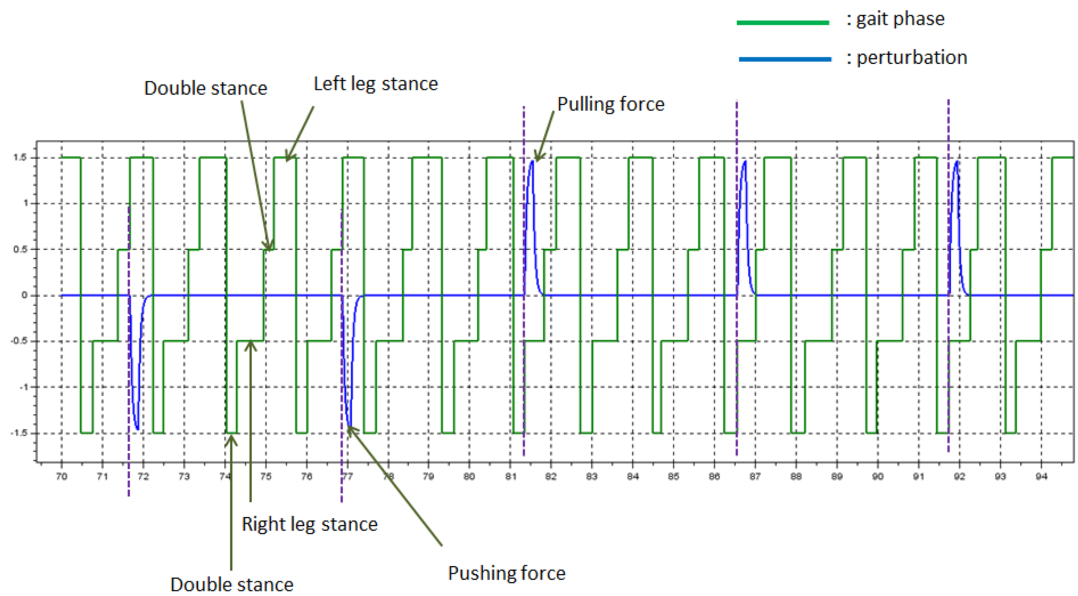


Figure 2. Onset of perturbations. (Size of perturbation was scaled down in order to plot together with gait phase graph)

4.2 Experimental results

In the experiments, normalized centroidal momentum was calculated in real-time in both unperturbed and laterally perturbed walking. Perturbation magnitude was set to 100 N and 150 N. Normalized centroidal angular and linear momenta in both cases are illustrated in Figure 3 respectively.

Statistical tests (Table 1 and Table 2) revealed that the variation of centroidal momentum due to perturbations has significantly different from that in the unperturbed case. For the statistical analysis**, the root mean square errors (**RMSE) of 6 elements of centroidal momentum were computed by

$$RMSE_i = \sqrt{\frac{\sum_{k=1}^{N} \left| X_{p_i,k}^{j} - X_{up,k}^{j} \right|^2}{N}} \tag{1}$$

where $X_{p_i,k}^{j}$ denotes each element in *j* direction (X, Y and Z for angular and linear momenta) at the *k*-th sampling instance under the *i*-th perturbation (*i*=1,…,6), $X_{up,k}^{j}$ the mean of each element in *j* direction at the *k*-th sampling instance in the unperturbed walking, and N total number of the samples in each gait cycle. In addition, the RMSE of the unperturbed gait cycles were also calculated for One-way ANOVA test.

Table 1. Statistical analysis of centroidal angular momentum: p-values related to ANOVA (p<0.05)

Pert. Mag	Gait phase											
	DS			SSL			DS			SSR		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
100 N	0.553	0.971	0.372	**<0.001**	**<0.001**	**0.002**	**<0.001**	0.308	**0.013**	**<0.001**	**0.009**	**0.009**
150 N	0.476	0.845	0.287	**<0.001**	**<0.001**	**0.001**	**<0.001**	0.259	**<0.001**	**<0.001**	**<0.001**	**<0.001**

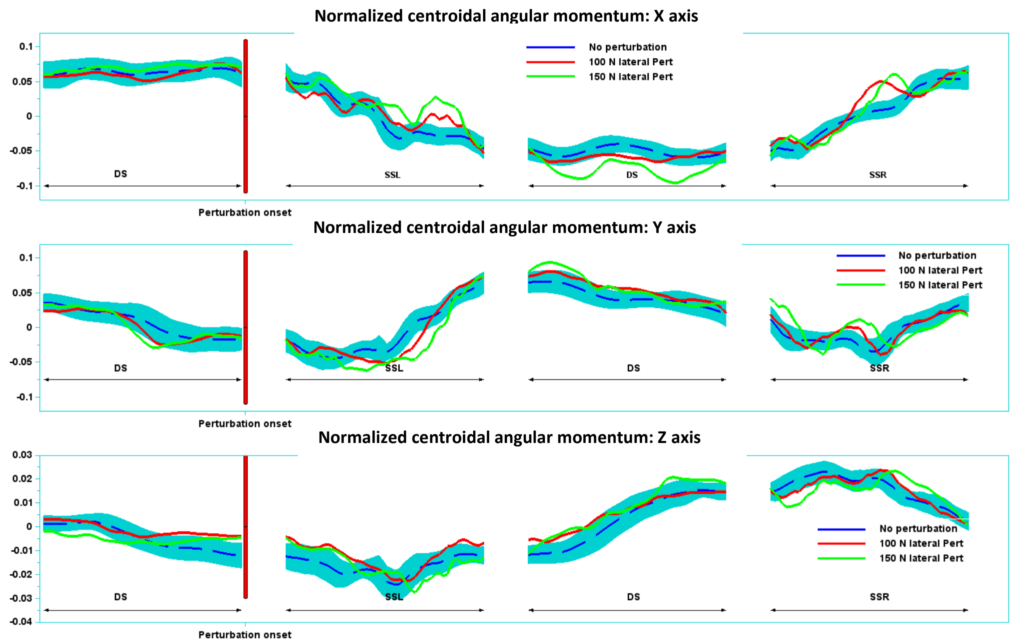
Table 2. Statistical analysis of centroidal linear momentum: p-values related to ANOVA (p<0.05)

Pert. Mag	Gait phase											
	DS			SSL			DS			SSR		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
100 N	0.621	0.861	0.097	0.068	0.728	**<0.001**	0.941	0.069	**0.016**	**0.047**	0.758	**<0.001**
150 N	0.228	0.552	0.550	0.093	0.306	**<0.001**	0.999	**0.037**	**<0.001**	0.06	0.408	**<0.001**

From the tables, it can be known that all elements of angular momentum changes immediately after the onset of the perturbations and the change in X and Z directional angular momenta lasts by the end of gait cycle while Y directional angular momentum changes significantly only in single support phase. This observation relates to direction of perturbation, which is laterally pushing force at pelvic position, expecting primary changes in X (anterior-posterior) and Z (vertical) directional angular momenta. In case of linear momentum, merely Z directional element significantly changes and others not, which means the vertical regulation of CoM is important for balancing. Interestingly, the results also indicates that the subject regulates linear momentum rather than angular momentum while walking even under lateral perturbations applying to CoM level that basically result in translational movement in media-lateral direction.

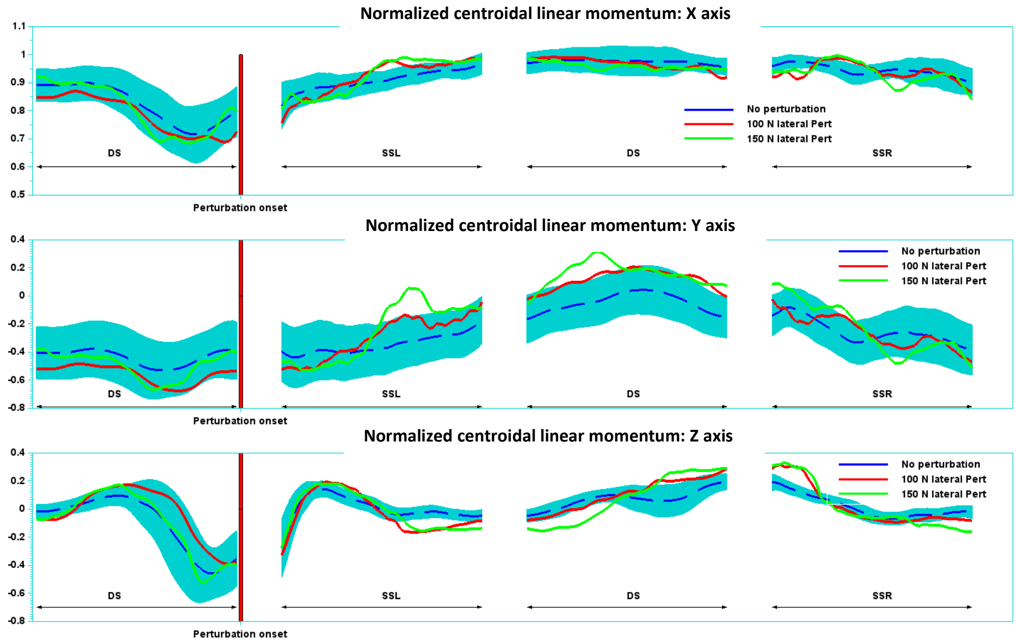
In summary, behaviour of the subject´s centroidal momentum in unperturbed walking with the exoskeleton differs from that in unperturbed walking and the difference is significant, especially in angular momentum. Hence the use of centroidal momentum as a stability index in real time would be feasible so as to monitor and assess an actual state of balance in the exoskeleton.

It would be worth noting that in the Figure 3 Y directional linear momentum stays below 0, indicating that CoM is moving in leftward direction, which didn't actually happen. This phenomenon may be explained by distorted IMU signals of Xsens suit due to EMF caused by the exoskeleton actuation systems although it requires further investigation.



Gait phase

(a) Centroidal angular momentum



Gait phase

(b) Centroidal linear momentum

Figure 3. Centroidal momentum versus gait phase: unperturbed vs. laterally perturbed walking. (DS: double stance, SSL: single stance with left leg, SSR: single stance with right leg). X axis denotes anterior-posterior direction (walking direction), Y axis media-lateral direction and Z axis vertical direction. Coloured regions are one standard deviation about the mean of each momentum without perturbation.

5 Conclusions

In this deliverable, we presented the evaluation results of postural stability index based on CM in gate training exoskeleton robot and perturbation platform. The experimental results in the perturbation platform showed large variation of CMSI, specifically, centroidal angular moment, in response to anteroposterior and mediolateral perturbations applied to pelvis in treadmill walking. The findings support that CMSI, specifically one of its element, angular momentum can be used as a stability observer. In addition, the experimental results with the exoskeleton robot showed that behaviour of the subject´s CMSI in unperturbed walking with the exoskeleton differs from that in unperturbed walking and the difference is significant, especially in angular momentum, indicating that the use of CMSI based stability index in real time would be feasible so as to monitor and assess an actual state of balance in the exoskeleton. Both results reveal that centroidal angular momentum is a crucial measure that reflects human reaction to the perturbations.

While the findings from the experiments reveal acceptable feasibility and applicability of the postural stability observers based on the CM in human walking both with/without the exoskeleton, some further works still remain as there was deviation from original plan due to delay of the targeted exoskeleton;

- Additional evaluation of postural stability observers in turning, gait initiation and termination, etc. beyond steady state straight walking.
- Implementation and evaluation of postural stability observers in targeted exoskeleton.