2013 IEEE/RSJ International Conference on
Intelligent Robots and Systems (IROS)
November 3-7, 2013. Tokyo, Japan

Closed-loop control of a human Center-Of-Pressure position based on somatosensory feedback

Fabien Vérité, Wael Bachta and Guillaume Morel

Abstract— **Supplementary visual, audio and tactile inputs have been shown to enhance postural control. In particular the light touch on a stable surface has been proven to significantly increase postural stability. Furthermore, it has been reported that the Center of Pressure (CoP) can be sinusoidally driven thanks to somatosensory inputs. In this paper, these results are extended to improve balance control. A closed loop control of the CoP position based on somatosensory feedback is developed. This control strategy allows both set-point tracking and path following of the CoP. The effectiveness of the proposed somatosensory feedback is assessed through experiments involving 11 naive subjects.**

I. Introduction

Human postural control relies on the muscular system and the sensory inputs. The muscles power is required to maintain the upright posture. The sensory inputs provide the central nervous system (CNS) with the necessary feedback for the estimation of the body orientation with respect to the gravitational field. Either sensory or muscular deficiencies may lead to balance disorders, which are among of the main reasons of autonomy loss.

In this context, many robotic and intelligent systems have been developed for assistance purposes. Most of them are robotized walkers and canes [1], [2], [3]. They are often designed to monitor the user state and to move with respect to his intention. Some works focus more specifically on postural stability to avoid falling. In [4], a robotic walker is controlled to keep the user center of mass into a region of stability. The intelligent cane developed in [5] adapts its apparent dynamics depending on an estimate of the user balance. By adapting their behavior to the user postural state and increasing his support polygon, these devices decrease the consequences of the body attitude misestimation yielded by the sensorial inputs inaccuracies.

Other works propose to provide the central nervous system with supplementary sensorial feedback to help improving the postural state estimation and balance control. Visual, audio and tactile senses have been considered. In [6], a Nintendo Wii Balance Board is used to compute the Center of Pressure (CoP) position and to display it on a screen. This visual feedback helps people controlling their balance during rehabilitation tasks. Indeed, the CoP which is the point of application of the vertical ground reaction forces resultant, has to be kept into the base of support to guarantee postural stabiliy [7]. Audio feedback is provided in [8] thanks to a smartphone equipped with an Inertial Measurements Unit (IMU) and earphones. In [9], [10], vibrotactile actuators enclosed in a waist belt are used to supply the subjects with tactile information about their posture, monitored by the means of an IMU.

As regards of tactile sensing, the light touch has received a special attention in the last two decades. In [11], it has been reported that the postural sway *i.e.* the CoP excursion amplitude can be halved for subjects lightly touching a stable surface with their index tip. The light touch relies on interaction forces not exceeding 1 N. Although these forces are not large enough to provide mechanical support, they give to the CNS additional cues on the postural sway. This concept is appealing, especially for assistance purposes, since it requires neither attention nor cooperation from the subjects. Moreover, as the additional sensorial inputs are given through the hand, the light touch can be coupled to conventional mobility aids to associate physical support and sensorial augmentation. Indeed, the effectiveness of lightly gripping an unstable stick, that could simulate a cane, on the postural stabilisation has been proven in [12]. In addition, it has been reported in [13] that a cane used in a light touch fashion increases the walking stability in the mediolateral direction during walking for post-stroke subjects. In [14], the authors report that the CoP of subjects, having their index tip sticked on a sinusoidally moving surface under the light touch conditions, oscillates with the same frequency as the applied rhythmic somatosensory input. In [15], these results have been supported and extended. The same open-loop strategy has been adopted to let the CoP follow more complex periodic trajectories.

The aim of this paper is to investigate whether it is possible to control more precisely the CoP position and trajectory through somatosensory inputs. This possibility may lead to the development of more efficient rehabilitation exercises and assistance devices. A closed loop control of the CoP, based on somatosensory feedback, is proposed. It allows precise set-point and path-following control of the CoP. These two tasks are proven to be infeasible using open-loop somatosensory input. The effectiveness of the proposed somatosensory feedback is assessed through experiments involving 11 subjects.

The sequel of this paper is organized as follows. The developed experimental environment is described in section II. Moreover the postural sway composition is recalled. Open-loop control strategy is then evaluated in section III. The proposed closed loop control law is presented in section IV. Section V is dedicated to the

Institut des Systèmes Intelligents et de Robotique (ISIR)- UMR7222, CNRS, Université Pierre et Marie Curie. e-mail: {verite, bachta, morel}@isir.upmc.fr

978-1-4673-6357-0/13/$31.00 ©2013 IEEE

statistical analysis, to the comparison and to the discussion of the obtained results. A conclusion is finally given and the future developments are provided.

II. Experimental Setup and conditions with some background on postural sway

In this section, the experimental setup and conditions considered in the remainder of the paper are first introduced. The main results of the literature related to postural sway analysis are then reviewed.

A. Experimental setup

Figure 1 gives a view of the experimental setup. The CoP position is computed thanks to the forces and moments measurements given by a force plate (AMTI BP400600-1000) connected to its associated amplifier (AMTI mini amp). The somatosensory feedback is provided by a motorized belt-pulleys mechanism (Fig. 2). The subjects are asked to put their index tip on a double-sided adhesive tape sticked on a thin Flexiforce force sensor mounted on the belt. This allows positioning the fingertip and monitoring the vertical force applied on the belt. Every time the threshold of 1N is exceeded, an alarm sound is emitted. Moreover, given the allowed vertical force, the fingertip would slip if the subject was trying to benefit from a support in the horizontal directions. A DC (Direct Current) motor equipped with an incremental optical encoder drives the belt-pulleys mechanism. This motor is controlled by an Elmo SoloWhistle servo-drive that can perform either position or velocity control. A custom software implemented on a PC104 computer, equipped with DA (Digital to Analog) and AD (Analog to Digital) converters and running under the Xenomai realtime operating system, is used to acquire the force plate measurements and to send the reference position or velocity to the servo-drive at a rate of 500 Hz. Two powered servomotors are placed in a box besides the experimental setup to avoid that the sound generated by the motorized belt-pulleys system gives cues about the belt motion.

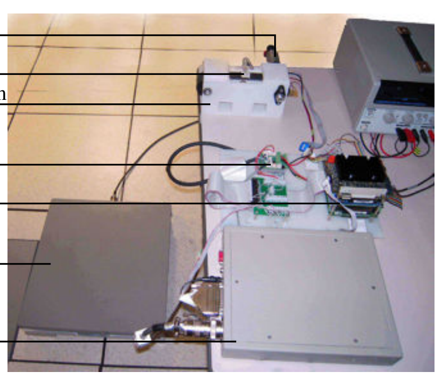


Fig. 1. Experimental Setup

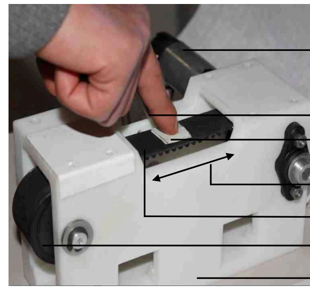


Fig. 2. Close view on the belt-pulleys mechanism

Fig. 3. Experimental conditions

B. Experimental conditions

Eleven consenting subjects (from 22 to 25 years) without known balance disorders have been selected to undergo the experiments. They are naive enough to not recognize any component of the experimental setup. Thus they cannot assume that they are undergoing a postural experiment and that the belt will move. The subjects posture used in [15] is adopted here : the subjects have been asked to stand as still as possible and barefoot on the force plate in a normal bipedal stance with their inter-feet distance equal to the pelvis width (see Fig. 3). They kept their eyes closed to simulate a sensory deficiency that can alter their balance control. They have been instructed to put their right index tip over the double-sided tape sticked on the belt while keeping the right arm aligned with the trunk side. The right wrist is left free and relaxed allowing the index to move according to the belt displacements. To avoid different left arm positions across the subjects, the left hand has been positioned in the crook of the right arm. In the considered stance position, the postural sway phenomenon is more significant in the sagittal plane, thus the belt-pulleys system is placed such that the belt motion lies in the anterior-posterior direction. Each subject has a trial phase to get used to the threshold of the vertical applied force.

C. Components of postural sway

The postural sway along the anterior posterior direction of a particular subject touching the belt when it is motionless is represented in Fig. 4. As reported in [16], the CoP trajectory is composed of a slow and a fast components, called respectively rambling and trembling. The rambling frequency upper bound is approximately 0.4 Hz whereas trembling frequencies lie between 0.4 and 1.5 Hz [17]. It is proven through identification procedures and numerical simulations that the trembling is due to the mechanical stabilization of the body around a given reference upright posture [18], [19]. Even if different hypotheses are made about the processes underlying the rambling component [19], [20], it is agreed that it is related to a moving reference posture reflecting improvement trials of the gravity direction estimation given by the sensory inputs.

In [16] a method for extracting the two components from the CoP trajectory is proposed. The rambling is supposed to correspond to the CoP positions where instant equilibrium states are observed *i.e.* when the tangential forces applied on the force plate are equal to zero. An algorithm detecting the zero-crossing instants of the tangential forces and storing the corresponding CoP points is developed. A cubic interpolation of the obtained CoP points provides the rambling trajectory. The trembling is computed by subtracting the obtained result from the whole CoP trajectory.

Figure 4 shows the two components extracted from the CoP trajectory using the algorithm described above. In Fig. 4, a superimposition of the obtained rambling and a filtered CoP trajectory suggests that low-pass filtering of the CoP excursion provides a good estimate of rambling.

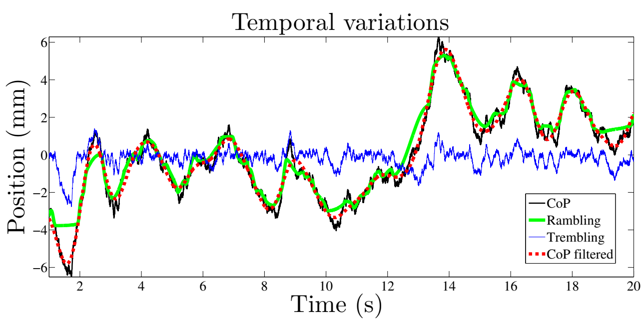


Fig. 4. Temporal variations of Cop in the anteroposterior direction (black thin line), rambling (green thick line), trembling (blue thin line) and CoP filtered (red dotline)

III. Open loop control of the Centre of Pressure

First, the results of the literature related to sinusoidal driving of the CoP are reproduced. Then, the section is dedicated to extend these results in order to control more precisely the CoP position and motion. Two tasks are considered. The first one corresponds to the displacement of the CoP and its stabilization around the new location for a given amount of time. The second one consists in moving the CoP along a pre-defined path.

A. Sinusoidal somatosensory input

The objective here is to prove that the developed experimental environment is well suited for reproducing the main results of the literature *i.e.* controlling the CoP trajectory through simple [14] or complex [15] sinusoidal somatosensory inputs. Some of the selected subjects participate to this experiment. They have been given instructions as described in II-B. The motor has been controlled such that the belt undergo first a sinusoidal motion with a varying frequency (0.1, 0.2, 0.3 Hz) and then a sum of sinusoids (0.1 Hz+0.2 Hz+0.3 Hz). Fig. 5.a and 5.b show one typical subject's CoP response to the considered inputs. The results support the findings of the literature : the subject's CoP follows the imposed belt motion, with almost a unit gain for the considered frequencies.

A typical subject CoP response to a complex non-periodic somatosensory input is also given in Fig. 5.c assessing the possibility to extend the available results. For the shown experiments, the belt starts moving after respectively 30s and 60s. The CoP trajectory is reported only during the belt motion.

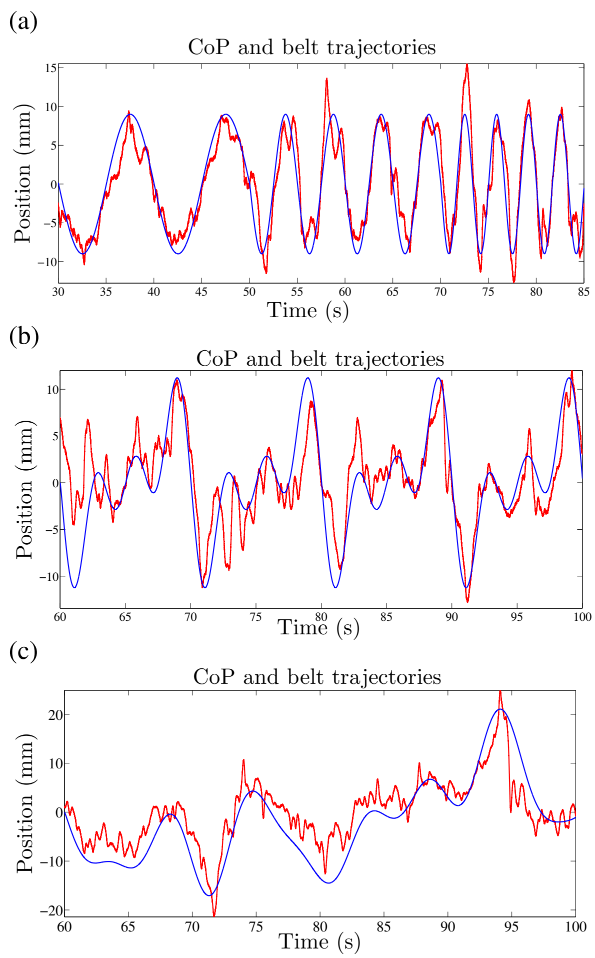
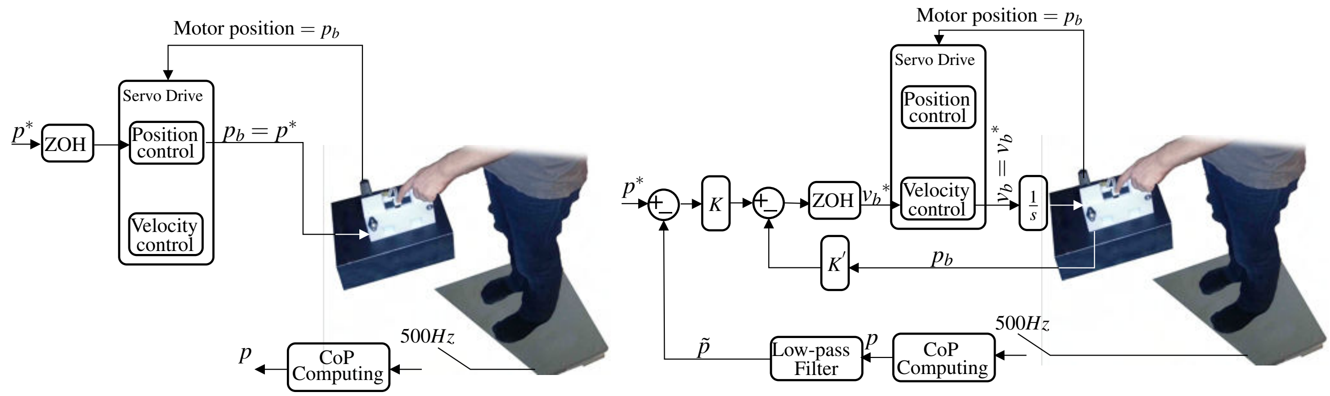


Fig. 5. Temporal variations of a typical subject Cop in the anteroposterior direction (red line) and the belt trajectory (blue line)

B. Set-point and path tracking of the Center Of Pressure

1) Somatosenosory input computing:

When a sinusoidal or a complex somatosensory input is provided, the CoP position follows the given input with a



(a) Open loop control

(b) Closed loop control

Fig. 6. A diagram of the control strategies

gain almost equal to one and with a limited lag. Therefore the somatosensory input *i.e.* the belt displacement is chosen to be equal to the desired CoP position. As shown in Fig. 6.a, the desired CoP position denoted p^* is directly sent through a DA converter represented by a Zero-Order-Holder (ZOH) to the servo drive. The latter is tuned to control the position of the motor driving the belt. In order to simplify the proposal and the diagram, the gear ratio induced by the pulleys is omitted. The belt and the motor positions are thus considered to be equal. This ratio has been, of course, taken into account for the control implementation. As the belt-pulleys mechanism control loop is faster than the human postural control, the belt position p_b is considered equal to the desired CoP position p^*.

2) *Protocol:*

The first task consists in moving the CoP to 8 mm away from its initial position in the anteroposterior direction and maintaining it 40 s around its new location. The 8 mm distance has been chosen since it represents a significant displacement of the CoP. The second task goal is to displace the CoP 8 mm forward, then to keep it 60 s around the new position, and finally to bring it back to its initial position following a ramp in 60 s.

The experimental protocol is composed of four trials corresponding to different references signals p^*. The three first trials correspond to different ways of achieving the first task. The last trial is dedicated to the second task:

i. The trial 1 duration is 60 s. p^* is a step of -8 mm occurring 10 s after the trial beginning. Assuming a 10 s response time, the CoP should be located around 8 mm away from its initial position during the remaining 40 s.
ii. The trial 2 duration is 60 s. p^* is a ramp with a slope of -0.8 mm per second. The ramp lasts 10 s and starts 10 s after the beginning of the trial. This reference signal is chosen to minimize the high frequency content compared to the step signal. Indeed, the goal is to influence the moving reference frame *i.e.* the rambling component.
iii. The trial 3 duration is 60 s. p^* is a parabola moving the belt by -8 mm in 10 s. This reference signal starts 10 s after the beginning of the trial. This signal has been chosen to keep a smooth belt motion while presenting velocity variations since both position and velocity influence postural sway [14].
iv. The trial 4 duration is 150 s. It is composed of an 8 mm amplitude step occurring 30 s after the beginning, and a -0.13 mm/s slope ramp lasting 60 s and starting 60 s after the step. The CoP is supposed to lie 8 mm away from its initial position during 60 s and then to follow the ramp path reference. Unlike trial 2, the CoP is supposed to move along the ramp and not only to move freely until its final value.

The 11 subjects have participated to these trials which have been conducted in a random way.

3) *Results:*

Plots of subject 2 results are given in Fig. 7 to illustrate the CoP behavior during the trials. The obtained results are not satisfying. Indeed, even if the subject CoP begins to follow the reference, there is no stabilization around the targeted reference.

Tables I and II (trials 1b and 4b will be presented later) summarize subjects scores for respectively the three set-point tracking trials and the path-following task. The scores are obtained as following:

- Setpoint tracking trials: The CoP trajectory mean is first computed during 10 s before the belt starts moving. This gives the CoP position before applying the somatosensory input. The CoP mean is then computed during the last 40 s of the trial providing the new CoP position. The difference between the two values provides the CoP displacement which is compared to the targeted 8 mm reference. The score is the absolute value of the obtained difference.
- Path-following: The CoP trajectory is shifted such that its mean value during the first 10 s is made equal to the initial belt position. Then, the score is computed

as the absolute value of the mean tracking error *i.e* $\left|\frac{1}{N}\sum_N(p^*-p')\right|$ where N is the number of samples composing the trial and p' the shifted CoP trajectory.

The score for setpoint-tracking and path-following tasks are computed in a different way. For the setpoint-tracking task, only the reference around which the CoP oscillates is of interest, whereas for the path-tracking the CoP should track the moving reference. For the setpoint tracking task, the average error across the subjects is greater than 4 mm *i.e.* the half of the expected displacement. For the path following task, the average error is also about 4 mm indicating poor tracking.

TABLE I

ERROR SCORES FOR SETPOINT-TRACKING TRIALS

Subjects	Trial 1	Trial 2	Trial 3	Trial 1b p^*	Trial 1b p^{**}
1	2.90	3.11	0.78	1.25	0.51
2	3.51	6.60	5.35	0.91	0.18
3	7.97	6.73	6.38	2.57	1.20
4	3.12	5.98	7.43	2.47	1.37
5	9.11	6.73	10.27	1.66	0.58
6	8.25	1.83	3.16	0.50	0.24
7	2.83	5.66	5.21	2.90	1.44
8	4.40	4.50	4.65	0.73	0.15
9	0.32	3.02	8.55	1.29	0.33
10	3.20	5.08	7.65	2.35	1.50
11	8.49	10.69	6.99	0.53	0.03

TABLE II

ERROR SCORES FOR PATH-TRACKING TRIALS

Subjects	Trial 4	Trial 4b p^*	Trial 4b p^{**}
1	0.14	0.38	0.03
2	5.50	1.19	0.41
3	4.14	1.14	0.41
4	2.95	1.76	0.92
5	1.26	4.07	3.25
6	4.45	0.75	0.41
7	2.55	0.17	0.16
8	3.75	0.76	0.18
9	10.50	0.18	0.48
10	2.67	0.30	0.04
11	7.43	0.83	0.39

IV. CLOSED LOOP CONTROL OF THE CENTER OF PRESSURE

The results obtained in the previous section show that open-loop control is not well suited for set-point control of the CoP. Moreover, paths including sharper position transients and trajectories less smoother than low frequency sinusoids sums can not be precisely followed. In this section, a closed loop control that deals with these mentioned issues is developed. This control strategy is designed to give the necessary somatosensory feedback to stabilize the CoP around a given set-point and to let it follow a predefined path.

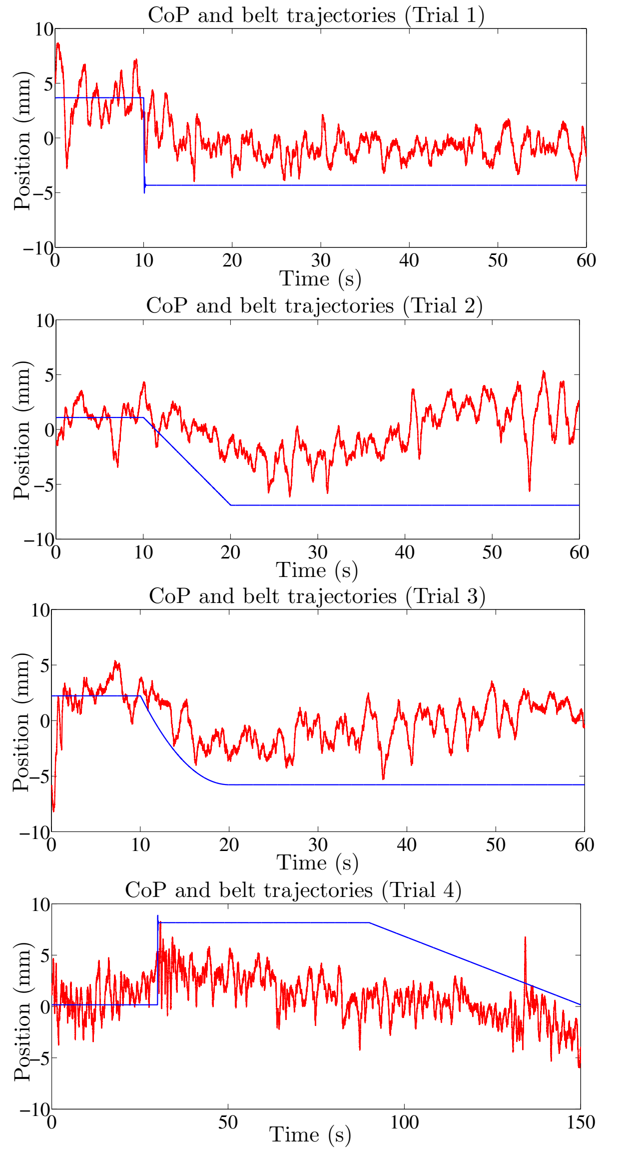


Fig. 7. Open-loop strategy trials, CoP of a typical subject in the anteroposterior direction (red line) and p^* (blue line)

A. Somatosenosory input computing

The velocity of the somatosensory feedback is based on the CoP position error. As shown in Fig. 6.b, the implemented control law can be written:

$$v_b^* = K(p^* - \tilde{p}) - K' p_b \tag{1}$$

where

- $\tilde{p}$ represents the rambling extracted form the CoP position p through a low-pass filtering. The rambling is used since it is the reference trajectory around which the CoP trajectory oscillates. In the proposed control scheme, high frequencies are only due to the fast transients of $p*$.
- K is the gain adjusting the somatosensory input velocity depending on the CoP error.

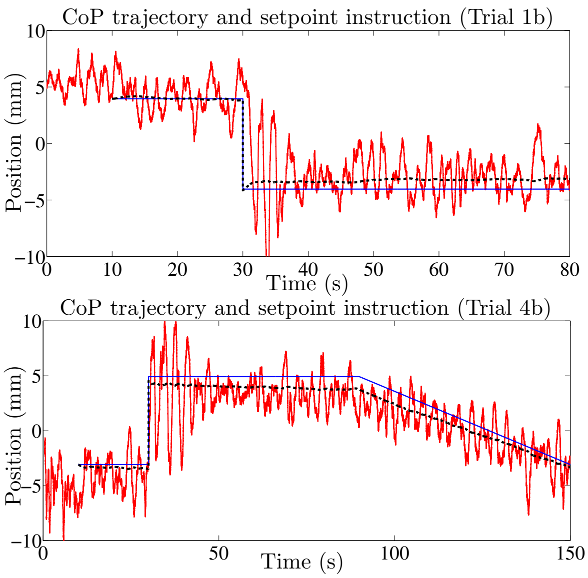


Fig. 8. Closed loop control trials, CoP of a typical subject in the anteroposterior direction (red line), p^* (blue line) and p^{**} (black dotted line).

- $-K^{'} p_b$ is an additional control component that aims to bring the belt back to its initial position *i.e.* the zero position. This avoids the subject finger leaving the allowed workspace and hitting the mechanical part hosting the pulleys. $K^{'}$ is chosen 16 times lower than K in order to not significantly disturb the main control law.

K (1.94 s^{-1}) and $K^{'}$ (0.12 s^{-1}) have been tuned experimentally using trials and errors.

B. Protocol

The same tasks studied for the open-loop somatosensory input are considered here. The experimental protocol is composed of the following two trials:

- The trial $1b$ duration is 80 s. The value of the CoP trajectory mean is computed during the first 10 s. p^* is set equal to this mean value during the next 20 s. For the remainder of the trial, p^* is equal to the mean value decreased by 8 mm.
- The trial $4b$ duration is 150 s. The value of the CoP trajectory mean is computed during the first 30 s. p^* is then obtained by adding the path described in the last trial of III-B.2 to the mean value.

The trials described here and those of III-B.2 were conducted in the same time and randomly for all the subjects.

C. Results

The plots of subject 2 results, given in Fig. 8, suggest satisfying set-point tracking and path-following. The oscillations observed just after the step input are due to the sharp transition and the important setpoint magnitude change. These oscillations, which do not represent a postural instability, are indeed not present at the beginning of the ramp. The fourth and the second columns of tables I and II summarize subjects scores for respectively set-point tracking and the path-following tasks using the closed loop control. The scores are computed similary to III-B.3. For the path-following task, no shift of the CoP trajectory is necessary since p^* takes into account the initial CoP position. These scores are obtained with respect to the reference signal p^*. The fifth and the third columns of tables I and II report the scores with respect to a modified reference p^{**}. Indeed the component $-K^{'} p_b$ of the control law changes slightly the reference. In fact, equation (1) can be rewritten as:

$$v_b^* = K(p^* - \tilde{p}) - K^{'} p_b = K(p^{**} - \tilde{p}) \quad (2)$$

with $p^{**} = p^* - \frac{K^{'}}{K} p_b$.
Average results across all the subjects show better performances than the open loop strategy.

V. Discussion

As regards of the open loop strategy, the subjects scores averages (and standard deviations) in mm are 4.91($\pm$2.97), 5.45($\pm$2.41) and 6.02($\pm$2.61) for respectively the step, the ramp and the parabola trials considered for the set-point tracking task. For the proposed closed loop control, the averages (and standard deviations) in mm are 1.56($\pm$0.88) and 0.7($\pm$0.56) when considering respectively the p^* and the p^{**} references. These values are shown in Fig. 9.a.
The average (and the standard deviation) in mm across the 11 subjects for the path-following task using the open loop somatosensory input is 4.12($\pm$2.90). This value is reduced to 1.05($\pm$1.11) and 0.61($\pm$0.91) for the developed closed loop control when considering respectively the p^* and the p^{**} references. These values are shown in Fig. 9.b.
The closed loop control of the CoP allows better set-point and path-following when compared to the open loop somatosensory input. The statistical effectiveness of the scores improvements is proved through t-test analysis. For the two tasks, the null-hypothesis is rejected with a p-value lower than 0,05. The null-hypothesis means that there is no significant difference between the two somatosensory inputs. Moreover, it can be asserted that the average set-point tracking error is divided by 1.9 ($p < 0.05$) when comparing the open-loop strategy step errors to those obtained with respect to the p^* reference using closed loop. This factor is even better 4.2 ($p < 0.05$) when considering the results with respect to the p^{**}. In the same way the path-following error is divided by 2 and 3.2 ($p < 0.05$) when using the closed loop control and considering respectively the p^* and the p^{**} references. No statistically significant difference appears between the studied open loop strategies.
It is worth noticing that unlike audio [21], vibrotactile [10] and visual [8] feedbacks, the developed closed loop control of the CoP does not require active conscious reactions from the subjects neither training sessions. Indeed the subjects were naive about the study purposes. Furthermore, even after the experiment, they were not aware that their posture have been changed during the trials. The developed somatosensory feedback is thus thought to interact with the low level

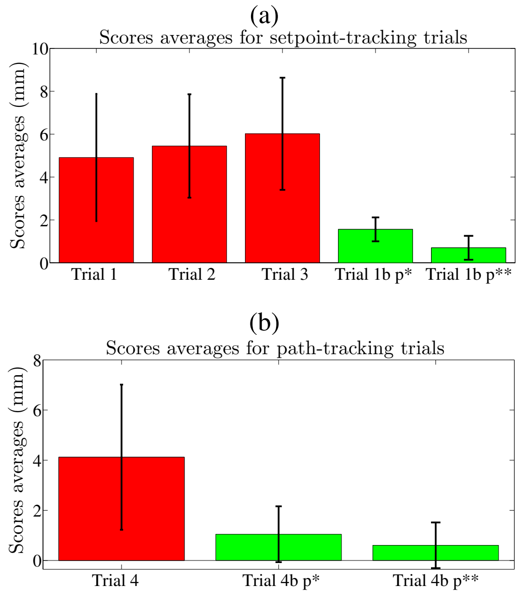


Fig. 9. (a) Scores mean for setpoint tracking trials in open-loop control (Red bars), Scores mean for setpoint tracking trials in closed loop control (Green bars) / (b) Scores mean for path-tracking trials in open-loop control (Red bars), Scores mean for path-tracking trials in closed loop control (Green bars).

postural control mechanisms.

VI. Conclusion

In this paper, closed loop control of the CoP position based on a somatosensory feedback is presented. This method outperforms the open-loop strategies. Its effectiveness is proved through experiments involving 11 subjects. Future work will be focused on the extension of the obtained results to a planar context to take into account the medio-lateral postural sway. Moreover, more experimental conditions will be included to the adopted protocol. Stability conditions have to be explored as well. It is worth noticing that instability was never observed experimentally. The development of rehabilitation exercises based on the proposed somatosensory feedback will also be considered.

Acknowledgment

This work was performed within the Labex SMART supported by French state funds managed by the ANR within the Investissements d'Avenir programme under reference ANR-11-IDEX-0004-02

References

[1] A. Morris, R. Donamukkala, A. Kapuria, A. Steinfeld, J. Matthews, J. Dunbar-Jacobs, and S. Thrun, "A robotic walker that provides guidance," in *Proceedings of IEEE International Conference on Robotics and Automation (ICRA 03)*, 2003, pp. 25–30.

[2] M. Spenko, H. Yu, and S. Dubowsky, "Robotic personal aids for mobility and monitoring for the elderly." *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 14, no. 3, pp. 344–51, Sep. 2006.

[3] L. Saint-Bauzel, V. Pasqui, and I. Monteil, "A Reactive Robotized Interface for Lower Limb Rehabilitation: Clinical Results," *IEEE Transactions on Robotics*, vol. 25, no. 3, pp. 583–592, Jun. 2009.

[4] Y. Hirata, a. Hara, and K. Kosuge, "Motion Control of Passive Intelligent Walker Using Servo Brakes," *IEEE Transactions on Robotics*, vol. 23, no. 5, pp. 981–990, Oct. 2007.

[5] S. Suzuki, Y. Hirata, and K. Kosuge, "Development of Intelligent Passive Cane controlled by servo brakes," *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication*, pp. 97–102, Sep. 2009.

[6] W. Young, S. Ferguson, S. Brault, and C. Craig, "Assessing and training standing balance in older adults: a novel approach using the 'Nintendo Wii' Balance Board." *Gait & posture*, vol. 33, no. 2, pp. 303–5, Feb. 2011.

[7] P. Sardain and G. Bessonnet, "Forces Acting on a Biped Robot . Center of Pressure Zero Moment Point," *IEEE transactions on systems, man and cybernetics - Part A : Systems and humans*, vol. 34, no. 5, pp. 630–637, 2004.

[8] C. Franco, a. Fleury, P. Y. Gumery, B. Diot, J. Demongeot, and N. Vuillerme, "iBalance-ABF: A Smartphone-Based Audio-Biofeedback Balance System." *IEEE transactions on biomedical engineering*, vol. 60, no. 1, pp. 211–5, Jan. 2013.

[9] A. Gopalai, "A Wearable Real-Time Intelligent Posture Corrective System Using Vibrotactile Feedback," *IEEE/ASME Transactions*, vol. 16, no. 5, pp. 827–834, 2011.

[10] A. A. Gopalai and S. M. N. A. Senanayake, "Assistive Vibrotactile Biofeedback System for Postural Control on Perturbed Surface," *Journal of Mechanics in Medicine and Biology*, vol. 13, no. 01, p. 1350006, Feb. 2013.

[11] J. J. Jeka and J. R. Lackner, "Fingertip contact influences human postural control." *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, vol. 100, no. 3, pp. 495–502, Jan. 1994.

[12] I. M. Albertsen, J. J. Temprado, and E. Berton, "Effect of haptic supplementation on postural stabilization: A comparison of fixed and mobile support conditions." *Human movement science*, vol. 29, no. 6, pp. 999–1010, Dec. 2010.

[13] R. Boonsinsukh, L. Panichareon, and P. Phansuwan-Pujito, "Light touch cue through a cane improves pelvic stability during walking in stroke." *Archives of physical medicine and rehabilitation*, vol. 90, no. 6, pp. 919–26, Jun. 2009.

[14] J. Jeka, K. Oie, G. Schöner, T. Dijkstra, and E. Henson, "Position and velocity coupling of postural sway to somatosensory drive." Department of Kinesiology, University of Maryland, College Park, Maryland 20742, USA., Tech. Rep. 4, 1998.

[15] A. M. Wing, L. Johannsen, and S. Endo, "Light touch for balance: influence of a time-varying external driving signal." *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, vol. 366, no. 1581, pp. 3133–41, Nov. 2011.

[16] V. M. Zatsiorsky and M. Duarte, "Rambling and trembling in quiet standing." *Motor Control*, vol. 4, no. 2, pp. 185–200, 2000.

[17] ——, "Instant Equilibrium Point and its Migration in Standing Tasks: Rambling and Trembling Components of the Stabilogram," pp. 28–38, 1999.

[18] R. Johansson, M. Magnusson, and M. Akesson, "Identification of human postural dynamics." *IEEE transactions on bio-medical engineering*, vol. 35, no. 10, pp. 858–69, Oct. 1988.

[19] T. M. Dijkstra, "A gentle introduction to the dynamic set-point model of human postural control during perturbed stance," *Human Movement Science*, vol. 19, no. 4, pp. 567–595, Oct. 2000.

[20] T. Kiemel, K. S. Oie, and J. J. Jeka, "Slow dynamics of postural sway are in the feedback loop." *Journal of neurophysiology*, vol. 95, no. 3, pp. 1410–8, Mar. 2006.

[21] M. Dozza, F. B. Horak, and L. Chiari, "Auditory biofeedback substitutes for loss of sensory information in maintaining stance." *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, vol. 178, no. 1, pp. 37–48, Mar. 2007.