

# PHYSICAL IMPLEMENTATION OF A PD CONTROLLER FOR IMPROVING HUMAN BALANCE DURING QUIET STANCE

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## Abstract

Our studies have recently demonstrated that a proportional and derivative (PD) feedback controller, which takes advantage of the position and velocity information of the body sway, is capable of effectively generating a needed anticipatory control command in order to facilitate stable quiet standing. Furthermore, we identified gain pairs that ensured that the system behaved in a robust manner and that it had a dynamic behavior similar to the one observed in quiet standing experiments. The purpose of the present study was to experimentally demonstrate that the aforementioned PD controller can facilitate stable quiet standing. Our real-time closed-loop control system consisted of a center of mass position sensor, functional electrical stimulation regulated by the PD controller and a subject who had difficulty maintaining balance during quiet standing due to a neurological disorder called von Hippel-Lindau disease. The experiments were conducted in order to evaluate the subject's stability in the anterior-posterior plane only. In conclusion, the achieved results strongly suggest that the proposed feedback control system is capable of improving human balance during quiet stance in subjects with certain neuromuscular disabilities. The observed performance of the PD controlled feedback system supports our findings that the CNS adopts a control strategy that relies heavily on the velocity information.

## Introduction

The improvement of standing capabilities has various therapeutic and functional benefits for subjects that suffer from spinal cord injuries and other neurological disorders. Therefore, open- and closed-loop applications of functional electrical stimulation (FES) for the purpose of facilitating stable standing have been subjects of research for many years. To compensate for significant time delays in the closed-loop control system of human bipedal quiet stance, it has been suggested that an anticipatory command to the body sway position can be achieved by using a feed-forward control system [1,2]. By contrast, a nested feedback system regulated by a torque controller has been

developed and evaluated by Hunt et al. [3,4]. Our team has recently demonstrated that a feedback system regulated by a simple proportional and derivative (PD) position controller is capable of providing the active torque component that is being applied by the CNS in order to regulate the body sway in spite of long neurological time delays [5,6].

The purpose of the present study was to evaluate our theoretical results experimentally and to investigate whether a PD controller can provide satisfactory control of balance during quiet standing. We applied and evaluated a real-time control system that was characterized by the following components: 1) a displacement sensor measuring the fluctuation of the approximated center of mass (COM), 2) a PD controller with  $K_p$  and  $K_d$  gains obtained in our theoretical studies ( $K_p = 750 \text{ Nm/rad}$  and  $K_d = 350 \text{ Nms/rad}$ ) [6], and 3) the controlled level of ankle torque generated by means of FES.

## Materials and Methods

### *Experimental Setup*

Figure 1 shows a schematic of the experimental setup. The PD controlled system received its input from a laser displacement sensor (Keyence LK-2500, Japan), which recorded the fluctuation of the body sway in the anterior-posterior direction. The laser sensor was placed at the height of the subject's COM and used reflection to determine the distance to the reflection plate on the subject's back. Additionally, the subject stood on force plates (Kistler, Switzerland) that recorded the fluctuation of the center of pressure (COP). While only the COM was used for balance control, both COM and COP were used for stability analysis.

The laser displacement measurements were sent to the controller, which determined the level of active ankle torque that was needed to stabilize the system. After dividing the required torque into equal portions for each leg, the stimulator provided the necessary level of FES for both ankle extensors (Compex Motion, Switzerland). Please note that for safety reasons the two inputs to the stimulator were optically isolated from the rest of the system.

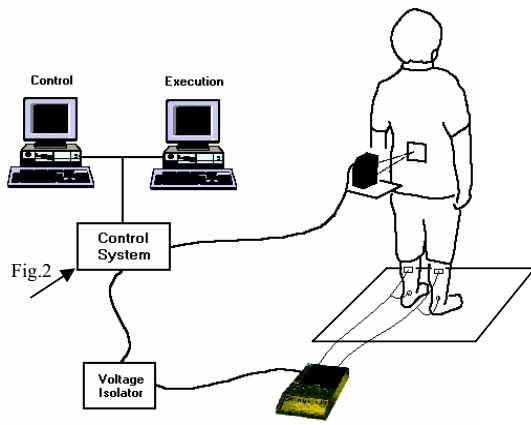


Figure 1: Feedback Circuit for Balance Control

The applied stimulation pulses had a constant frequency (35Hz) as well as pulse width (300 $\mu$ s), and were controlled by amplitude variation (mA). In order to produce the torque as calculated by the controller, we determined the amplitude-torque relationship of the subject in a preliminary experiment. The complete real-time system was executed by a C++-based kernel (MS Visual C++) that was controlled via a serial connection using the Matlab software (version 6.5) and the xPC toolbox (version 2.0). A National Instruments data acquisition board (PCI-MIO-16E-4) performed the necessary A/D and D/A conversions.

The closed-loop time delay of the feedback circuit consisted of the group delay time of the noise filter, the signal processing time within the circuit and the electromechanical response time of the plantar flexors. The delay was set within the range of 80-135ms to correspond with the physiological closed-loop time delay that is observed in able-bodied subjects during quiet standing.

### Control System

Figure 2 shows the control system that was executed on the PC which regulated the level of muscle stimulation in real-time. The main components of this system were:

- A/D interface
- Butterworth 3<sup>rd</sup> order low-pass filter with 10Hz cut-off frequency
- PD controller with gains set to  $K_p = 750$  Nm/rad and  $K_d = 350$  Nms/rad
- Limits for minimum (0 Nm) and maximum torque (40 Nm)
- D/A Interface

In our setup, the positive values of the controller

output represented the torque that was expected to be generated by the plantar flexors. By contrast, the negative values represented the torque that the dorsiflexor muscles were meant to produce. Since we only stimulated plantar flexors, only positive values of the controller output were delivered whereas the negative values had no effect. Future research will consider the less dominant negative torque by including a stimulation branch for dorsiflexor muscles.

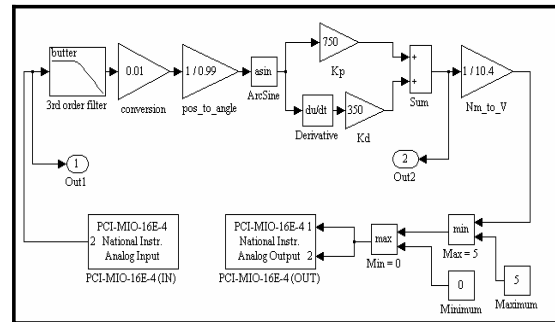


Figure 2: Control System for Balance Control

### Procedure

In order to determine whether the proposed system was capable of improving balance during quiet standing, we compared the subject's performance for three different treatments:

- NTR: Natural performance without stimulation
- CST: Performance with constant stimulation
- CTR: Performance with controlled stimulation

For each treatment, three trials of equal length were recorded. During the 120 seconds of each trial, the subject was asked to stand still and maintain a balanced position (eyes open). The signals of the COM and COP fluctuation were logged at a sampling frequency of 1000Hz, filtered (4<sup>th</sup> order Butterworth, 5Hz cut-off frequency) and analyzed by means of a one-way ANOVA with a common significance level of  $\alpha = 0.10$ .

The fluctuation of the COM position and velocity was analyzed by means of the following *statistics*: 1) range of motion, 2) average amplitude, and 3) standard deviation. The COP fluctuation was analyzed by a method that was derived from the stability criterion for controlling standing in able-bodied subjects that has been suggested by Popovic et al. [7]. As a first part of the COP analysis, we determined the high preference and low preference zones for each recording. The high preference zone (HPZ) was defined by a circle that included 99% of the two-dimensional points. The circle that contained all two-dimensional points represented the low preference zone (LPZ). As a second part, the COP's HPZ and LPZ for the three

treatments were put into relation, allowing a statement on the subject's stability for each case: The smaller the respective preference zones, the higher the subject's balance control.

### Subject

The proposed system was tested with a male subject that has difficulty keeping balance during quiet standing due to a neurological disorder called von Hippel-Lindau disease (VHL). The subject was 36 years of age, had height 173 cm, mass 59 kg, and suffered from VHL since birth. VHL is a rare genetic multi-system disorder characterized by the abnormal growth of tumors in certain parts of the body. The tumors of the central nervous system are called hemangioblastomas and may develop in the brain, the retina of the eyes, and other areas of the nervous system. Symptoms of VHL vary among patients and depend on the size and location of the tumors. The subject of our study had balance problems and impaired gait due to partial loss of sensation and proprioception. Furthermore, he experienced vision problems, dizziness and significant muscle weakness in the legs.

### Results

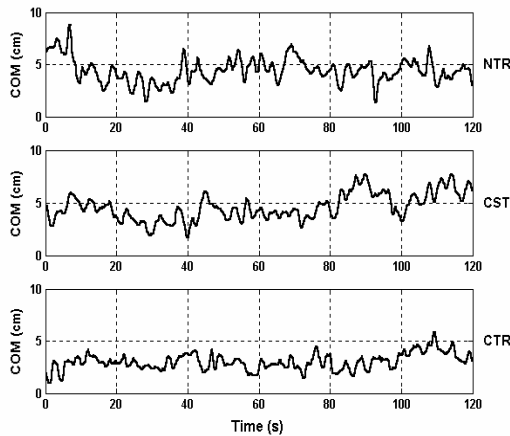


Figure 3: COM Fluctuation during Quiet Stance. COM fluctuation without stimulation (NTR), with constant stimulation (CST), and with controlled stimulation (CTR).

Figure 3 shows the time dependent COM displacement of the subject for three trials, each representing a different treatment. Already a visual inspection suggests that the body sway in CTR has a smaller magnitude than it does in NTR. The phase plots of the three COP recordings are shown in Figure 4, where each row represents the same treatment as in Figure 3. As with the COM, the smallest fluctuation is seen in CTR.

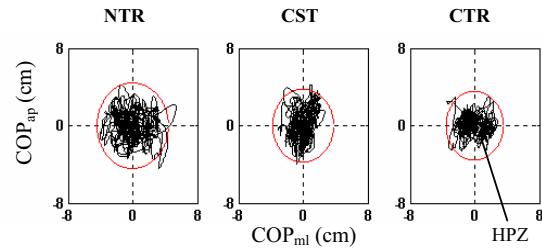


Figure 4: COP Fluctuation during Quiet Stance

Table 1 shows the results of the COM and COP analysis. Please note that the stated values represent the mean of three condition-specific results. For each of the eight statistics (range, amplitude, standard deviation, etc.), the smallest averaged value among the three treatments has been marked (bold font). It was revealed that the differences in treatment were significant for seven out of eight statistics.

Table 1: Average Stability Results for each Treatment

COM Position	NTR	CST	CTR
Range of Pos.	6.642 cm	6.795 cm	<b>5.575 cm</b>
Avg. Amplitude	0.852 cm	1.102 cm	<b>0.701 cm</b>
Std. Deviation	1.112 cm	1.321 cm	<b>0.898 cm</b>
COM Velocity	NTR	CST	CTR
Range of Vel.	11.812 cm/s	9.516 cm/s	<b>7.615 cm/s</b>
Avg. Amplitude	0.939 cm/s	0.882 cm/s	<b>0.776 cm/s</b>
Std. Deviation	1.240 cm/s	1.132 cm/s	<b>1.020 cm/s</b>
COP Position	NTR	CST	CTR
Radius of HPZ	4.807 cm	4.316 cm	<b>3.756 cm</b>
Radius of LPZ	6.339 cm	5.618 cm	<b>4.745 cm</b>

### Discussion

The trials using a controlled level of stimulation had the smallest average value for all methods of analysis, suggesting a reduced body sway for this treatment. We also observed that the constant stimulation showed smaller values than the natural treatment for five out of eight statistics. Since the constant stimulation increases the level of stiffness around the ankle joint by providing additional muscle tonus, it improved the subject's balance in some regard. However, due to the findings that all statistics were larger for the constant stimulation than for the controlled stimulation, the role of the PD controller is clear: It is capable of effectively improving balance during quiet stance by mimicking the active part of the physiological control task. Hence, the feedback control system represents a valid setup for improving stability of subjects with certain neuromuscular disorders.

The question of whether a feedback system can control unsupported standing was also addressed by Hunt et al. They established and evaluated a feedback system that was regulated by a torque controller [3,4]. The inner loop provided feedback control of muscle moment, while the outer loop controlled the angle. The system performed reliably and according to the design formulation. Due to the fact that we applied a controller that emphasizes the velocity information of the body, we did not consider a nested structure: The information of the body angle – position and velocity – was sufficient to control the ankle moment. In spite of the different structures of the control systems, both studies agree that a feedback system is capable of stabilizing the human body during quiet stance, though several studies proposed the necessity of a feed-forward system [1,2].

### *Conclusion*

The findings presented herein strongly suggest that human balance can be improved by means of a PD controlled feedback system that mimics the control task of an intact CNS. Furthermore, the system's effectiveness shows once more that the CNS adopts a control strategy that relies highly on the velocity information. Future research will test the proposed control system with a larger group of subjects who have poor control of balance due to age or neuromuscular disorders. Additionally, our system should incorporate stimulation of the dorsiflexor muscles. This allows the delivery of all control actions produced by the controller and not only the component in the posterior direction.

### **References**

- [1] Gatev P, Thomas S, Kepple T, and Halett M: Feedforward ankle strategy of balance during quiet stance in adults. *J Physiol*, 1999, 514: 915-928.
- [2] Fitzpatrick R, Burke D, and Gandevia C: Loop gain of reflexes controlling human standing measured with the use of postural and vestibular disturbances. *J Neurophysiol*, 1996, 76: 3994-4008.
- [3] Hunt KJ, Munih M, and Donaldson N: Feedback Control of unsupported standing in paraplegia – Part I: Optimal control approach. *IEEE Trans. Rehab. Eng.*, 1997, 5(4): 331-340.
- [4] Hunt KJ, Gollee H, Jaime RP, and Donaldson N: Design of feedback controllers for paraplegic standing. *IEEE Proc.-Control Theory Appl.*, 2001, 148(2): 97-108.
- [5] Masani K, Popovic MR, Nakazawa K, Kouzaki M, and Nozaki D: Importance of body sway velocity information in controlling ankle extensor activities during quiet stance. *J Neurophysiol* 2003a, 90: 3774-3782.
- [6] Masani K, Popovic MR, Nakazawa K, Kouzaki M, and Nozaki D: An estimate of control gains in human balance control system. *Society for Neuroscience's 33th Annual Meeting*, 272.10, 2003b.
- [7] Popovic MR, Pappas I, Nakazawa K, Keller T, Morari M, and Dietz V: Stability criterion for controlling standing in able-bodied subjects. *J Biomechanics*, 2000, 33: 1359-1368.

### **Acknowledgements**

Canadian Fund for Innovation; Ontario Innovation Trust; Faculty of Medicine Dean's Fund, University of Toronto.

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