Implementation of a PD Controller for Improving Human Balance

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Abstract

Our studies have recently demonstrated that a proportional and derivative (PD) feedback controller can effectively generate a control command that precedes body sway by 0.1 to 0.2s. We also identified gain pairs that ensured a robust system with a dynamic behaviour similar to the one observed in quiet standing experiments. The purpose of the present study was to experimentally demonstrate that the PD controller can facilitate stable quiet standing. The real-time control system consisted of a center of mass (COM) 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. Our stability analysis using common COM and center of pressure measures revealed that body sway could significantly be reduced with the PD control effort. In consequence, it can be concluded that the proposed feedback control system is capable of improving human balance during quiet stance in subjects with certain neuromuscular disabilities. Additionally, the observed effectiveness of the PD controlled feedback system supports our findings that the CNS adopts a control strategy that relies highly on the body's velocity information.

1. INTRODUCTION

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. By contrast, a nested feedback system regulated by a torque controller has been developed and evaluated by Gollee et al. [1]. Our team has recently demonstrated that a feedback system regulated by a simple proportional and derivative (PD) position controller can provide 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 [2, 3]. The purpose of the present study was to evaluate these results experimentally and to investigate whether a PD controller can in fact provide satisfactory control of balance during quiet stance.

2. METHODS

2.1. Experimental Setup

The PD controlled system received its input from a laser sensor (Keyence, Japan), which recorded the anterior-posterior (AP) fluctuation of the approximated center of mass (COM). In addition, force plates (Kistler, CH) measured the fluctuation of the center of pressure (COP). While only the COM was used for balance control, both COM and COP were subject to the stability analysis. Using the laser displacement measurements, the controller determined the level of active ankle torque 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, CH).

The applied stimulation pulses had a constant frequency (35Hz) as well as pulse width (300μs), 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++ 5.0), while 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 was ensured to lie within the range of 80-135 ms that corresponds to the physiological closed-loop time delay observed in able-bodied subjects during quiet standing.

2.2. Control System

The PD controller capable of compensating for the neurological delay times by producing a motor command that precedes body sway by 100 to 200 ms has been shown to have a relatively high velocity component [2]. In systematic simulations following this conclusion, we determined PD gains that not only evoked the preceding motor command, but also ensured a robust system with dynamic features observed in able-bodied standing [3]. The real-time system implementing this velocity accentuated controller regulated the level of necessary ankle torque and consisted of the following main components:

- Butterworth 3rd order low-pass filter with 10 Hz cut-off frequency
- PD controller with gains set to Kp = 750 $\mathrm{Nm \cdot rad^{-1}}$ and Kd = 350 $\mathrm{Nm \cdot s \cdot rad^{-1}}$ [3]
- Limits for minimum (0 Nm) and maximum torque (52 Nm)

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 while negative values had no effect.

2.3. Procedure

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

- NTR: Trials without stimulation
- CST: Trials with constant stimulation
- CTR: Trials with controlled stimulation

For every treatment, three trials of 120 seconds each were recorded. In each trial, the subject was asked to stand still and maintain a balanced position with eyes open. The signals of the COM and COP fluctuation were logged at a sampling frequency of 1 kHz, filtered (4th order Butterworth, 5 Hz cut-off frequency [4]) and analyzed using a one-way ANOVA ($\alpha = 0.10$). In order to adequately characterize the performance for each treatment, the COM and COP fluctuation was analyzed by means of measures of postural steadiness as suggested by Prieto *et al.* [4]: I) Distance measures (MDIST: mean distance, RDIST: rms distance, RANGE); II) velocity measures (MVELO: mean velocity, RVELO: rms velocity); and III) frequency measures (CFREQ: centroidal frequency). Furthermore, the results were related to respective values of able-bodied subjects performing quiet standing (not shown).

2.4. 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 experienced VHL from birth on. VHL is a rare genetic multi-system disorder characterized by the abnormal growth of tumors in certain parts of the body including the nervous system. The subject of our study had balance problems and impaired gait due to partial loss of sensation and proprioception. Furthermore, he experienced dizziness and muscle weakness in the legs.

3. RESULTS

Figure 1 shows the subject's COM fluctuation for three trials, each representing a different treatment. Already evident by a simple visual inspection, the body sway in CTR had a smaller magnitude than it did in NTR (dashed lines: ±1 SD). Note that the constant stimulation used in CST (33.0 mA) was of the same order as the average stimulation current provided by the control system in CTR (33.9 mA).

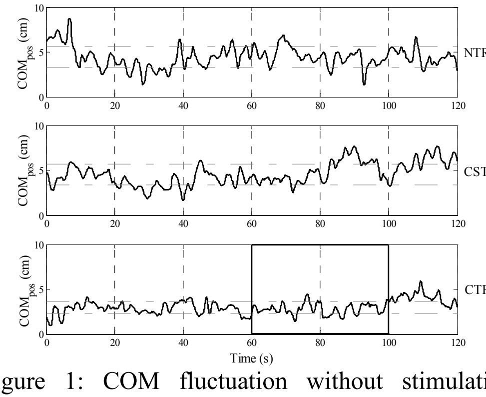

Figure 1: COM fluctuation without stimulation (NTR), with constant stimulation (CST), and with controlled stimulation (CTR).

The marked portion of the controlled treatment in Figure 1 (black rectangle) is also shown in Figure 2a. Here, the COM fluctuation is related to the controller output and to the fluctuation of the resulting stimulation current (Fig. 2b). It can be seen that the control effort stabilized the system and that the fluctuation of the control and stimulation signals preceded the fluctuation of the COM. The maximum stimulation current of the complete trial was 36 mA, generating approximately 21 Nm per ankle.

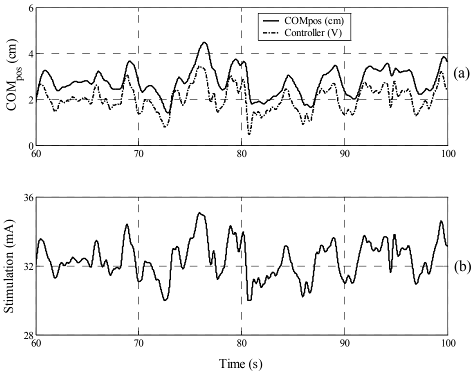

Figure 2: Excerpt from the COM fluctuation for CTR (a) and resulting stimulation current (b).

Table 1 summarizes the results of the COM and COP analysis. The trials using a controlled level of stimulation had the smallest average value (bold font) for all COM measures except for the frequency at which the spectral mass is centered (CFREQ). The COP analysis on the other hand revealed that the distance measures were smallest for CTR whereas the velocity and frequency measures were smallest for NTR and largest for CTR. The differences in treatment were significant for eight measures (*).

Table 1: Average stability results for each treatment

	COM	**NTR**	**CST**	**CTR**
I	MDIST_{AP} *	0.852 cm	1.101 cm	**0.690 cm**
	RDIST_{AP} *	1.112 cm	1.321 cm	**0.898 cm**
	RANGE_{AP}	6.642 cm	6.795 cm	**5.575 cm**
II	MVELO_{AP} *	0.938 cm/s	0.881 cm/s	**0.776 cm/s**
	RVELO_{AP} *	1.240 cm/s	1.132 cm/s	**1.020 cm/s**
III	CFREQ_{AP} *	0.312 Hz	**0.298 Hz**	0.345 Hz
	COP	**NTR**	**CST**	**CTR**
I	MDIST_{AP} *	1.093 cm	1.188 cm	**0.856 cm**
	RDIST_{AP} *	1.405 cm	1.486 cm	**1.102 cm**
	RANGE_{AP}	9.820 cm	8.854 cm	**7.673 cm**
II	MVELO_{AP}	**2.611 cm/s**	2.705 cm/s	2.778 cm/s
	RVELO_{AP}	**3.546 cm/s**	3.589 cm/s	3.774 cm/s
III	CFREQ_{AP} *	**0.562 Hz**	0.615 Hz	0.721 Hz

4. DISCUSSION AND CONCLUSIONS

Due to the fact that all COM time domain measures are smallest for CTR, body sway has evidently been reduced during this treatment. The stated difference between the COP distance and velocity measures can be explained by their meaning during quiet standing: Distance measures have been related to the effectiveness of, or the stability achieved by, the postural control system; and velocity measures have been related to the amount of regulatory activity associated with this level of stability [4]. Hence, it can be concluded that during CTR the postural control system is achieving a higher level of stability (lower distance measures) by applying a higher level of regulatory activity (higher velocity measures).

The question of whether a feedback system can control unsupported standing was also addressed by Gollee *et al*. They established and evaluated a feedback system regulated by a torque controller [1]. 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 emphasizing the velocity information of the body, a nested structure was not considered. In spite of the different structures of the control systems, both studies agree that a feedback system can stabilize the body during quiet stance, though several studies proposed the necessity of a feed-forward system.

The findings presented herein strongly suggest that human balance can be improved by means of a PD controlled feedback system that successfully mimics the physiological control task of an intact CNS. Furthermore, the system's effectiveness verifies our hypothesis that the CNS adopts a control strategy that relies highly on the velocity information [2]. Future research will test the control system with a larger group of subjects and will also consider the less dominant negative torque by including a stimulation branch for dorsiflexors.

References

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