34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Independent Ankle Motion Control Improves Robotic Balance Simulator

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Abstract—**We present a validation study for the effectiveness of an additional ankle-tilt platform to enhance somatosensory ankle feedback available to subjects actuating a 6-axis robotic balance simulator platform. To address this need, we have developed and integrated a device to permit independent manipulation of ankle rotation while the whole-body is actuated by the balance simulator.**

The addition of ankle rotation is shown to provide both quantitative and qualitative improvements to the balance simulation experience compared to when the ankle joint is referenced to the motion of the balance simulator. Eight out of ten subjects reported that balancing on the simulator with ankle motion required less conscious effort. This self-reported improvement corresponded to a 32% decrease in the mean-removed RMS amplitude for sway angle, demonstrating better balance control for subjects actuating the simulator. The new ankle-tilt platform enables examination of the contributions of ankle proprioception to the control of standing balance in human subjects.

I. Introduction

Standing balance plays a pivotal role in daily life. While most take this innate ability for granted, the simple act of standing can be a major challenge for older persons and those living with pathologies including stroke, vestibular impairment and Parkinson's Disease. Such pathologies contribute to the risk of falls, a leading cause of death among older adults [1]. Improved understanding of balance biomechanics and physiology is important for developing appropriate therapies for these clinical populations.

While the main inputs – vision, vestibular information and proprioception [2][3] – and outputs (muscle activity) of the human balance system are generally well understood, the on-going control that takes place to integrate the input information and produce an appropriate response remains an area of active investigation [4][5][6]. Understanding how the human balance system adapts to missing or erroneous sensory input can provide insight into the mechanisms underlying the control of standing balance.

There are, however, limitations to modifying the sensory information available to subjects standing freely. Subjects have inherent balance parameters such as mass and height. Additionally, when balance system inputs are sufficiently distorted, the subject will fall. These considerations significantly limit the potential to explore the human balance system in freely standing subjects.

We have previously demonstrated that the task of maintaining standing balance in the sagittal plane can be simulated by having a subject stand on a force plate mounted on a 6 degree-of-freedom Stewart platform (6DOF2000E, MOOG Inc., East Aurora, NY) [7][8]. The system was originally configured such that, with the subject safely secured to the platform via a backboard, ankle moments applied to the force-plate cause the robotic platform (and subject) to rotate about an axis passing through the ankle joints. This balance simulation behaves as an inverted pendulum, with parameters based on the subject's mass and body type.

As the subjects balance an immersive computer model (as implemented on the simulator) rather than their own body, parameters such as mass and gravitational acceleration are no longer fixed, allowing exploration of the effect of varying these parameters on the balance response.

While promising, the simulator presented by [8] does not accurately reproduce a key element in balance control: ankle proprioception [9]. As both the force plate and the subject are fixed to the Stewart platform at a constant angle (at the subject's natural standing angle), the subject performs near isometric contractions during the balance simulations. This situation eliminates the contribution of ankle somatosensory feedback to

*Research supported by the National Sciences and Engineering Research Council of Canada.

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the balance control loop [2], potentially resulting in diminished balance control. In [8], lack of ankle somatosensory feedback was raised as the primary reason that the RMS of sway angle in the simulation was approximately twice that observed in free standing.

To facilitate ankle motion while still maintaining the safe, experimental benefits of the balance simulator, an additional degree of freedom is required to manipulate the ankles independently from the rest of the body. Thus, we developed an 'ankle-tilt' platform that permits independent ankle position control (Fig. 1, inset). We hypothesized that the enabling of ankle somatosensory feedback via the ankle-tilt platform would improve the simulation as measured by reduced RMS sway.

II. METHODS

A. Technical Implementation and Validation

To simulate the task of human standing accurately, the ankle-tilt platform must reproduce accelerations, velocities, and positions that are typical of anterior-posterior sway, while synchronizing with the base Stewart platform. The device must be capable of angular velocities of up to 10 °/s, the maximum velocity typically observed in human standing balance [10], and (ideally) angular accelerations of up to 500 °/s^2 to match the capabilities of the Stewart platform [8]. During motion, the platform should remain within 0.2° of the target location, the smallest angular displacement that can be detected during passive rotations of the ankle joint [11].

To conform to the above requirements, we developed an ankle manipulator for the balance simulator, as shown in Fig. 1. The device includes separate force plates for each foot (BP400600, AMTI, Watertown, MA), supported by a pair of machined aluminum 'foot plates'. The plates are supported by a pair of bearings (NTN Inc., Mississauga, Ontario), and driven by a linear actuator (2-B.M82C7-DC427_24-8-2NO-ST4/4, Ultra Motion, Cutchogue, NY). Control integration was accomplished with LabVIEW™ 2010 and a NI7350 motion card (National Instruments, Austin, TX). The motion card performs PID control at 2 kHz.

To produce a smooth trajectory profile, the LabVIEW™ controller writes motion commands to a three-sample buffer in the motion controller at

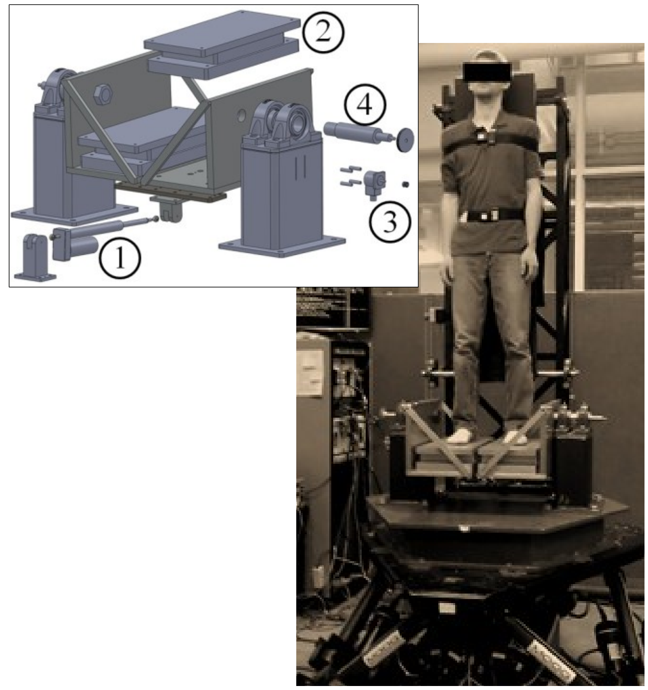

Figure 1. Balance Simulator. Subject secured to backboard and standing on tilt platform.The Stewart platform controls the position of the subject's body via the backboard, the ankle-tilt platform controls the ankles. Inset: Exploded rendering of the ankle-tilt platform assembly. Linear actuator (1) is mounted via ball bearing rod ends below the force plates (2), belt drive to encoder (3) is not shown. The entire balance system rotates about the support shafts (4), which are located at the ankles.

60 Hz. The buffering introduces 50 ms of pure delay on top of the controller and plant delays, so we use spline-fitting extrapolation on the commanded position to compensate for both delays [12]. As the Stewart platform also has an inherent delay of approximately 41.5 ms [8], we tuned the predictor to eliminate any relative delays (so that the ankle tilt platform and Stewart platform would move synchronously). We cross-correlated the encoder feedback signals from the ankle-tilt platform and Stewart platform and found that a prediction time of 22 ms was required to minimize overall delay errors in the coordinated motion.

The simulation models subjects as an inverted pendulum with mass m at a distance l from their ankles to their centre of mass (and gravity g) [8]. The static relationship between the required ankle moment M and the angular position θ from the vertical can be expressed as

$$M = mgl \sin\theta \qquad (1)$$

We set the axis of rotation for the trajectory of the Stewart platform to coincide with the rotational axis of the ankle-tilt platform. We positioned the force plates 0.071 m below this axis, corresponding to the average ankle height measured for ten adult human subjects in a pilot trial to this study (SD 0.007 m). This axis placement ensured that the entire system rotated about the subject's ankles, a location that has been shown to be a good approximation of the pivot point for an inverted pendulum model of anterior-posterior postural sway [13]. The desired angle of the foot plates was calculated from the commanded angle of the Stewart platform relative to the global (fixed) frame of reference, so a commanded angle of 0° caused the ankle-tilt platform to move in such a manner that it remained level regardless of the Stewart platform's pitch angle.

We examined the ankle-tilt platform's closed loop system performance by generating sinusoidal position commands doubling in frequency from 0.1 to 6.4 Hz. We generated additional sinusoids in the range of 3.2 Hz - 6.4 Hz to examine the behaviour near the tilt platform's observed natural frequency (3.3 Hz). At each frequency, we increased the amplitude until the angular acceleration or velocity gain dropped below 0 dB to determine the performance limits of the actuator.

We used encoder feedback data from the Stewart and ankle-tilt platforms to validate performance. Using the encoder data, we also calculate the real-time angular position and acceleration of the force plates relative to gravity (which now depends on the motion of both platforms) to remove components due to the rotation of the force plates from the torque measurements [8].

B. Validation with Human Subjects

To examine the platform's improvements in simulating balance, ten healthy subjects (M/F = 6/4) participated in a validation study. The University of British Columbia's Clinical Research Ethics Board approved all experimental procedures, and all subjects provided written informed consent before participating. We report all group data as means ± standard deviations. Participants were 27.9 ± 9.2 years old, had a mass of 64.3 ± 8.6 kg, and a centre of mass located 0.89 ± 0.06 m above the ankles.

Subjects were asked to lie flat on a balance board and adjust their body position until the board was balanced (that is, their centre of mass was directly above the pivot point). The centre of mass height was recorded as the distance from the pivot point to the subjects' ankles.

The experimenter positioned the subjects' feet on the ankle-tilt platform force plates so that their ankles were in line with the rotational axis of the platforms, and adjusted the backboard until it gently pressed against the shoulders and lower back without modifying the subjects' preferred standing angle. The experimenter recorded the weight of the subject using the force plates, and then secured the subject to the backboard using chest and waist seatbelts, as shown in Fig. 1.

The subjects balanced the simulation in two randomly ordered conditions. Condition A presents a locked ankle-tilt platform actuator, replicating the condition presented in [8] in which the ankle joint was fixed and constrained to the motion of the Stewart platform. In this case, the dynamic properties of the ankle joint, such as passive ankle torque [14] and ankle damping [15], were simulated in the inverted pendulum model. In Condition B, we programmed the ankle-tilt platform to maintain a constant angle of 0° relative to horizontal, to replicate standing on a flat surface. As the platform no longer held the ankles in a fixed orientation, we disabled the simulated dynamics of the ankle joint. In each condition, before collecting data, the experimenter gave subjects 2 minutes to become accustomed to balancing the system.

The relationship between ankle torque and sway angle (i.e., load stiffness) has been presented as an important criterion in validating the balance simulation [8]. Load stiffness is examined by plotting the measured ankle moment against the angular position (pitch rotation) θ of the Stewart platform, which corresponds to the angle of the inverted pendulum simulation. For each condition, the experimenter instructed subjects to sway the simulator within a comfortable balance range at approximately 0.1 Hz for 1 minute. Their motion was guided by an audible metronome. This sway frequency is low enough to minimize dynamic effects on the load stiffness that come from the subject's inertia and muscle activation [8]. From Equation 1, the load stiffness curve should remain approximately linear within the typical angular range of human standing balance. Two performance metrics were extracted from the load stiffness curves: the slope of the best-fit line to the data and the RMS error of the fit. In [8] the RMS error of the simulator was larger than that observed in free standing, leading to our current hypothesis.

We also examined the sway profiles for each condition. The subjects balanced the simulator for 2 minutes while maintaining quiet stance. We measured sway angle from the Stewart platform encoders and measured the RMS of the sway after mean removal. The signal was also converted into the frequency domain for analysis and comparison to other reported sway frequency data [8][16].

During the balance trials, we collected additional data for the technical validation. As the ankle-tilt platform was commanded to maintain a 0° angle in Condition B, any deviations measured through the encoder feedback were recorded. These results provided an indication of the tracking errors present during typical operation.

We collected qualitative feedback by asking subjects, "What did you think about that condition?" Subjects had previously reported that balancing the platform was more difficult than maintaining free standing balance, suggesting that subject perceptions are another valuable measure of the realism of the balance-task simulation.

We performed all statistical analyses using pair-wise t-tests with a significance level of $p < 0.05$.

III. Results

A. Results of Technical Validation

The frequency analysis showed that the ankle-tilt platform met all performance requirements for the frequency ranges observed in standing balance (0 – 3 Hz) [16]. During testing the maximum positional error was 0.127° (occurred at the system's natural frequency of 3.3 Hz), which meets the 0.2° requirement. The platform met the acceleration and velocity performance requirements (500°/s^2 and 10°/s, respectively) with peak accelerations of 720°/s^2 (measured with a 0.35° amplitude sine wave, 8.0 Hz) and a peak velocity of 18.5°/s (measured at 10°, 0.5 Hz).

B. Results of Validation with Human Subjects

We present the load stiffness curves for a single subject in Fig. 2. By visual inspection, the addition of the ankle-tilt platform produced a reduction in the number and amplitude of the "torque loops" (hysteresis) occurring as the subject swayed back and forth on the simulator. A similar result was observed for all subjects. This corresponded to a significant decrease in the load stiffness RMS (Fig. 3) about the best fit line ($t(10) = 6.17$, $p < 0.001$),

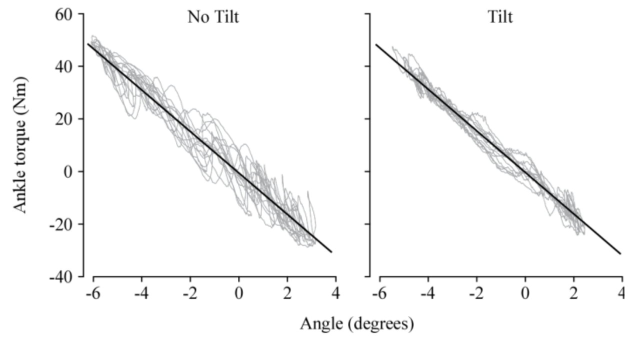

Figure 2. Load stiffness plots for a representative subject, with the ankle-tilt platform locked (left) and engaged (right). Subjects swayed within a comforable range at 0.1 Hz to approximate static conditions. The slope of the best fit curve was similar across conditions (102.2% and 102.3% of mgl, respectively). The reduced deviations from the line (RMS error) with the ankle-tilt platform enabled (right) indicates improved balance control.

and a significant decrease in the RMS sway trials from 0.625° ± 0.159° to 0.423° ± 0.153° when the ankle-tilt platform was enabled ($t(10) = 5.35$, $p < 0.02$). As expected, no significant difference in the slope of the load stiffness curves was apparent when the ankle-tilt platform was enabled ($t(10) = 0.57$, $p = 0.29$).

Similar to quiet standing [16], the maximum frequency content (signal attenuated to 1% of maximum) identified in the sway profiles was less than 2.5 Hz for all subjects in both conditions. This finding further supports the 0 – 3 Hz performance requirements for the ankle-tilt platform. The maximum angular errors measured for the this platform during the balance trials were 0.048° ± 0.016° and did not exceed 0.07° for any subject.

When asked, "What did you think about that condition?" a majority (6/10) of subjects reported finding the ankle-tilt platform-locked condition "challenging." After trying both conditions, all ten subjects stated that they found it easier to balance with the ankle-tilt platform engaged. The reasons given were similar: 8 subjects reported that they did not have to concentrate as much on the task to retain balance, 5 subjects reported finding the system easier to balance, and 3 subjects reported that the task required less effort.

IV. Discussion

A. Technical Performance

The technical performance requirements for angular velocity and acceleration have been met in this implementation. Angular position errors of the ankle-tilt platform were four times below reported thresholds of human detection [11].

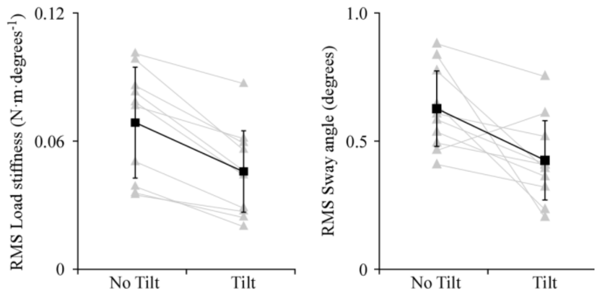

Figure 3. RMS Results. Individual subject data are shown in grey, and the mean and standard deviation for the population are shown in black. Group mean data for the load stiffness trials (left) and free sway trials (right) both show a significant (p < 0.05) decrease in RMS amplitude with the ankle-tilt platform engaged.

While there are other platform designs for investigating the effects and perceptions of ankle motion [5][11], our novel design provides both independent control of the ankle motion and permits whole-body movement. This flexibility offers new research avenues for experimentally manipulating proprioception during balance tasks, which may also be valuable for investigating rehabilitation techniques [17].

B. Validation with Human Subjects

Our previous study [8] showed that when the ankle joint was constrained to the motion of the simulator, the mean-removed RMS of sway for the balance simulator was 60% greater than the RMS observed in free standing sway. With the addition of the ankle-tilt platform in the present study, we have reduced the RMS of sway for the balance simulator by 32%, indicative of improvement in the balance simulation. This improvement is also reflected in the reduction of hysteresis in the load stiffness curves when the ankle-tilt platform is engaged, and a consequent decrease in RMS amplitude. Furthermore, the subjects' perception of the system indicates that the addition of ankle motion reduced the effort and concentration required to maintain quiet stance.

All three measures indicate that the ankle-tilt platform's addition has improved control and fidelity for simulating quiet stance.

V. Conclusion

The results of the study strongly support the hypothesis that enabling of ankle somatosensory feedback via the ankle-tilt platform improves the robotic balance simulation [8]. While it was possible to simulate passive ankle stiffness and ankle damping without the ankle-tilt platform (the slopes of the load-stiffness curves were the same), the addition of ankle motion improved the balance performance, with a significant reduction in sway and load stiffness RMS, and all subjects reported this simulation as being easier to control.

Acknowledgment

The authors would like to thank Thomas Huryn, Hina Shah, Max Ittermann, and the UBC MECH 458 Capstone "Tilt" Team for their assistance in the implementation of the ankle-tilt platform.

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