9-2014

Locomotor Sensory Organization Test: A Novel Paradigm for the Assessment of Sensory Contributions in Gait

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LOCOMOTOR SENSORY ORGANIZATION TEST: A NOVEL PARADIGM FOR THE ASSESSMENT OF SENSORY CONTRIBUTIONS IN GAIT

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Abbreviated title: Locomotor Sensory Organization Test

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ABSTRACT

Feedback based balance control requires the integration of visual, proprioceptive and vestibular input to detect the body's movement within the environment. When the accuracy of sensory signals is compromised, the system reorganizes the relative contributions through a process of sensory recalibration, for upright postural stability to be maintained. Whereas this process has been studied extensively in standing using the Sensory Organization Test (SOT), less is known about these processes in more dynamic tasks such as locomotion. In the present study, ten healthy young adults performed the six conditions of the traditional SOT to quantify standing postural control when exposed to sensory conflict. The same subjects performed these six conditions using a novel experimental paradigm, the Locomotor SOT (LSOT), to study dynamic postural control during walking under similar types of sensory conflict. To quantify postural control during walking, the net Center of Pressure (netCOP) sway variability was used. This corresponds to the performance index of the center of pressure (COP) trajectory, which is used to quantify postural control during standing. Our results indicate that dynamic balance control during locomotion in healthy individuals is affected by the systematic manipulation of multisensory inputs. The sway variability patterns observed during locomotion reflect similar balance performance with standing posture, indicating that similar feedback processes may be involved. However, the contribution of visual input is significantly increased during locomotion, compared to standing in similar sensory conflict conditions. The increased visual gain in the LSOT conditions reflects the importance of visual input for the control of locomotion. Since balance perturbations tend to occur in dynamic tasks and in response to environmental constraints not present during the SOT, the LSOT may provide additional information for clinical evaluation on healthy and deficient sensory processing.

Keywords: biomechanics, posture, sway variability, sensory organization test, performance index, walking.

Abbreviations

LSOT – Locomotor Sensory Organization Test

SOT – Sensory Organization Test

netCOP – net Center of Pressure

PI – Performance Index

Introduction

The maintenance of upright posture during standing and walking requires integration of visual, somatosensory and vestibular inputs. Each of these inputs is sensitive to particular characteristics of self-motion and motion within the environment that uniquely contributes to the detection of postural sway. Upon sway detection, the central nervous system initiates corrective postural adjustments by implementing the appropriate muscular responses[1]. Inherent ambiguities in each of the modalities need to be solved before sensory signals provide useful contributions. For example, the somatosensory modality is unable to differentiate between movement of the support surface and movement of the body. This ambiguity can be resolved through access to visual information, which provides self-motion information independent of the support surface. This solution process could be modeled following a Bayesian framework. Sensory ambiguity leads to a broader probability curve of postural sway estimation and uncertainty regarding necessary postural corrections when a single modality is involved. When an additional sensory signal is available, the integrated signal leads to a more precise estimation[2-3] and subsequently more appropriate postural corrections. In conditions of reduced sensory accuracy as a result of internal or external perturbations, the system recalibrates sensory contributions, reciprocally lowering the gain of inaccurate signals and increasing the gain of accurate signals[1]. Body sway and sway variability increase when vision is absent, compared to standing with accurate visual input. However, this increase is significantly lower than the degree of sway observed in individuals with a reduced capacity for sensory reweighting[4]. Whereas the reported reweighting patterns have been observed during standing, similar sensory processes may be involved in locomotion[5].

In order to quantify sensory contributions and the adaptive mechanisms involved in the control of posture during sensory conflict, the Sensory Organization Test (SOT) has been used in patients with vestibular disorder[6 - 8], concussion[9], stroke[10], and Parkinson's Disease[11]. Through the systematic manipulation of sensory input, the SOT intends to perturb the system and induce adaptive sensory recalibration processes. It can manipulate singly or in combination somatosensory and visual inputs to allow for the assessment of a patient's ability for maintaining balance[11]. It has been found that when healthy adults stand on a firm surface with available visual input, sensory contributions consisted of 70% somatosensory input, 20% vestibular input and 10% visual input[12]. When somatosensory accuracy was reduced through support surface oscillations, sensory recalibration changed the relative contributions to 70% vestibular information, 20% visual information and 10% somatosensory information to maintain postural stability[12]. Based on these results, the somatosensory and vestibular systems seem to be the dominant sensory systems as compared to the visual system to achieve postural control during standing[12]. Whereas this process has been studied extensively in standing, less is known about whether similar strategies are also utilized to resolve sensory conflicts during more dynamic situations of postural control such as walking.

Visual input during walking is uniquely capable of encoding task specific information including travelled distances, navigation, planning walking trajectories and perceiving environmental features[13]. When visual input was manipulated by prism goggles in healthy young adults, subjects demonstrated a significant lateral deviation from their destination[14]. The somatosensory system also provides information about the ground conditions during locomotion, such as the presence of slippery or icy surfaces. Thies and colleagues (2005) indicated that individuals with peripheral neuropathy increased step time and decreased step length when walking on an irregular surface as compared to walking in a dim light condition[15]. These results suggest that the CNS might have to recalibrate multisensory interactions in patients with inaccurate somatosensory perception, by adjusting their gait patterns. Ishikawa and colleagues showed that patients with unilateral vestibular disorders had an asymmetric walking pattern[16 - 17]. The significantly shorter step length and longer swing time was observed on the side where the vestibular system was affected. The same is observed using vestibular stimulation during locomotion[31]. Adjusting step length and step time was suggested as a strategy to maintain balance and prevent falling during locomotion[18]. Based on the above, it is evident that a deficit in a sensory system can affect gait patterns and balance during locomotion. However, a comprehensive study of how sensory information from all three systems is integrated to achieve dynamic postural control during walking has not been performed. It is possible that the reason for such a knowledge gap is the absence of an experimental apparatus like the SOT for walking.

In the present study we developed and implemented an experimental apparatus, consisting of an integrated instrumented multisensory virtual reality environment: the Locomotor Sensory Organization Test (LSOT). This allowed for the assessment of sensory contributions to the dynamic postural control during walking. We hypothesized that dynamic postural control during walking would be affected by unimodal and multimodal sensory perturbations, inducing sensory recalibration. In addition, we hypothesized that maintaining dynamic postural control during walking shares similar feedback control mechanisms with maintaining postural control in standing, reflected in similar postural sway behavior in the SOT and LSOT. Finally, we hypothesized that the importance of vision in the locomotor task will significantly increase in postural perturbations induced by visual conditions.

Methods

Subjects

Ten healthy young adults (five males and five females; age 27.20±4.92 years, height 171.30±7.01 cm and weight, 64.70±9.90 kg) participated in this study. Subjects were free from any musculoskeletal impairments, had no history of significant lower extremity injuries which may have affected their posture or gait and had no visual, somatosensory or vestibular deficits. We excluded individuals without normal or corrected to normal vision, scored above zero on the dizziness handicap inventory for a vestibular deficit,[30] and with any type of peripheral neuropathy that can affect somatosensory function. Prior to the experiment, each subject signed an informed consent approved by our University's Medical Center Institutional Review Board.

Protocol

The experiment entailed exposing subjects to sensory perturbations in the SOT and LSOT environments. The SOT was conducted in a quiet room using the Balance Master System 8.4 (NeuroCom International Clackamas, OR, USA) (Figure 1). The system contains a moveable visual surround and support surface that rotate in the anterior-posterior (AP) plane. Two 22.9 x 45.7 cm force plates connected by a pin joint are used to collect center of pressure data at 100 Hz. Foot placement is standardized based on subjects' height according to manufacturer guidelines. The SOT contains six conditions to manipulate the combinations of visual, vestibular, and somatosensory information used for postural control during standing. While standing in the Balance

Master system, subjects wore a vest according to SOT procedures, attached to the safety harness of the system.

The LSOT apparatus consisted of a virtual reality (VR) environment and an instrumented treadmill containing two embedded force plates (Bertec Corp., Columbus, OH, USA; Figure 2), integrated into a single system allowing for synchronized data collection and stimulus presentation. A motion capture system (Optotak Certus; Northern Digital Inc., Waterloo, Canada) was used to capture the three-dimensional marker trajectories at a sampling rate of 100Hz. Active rigid body markers were placed on the toe and heel of each leg. The unfiltered position data for the x, y, z coordinates were exported using Optotrak Certus' proprietary software. Data processing was performed using custom Matlab code (Mathworks Inc., Natick, Massachusetts) for the calculation of step length and step width. Ground reaction force data were acquired from the force plates at 100 Hz. The Heel-Strike was considered to occur at the first frame in which the vertical component of the ground reaction force exceeded a threshold level of 10N and continuously exceeded this threshold for 40 ms. The Toe-Off was considered to occur at the first frame in which the vertical component of the ground reaction force fell below the 10N threshold, sustained continuously for 40ms[34-36]. This 10N threshold was calculated as three times the standard deviation of the vertical ground reaction force during the initial 100 ms (100 frames) of the trial[34-36]. A gait cycle was defined as the time elapsed between two consecutive heel strikes of the ipsilateral leg.

The custom VR environment provided self-motion information through optic flow manipulation and was written in Python using the WorldViz LLC graphics library (Santa Barbara, CA, USA). The virtual environment was projected by three commercial projection systems (Optoma TX 774, Optoma Technology Inc., Milpitas, CA) on three 2.51 m x 1.72 m flat screens that were positioned 1.5 m away from the plane of motion. The angle between side and middle screen was 120 deg. A moving virtual corridor was projected onto the screen to generate the optic flow stimulus. Custom software, written in Visual Basic (Microsoft Corp., Redmond, WA), was utilized to vary the treadmill speed in real time. In order to manipulate vision, we used light intensity goggles (MSA Safety Work, Pittsburgh, PA) which reduced the light intensity from 22 lux to 0.7 lux. The LSOT contained six conditions similar to the SOT to manipulate the visual, vestibular, and somatosensory information during walking (Figure 3). In order to increase safety while on the treadmill, subjects also wore the same SOT vest, attached to a LiteGait harness system (Mobility Research, AZ, USA).

Subjects were required to complete all SOT and LSOT conditions in a single session. Subjects first completed the SOT conditions, followed by the LSOT conditions. Experimenters explicitly instructed subjects to “try your best to keep your balance” during the SOT and LSOT conditions. For the SOT, subjects were positioned standing upright on the Balance Master. Each SOT condition followed a standard protocol of three trials lasting 20 seconds each and the sequence of conditions given to subjects followed a predetermined order (conditions 1 - 6). Between the SOT conditions, subjects received a 30 seconds rest period. For the LSOT, prior to the data collection each subject walked for five minutes on the treadmill to determine their preferred walking speed (PWS). Subjects stood on the sides of the treadmill without touching the belts. Subsequently, treadmill belt velocity was incremented from 0 to 0.8 m/s. Then the subject were asked to step on treadmill while holding the handrail. After the subject started walking on the treadmill, experimenters asked the subject to evaluate the speed as following: “Is this walking speed comfortable like walking around the grocery store?” The treadmill velocity was increased or decreased, following subject directions. Once a comfortable walking velocity was attained, the subject walked continuously for 5 minutes. After the PWS was determined, all subjects walked on the treadmill at their PWS for two minutes in each of the six conditions of the LSOT and each LSOT condition was matched to its respective SOT counterpart and sequence. The LSOT conditions were the following:

1) Normal walking condition: both the speed of the virtual corridor and the treadmill speed were matched with PWS.

2) Reduced visual condition: no VR was presented, the treadmill speed matched with PWS, and the subjects wore vision-reduced goggles.

3) Perturbed visual condition, achieved by manipulating the optic flow speed: the speed of the virtual corridor was pseudo-randomly varied between 80% and 120% (restricted randomization between 80% and 120% in steps of 1) of the selected PWS in pseudo-randomly assigned time intervals within 1 to 10 seconds (restricted randomization between 1 and 10 in steps of 1). Such a range was used in previous studies to manipulate walking speed[19-20]. Moreover, we gave 1 to 10 seconds time intervals of perturbations to reduce adaptation of walking in the perturbed environment. The treadmill speed matched with PWS.

4) Perturbed somatosensory condition by manipulating the treadmill speed: the speed of the virtual corridor matched with PWS, while the treadmill speed was varied between 80% and 120% of the PWS in pseudo-randomly assigned time intervals within 1 to 10 seconds. Walking speed is highly associated with the sensitivity of somatosensory

system[31] and is very crucial during stance-to-swing transition[33]. Changing walking speeds immediately affects the time of stance-to-swing transition. This is why fast walking is an excellent selection for quantifying somatosensory impairment[32] and why walking speed has been used in the present study for our somatosensory perturbation[31-33].

5) Perturbed visual and somatosensory condition by reducing vision and manipulating treadmill speed: no VR was presented, the treadmill speed was varied between 80% and 120% of PWS in pseudo-randomly assigned time interval within 1 to 10 seconds, and the subjects wore vision-reduced goggles.

6) Perturbed visual and somatosensory condition by manipulating optic flow and treadmill speed: both the speed of the virtual corridor and the treadmill speed was varied between 80% and 120% of the selected PWS in pseudo-randomly assigned time intervals of 1 to 10 seconds duration. In this condition the velocity of the virtual corridor and treadmill were synchronized with a unitary gain relationship.

Subjects were allowed to rest for one minute with eyes-closed between conditions. Optic flow and treadmill speed were varied between 80 to 120%, as the impact of different walking speeds on gait variability was conventionally investigated in this range[19-20]. Indeed, the amount of gait variability has shown a negative linear correlation with different walking speeds in this range in healthy young adults. However, literature also indicated that over 120% of PWS, muscle activity had a significant jump in comparison with the muscle activity at 120% of PWS[21].

Data Analysis

Postural performance was assessed using the Performance Index (PI). This metric was used to determine the extent to which sway approached the body's stability limits during standing and walking[4]. The calculation method of the PI is conceptually similar to the standard deviation. The PI is calculated by numerically integrating the rectified sway signal (with the steady-state offset removed), and then scaling the result as a percentage of the maximum sway possible during standing. A PI value approaching zero indicates stable postural control. PI values that approach 100 indicate loss of balance. The PI allowed us to compare postural performance and assess sensory contributions during standing[22]. The PIs in both the AP and medial-lateral (ML) directions were calculated in this study for the SOT.

$$\mathrm{PI} = \sum \frac{|\text{COP position in each frame} - \text{origin COP position}|}{\text{Max COP sway position} - \text{origin COP position}} \quad (1)$$

For walking and the LSOT, the ground reaction force data were low-pass filtered at 10Hz (with a 4th order Butterworth filter). The netCOP sway variability metric was calculated using the filtered data. The netCOP is the point where the total sum of a pressure field acts on a body during walking[23]. The netCOP measure allows for a direct comparison of the COP measures between standing and locomotion. The netCOP variable requires the identification of four specific netCOP points: right heel strike (RHS), left heel strike (LHS), right toe-off (RTO), and left toe-off (LTO). These four points were defined by using the data from the instrumented treadmill. The right leg heel strike was defined as the largest positive value in the anterior-posterior direction and largest positive value in the medial-lateral direction per gait cycle. The left leg heel strike was defined as the largest positive value in the anterior-posterior direction and largest negative value in the medial-lateral direction per gait cycle. The right toe off was defined as the largest negative value in the anterior-posterior direction and largest positive value in the medial-lateral position per gait cycle. The left toe off was defined as the largest negative value in the anterior-posterior direction and largest negative value in the medial-lateral position per gait cycle (Figure 4). In order to estimate the postural sway during walking, we calculated the netCOP area by calculating the two area triangles created. One triangle consisted of the LHS, LTO, and intersection point between the two triangles. The other consisted of the RHS, RTO, and intersection point. We then added these two triangles to find the total area of netCOP for one gait cycle. The mean and the standard deviation for each subject were calculated by averaging all 90 gait cycles. Then, the netCOP sway variability was calculated as the coefficient of variation for each subject. In the current study, 90 gait cycles were used to calculate the netCOP sway variability for each subject. This was the lowest number of gait cycles performed by the slowest subject within the two minutes of data collection. Thus all data were truncated to 90 gait cycles per subject. The smaller the netCOP sway variability, the better the dynamic postural control during walking. This approach in terms of interpretation, it is the same that is given to the SOT outcome measure. Figures 5 and 6 include trials of all SOT and LSOT conditions to demonstrate how the variables of interest changed due to the perturbations presented.

Step length and step width were determined based on the heel-strike and toe-off. Step length was defined as the distance between heel strike and subsequent heel strike of the contralateral foot. Step width was defined as the mediolateral distance between heel markers at successive heel strikes. Step length, and step width variability were defined as the coefficient of variation of these spatial parameters to determine how spatial parameters shifted during walking.

One-way repeated measures ANOVA's were performed using SPSS 18.0 (IBM Corporation, Somers, NY) to determine condition effects for the LSOT and SOT. Specifically, the dependent measures were: a) the PI for the SOT in the anterior-posterior (AP) direction, b) the PI for the SOT in the mediolateral (ML) direction, c) the spatial parameters (step length, and step width) for the LSOT, d) the spatial parameters variability (step length and step width variability), and e) the netCOP sway variability for the LSOT (as derived from an area and not a length contains both the AP and ML directions). Pairwise comparisons were performed to determine specific differences between conditions using Bonferroni adjustments. The level of significance was set at 0.05.

Results

Anterior-posterior PI in the SOT

The one-way repeated ANOVA revealed a significant condition effect (F = 55.38, $p < 0.001$) (Table 1). The post-hoc pairwise comparisons revealed numerous differences between conditions. The conditions 1, 2, and 3 were statistically similar, while the group mean values increased significantly in conditions 4, 5 and 6. The largest group mean value was present in condition 5 (eyes closed with sway-referenced surface), followed by condition 6 (eyes open with sway-referenced surface and visual surroundings). However, there was no significant difference between conditions 5 and 6 ($p = 0.081$).

Medial-lateral PI in the SOT

The one-way repeated ANOVA revealed a significant condition effect (F = 21.06, p < 0.001) (Table 1). The pairwise comparisons revealed similar results with the AP direction, however, this time the largest group mean value by a very small non-significant margin was in the sixth condition. The group mean values were all smaller than the AP.

Spatial parameters in the LSOT

The one-way repeated ANOVA revealed a significant condition effect for step length (F = 12.7, p < 0.001) and step width (F = 4.47, p = 0.002). The post-hoc analysis showed that the step length was statistically longer in condition 1 than conditions 2, 5, and 6 (Table 1). However for step width and due to the Bonferroni adjustment the post-hoc pairwise comparisons did not show any statistically differences between conditions.

Spatial parameters variability in the LSOT

The one-way repeated ANOVA showed a significant condition effect in step length ($F = 36.37$, $p < 0.001$) and in step width ($F = 10.52$, $p < 0.001$). The post-hoc pairwise comparisons showed that the step length variability was statistically smaller in condition 1 than conditions 2, 4, 5, and 6 (Table 1). For step width variability, condition 1 was statistically smaller than condition 2, 3, 4, 5, and 6 (Table 1).

Sway variability in the LSOT

The one-way repeated ANOVA revealed a significant condition effect ($F = 24.79$, $p < 0.001$) (Table 1). Subsequent pairwise comparisons revealed numerous significant differences (Table 1). The group mean netCOP value for condition 1 was significantly smaller than the other conditions. In addition, condition 5 (reduced visual information, variable treadmill velocity) had the largest group mean value. Condition 6 (variable optic flow and variable treadmill velocity) displayed the second largest group mean value. The third largest value was for condition 2 (reduced visual information, treadmill speed matched with PWS).

Discussion

In the present study we investigated how individuals recalibrate sensory contributions to locomotion in conditions of ambiguous sensory inputs. The LSOT, a novel experimental paradigm, was developed to study sensory contributions to dynamic postural control during walking. Our results supported our first hypotheses that walking would be affected by unimodal and multimodal sensory perturbations, inducing sensory recalibration. However, our results partially supported our second hypotheses that maintaining dynamic postural control during walking shares similar feedback control mechanisms with maintaining postural control in standing, as postural sway was similar between the two tasks only when visual and somatosensory systems were perturbed simultaneously. Finally, the result supported the hypothesis that vision will be the dominant sensory system during walking.

Specifically, the significant differences found between conditions for the netCOP values in the LSOT supported our first hypothesis (Table 1), indicating the LSOT can be used to elicit systematic sensory recalibration processes. Importantly, our results almost mirrored those found at the SOT, particularly in the AP direction (Table 1). This direction is the dominant direction of sway movement during the SOT, since the perturbations are presented in the AP direction (see Table 1). The PI values in the various perturbation conditions conform to what is commonly reported in the literature[4]. The similarities between the SOT and LSOT results suggest that similar feedback based perceptual mechanisms could be involved. However, contrary to the SOT results, the LSOT also resulted in significantly increased variability when vision was reduced, reflecting the importance of visual input during locomotion.

During standing, our findings showed that the combination of perturbed visual and somatosensory inputs resulted in much larger reliance on the vestibular system resulting in significantly increased levels of COP variability. This also appears to be the case in walking. However, the effect of visual input on walking is more clearly demonstrated when it is reduced (condition 2) while somatosensory input is not perturbed. This condition produced the only practical difference between the SOT and the LSOT and demonstrated a much larger effect in the LSOT. The LSOT conditions 2 and 5 provide a particularly interesting perspective on sensory contributions to locomotion. In the control of upright posture, vision provides indispensable positional information and is the only modality containing the functional organization to allow for this type of contribution. Neither vestibular nor somatosensory input is sufficient to provide positional information during locomotion. In conditions of reduced vision, subjects have limited information of their location on the treadmill. This reduction in positional information may have resulted in a positional drift towards the front or back edges of the treadmill. Theoretically, if subjects walked on the treadmill and had positional drift towards the front and back, the variability should be bigger in the sensory conflicted conditions than the normal conditions. The results we provided in terms of step length and width variability indicated that subjects indeed shift front and back and left and right, in a greater extend in the sensory-conflicted conditions than in the normal walking condition. The corrective motions employed when the limits of the treadmill are reached increased the degree of variability of the netCOP since the netCOP area varies as a function of the stride length on the treadmill. Such large excursions on the treadmill remain unperceived by the vestibular sense, which lacks the sensitivity to detect this type of drift[2]. From a Bayesian perspective, uncertainty in dynamic postural control during walking significantly increases, as vision capacity which is the primary source of stabilizing sensory input, is reduced. Similar observations have been made in step variability patterns in individuals afflicted with peripheral neuropathy under low light environmental conditions[24].

In persons with peripheral neuropathy, gait variability significantly increased on irregular surfaces under the low lighting condition as compared to walking on a level surface under regular lighting condition. The somatosensory perturbation of the irregular support surface increased vestibular gain, which is less effective for the task of feedback control of posture and gait variability. Similarly, in the current study the combined perturbation conditions were implemented to investigate the vestibular control of locomotion. Walking is a complicated behavior involving coordination of multiple systems within the body and the sensory system provides reliable environmental information to these systems[25]. As controlled by visual and vestibular perception, the primary role of intersegmental postural coordination is the stabilization of the head in space. This is why both visual and vestibular rotational stimuli lead to balance responses in the roll plane, the magnitude of which decreases from proximal to distal segments. Subsequently, during constant rotational stimuli the head consistently displays the largest coupled angular deviation, followed by the torso and peripheral effectors[26-27]. We found that netCOP variability significantly increased when walking with both the visual and somatosensory input perturbed as compared to other sensory conflicted conditions. When only the vestibular system was reliable, subjects increased the netCOP area sway variability to maintain dynamic postural control.

Do the mechanisms governing the control of both standing and walking share commonalities in terms of maintaining balance? It has been argued that the control mechanisms used to maintain balance during walking is quite different and complicated from those used during standing because the center of gravity during walking is always outside the base of support[26]. Further, O'Connor and Kuo (2009) stated that the fundamental mechanism to control walking posture may be different from standing posture[28]. They supported this statement with the observation that posture was more sensitive to visual stimuli in the frontal plane than in the sagittal plane during walking. For standing, the visual stimuli affected the postural control only in the sagittal plane and not in the frontal plane. Our results were line with their study in terms of walking where giving visual perturbation led to higher variability in the frontal plane than in the sagittal plane. However, when multiple sensory systems are perturbed concurrently, the mechanism to control walking and standing posture may be the same since spatial variability increased in both the frontal and sagittal plane in our study. Moreover, the overall netCOP sway variability significantly increased in these multiple sensory conflicting conditions. Based on a Bayesian perspective,[2-3] multiple sensory conflicting conditions resulted in an increased uncertainty of the system to maintain postural control regardless of the task; standing or walking. This is why our results partially supported our second hypothesis that a degree of similarity of control mechanism exists between maintaining dynamic postural control during walking and maintaining postural control in standing.

Interestingly, when we compared conditions 1,2, 3 and 4 during walking, we found no significant differences between conditions 2, 3, and 4, while all three of them were different than condition 1. This result may indicate that for walking both the visual and the somatosensory system have significant contributions when perturbed singly. However, this was not the case during standing where conditions 1, 2, and 3 were not significantly different from each other, while all of them were significantly different from condition 4. This result may indicate that for standing, visual information is not as important as somatosensory information when manipulated singly. This is a very interesting dichotomy between the two tasks that is revealed by the examination of the non-significant results and this is why we have partially supported our second hypothesis. Practically, our results point to the importance of visual information during walking as the continuous assessment of our surroundings is fundamental to maintain postural control. By factoring out vision during walking, we can suggest that the two tasks share similar sensory contributions to postural control.

Our step width results were similar to those reported by Altman et al[29], confirming that a split belt treadmill could cause people to walk with wider steps. In the O'Connor and Kuo study, the authors did not use a split belt treadmill and their dependent measure was a modified step width parameter. This may affect direct comparison between our results and theirs with respect to step width. Furthermore, in the O'Connor and Kuo's study, the dependent measures used were the discrete foot placement during walking and the continuous COP trajectory during standing. The selection of these parameters could be a limitation of their paper, when standing and walking are compared, as these parameters are quite different in nature (discrete versus continuous). In our study, we used in both standing and walking continuous measurements to quantify postural control. To our knowledge this is also the first study that attempted to mimic the

SOT paradigm in walking. In the current study, we found that increasing the amount of sway variability seems to be a consistent strategy in standing and walking regarding the sensory conflicting conditions. This was actually similar to O'Connor and Kuo's work. We also found that in conditions 5 and 6, the variability significantly increased in both walking and standing. Thus, we believe that the control mechanisms of standing and walking share a certain degree of similarity.

A possible limitation of the present study is the type of somatosensory perturbation used for the LSOT; variable speeds. This is not identical to the tilting ground perturbation used in the SOT. Thus, it can be argued that changing gait speed not only alters somatosensory input, but also vestibular system input and the mechanical, metabolic and general physiological demand placed on the subjects. However, variable ground tilting during walking would have been a very difficult perturbation to be achieved during walking and such technology is extremely expensive to have any type of clinical applicability at present. Our designed perturbation, namely varying speeds, as we explained in the methods does affect the somatosensory system based on the available literature. On the other hand tilting the ground, as in the SOT somatosensory condition, could possibly also affect the vestibular system by disturbing the torso dynamics resulting in head movement[37]. Another possible limitation of the present study is that tactile sensation is also available from the safety harness. We attempted to reduce this effect by asking subjects not to hold onto the harness and by adjusting the harness to achieve maximum possible comfort. The safety harness is also included in the standard clinical SOT procedures and thus the utilization of such a harness in our experimental design did improve external validity.

In conclusion, the LSOT results demonstrated that a degree of similarity exists in postural control mechanisms that are active during standing and walking in healthy individuals. The primary difference between them appears to be the nature of the visual contribution. Vision uniquely provides positional information during locomotion. In healthy individuals, compensation by somatosensory mechanisms is more effective during standing, as reflected in a relatively minor increase in COP variability. In locomotion on the other hand, the visual perturbation significantly increased variability. Thus this phenomenon of increased importance of unimodal visual over somatosensory input during locomotion is the inverse of what is observed during standing. SOT has been widely used to examine feedback based postural control during standing and these results have been generalized to infer postural control during walking. However, the LSOT was specifically designed to explore postural control mechanisms during walking and revealed additional patterns of multisensory interactions, not reflected in performance on the SOT. As falls tend to occur in dynamic tasks and in response to environmental constraints not present during the SOT, the LSOT may provide additional information on healthy and deficient sensory processing.

Acknowledgments

This study was supported by the NASA EPSCoR NNX11AM06A.

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Tables, Figures and Captions

Table Captions

Table 1: Group means and standard deviations for all conditions for the 7 dependent measures evaluated. Significant differences between conditions are indicated with superscripts.

Captions to Figures

Figure 1. The SMART balance Master (NeuroCom International Clackamas, OR, USA) is used to perform the Sensory Organization Test (SOT). This test contains six conditions: 1) eyes open with fixed surface and fixed visual surrounding; 2) eyes closed with fixed surface; 3) eyes open with fixed surface and sway-referenced visual surroundings; 4) eyes open with sway-referenced surface and fixed visual surroundings; 5) eyes closed with sway-referenced surface; 6) eye open with sway-referenced surface and visual surroundings.

Figure 2. The components of Locomotor Sensory Organization Test (LSOT): virtual reality and the instrumented treadmill.

Figure 3. The six conditions of Locomotor Sensory Organization Test (LSOT) that mirrors those of the SOT: 1) normal walking condition 2) Reduced visual condition by reducing vision capability condition 3) Perturbed visual condition by manipulating optic flow speed condition 4) Perturbed somatosensory condition by manipulating treadmill speed condition 5) Perturbed visual and somatosensory condition by reducing vision capability and manipulating treadmill speed condition and 6) Perturbed visual and somatosensory condition by manipulating optic flow and treadmill speed condition.

Figure 4. The netCOP sway area was composed by two-triangle areas that are represented as the areas with dashed lines. Five points was used to generate these two-triangle areas as following: intersection point, right heel-strike, right toe-off, left heel-strike, left toe-off.

Figure 5. Representative trials from a single subject from the six SOT conditions -- the COP sway in the six conditions for the SOT during standing.

Figure 6. Representative trials from a single subject from the six LSOT conditions -- the netCOP sway in the six conditions for the LSOT during walking.

Table 1.

Conditions	1	2	3	4	5	6
PI in AP for SOT	7.26(1.41)[$^&]	9.18(2.94)[$^&]	9.36(2.72)[$^&]	17.56(5.01)[*!#^&]	38.10(12.72)[*!#$]	28.64(10.59)[*!#$]
PI in ML for SOT	5.09(2.28)[$^&]	5.27(2.45)[^&]	5.44(2.37)[^&]	8.86(4.04)[*]	11.22(2.09)[*!#]	11.41(2.44)[*!#]
Step Length for LSOT (m)	0.58(0.05)[!^&]	0.49(0.07)[*$]	0.53(0.07)	0.53(0.05)[!^]	0.47(0.05)[*^]	0.46(0.04)[*]
Step Width for LSOT (m)	0.19(0.07)	0.22(0.06)	0.24(0.03)	0.24(0.04)	0.28(0.06)	0.28(0.07)
Step Length Variability for LSOT	2.96(0.87)[!$^&]	4.59(0.89)[*#^&]	2.23(0.48)[!$^&]	5.78(1.12)[*#]	7.92(2.02)[*!#]	6.36(0.69)[*!#]
Step width Variability for LSOT	15.6(2.69)[!#$^&]	27.21(8.79)[*]	24.47(5.51)[*]	25.23(5.63)[*]	31.29(5.74)[*]	30.07(7.55)[*]
netCOP sway variability for LSOT	5.30(0.67)[!#$^&]	13.13(3.74)[*^]	9.21(2.47)[*^&]	10.63(1.99)[*^&]	20.99(6.31)[*!#$]	15.78(5.04)[*#$]

1. *: significant difference exhibited when compared to condition 1.
2. !: significant difference exhibited when compared to condition 2.
3. #: significant difference exhibited when compared to condition 3.
4. $: significant difference exhibited when compared to condition 4.
5. ^: significant difference exhibited when compared to condition 5.
6. &: significant difference exhibited when compared to condition 6.

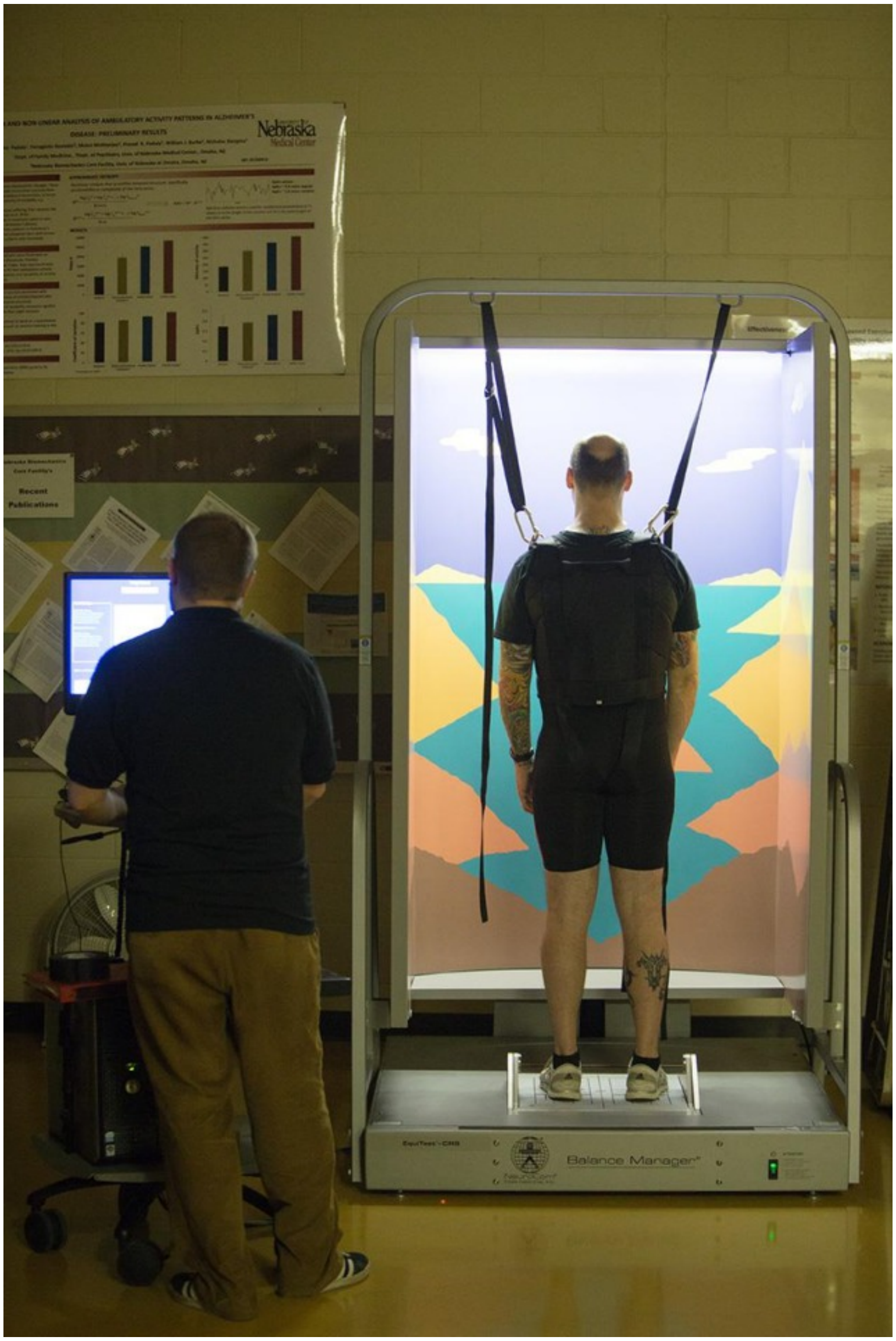

Nebraska
Medical Center
Recent
Publications
Balance Manager

Figure 1

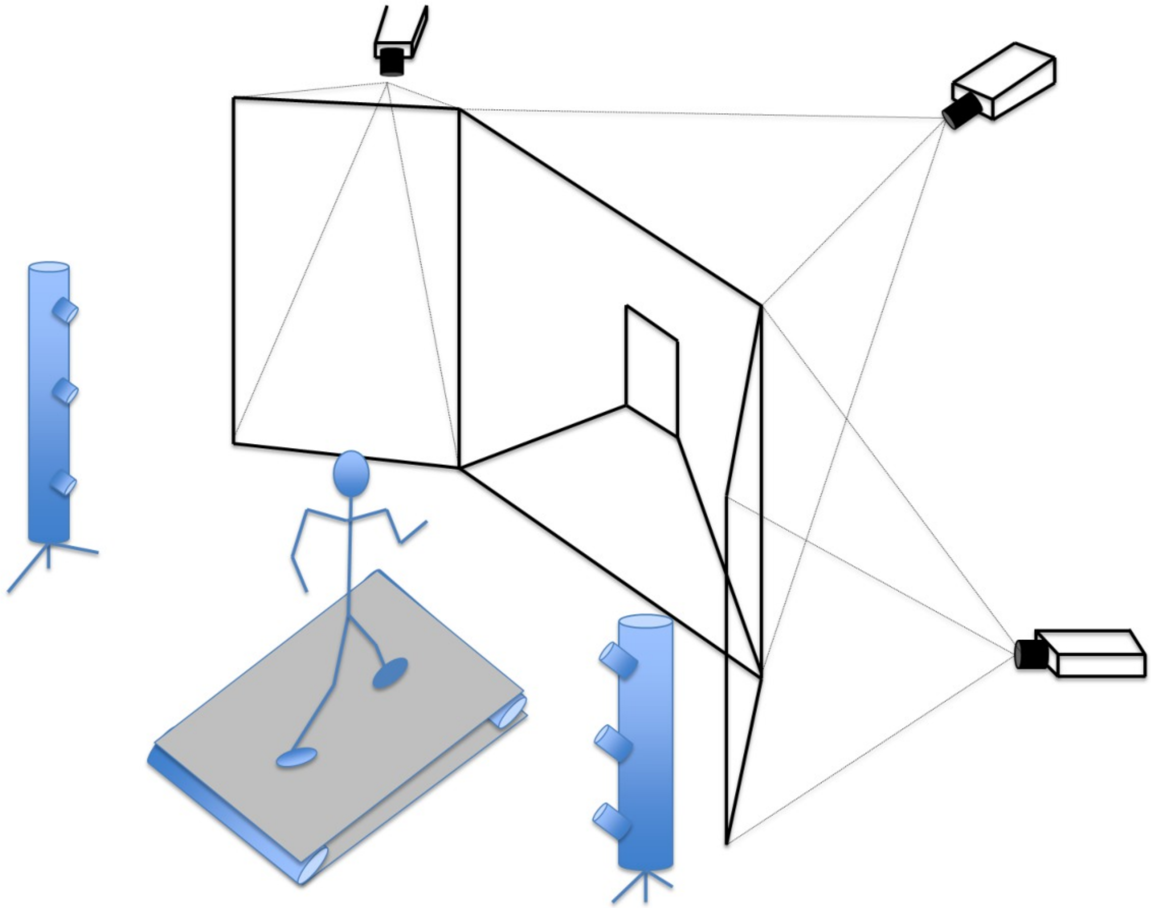


Figure 2

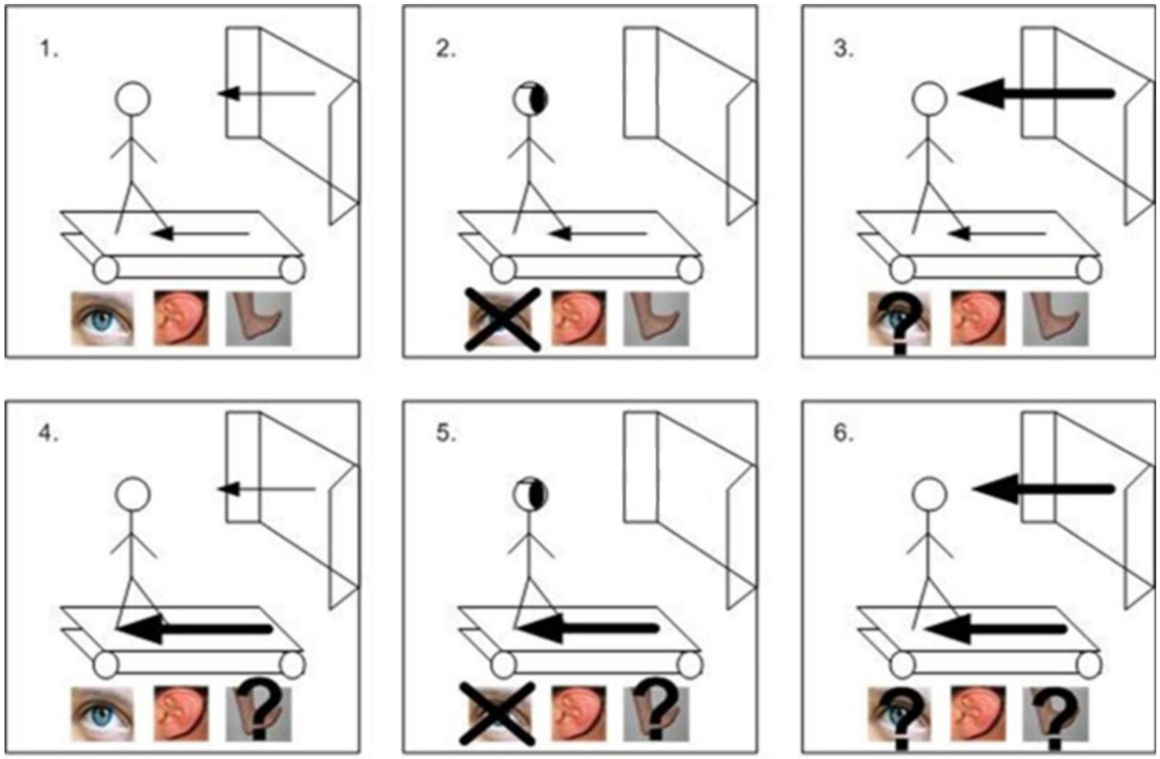
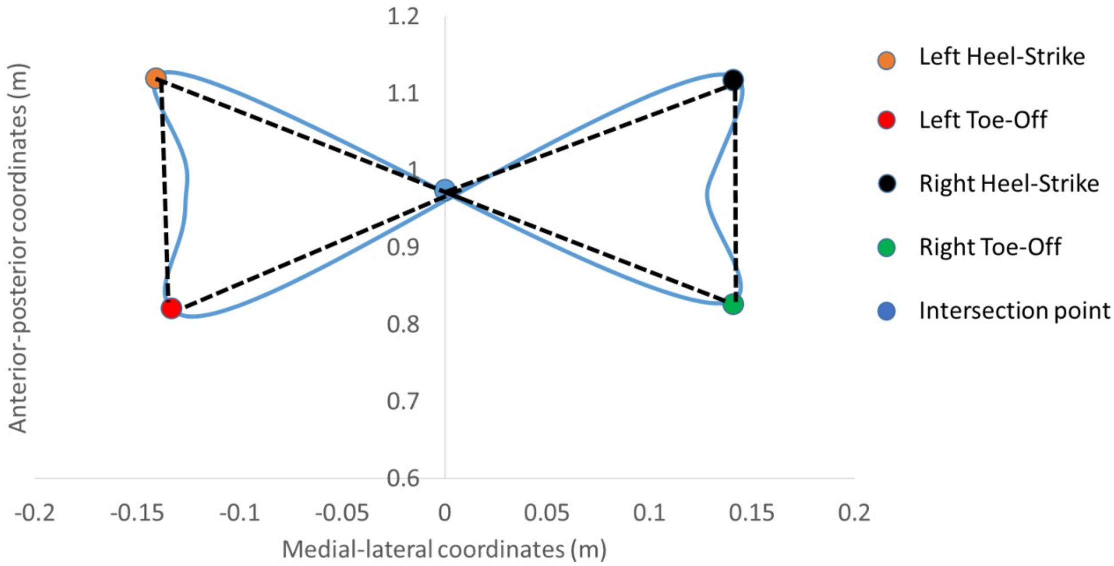


Figure 3



1.2
1.1
1
0.9
0.8
0.7
0.6
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
Anterior-posterior coordinates (m)
Medial-lateral coordinates (m)
Left Heel-Strike
Left Toe-Off
Right Heel-Strike
Right Toe-Off
Intersection point

Figure 4

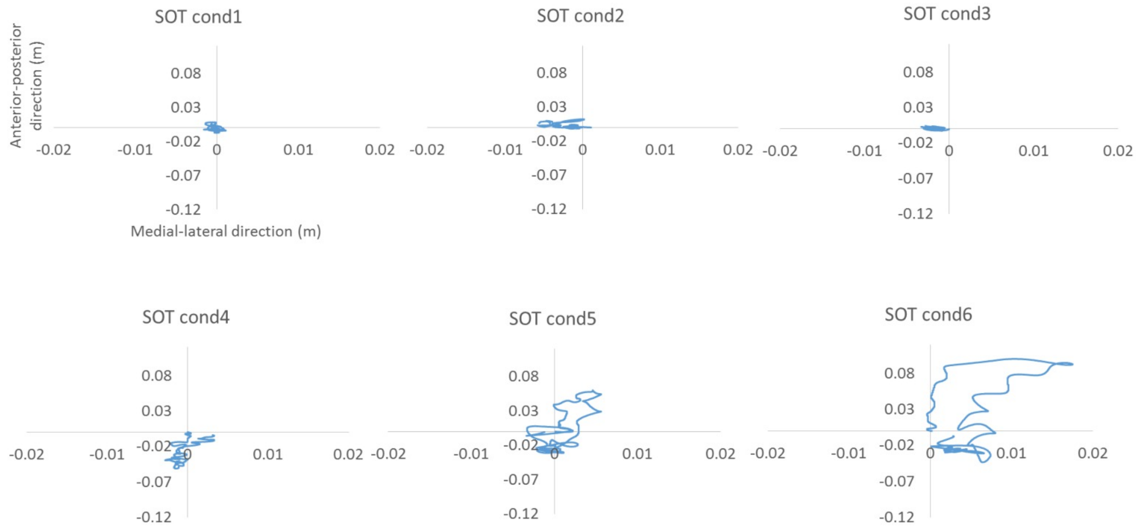

SOT cond1
SOT cond2
SOT cond3
SOT cond4
SOT cond5
SOT cond6
Anterior-posterior direction (m)
Medial-lateral direction (m)
0.08
0.03
-0.02
-0.07
-0.12
-0.02
-0.01
0
0.01
0.02

Figure 5

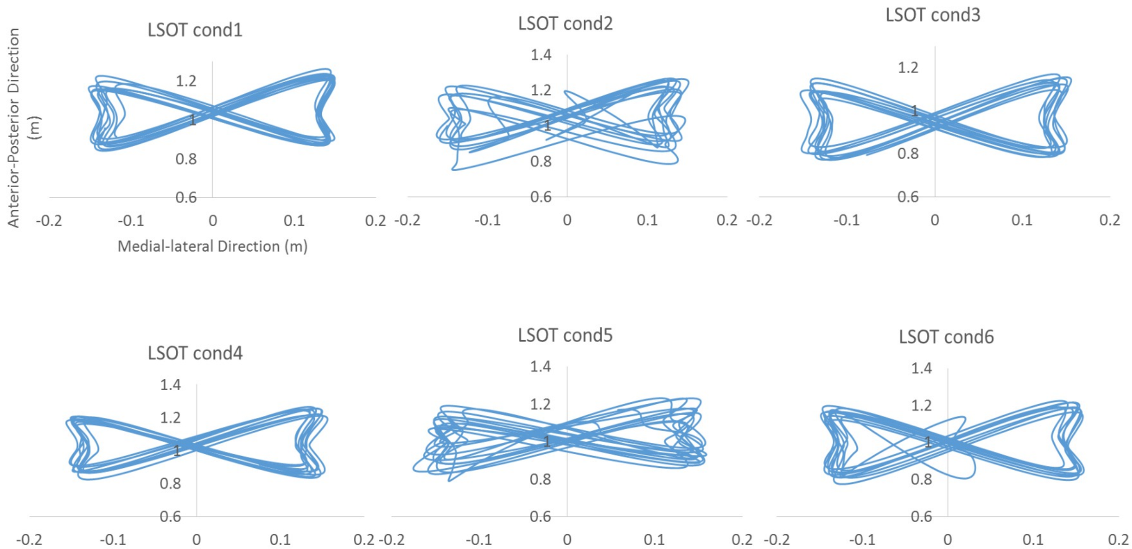

LSOT cond1
LSOT cond2
LSOT cond3
LSOT cond4
LSOT cond5
LSOT cond6
Anterior-Posterior Direction (m)
Medial-lateral Direction (m)
1.4
1.2
1
0.8
0.6
-0.2
-0.1
0
0.1
0.2

Figure 6