2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Can the Clinical Test of Sensory Integration and Balance Predict Performance in Perturbed Walking? *

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Abstract— **Human balance control is a critical prerequisite to nearly all activities, and human falls are a major health concern. The most robust way to assess reactive balance is to apply external perturbations. Perturbations are typically delivered with destabilizing motorized surfaces, external forces, visual motion, or neural stimulation. However, most devices that perturb walking in research settings are not likely to see wide clinical use due to cost, space, and time constraints. In contrast, there are low-cost destabilizing clinical tests that might require similar neural control mechanisms as walking. The present study examines and compares frontal plane balance responses with a research-based surface perturbation walking device to balance responses in a clinical standing balance assessment. We found that correlations between these walking and standing tests varied widely depending on the conditions compared. Correlations between standing and walking balance were highest when 1) a perturbation was present in walking tests, 2) subjects walked slowly, and 3) the standing tests were on foam as opposed to firm surface.**

Clinical Relevance— **This study helps to clarify the relationship between standing and walking balance. We use the clinical test of sensory integration in standing balance and a perturbation treadmill device to measure walking balance.**

I. INTRODUCTION

Every year, 800,000 patients are hospitalized due to fall injuries in the United States [1]. In 2015 alone, the total medical costs for falls exceeded $50 billion, and Medicare and Medicaid shouldered 75% of these expenses [2]. Older people are particularly vulnerable, as 1 in 3 people over the age of 65 experience a fall each year [3]. As the global population ages, total falls and fall severity are also increasing. Between 2007 and 2016, the fall death rate from falls in older adults in the United States increased 30 percent [1]. As the general population continues to age and technological advances forecast a future in which medical interventions could substantially reduce this risk, the geriatric industry has launched a conscientious effort to both better understand balance and to identify clinical measurements and tests which accurately predict an individual's risk for suffering a fall.

Balance control is generally defined as one's ability to maintain upright posture against gravity and in response to perturbations. Balance relies on sensory feedback and passive stiffness and damping from muscles and tendons [4]. Falls are most common when walking, navigating stairs, and transitioning [5,6]. Since walking straight ahead over level terrain is neither challenging nor representative of real-life fall scenarios, treadmills that can add perturbations to walking have become an emerging method to train and assess dynamic balance in such high-risk scenarios [7-11]. Moreover, perturbing balance is the most robust method to assess reactive balance control [12]. Perturbed walking devices often elicit balance responses in the frontal plane because the frontal plane is more associated with neural control [13] and linked to falls and hip fractures [14,15], which often lead to mortality [16].

However, these highly technical devices are not accessible to most clinical sites due to high costs, steep learning curves, and the time requirements to set up patients [11]. In contrast, clinical sites typically use balance assessments that rate patients' performance of several movement patterns and/or quiet standing under various conditions. One of the popular standing clinical tests is the clinical test of sensory integration and balance (CTSIB [17]). This tests generally challenges standing balance and requires subjects to shift reliance from one sensory system (i.e., modality) to another depending on the test condition. The different CTSIB tests assess vision, vestibular, and somatosensory reliance.

The balance mechanisms used in standing may differ from walking. In walking, base of support is changing with each step and the center of mass is rhythmically moving in and out of the base of support in a "continual state of imbalance" [18]. But in standing, center of mass motion is smaller and remains within the stationary base of support (i.e., both feet on the ground). Previous investigations relating anterior-posterior perturbed walking to standing have reported disparate results [9-10]. When focused on the frontal plane, a systematic review found evidence linking increased medial-lateral sway in standing with falls [15]. While this supports the importance of frontal plane balance, it provides no mechanistic information because falls at home substantially differ in direction, circumstance, and cause. One research team showed walking participants were more sensitive to visual feedback for balance in the frontal plane compared to the sagittal plane [13]. But the relation across walking balance, standing balance, and sensory integration is unknown.

Therefore, in the current study we examine the relation between standing balance (CTSIB) and walking balance with and without a perturbed treadmill system in the frontal plane. Because the standing conditions include a variety of sensory manipulations and our walking paradigm includes three gait speeds, results in the current study will also provide greater insight into the factors that can increase or decrease the relationship between walking and standing balance. Understanding this relationship will help us better interpret balance metrics in perturbed walking and better understand the benefits and limitations of standing balance tests that are widely used in the clinical setting.

*Research supported by Department of Defense grant W81XWH-19-1-0870 (PI: Goodworth)

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II. Methods

A. Subjects

Twelve healthy subjects participated (5 males, 7 females, and mean age of about 28 years). Subjects had no history of orthopedic impairment in the last 6 months and no known balance disorders. Subjects provided written informed consent. All tests were approved by the Institutional Review Board at the University of Hartford.

B. Protocol

Subjects performed a total of 12 walking balance tests and 6 standing balance tests.

Walking tests. The walking balance tests were described in detail previously [19]. In summary, walking balance tests included various gait speeds and medial-lateral perturbation conditions using a treadmill mounted on a rotating platform (Fig. 1). All subjects were instructed to walk and respond naturally to any movements of the platform. Subjects crossed their arms over their chest in a comfortable walking style. Limiting arm reactions allowed us to better isolate the balance response in the trunk, although we acknowledge swinging arms is common in gait. Subjects wore headphones that played a story to eliminate background noise and normalize cognitive contributions. Each walking trial lasted 60 s. Prior to data collection, subjects were administered a warmup test on the treadmill with and without the perturbation to minimize any anxiety or early adaptations, and to select their comfortable walking speed.

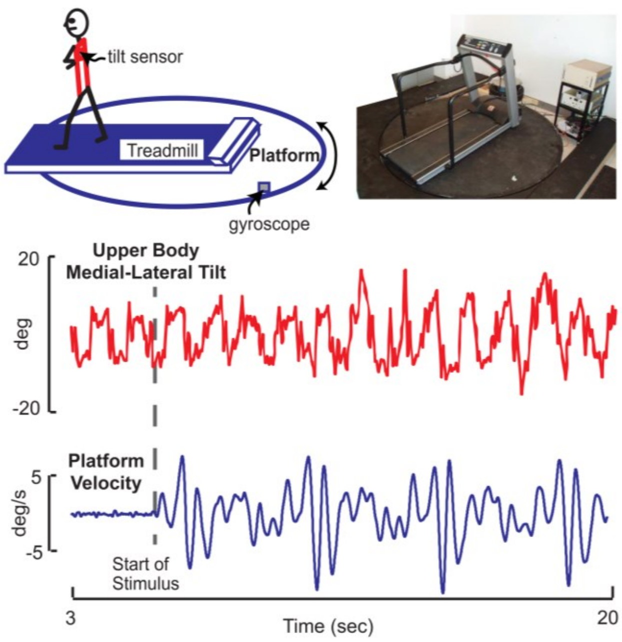

Figure 1. Sample data from one subject. The photo shows the perturbation treadmill system. The subject walked toward the platform edge and so that surface perturbations were primarily in the frontal plane. Medial–lateral (ML) body motion is shown at a chosen comfortable gait speed with perturbations. Upper body motion during non-perturbed conditions looked similar to the waveform in Figure 1 prior to the perturbation onset, and other perturbation conditions looked similar to the sample shown.

The 12 tests were randomly ordered and consisted of 2 different visual conditions, 2 perturbation conditions, and 3 gait speeds. The 2 visual conditions were selected to answer a different research question in our previous publication [19]. These conditions included looking down at one's feet while obstructing the superior peripheral visual field and looking straight ahead. In the current study, the correlation trends were similar between visual conditions, so we took the mean between the two visual condition trials to increase confidence in our metrics of walking balance and to simplify the presentation of results.

Subjects self-selected a "comfortable" walking speed which we limited to be between 0.9 and 1.0 m/s. Then 0.14 m/s was added and subtracted to the chosen speed to determine each subject's fast and slow gait speeds, respectively. The combination of limiting the comfortable walking speed and adding / subtracting 0.14 m/s was a feasible way for all subjects to walk at distinct and evenly spaced speeds. Without this, our pilot studies indicated that some subjects wanted to jog at higher speeds or walk unnaturally at lower speeds.

The two perturbation conditions were either "no perturbation" (NP), whereby the treadmill remained stationary, or "with perturbation" (WP), whereby the platform rotated about the vertical axis. The perturbations were initiated by a sum of 5 sine waves (0.5, 1.0, 1.5, 2.0, 2.5 Hz) with decreasing amplitude at higher frequencies. This motion appeared random to the subjects. Subjects were positioned on the treadmill 0.85 m away from the center of the platform. At this location, the perturbation was primarily a frontal plane surface translation with peak-to-peak displacement of 0.032m and peak velocity of 0.14 m/s.

In each test, kinematics in the frontal plane were measured using an accelerometer-based dual-axis tilt sensor (Crossbow, CA). The sensor was secured between the two scapulae at the level of the T7 vertebrae. The sensor output approximated the tilt with respect to vertical. The root-mean-square (RMS) of this kinematic tilt variable was defined as the dependent variable in walking. Larger RMS values represent greater body motion.

Standing tests. During standing tests, subjects performed the Clinical Test of Sensory Integration on Balance (CTSIB) with their arms crossed. This test included six trials lasting 90s each: 1) eyes open on a firm surface (*EO firm*); 2) eyes closed on a firm surface (*EC firm*); 3) eyes open on foam surface (*EO foam*); 4) eyes closed on foam surface (*EC foam*); 5) dome headpiece on a firm surface (*dome firm*); and 6) dome headpiece on foam surface (*dome foam*). The dome was placed over subjects' heads and included a horizontal and vertical line on the interior to provide subjects with a visual reference frame that matched their head orientation and not earth vertical (Fig. 2). In contrast to eyes closed, when looking into a dome, subjects may rely on visual feedback, but this visual feedback is not useful for balance because the visual cues do not change with body sway.

These conditions tested sensory integration for balance because the different surfaces and visual availability required subjects to shift reliance to different sensory systems.

Reliance on somatosensory feedback is expected to be fairly high when standing on the firm surface while reliance on vision and vestibular is expected to increase when standing on foam. Specifically, reliance on vestibular feedback increases in *EC foam* and *dome foam* tests. Reliance on both vision and vestibular increases in *EO foam*.

In standing tests, tilt sensors were attached to the upper trunk at subjects' seventh cervical vertebrae and to their hip at the greater trochanter. Center of mass (CoM) motion was estimated using anthropometrics [20]. The CoM RMS tilt with respect to vertical was calculated from sensor outputs and defined as the dependent variable in standing.

C. Analysis

To compare walking to standing balance, Pearson's correlation coefficients were used between dependent variables for each combination of the 6 standing and 6 walking trials. We defined correlations 0-0.1 as zero, 0.1-0.4 as weak, 0.4-0.7 as moderate, and 0.7-0.9 as strong [21]. A high correlation for any combination indicates that the subjects who swayed more on that particular standing trial also swayed more on that particular walking trial.

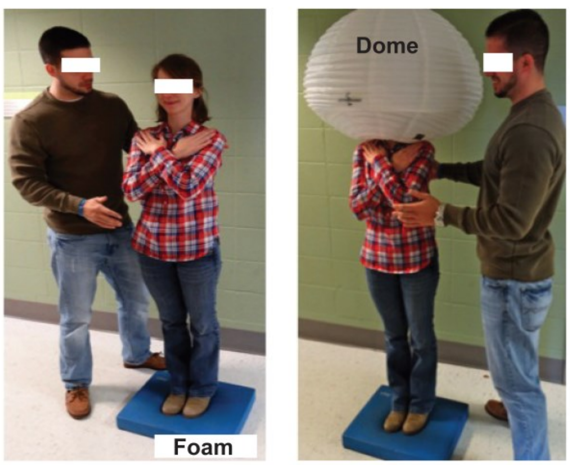

Figure 2. Protocol for foam and dome test.

III. Results

Figure 1 also illustrates sample trunk data in the frontal plane. The trunk naturally tilts right and left during gait, but this increases in magnitude after the onset of the platform motion. Figure 3 shows a sample of four correlations between standing and walking balance tests. The horizontal axis is the RMS trunk tilt during non-perturbed (left) and perturbed (right) walking. The vertical axis is the RMS CoM tilt during the standing tests. Strong and moderate correlations were found between standing and walking when subjects' walking was perturbed, but correlations ranged from zero to weak for non-perturbed walking.

Table 1 displays R-values for all the test combinations. This table points out a few clear trends. First, correlations varied greatly across conditions. Second, correlations were much higher in conditions with perturbed versus non-perturbed walking. Figure 4 shows that the average R-value between walking and standing balance was moderate (0.4) with perturbations but was close to zero (0.06) without perturbations (left two bar graphs). Third, in walking with perturbations (bottom three rows), we found a monotonic increase in R-values with decreasing gait speed for all 6 standing test conditions (all 6 columns). When averaged across all standing conditions, R-values between standing and perturbed walking were 0.57, 0.44, and 0.33 for slow, comfortable, and fast walking, respectively. Finally, correlations were highest between standing and perturbed walking in standing conditions that required subjects to shift reliance away from somatosensory feedback (i.e., foam conditions). In WP trials, R-values were moderate (0.53) when subjects stood on foam but were weak (0.33) when standing on a firm surface. Across all walking trials, the average R-value was 0.32 for foam and 0.15 for firm. Moreover, the highest correlations consistently occurred in the standing condition most associated with vestibular reliance (*EC foam*, 5th column).

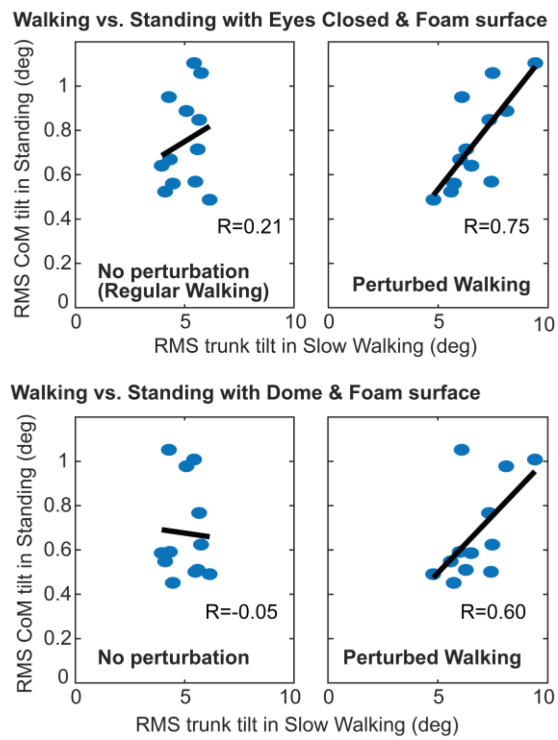

Figure 3. Sample correlations between standing and walking. Results show some of the highest correlations, which were found during slow perturbed walking.

R-Values	EO Firm	EC Firm	Dome Firm	EO Foam	EC Foam	Dome Foam
Slow NP	-0.07	-0.27	-0.03	0.12	0.21	-0.05
Comf NP	0.01	-0.21	-0.04	-0.04	0.31	.003
Fast NP	0.09	-0.15	-0.02	-0.02	0.35	-0.06
Slow WP	0.32	0.34	0.47	0.47	0.75	0.60
Comf WP	0.26	0.21	0.28	0.28	0.51	0.52
Fast WP	0.20	0.05	0.20	0.20	0.46	0.35

Table. 1. Summary table of R-values. "Comf" stands for the subjects' comfortable self-selected speed. Fast and slow treadmill speeds were determined by adding and subtracting .14 m/s from this value. NP stands for no perturbation and WP stands for with perturbation.

IV. Discussion

The present study found that correlations between walking and standing balance depended greatly on which conditions were examined. It was not possible to simply state that *walking balance was or was not correlated with standing* because correlations ranged from zero to strong, depending on the combination of trials considered. This underscores the importance of considering the various sensory and motor requirements when measuring balance and interpreting kinematics.

Correlations were much higher in WP trials than in NP trials. Moreover, these correlations were even higher when standing on foam. This implies that the balance requirements for standing on foam shared similarities with those in the perturbed walking conditions, consistent with conclusions from a previous study with anterior-posterior perturbations [10]. Additionally, the foam tests required more reliance on vision and vestibular feedback, and it is therefore reasonable to hypothesize that subjects also used visual and vestibular during walking tests.

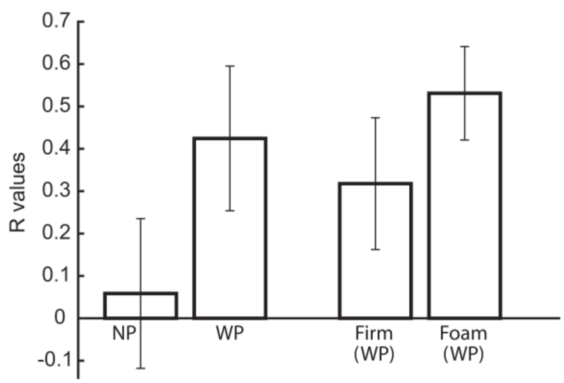

Figure 4. Average correlations for key comparisons. Left graphs compare no perturbation (NP) to with perturbation (WP) for all standing tests. The right two graphs show average R-values for standing tests on a firm versus foam surface for all with perturbation tests. The error bars represent 1 SD.

Additionally, the foam tests required more reliance on vision and vestibular feedback, and it is therefore reasonable to hypothesize that subjects also used visual and vestibular feedback to a greater extent during perturbed walking versus regular non-perturbed walking. Increased reliance on vision and vestibular during challenging balance conditions is consistent with many previous studies [4,19,22].

The highest correlations between standing and walking occurred during the standing conditions most associated with reliance on vestibular (*EC foam*). Subjects who swayed the most on foam with EC were most negatively impacted by the surface perturbations during walking. Interestingly, two subjects exhibited a vestibular nystagmus after the walking tests were concluded. This implies that something in the walking tests interacted with the vestibular system in a significant way for these subjects, consistent with the correlation finding. These subjects may have had a subclinical vestibular degradation [23].

Finally, we found correlations were higher when subjects walked at a slower speed. This finding suggests balance mechanisms may be on a continuum where balance control during slower walking begins to approximate standing. Gait speed is an important clinical measure for older individuals who typically walk slower than younger adults.

Limitations of this study include: 1) a fairly small and narrow population. A more clinically relevant population may include older adults, amputees, and those with neurological disorders. 2) limited kinematics and perturbation conditions were measured. For example, stepping characteristics were not measured nor was direct tripping induced, which may be more critical in the sagittal plane [9-11,24]. 3) we did not investigate the relation between weight and pad compression. Since our pad was a 6.4 cm high Airex balance pad, we do not anticipate major changes across weight as no subjects “bottomed out.” We can estimate that most subjects compressed the pad less than 25% since this percent reduction is associated with an 881 N force corresponding to about 89 kg person [25].

V. Conclusion

The results imply certain standing balance tests may approximate balance during perturbed walking in the frontal plane. The relation between standing and walking tests were stronger in 1) slow walking compared to fast walking, 2) walking with a perturbation compared to walking without a perturbation, 3) standing on foam compared to a firm surface, and 4) standing with altered vision compared to eyes open. These finding suggests that robust vestibular feedback is important to compensate for frontal plane perturbations in walking.

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