



Integrated testing of standing balance and cognition: Test–retest reliability and construct validity



Tony Szturm^{a,*}, Vedant Sakhalkar^{a,1}, Sue Boreskie^{b,2}, Jonathan J. Marotta^{c,3},
Christine Wu^{d,e,4}, Anuprita Kanitkar^{a,1}

^a School of Medical Rehabilitation, University of Manitoba, Canada

^b Reh-Fit Centre, Winnipeg, MB, Canada

^c Department of Psychology, University of Manitoba, Canada

^d Department of Mechanical Engineering, University of Manitoba, Canada

^e Department of Manufacturing Engineering, University of Manitoba, Canada

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ABSTRACT

Balance and cognitive impairments which are common with aging often coexist, are prognostic of future adverse health events, including fall injuries. Consequently, dual-task assessment programs that simultaneously address both stability and cognition are important to consider in rehabilitation and benefit healthy aging. The objective of this study was to establish test–retest reliability and construct validity of a dual-task computer game-based platform (TGP) that integrates head tracking and cognitive tasks with balance activities. Thirty healthy, community-dwelling individuals median age 64 (range 60–67) were recruited from a certified Medical Fitness Facility. Participants performed a series of computerized head tracking and cognitive game tasks while standing on fixed and sponge surfaces. Testing was conducted on two occasions, one week apart. Moderate to high test retest reliability (ICC values of 0.55–0.75) was observed for all outcome measures representing balance, gaze performance, cognition, and dual-task performance. A significant increase in center of foot pressure (COP) excursion was observed during both head tracking and cognitive dual-task conditions. The results demonstrate the system's ability to reliably detect changes related to specific and integrated aspects of balance, gaze, and cognitive performance.

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1. Introduction

As people live longer, they become increasingly vulnerable to the effects of sedentary lifestyles and chronic disabilities [1]. For example, balance and cognitive impairments are common with aging, often coexist, cause reductions in the levels of physical and

mental activities and are prognostic of future adverse health events, including fall injuries [2–4]. It is known that the tactile, vestibular and visual function and sensory processing that are relevant for balance control can be adversely influenced by aging [5–7]. Tools, such as the Sensory Organization Test (SOT), have been used to challenge specific sensory systems and to assess how well an individual integrates different sources of spatial information during balance [8,9]. Visual and vestibular coordination is also very important for gaze control in order to accommodate and adapt to target, head and body motions [10].

Dual-task assessment protocols that combine motor tasks and cognitive activities are also clinically relevant. Studies have demonstrated that the use of these more challenging dual-task conditions for evaluating balance control are necessary for the identification of older people who are at an elevated risk of falls [11,12]. Thus, we extended the protocol of Desai et al., 2010 [13] and others [14] to develop an assessment system that uses a computer controlled head tracking tasks and cognitive games. The test incorporates features of the Clinical Test of Sensory Interaction

* Corresponding author at: Department of Physical Therapy, School of Medical Rehabilitation, R106 – 771 McDermot Avenue, Winnipeg, MB R3E 0T6, Canada. Tel.: +1 204 787 4794; fax: +1 204 787 1227.

E-mail addresses: tony.szturm@med.university.ca (T. Szturm), vedant.sak@gmail.com (V. Sakhalkar), sue.boreskie@reh-fit.com (S. Boreskie), Jonathan.Marotta@umanitoba.ca (J.J. Marotta), cwu@cc.umanitoba.ca (C. Wu), anuprita.kan@gmail.com (A. Kanitkar).

¹ Medical Rehabilitation, School of Medical Rehabilitation, University of Manitoba, Winnipeg, Canada.

² MPE CSEP-CEP, Reh-Fit Center, Winnipeg, MB, Canada.

³ Department of Psychology, University of Manitoba, Canada.

⁴ Department of Mechanical and Manufacturing Engineering, University of Manitoba, Canada.

in Balance (CTSIB) [15]. The CTSIB uses a compliant sponge as an unstable support surface to emulate the SOT in terms of somatosensory distortion [15,16].

The computer-based gaming platform provides an integrated approach to evaluating balance, gaze stability, executive cognitive functions, either singly or in combination (dual-task). Dynamic visual acuity tests in which the target is stationary has been extensively studied, but little work has been performed on gaze control with both target and head motion. Most dual-task assessment protocols have utilized general cognitive tasks, such as animal enumeration or number subtraction, that are typically only assessed qualitatively, and do not involve visual-spatial processing [3,4,17,18].

The first objective of the present study was to establish test-retest reliability of outcome measures that represent balance, gaze stability, and cognition as examined in single and dual-task conditions. We hypothesized that the performance measures of balance, gaze and cognition would exhibit moderate to high test-retest reliability during the single and dual-task test conditions. The secondary objectives were to examine the construct validity of the computerized protocol, to evaluate the potential interaction effects that visuo-motor and cognitive loads have on stability. We expected to find that increased head tracking demands and cognitive load would increase body sway.

2. Methods

2.1. Participants

Thirty adults participated, median age of 64 years (range 60–67) who attended the Reh-Fit Center in Winnipeg, MB for exercise. The participants were living independently in the community, were able to walk outside without any walking aids, and had no self-reported history of falling. Exclusion criteria included histories of neurological or musculo-skeletal disorders (e.g., stroke, hip/knee joint surgery, and uncorrected visual impairments). All participants provided written consent, and the study was approved by the University of Manitoba human research ethics committee.

Prior to testing, each participant completed a 6-minute walk test on a 300-meter track, and the average walking speed was determined over a 25-meter distance.

2.2. Tests and Instrumentation

The experimental test protocol consisted of the following tasks, which were performed in a standing position for 45 s on a fixed floor surface and then repeated while standing on the compliant sponge surface; (a) eyes open (EO) and eyes closed (EC), (b) a head tracking task, and (c) two visual-spatial cognitive tasks. The tasks were repeated after a period of seven days.

Fig. 1 illustrates the experimental set-up. Participants stood on a treadmill (with hand rails and an overhead body support system) at a viewing distance of 100 cm from an 80 cm computer monitor. As described by Desai et al., 2010 [13], a 50.8 cm × 50.8 cm × 10.16 cm sponge pad was used with a density of 22.66 kg/m³ and a 25% IFD of 13.64 kg was used. A 25.4 cm × 40.64 cm × 1.91 cm wooden board was placed on top of the sponge to distribute the forces and to provide a solid flat surface for placement of the pressure mat. A pressure-sensing mat (Vista Medical Ltd., Canada) was used to compute the center of foot pressure (COP) position. The pressure mat consisted of an array of 256 piezo-resistive sensors (16 by 16), and each sensor covered a surface area of 2.8 cm². Each sensor was sampled at 30 Hz, and the vertical COP in the anterior-posterior (AP) and medial-lateral (ML) dimensions were computed [13,15].

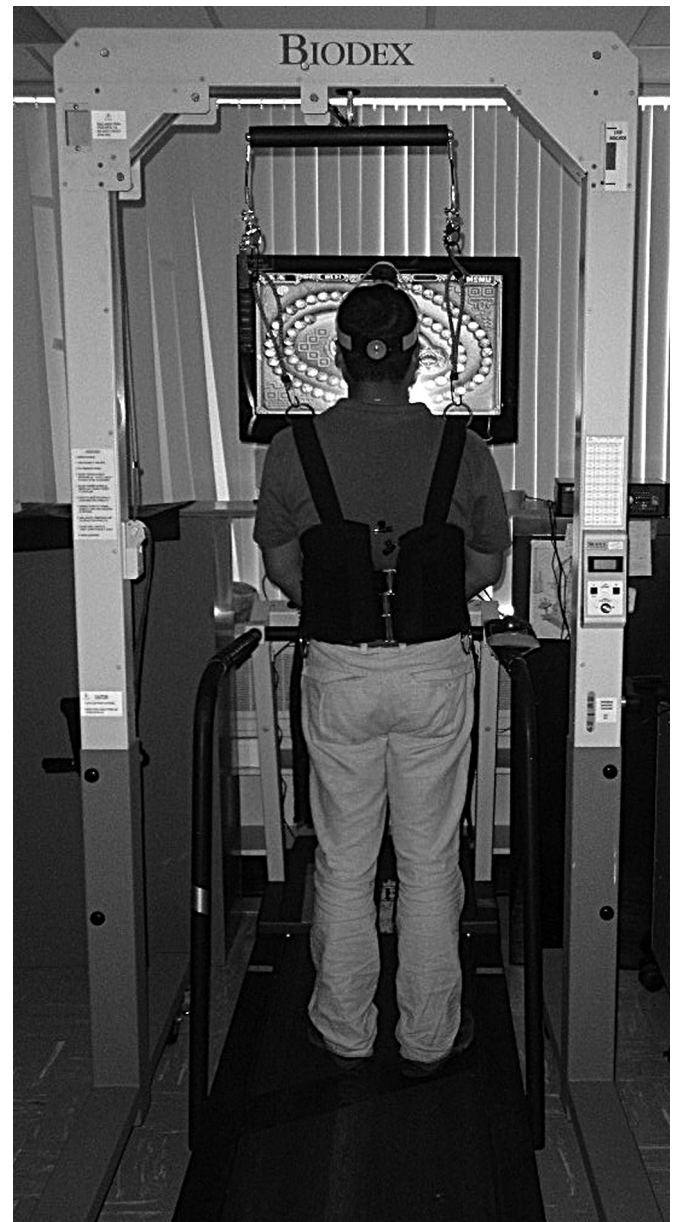


Fig. 1. Experimental setup. Participant is shown standing on the treadmill while viewing a computer monitor and wearing head band with motion mouse (head rotation) to interact with computer tracking and cognitive tasks.

A computer application with the following two assessment modules was developed:

- 1. Head tracking module:** This test involved tracking a visual target that moved horizontally left and right on a computer display for several cycles. Two cursors of different shape appear on the monitor. One was the target cursor (computer controlled), which moved at a predetermined frequency of 0.5 Hz with an amplitude of 80% of the monitor width. The second cursor was slaved to head rotation via a head-mounted wireless motion sense mouse (Gyration, SMK-LINK Electronics, USA). It uses inertial sensors to derive angular displacement, and functions in a manner identical to a standard computer mouse. Velcro secures the motion mouse to a headband and with this simple method head yaw rotation is required to control motion of the on-screen cursor. This

simple method can make seamless and responsive hands-free interaction with most computer applications possible [20,21]. During the head tracking task participants were instructed to move and overlap the head controlled cursor with the moving “target cursor” (computer controlled). At a viewing distance of 100 cm, the task required 80 degrees of head rotation to move the cursor from the left to the right edges of the monitor. At a frequency of 0.5 Hz, this equated to an average head rotation velocity of $80^\circ/s$ and a peak velocity of $120^\circ/s$. The goal of the task was to maintain the overlap of the two cursors as the target cursor moved.

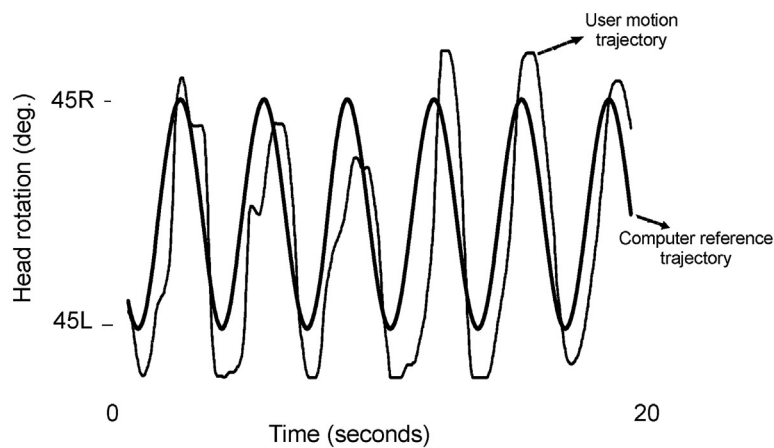
The tracking tasks were performed for 45 s while the participant stood on the fixed and sponge surfaces. The computer application also generated a logged data file to record coordinates of the target cursor and the head rotation at 80 Hz. This was used for offline analysis as described below.

2. **Cognitive game module:** A number of recent studies have used computer games to evaluate visual spatial perception, processing speed, and cognitive interference [22,23]. One such test is

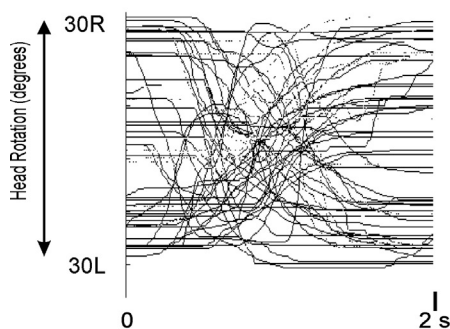
the Useful Field of View (UFOV), which is a validated, computer-based test that requires visual search mechanisms and the ability to select relevant information and ignore irrelevant information [24,25]. Similarly, the goal of the cognitive game of the present study was to move a paddle (the game sprite) to interact with moving objects (the speed of these objects was pre-programmed). During this task, head rotation (motion mouse) was used to move the game paddle. The task complexity was configurable such that it could be simple and involve a single target or more difficult and involve additional target objects to catch with distracter objects to avoid. The application generated a logged data file that synchronously recorded (80 Hz sampling rate); (i) the time index and position coordinates of each game object as it appeared and (ii) the coordinates of the game paddle, (slaved to head rotation) and represented the participant's actions and choices.

Prior to testing, the participants were allowed to play the tracking and game tasks while sitting for a few minutes to become familiar with each task.

A. Trajectories of computer target and head rotation



B. Segmented game events



C. Sorted game events

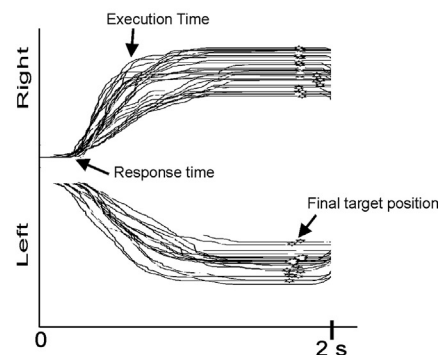


Fig. 2. Panel A presents synchronous plots of the reference (computer) cursor motion and user head rotation trajectories for a typical tracking task. Maxima are right most position and minima left most position. Panel B presents overlay plots of head rotation trajectories of individual segmented game events obtained from one game session. Time zero is onset of target appearance (event onset); end of event is time when target disappears plus 500 ms to examine overshoot. Shown are game movements for left and right direction, medium and large amplitudes. Panel C segmented game events shown in B are sorted by direction and amplitude and similar game movements are placed into one plot. In this case medium amplitude movements in leftward direction (upward trajectories), and rightward direction (downward trajectories). Arrows indicate response time and movement time to illustrate analysis methods.

2.3. Data analysis

- 1. Head tracking performance measures:** The position data of the computer target and the user's cursor (head horizontal rotation) were used to compute gaze performance. Fig. 2A presents synchronous plots of target and head cursor trajectories for a typical tracking task. A least squares algorithm was used to obtain a sine-wave function of the target waveform. Head rotation trajectories were fit to the sine-wave function, and the coefficient of determination (COD) was computed based on total and average residual difference between the trajectories of the target and head cursor motions. Values approaching one equate to perfect overlap of the two cursors and excellent gaze performance. The first two cycles of the tracking tasks were excluded to allow the participants' time to acquire the moving target and begin tracking. MATLAB (The MathWorks, Natick, MA, version 2010a) was used to compute the COD.
- 2. Cognitive performance measures:** Fig. 2B presents the overlay trajectories (head rotation) of the individual head pointing movements for each game event obtained from one game session. Each game event was 1.5 s in duration from target appearance to target disappearance. Different features of the segmented game movements provided a basis for the quantification of cognitive functions. For a detailed description of the game movement segmentation and analysis of the individual contextual game events see Lockery et al. 2011 [27] and Szturm 2013 [20]. As illustrated in Fig. 2B, the following variables, averaged over left and right game movements of medium amplitude, were determined; (a) average response time; i.e., the time from the appearance of the target to start of the paddle movement, (b) average movement execution time; i.e., the time from beginning of the movement to the final location (plateau). The game success rate was also determined as the percentage of target objects that were caught.
- 3. Balance performance measures under altered sensory and cognitive conditions:** The root mean squared (RMS) ML-COP and AP-COP excursions dimensions were computed for each task. Increases in RMS COP were interpreted as decreases in stability [28,29].

2.4. Statistical analyses

Test retest reliability: Relative reliability was assessed using a two-way random model intra-class correlation coefficient (ICC). Absolute reliability was analyzed using the standard error of measurement [SEM] [30,31]. The ICC scores were interpreted as high when equal to or greater than 0.70, as moderate between 0.5 and 0.69, and as low when less than 0.50 [32]. Systematic errors between the test periods were evaluated using *t*-tests.

Construct validity was evaluated using a repeated measures ANOVA to compare results of the single task and dual task conditions. For balance outcomes the single task condition is eyes open and the dual task condition is the head tracking and cognitive game task. For head tracking and cognitive game outcomes, the single task condition is when performed in standing on fixed surface and the dual task condition is when performed on the sponge surface.

SPSS software for Windows, version 20.0 (SPSS Inc., Chicago) was used for all statistical analysis procedures.

3. Results

Twenty-four females and six males participated. The median age was 64, range 60–67. The group average gait speed was 1.2 m/s (± 0.14), and the average distance walked in 6 min was 562 m (± 98).

Fig. 3 presents representative X–Y plots of the COP excursion and corresponding plots of the head tracking and cognitive game trajectories for the different test conditions. As illustrated in this figure, as the task demand increased, a progressive

increase in COP excursion was observed. The differences observed in the head tracking and cognitive game trajectories between the fixed and sponge surface conditions were minimal.

3.1. Test–retest reliability

Table 1 presents results of the test–retest reliability analyses of the COP measures. ICC scores for both the AP and ML RMS COPs were high to moderate during the eyes open and closed conditions. High to moderate ICC scores were also observed during the head tracking and cognitive game task conditions. The standard errors of measure (i.e., the SEMs normalized to group mean values) were similar in most conditions, and the values ranged from 8% to 12%. Based on the *t*-test analyses, no systematic errors in the COP excursion measures were observed between the test sessions.

As presented in Table 2, the ICC scores for gaze performance were moderate. The standard error of measure was 10%. The results of the *t*-tests revealed no significant differences in gaze performance between the two test periods.

As presented in Table 2, the ICC scores for the cognitive performance measures ranged from high to moderate. The standard error of measure ranged from 6% to 12%. The results of the *t*-tests revealed no significant differences in the cognitive performance measures between the two test periods.

3.2. Construct validity

When tested on the fixed surface there was no significant difference in COP excursion between eyes open and the dual-task conditions (head tracking or cognitive game task). However, when tested on the sponge surface the addition of either the head tracking or cognitive game tasks resulted in significant increases in COP excursion. Table 1 presents the group-mean (SD) RMS COP excursion values for the sponge surface. The main effect of head tracking on AP-COP excursion was $p < 0.001$ ($f = 24$, $df = 2, 28$), and that for the ML-Cop was $p < 0.001$ ($f = 41$, $df = 2, 28$). The main effect of the cognitive game task on the AP-COP excursion compared to the eye open condition was $p < 0.001$ ($f = 54$, $df = 2, 28$), and that for the ML-COP condition was $p < 0.001$ ($f = 34$, $df = 2, 28$). There was no significant difference in COP excursions between the target-only and target-plus-distracter conditions. There was no significant effect of surface condition on gaze performance.

Regarding the cognitive game tasks, there was a significant decrease in success rate when they were performed on the sponge surface compared to fixed surface ($p < 0.01$, $f = 9.6$, $df = 2, 28$). The success rate in the target-only condition was decreased from 95% when performed on the fixed surface to 87% on the sponge surface, and for the target-plus-distracter condition it decreased from 87% to 82%. There were no significant effects of surface condition on response or execution times. However, a significant increase in response time was observed when the distracter was added ($p < 0.01$, $f = 8.7$, $df = 2, 28$). The response time in the target-only condition was 0.421 s (± 0.042 s), and increased to 0.495 s (± 0.054 s) during the target plus distracter condition.

4. Discussion

This study illustrates the utility of the computer-based assessment tool. The moderate-to-high ICC values, SEMs less than 12%, and lack of systematic errors in the measures indicate that this tool has the ability to repeatedly record reliable data from the community of active older adults. Significant effects of the dual-task conditions on balance performance were observed for both the head tracking and cognitive games.

Lin et al. (2008) [33] reported high ICC values (0.77–0.9) for COP excursion measures while participants were standing on a fixed surface with their eyes open or closed. Similar ICC values have been reported when tested on a sponge surface [38]. Other studies have reported lower ICC reliability values for standing balance performance as task difficulty was increased. Pang et al., (2011) [8] examined the test–retest reliability of healthy older adults (mean age 60.3) during the head-shake SOT. The ICC values were 0.64 during the SOT condition 2 (i.e., eyes closed, fixed surface) and decreased to 0.55 during the SOT condition 5. The National Institute of Health supported the development of an objective test of standing balance as part of its motor function test battery [34]. The test–retest reliability was examined in healthy adults aged 18–85 ($n = 101$). The ICC values for balance performance were found to be greater on a fixed surface than on a sponge surface (0.86 versus 0.74, respectively). In the present study, comparable moderate-to-high ICC values were observed in the eyes-closed sponge condition. Moderate-to-high ICC values were also observed

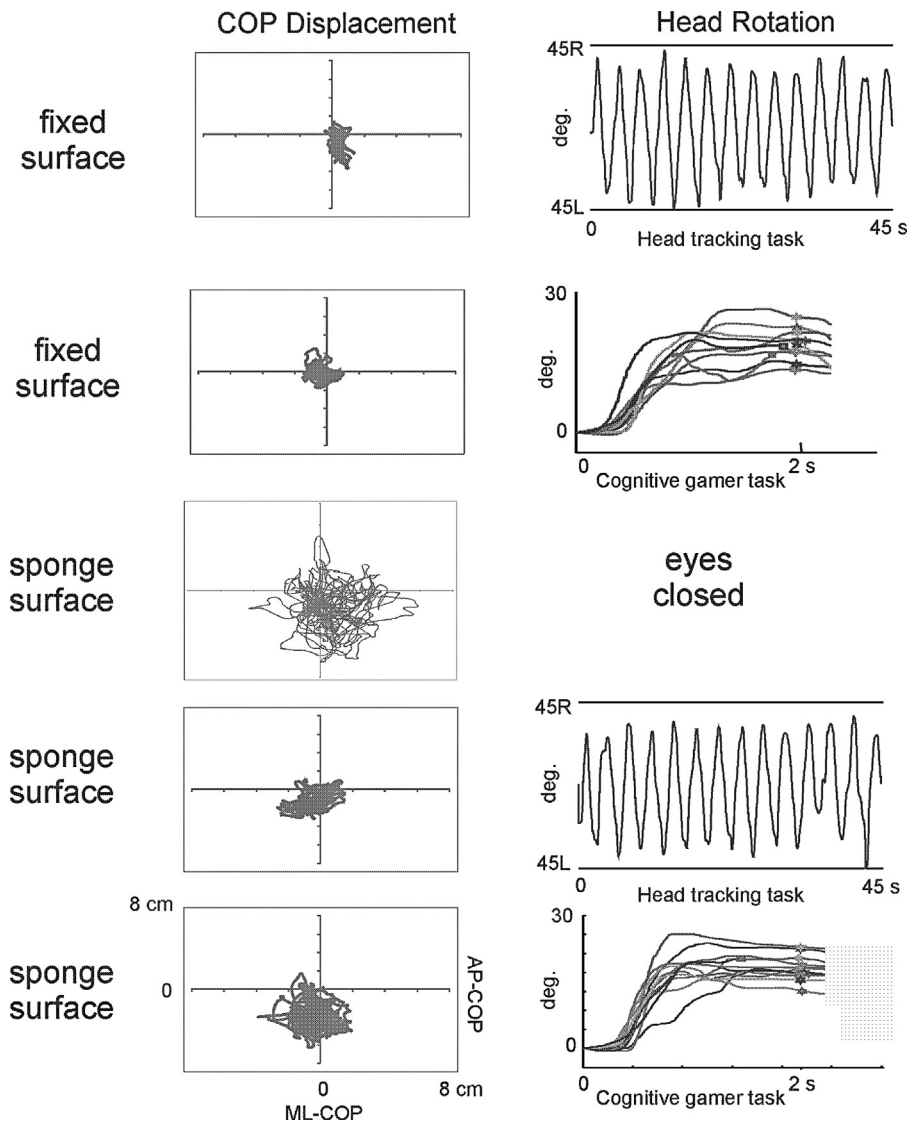


Fig. 3. Presents representative X–Y plots of ML-AP COP excursion and corresponding plots of head tracking trajectories and cognitive game trajectories for the different tasks. Also shown are plots of COP excursion for eyes open fixed surface and eyes closed sponge surface conditions.

for the head tracking and cognitive tasks, both of which combined target and head motions.

A number of studies have shown that, when two sensory inputs are eliminated or distorted, for example, in the sponge surface and eyes-closed conditions [13,35,36] or conditions 5 and 6 in the SOT [8,9], significant increases in body sway and loss of balance

Table 1
Results of statistical analysis, ICC, SEM and *t*-statistics for RMS of AP and ML-COP excursions obtained on sponge surface.

Conditions	ICC	SEM	Mean ± SD (test1)	Mean ± SD (test2)	<i>t</i> -Statistics
AP-EO	0.55	0.23	1.4 (0.3)	1.3 (0.25)	NS
AP-EC	0.6	0.4	5.08 (2.03)	5.33 (2.2)	NS
AP-HT	0.6	0.3	4.1 (1.22)	3.9 (1.27)	NS
AP-TO	0.7	0.2	3.5 (1.39)	3.9 (1.52)	NS
AP-T+D	0.6	0.4	4.06 (1.77)	4.3 (2.03)	NS
ML-EO	0.55	0.3	1.1(.07)	1.2 (0.7)	NS
ML-EC	0.6	0.4	3.8 (2)	3.3 (1.1)	NS
ML-HT	0.7	0.2	2.9 (1.04)	2.71 (0.68)	NS
ML-TO	0.6	0.2	2.4 (0.89)	1.9 (0.43)	NS
ML-T+D	0.55	0.2	2.5 (1.09)	2.0 (0.53)	NS

EO, eyes open; EC, eyes closed; HT, head tracking; TO, target only; T+D, target plus distractor.

frequently occur in older adult. Desai et al. (2011) [13] examined standing balance in a community of ambulatory older adults with and without histories of falls. The group with fall histories exhibited greater COP excursions and an increased frequency of loss of balance compared to the non-faller group when balance was assessed using an unsteady, sponge surface, but no difference was observed between the fallers and non-fallers when assessed on a fixed surface. The present results extend these findings and demonstrate that, in addition to the eyes-closed condition on the sponge surface, the COP excursions were significantly increased with the addition of the head tracking and cognitive game tasks. Other studies have also reported increased COP excursions when participants perform cognitive tasks that do not require head motion (i.e., a verbal Stroop test or a subtraction task) [14,37,38].

Several studies have measured dynamic visual acuity while sitting using stationary letters. Herdman et al. (1998) [39] observed high test–retest reliability (ICC of 0.87) in the dynamic visual acuity test (DVA). In a study by Rine et al. (2012) [19] a computerized version of the DVA was examined during active cyclic head rotations and confirmed via the feedback of a head-mounted inertial motion monitor. The test–retest reliability of the DVA test while sitting produced an ICC score of 0.58. Studies have

Table 2Results of statistical analysis, ICC, SEM and *t*-statistic for COD scores and cognitive performance measures performed on sponge surface.

	ICC	SEM	Mean ± SD (test1)	Mean ± SD (test2)	<i>t</i> -Statistic
Head tracking (COD)	0.6	0.08	0.80 (0.09)	0.79 (0.08)	NS
<i>Cognitive game</i>					
Target only					
Success rate%	0.6	2.2	90 (3.6)	92 (3.2)	NSS
Response time (s)	0.73	0.02	0.421 (0.04)	0.415 (0.038)	NS
Execution time (s)	0.65	0.04	0.505 (0.067)	0.96 (0.058)	Ns
Target + distractor					
Success rate%	0.6	2.5	87 (6.32)	91.93 (3.53)	NS
Response time (s)	0.7	0.03	0.495 (0.054)	0.499 (0.062)	NS
Execution time (s)	0.65	0.05	0.49 (0.088)	0.48 (0.096)	NS

shown that smooth pursuit becomes more difficult during head motion and when visual targets move large distances and at speeds approaching 1000 s^{-1} [40]. The present findings of high-to-moderate ICC scores extend the scope of the above studies to include moving visual targets and conditions of standing on a sponge surface, which results in increased body sway.

Most dual-task studies have utilized cognitive tasks such as number subtraction or animal enumeration [18,41]. However, the information about the dual-task effects on visual-spatial processing tasks is limited. Visual search tasks and the processing of object locations/trajectories and their spatial relations with respect to other objects and the body are key aspects of balance control and are aspects of cognition that are important for the risk of falls [17,42]. A visual-spatial cognitive task was used in the present study to examine dual-task effect. High-to-moderate test-retest reliabilities were observed for success rate, response time and movement execution time. Success rate was significantly reduced when tested on the sponge surface compared to the fixed surface; however, the response and execution times were not affected by the increased balance demands of the unstable surface. Temporal parameters, such as, response times and movement durations would not be the only factors that contribute to movement accuracy. Control of movement trajectory and other spatial parameters would also contribute to success rate.

The present assessment tool broadens the range of testing tools that have previously been reported by others and provides an integrated approach to the evaluation of balance, gaze stability, and specific executive cognitive functions, either singly or in combination (i.e., in dual-task conditions). Blended analyses of balance, gaze and cognition will contribute to a better understanding of the functional consequences of the decline in physical and mental skills that occurs with age and in the early stages of disease.

Author contributions

Tony Szturm, Vedant Sakhalkar: study concept and design; acquisition, analysis, and interpretation of data; preparation of manuscript.

Jonathan Marotta, Anuprita Kanitkar: study concept and design; and interpretation of data; preparation of manuscript.

Sue Boreskie, Christine Wu: analysis and interpretation of data, preparation of manuscript.

Sponsor's role

The sponsor had no involvement in any aspect of the research or in the preparation of this manuscript.

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References

- [1] Hirvensalo M, Rantanen T, Heikkinen E. Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. *J Am Geriatrics Soc* 2011;48(5):493–8.
- [2] Verghese J, Holtzer R, Lipton RB, Wang C. Quantitative gait markers and incident fall risk in older adults. *Series A Biol Sci Med Sci J Gerontol* 2009;64(8):896–901.
- [3] Herman T, Mirelman A, Giladi N, Schweiger A, Hausdorff JM. Executive control deficits as a prodrome to falls in healthy older adults: a prospective study linking thinking, walking and falling. *Series A Biol Sci Med Sci J Gerontol* 2010;65(10):1086–92.
- [4] Coelho FG, Stella F, de Andrade P, Barbieri FA, Santos-Galduroz RF, Gobbi S, et al. Gait and risk of falls associated with frontal cognitive functions at different stages of Alzheimer's disease. *Neuropsychol Dev Cogn Section B Aging Neuropsychol Cogn* 2012;19(5):644–56.
- [5] Peterka RJ. Sensorimotor integration in human postural control. *J Neurophysiol* 2002;88(3):1097–118.
- [6] Horak FB, Nashner LM, Diener HC. Postural strategies associated with somatosensory and vestibular loss. *Exp Brain Res* 1990;82(1):167–77.
- [7] Simmons RW, Richardson C, Pozos R. Postural stability of diabetic patients with and without cutaneous sensory deficit in the foot. *Diab Res Clin Pract* 1997;36:153–60.
- [8] Pang MY, Lam FM, Wong GH, Au IH, Chow DL. Balance performance in head-shake computerized dynamic posturography: aging effects and test-retest reliability. *Phys Ther* 2011;91(2):246–53.
- [9] Cohen H, Heaton LG, Congdon SL, Jenkins HA. Changes in sensory organization test scores with age. *Age Ageing* 1996;25(1):39–44.
- [10] Land MF. Eye movement and the control of actions in everyday life. *Retinal Eye Res* 2006;25:296–324.
- [11] Swanenburg J, de Bruin ED, Favero K, Uebelhart D, Mulder T. The reliability of postural balance measures in single and dual tasking in elderly fallers and non-fallers. *BMC Musculoskeletal Disorders* 2008;9: 162–2474–9–162.
- [12] Moghadam M, Ashayeri H, Salavati M, Sarafzadeh J, Taghipoor KD, Saeedi A, et al. Reliability of center of pressure measures of postural stability in healthy older adults: effects of postural task difficulty and cognitive load. *Gait Posture* 2011;33(4):651–5.
- [13] Desai A, Goodman V, Kapadia N, Shay BL, Szturm T. Relationship between dynamic balance measures and functional performance in community-dwelling elderly people. *Phys Ther* 2010;90(5):748–60.
- [14] Strang AJ, Haworth J, Hieronymus M, Walsh M, Smart Jr LJ. Structural changes in postural sway lend insight into effects of balance training, vision and support surface on postural control in a healthy population. *Eur J Appl Physiol* 2011;111:1485–95.
- [15] Betker AL, Moussavi ZM, Szturm T. On modeling center of foot pressure distortion through a medium. *IEEE Trans Bio-Med Eng* 2005;52(3):345–52.
- [16] Ransson PA, Gomez S, Patel M, Johansson L. Changes in multi-segmented body movements and EMG activity while standing on firm and foam support surfaces. *Eur J Appl Physiol* 2007;101(1):81–9.
- [17] Nagamatsu LS, Liu-Ambrose TY, Carolan P, Handy TC. Are impairments in visual-spatial attention a critical factor for increased falls risk in seniors? An event-related potential study. *Neuropsychologia* 2009;47(13):2749–55.
- [18] Al-Yahya E, Dawes H, Smith L, Dennis A, Howells K, Cockburn J. Cognitive motor interference while walking: a systematic review and meta-analysis. *Neurosci Bio-behav Rev* 2011;35(3):715–28.
- [19] Rine RM, Roberts D, Corbin BA, McKean-Cowdin R, Varma R, Beaumont J, et al. New portable tool to screen vestibular and visual function—national institutes of health toolbox initiative. *J Rehabil Res Dev* 2012;49(2):209–20.
- [20] Szturm T, Maharjan P, Marotta JJ, Shay B, Shrestha S, Sakhalkar V. The interacting effect of cognitive and motor task demands on performance of gait, balance and cognition in young adults. *Gait Posture* 2013;38(4): 596–602.
- [21] Szturm T, Marotta J, Wu C, Nayak A. Technology-assisted and motivational program for a blended approach to prevent and manage balance, gaze, mobility and cognitive decline with age. *OA Evidence-Based Med* 2013;11–8.
- [22] Jimison HB, McKanna J, Ambert K, Hagler S, Hatt WJ, Pavel M. Models of cognitive performance based on home monitoring data. *IEEE Eng Med Biol Soc Conf* 2010;5234–7.

- [23] McPherson J, Burns NR. Assessing the validity of computer-game-like tests of processing speed and working memory. *Behav Res Methods* 2008;40(4):969–81.
- [24] Ball K, Edwards JD, Ross LA. The impact of speed of processing training on cognitive and everyday functions. *J Gerontol Series B Psychol Sci Soc Sci* 2007;62 Spec No 1:19–31.
- [25] Wood JM, Chaparro A, Lacherez P, Hickson L. Useful field of view predicts driving in the presence of distracters. *Optometry Vision Sci* 2012;89(4):373–81.
- [27] Lockery D, Peters JF, Ramanna S, Shay BL, Szturm T. Store-and-feed-forward adaptive gaming system for hand-finger motion tracking in telerehabilitation. *IEEE Trans Inform Technol Biomed* 2011;15(3):467–73.
- [28] Lafond D, Duarte M, Prince F. Comparison of three methods to estimate the center of mass during balance assessment. *J Biomech* 2004;37(9):1421–6.
- [29] Santos BR, Delisle A, Lariviere C, Plamondon A, Imbeau D. Reliability of center of pressure summary measures of postural steadiness in healthy young adults. *Gait Posture* 2008;27(3):408–15.
- [30] Adsuar JC, Olivares PR, Parraca JA, Hernandez-Mocholi MA, Gusi N. Applicability and test–retest reliability of isokinetic shoulder abduction and adduction in women fibromyalgia patients. *Arch Phys Med Rehabil* 2013;94(3):444–50.
- [31] Weir JP. Quantifying test–retest reliability using the intra-class correlation coefficient and the SEM. *J Strength Condition Res* 2005;19(1):231–40.
- [32] Lexell J, Downham D. How to assess the reliability of measurements in rehabilitation. *Am J Phys Med Rehabil* 2005;84(9):719–23.
- [33] Lin D, Seol H, Nussbaum MA, Madigan ML. Reliability of COP-based postural sway measures and age-related differences. *Gait Posture* 2008;28(2):337–42.
- [34] Rine RM, Schubert MC, Whitney SL, Roberts D, Redfern MS, Musolino MC, et al. Vestibular function assessment using the NIH toolbox. *Neurology* 2013;80:25–31.
- [35] Teasdale N, Stelmach GE, Breunig A. Postural sway characteristics of the elderly under normal and altered visual and support surface conditions. *J Gerontol* 1991;46(6):B238–44.
- [36] Abrahamova D, Hlavacka F. Age-related changes of human balance during quiet stance. *Physiol Res* 2008;57(6):957–64.
- [37] Barra J, Bray A, Sahni V, Golding JF, Gresty MA. Increasing cognitive load with increasing balance challenge: recipe for catastrophe. *Exp Brain Res* 2006;174(4):734–45.
- [38] Moghadam M, Ashayeri H, Salavati M, Sarafzadeh J, Davatgaran K, Taghipoor D, et al. Reliability of center of pressure measures of postural stability in healthy older adults: effects of postural task difficulty and cognitive load. *Gait Posture* 2011;33:651–5.
- [39] Herdman SJ, Tusa RJ, Blatt P, Suzuki A, Venuto PJ, Roberts D. Computerized dynamic visual acuity test in the assessment of vestibular deficits. *Am J Otol* 1998;19(6):790–6.
- [40] Barnes GR. Cognitive processes involved in smooth pursuit eye movements. *Brain Cogn* 2008;68(3):309–26.
- [41] Montero-Odasso M, Muir SW, Speechley M. Dual-task complexity affects gait in people with mild cognitive impairment: the interplay between gait variability, dual tasking and risk of falls. *Arch Phys Med Rehabil* 2012;93(2):293–9.
- [42] Murray ME, Senjem ML, Petersen RC, Hollman JH, Preboske GM, Weigand SD, et al. Functional impact of white matter hyper intensities in cognitively normal elderly subjects. *Arch Neurol* 2010;67(11):1379–85.