A preliminary study comparing challenging standing and walking balance tasks to discriminate between experts and novices

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Abstract

There are no established techniques to reliably discriminate between groups of healthy individuals based on balance skill. Current balance assessment techniques often fail to detect subtle differences in balance skill, which poses a challenge for both diagnosing balance impairments and assessing progress after rehabilitation. Our objective was to test whether balance performance on challenging standing and walking balance tasks could discriminate between highly skilled and untrained individuals. We compared single leg stance and beam walking performance in professional ballet dancers and healthy young adults without dance training. First, we tested whether group-level differences existed in beam walking distance or time standing, fractal dimension, and mean velocity during both eyes open and eyes closed single limb stance. We then tested whether any of these variables could predict group membership across individuals. We found that beam walking distance, along with time standing and fractal dimension during eyes closed single limb stance, were the most effective metrics for discriminating experts from novices. Distance walked had the highest true positive rate (sensitivity of identifying experts) at 0.90, but also had a false positive rate of 0.43. Time standing and fractal dimension during eyes closed single limb stance had slightly lower sensitivity but overall better discriminatory power as quantified by the area under the Receiver-Operating curve. For both eyes closed single limb stance and beam walking, 88% of subjects failed to achieve perfect performance across all trials. For eyes open single limb stance, only 29% of subjects failed to achieve perfect performance across all trials. Eyes open single limb stance metrics failed to reliably classify experts and novices. This suggests that challenging tasks that elicit frequent balance failures may be able to more accurately identify individual differences in balance skill.

Introduction

Quantifying differences in balance ability in highly skilled individuals is difficult [1], but it is necessary in order to measure progress through rehabilitation [2], to assess concussion severity [3], and to evaluate stability after ankle sprains [4]. Clinical and laboratory balance tests have limited ability to detect subtle balance impairments because there are no objective criteria that define abnormal balance [5]. Clinical balance tests, such as the Balance Error Scoring System, rely on subjective observations and have been reported to have interrater reliability intraclass correlation coefficients as low as 0.57 [6]. This has motivated investigation to develop objective and quantitative metrics for balance testing [2, 7, 8]. One potential metric is measuring center-of-pressure (CoP), which refers to the average position of the resultant ground reaction force beneath the foot, from which a variety of metrics can be calculated to describe how the ground reaction force is controlled to stabilize the center-of-mass [9].

Many studies show that decreased CoP sway during standing is indicative of better balance ability in both impaired and athletic populations [2, 10]. Increased sway is associated with balance impairments due to age and neurological disorders [9, 11, 12], and decreased sway is associated with increased balance ability in athletes [10, 13-18]. For example, CoP area increases in football players after concussion [19], and dancers have lower mean CoP velocity than non-dancers [18]. Despite the above evidence, the relationship between CoP sway and balance ability remains unclear [2, 12].

Some studies have challenged the assumption that less sway is better [20-24]. In older adults, the mean CoP velocity was not predictive of successful recovery from balance perturbations [22], and lower mean CoP velocity has been associated with the inability to recover balance after tripping over an obstacle while walking [23]. Furthermore, certain athletes, such as volleyball players, show increased sway compared to controls [20]. While it is reasonable to assume that dancers have more finely-tuned postural control than most other

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athletes, dancers have been shown to sway more than judoists and even non-dancers [14, 15, 20].

Measures of CoP complexity, such as fractal dimension, may provide more insight into balance control than linear measures such as mean velocity [7, 18, 21, 25]. Fractal dimension is a dimensionless measure that quantifies how much space the CoP path fills within the curve it bounds [9]. CoP fractal dimension is lower in patients with ankle sprains compared to healthy controls [26], and is lower in non-dancers compared to dancers [27]. However, fractal dimension in older adults reportedly decreased after a contemporary-dance based rehabilitation intervention [25]. As with other CoP metrics, it still remains unclear whether high or low values of CoP fractal dimension correspond to balance ability.

One possible explanation for why it has been difficult to establish a strong link between CoP behavior and balance skill is that studies rarely compare successes and failures during balance tasks. Failures can shed light on differences between skilled, average, and impaired balance [26, 28, 29]. Tasks that are too easy to elicit failures, such as quiet standing, are not sufficiently challenging to identify balance differences between dancers and non-dancers [28]. Even when challenging tasks are used, failed trials are often excluded from analysis [26]. For example, Gerbino et al. found differences in CoP sway between dancers and non-dancers during single limb stance, but trials in which balance failures occurred (i.e. stepping with non-standing leg) were discarded [1].

To our knowledge, very few studies have investigated CoP during balance failures. One study found that balance failures during eyes-closed single limb stance (EC-SLS) were associated with decreased fractal dimension [26], and another showed that balance failures during eyes open single limb stance (EO-SLS) increased mean CoP velocity [30]. However, the relationship between CoP behavior and balance failure in SLS has not been investigated using skilled and unskilled cohorts.

Prior studies of balance have not investigated methods to classify healthy individuals on the basis of balance performance. Studies claiming superiority of a metric often report statistically significant group differences, but few studies report values of sensitivity or specificity. Large group differences do not necessarily yield high sensitivity or specificity [2]. To implement novel balance tests in the clinic, we need to show known-groups construct validity, not just group differences in strategy. Developing tools that are sensitive to subtle balance differences would improve the detection of mild impairments in early stages of disease and impairments in populations with better than average balance, such as concussed athletes.

Sawers et al. previously showed that distance walked along a narrow beam reveals differences in balance skill between professional ballet dancers (balance experts) and untrained novices [31]. However, standing balance tasks may be a more practical way to measure balance skill in space-constrained clinical settings. Here our goal was to compare the ability of standing and walking balance tasks that are easy to administer to discriminate between experts and novices. We used center of pressure to assess standing balance during both eyes open and eyes closed single limb stance (EO-SLS, EC-SLS).

Therefore, our objective was to test whether balance performance on challenging standing and walking tasks could discriminate highly skilled from untrained individuals. We compared single leg stance and beam walking performance in professional ballet dancers and healthy young adults without dance training. Specifically, we tested whether group-level differences existed in beam walking distance or time standing, fractal dimension, and mean velocity during both EC-SLS and EO-SLS. Standing on one leg is challenging in general, but we expected people to lose their balance more frequently with eyes closed. We then tested whether standing and walking balance metrics could accurately predict group membership across individuals.

We found that beam walking distance, along with time standing and fractal dimension during EC-SLS were the most effective metrics for discriminating experts from novices. Time

standing, fractal dimension, and mean velocity on EO-SLS failed to discriminate experts from novices. In single limb stance with vision, both groups had near perfect performance, with no significant group differences in time standing, fractal dimension, and mean velocity. Accordingly, none of these metrics were suitable to differentiate experts and novices in the eyes open condition. These results suggest that more challenging tasks are better suited to identify both group and individual differences in balance skill.

Methods

Participant recruitment

Two groups of participants were recruited: trained experts (professional trained ballet dancers with eight or more years of dance experience) and untrained novices (no dance or gymnastic history). All participants were at least 18 years old. Subjects with any self-reported medical conditions that could impair balance, such as musculoskeletal or neurological injury were excluded.

Ten experts and seven novices performed a beam walking task along with eyes open and eyes closed single-limb stance. These subjects are a subset of subjects from a previous study who completed both standing and walking tasks [31]. Written, informed consent was obtained from each subject prior to participation. All protocols were approved by the Institutional Review Board of Georgia Tech and Emory University.

Experimental protocol

Single limb stance. Seventeen subjects were asked to maintain their balance for up to 30 seconds while performing a single limb stance task with eyes open or closed and with their arms folded across their chest (Figure 1A). A failure was defined as the non-standing leg or foot contacting either the ground or the contralateral standing leg. Data collection began when the subject lifted their non-standing foot off the floor, and was stopped when either a failure occurred or when balance was successfully maintained for 30 seconds. Subjects performed

three trials per leg, per condition. The order of eyes open/eyes closed and left/right foot was counter-balanced. All participants were barefooted.

     Beam walking. Seventeen participants performed six trials of a narrow beam walking task (3.66 m long, 1.8 cm wide, and 3.25 cm high) (Figure 1B) [31]. Step length was not constrained and subjects were instructed to keep their arms still and folded across their chest. A failure in the beam-walking task could occur in two ways: either stepping off the beam before reaching the end or uncrossing the arms. If a failure occurred, the trial ended and data collection was stopped. Standardized shoes were worn for this portion of the experiment.
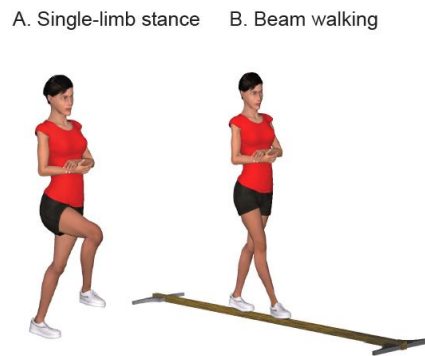
A. Single-limb stance   B. Beam walking

Figure 1. *Walking and standing balance tasks*. A) Single limb stance task. Successful trials ended at 30 seconds. Failures were those trials where subjects touched the ground with their non-standing leg. B) Beam walking. Subjects had six attempts to cross a narrow beam (3.66 m long and 1.8 cm wide). Balance failures were defined as stepping off the beam or uncrossing arms. Distance until failure was measured using a motion capture system.

Single limb stance.

    Data Collection. Center of pressure (CoP) was determined from ground reaction forces and moments collected at 1080 Hz with a six-axis force plate (AMTI, Boston, MA). The CoP time series was low-pass filtered using a fourth-order Butterworth filter with a 5 Hz cutoff frequency.

    CoP Time Series Truncation. To avoid the spurious inflation of CoP metrics by balance failures, balance failure onsets were identified in trials containing failures, and only data prior to failure onsets were analyzed. Consistent with the approach reported by Hasan et al., balance

failures were identified as sharp increases in the instantaneous velocity of the CoP (Figure 2B) [30]. Using a Teager–Kaiser energy operator, a signal conditioning algorithm commonly used to identify the onset of muscle activity in electromyogram recordings [32], we identified bursts in the time series of the CoP instantaneous velocity and manually determined a threshold to classify these bursts as indicators of losses of balance. We truncated the CoP time series at the onset of imbalance, defined as one second prior to the instantaneous velocity threshold crossing [30]. For sixty-six percent of the trials, this algorithm identified a fall where none had occurred and the truncation time was corrected by visual inspection. The algorithm failed to identify a loss of balance in only two trials.

Calculation of CoP metrics. Time standing was determined from the truncated CoP time series to assess performance on the EC-SLS task. Fractal dimension and mean velocity of the CoP trajectory were also calculated from the truncated CoP time series to provide further insight into task performance [9].

<u>Beam walking</u>

Data Collection. The position of a reflective marker placed on the seventh cervical vertebrae (C7) was tracked using an eight-camera motion capture system sampling at 120 Hz (Vicon, Centennial, CO). To assess beam-walking performance, the filtered C7 marker coordinates (third-order 30 Hz low-pass Butterworth filter) were used to calculate the normalized distance walked along the beam. A more detailed description of kinematic data collection and processing has been presented previously [31].

Calculation of beam walking scores. The normalized distance walked was calculated as the ratio of the average distance walked per trial and the maximum possible distance (i.e. 12 feet). A normalized distance walked of 1.0 would indicate perfect performance on each trial (i.e. no failures) [29].
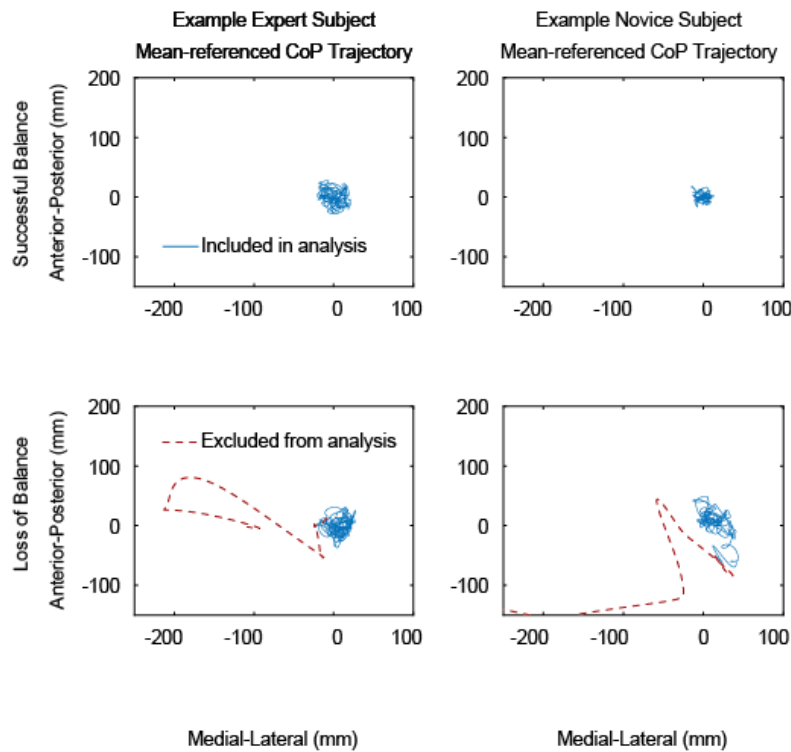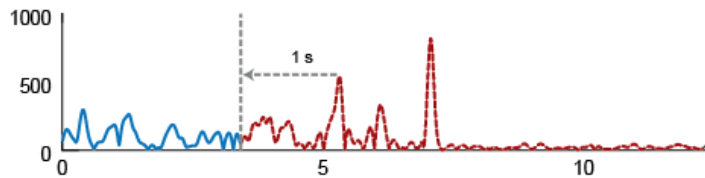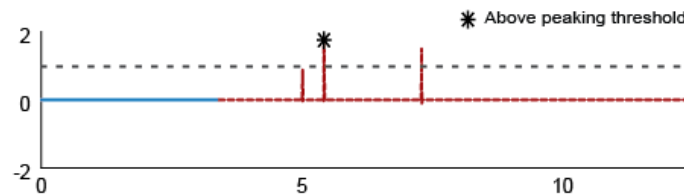
Figure 2. *Identification of balance failure timepoints based on the center of pressure time series*. A) Example center of pressure (CoP) time series from expert and novice successful and failed single limb stance trials. Red dashed lines indicate portions of CoP data collected during a loss of balance that were excluded from analysis to calculate CoP metrics. B). Center of pressure (CoP) analysis. Using Teager–Kaiser energy operator (TKEO) we truncated the CoP time series prior to loss of balance to avoid the spurious inflation of CoP metrics. Time standing was defined as one second before the peaking threshold was exceeded, shown by the end of the blue trace.

Statistical Analysis. A one-sample Kolmogorov-Smirnov test was used to determine whether normalized distance walked, time standing, mean CoP velocity, and fractal dimension were normally distributed. Kolmogorov-Smirnov tests revealed that standing and walking balance metrics were not normally distributed (all p-values <0.001), therefore we used student's t-tests for group comparisons. To test our hypothesis that experts would outperform novices in both standing and walking balance tasks we compared differences between groups using student's two-sample t-tests. We predicted that experts would have a higher normalized distance walked, longer time standing, lower mean CoP velocity, and higher fractal dimension. To test our hypothesis that CoP metrics and time standing would differ between eyes-open and eyes-closed conditions, we used student's paired t-tests to compare metrics within groups. Effect sizes for significant differences between experts and novices or between eyes open and eyes closed conditions were calculated using Cohen's d. To determine whether fractal dimension or time standing was correlated to beam walking performance, we computed R - values for distance walked, time standing, and fractal dimension.

Discriminating individuals using beam walking and single limb stance metrics. To test our hypothesis that beam walking is more effective than EC-SLS and EO-SLS at discriminating between expert and novice balance performance we used receiver operating characteristic (ROC) curves. ROC curves were constructed to visualize discriminatory power of normalized distance walked, time standing, mean velocity, and fractal dimension. Logistic regressions were performed using the 'fitglm' function in MATLAB. The 'perfcurve' function was used to generate the ROC curves and compute sensitivity, specificity, and area under the curve for each metric. All statistical analyses were performed in MATLAB. The 'perfcurve' function returned the point on the ROC curve where the tradeoff between true positive rate and false positive rate is optimized based on default settings. For metrics showing strong discriminatory power, we used the coefficients generated by the model to calculate a threshold to distinguish between experts and novices that corresponded to the optimal point on the ROC curve.

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Results

Experts had between 8 and 18 years (14±3 years) of dance experience. All subjects were female. Average height (novices: 165.7 ± 5.8 experts: 165.0 ± 6.2 cm), weight (novices: 61.0 ± 13.0, experts: 55.0 ± 6.5 kg), and age (novices: 21.4 ± 3.8, experts: 21.6 ± 2.5 years) were not significantly different between groups (p<0.05).

Experts stood for longer and walked further than novices during eyes closed single leg stance and beam-walking tasks respectively (Figure 3A,B). However, the difference in distance walked was not significant between groups (mean ± SD; experts: 0.77 ± 0.07; novices: 0.63 mean ± 0.07, p>0.05). No significant differences appeared between groups for any eyes open single limb stance metrics (Figure 3B,C,D).

Time standing was significantly lower in EC-SLS than EO-SLS for both groups, and the effect size of this difference was larger for novices than experts (mean ± SD; EO experts: 28.5± 1.15 s; p= 0.0089; Cohen's d= 1.33; EO novices: 27.0± 2.11 s; p<0.001, Cohen's d= 1.93). Time standing was significantly greater in experts than novices in EC-SLS (experts: 24.4 ± 2.47 s; novices: 15.7 ± 4.36 s; p = 0.003; Cohen's d: 1.49) (Figure 3B).

Fractal dimension of the CoP time series was higher in experts than novices, but this difference was only significant in EC-SLS (EC experts: 6.46 ± 0.23; EC novices: 5.95 ± 0.38; p=0.004; Cohen's d= 1.47). Fractal dimension did not change significantly between conditions for either subject group (EO experts: 6.45 ± 0.23; EO novices: 6.16 ± 0.27) (Figure 3C).

Both experts and novices showed significant increases in mean velocity from EO-SLS to EC-SLS, and the effect size of this difference was larger for experts than novices (experts: p<0.001; Cohen's d=2.54; novices: p=0.002; Cohen's d= 1.77). Novices had larger mean CoP velocities than experts during EO-SLS and smaller mean velocities than experts during EC-SLS, but these differences did not reach statistical significance (EC experts: 72 ± 8.17 mm/s; EC novices: 68.8 ± 13.5mm/s; p =0.81; EO experts: 32.3 ± 2.76 mm/s; EO novices: 34.7± 4.67 mm/s; p =0.66) (Figure 3D).
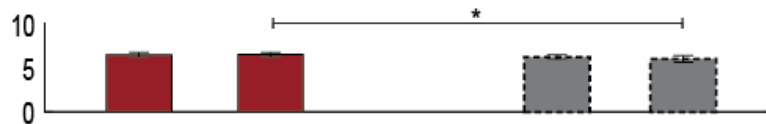
A. Normalized Distance Walked

B. Single Limb Stance Time Standing (s)
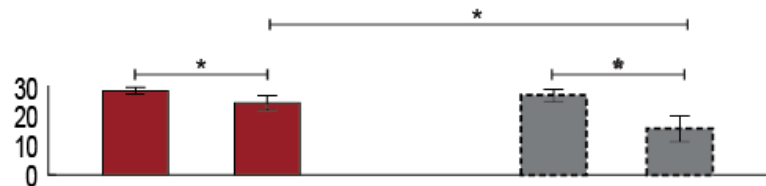
C. Single Limb Stance Fractal Dimension

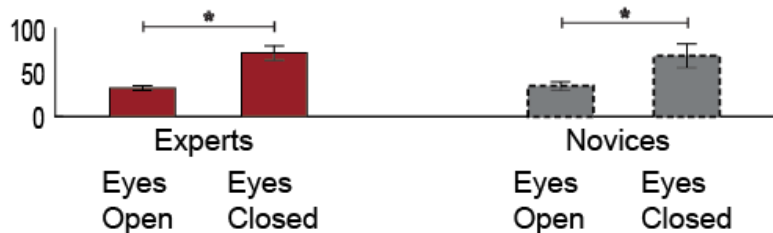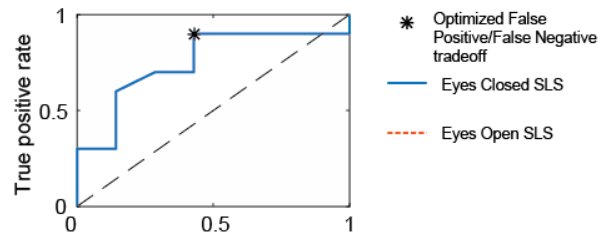**D. Single Limb Stance Mean Velocity (mm/s)**

Figure 3. *Comparison of expert and novice balance metrics during challenging tasks. A:* On average, distance walked was larger in experts than novices, but was not significant (mean ± SD; experts: 0.77 ± 0.07; novices: 0.63 mean ± 0.07). *B*: Time standing was significantly higher in experts for EC-SLS, and was significantly lower during EC-SLS than EO-SLS (experts: 24.4 ± 2.47 s; novices: 15.7 ± 4.36 s; p = 0.003; Cohen's d: 1.49). *C:* Fractal dimension during EC-SLS was significantly higher in experts than novices (experts: 6.46 ± 0.23; novices: 5.95 ± 0.38; p=0.004; Cohen's d= 1.47), but was not significantly different between EC-SLS and EO-SLS for either group *D*: Mean velocity did not show significant differences between groups for either EC or EO-SLS but was significantly higher in EC-SLS than EO-SLS for both groups (EC-experts: 72 ± 8.17 mm/s; EO-experts: 32.3 ± 2.76 mm/s ;EC-novices: 68.8 ± 13.5mm/s; EO-novices: 34.7± 4.67 mm/s).

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Time standing during EC-SLS had the largest area under the ROC curve (AUC), a measure of classifier accuracy (AUC= 0.89), followed by fractal dimension during EC-SLS (AUC=0.87), and distance walked (AUC= 0.75) (Figure 4A,B,C). Overall, discrimination between experts and novices was more accurate using EC-SLS metrics than EO-SLS (time standing AUC=0.72, fractal dimension AUC= 0.70). Mean velocity did not follow this trend, however, the AUCs for mean velocity were much lower than other metrics in both conditions (EO AUC= 0.56; EC AUC= 0.54) (Figure 4D).

True positive rate, or sensitivity, was higher for distance walked than fractal dimension or time standing in EC-SLS (distance walked: 0.90; fractal dimension: 0.80; time standing: 0.80). However, fractal dimension and time standing both had lower false positive rates than distance walked (distance walked: 0.43; fractal dimension: 0.14; time standing: 0.14) (Figure 4A,B,C).
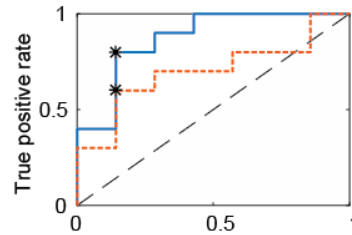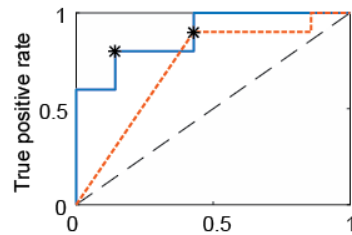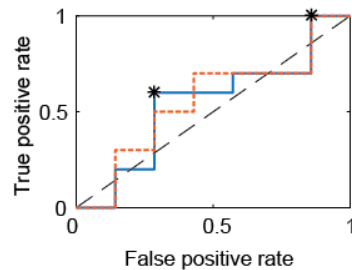
Figure 4. *False positive rates (FPR) and true positive rates (TPR) of walking and standing balance metrics.* Black asterisks show optimal operating point of the curve where tradeoff between true and false positive rates is maximized. Discrimination between experts and novices was most reliable with EC-SLS fractal dimension, EC-SLS time standing, or distance walked. All EO-SLS metrics and Mean Velocity EC-SLS had less discriminatory power than other metrics. *A*: Distance walked: AUC= 0.75; FPR= 0.43; TPR=0.90; threshold: 0.75. *B*: Time standing EC-SLS: AUC= 0.89; FPR= 0.14; TPR=0.80; threshold: 22.1. *C*: Fractal dimension EC-SLS: AUC= 0.87; FPR= 0.14; TPR=0.80; threshold: 6.3. *D*: Mean velocity EC-SLS: AUC= 0.54; FPR= 0.29; TPR=0.60. Fractal dimension EO-SLS: AUC= 0.70; FPR= 0.14; TPR=0.60. Time standing EO-SLS: AUC= 0.72; FPR= 0.43; TPR=0.90. Mean velocity EO-SLS: AUC= 0.56; FPR= 0.857; TPR=0.1.

Subjects who made it across 75% of the length of the beam, stood for longer than 22.1 seconds during EC-SLS, or had CoP fractal dimensions above 6.3 for EC-SLS were classified as experts (Figure 5). We then investigated whether a relationship existed between the standing and walking metrics that had the highest AUC, i.e. fractal dimension and time standing during EC-SLS and distance walked. We did not find a clear relationship between time standing and distance walked (R=0.039), but a moderate positive correlation emerged between fractal dimension and distance walked (R=0.56).

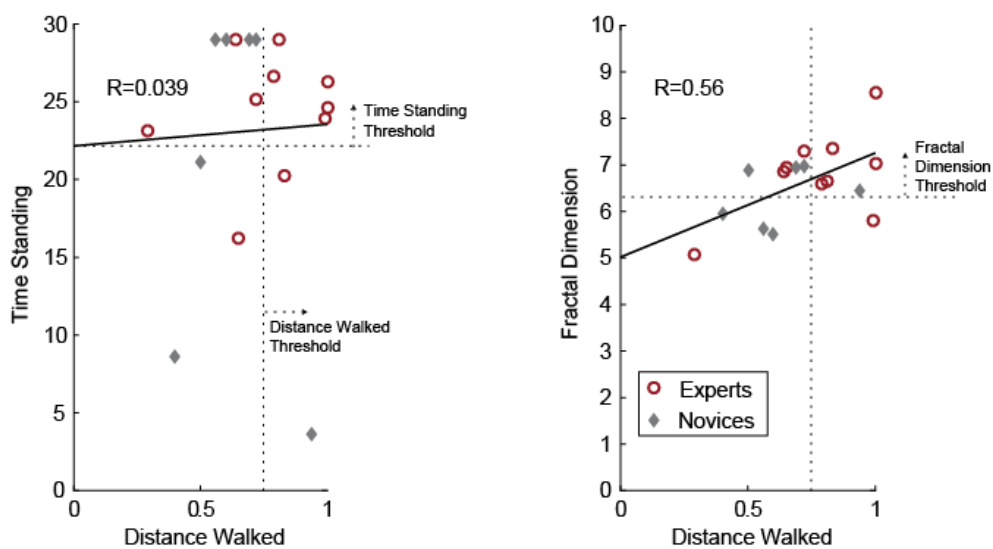**Figure 5**. *Relationship between standing and walking balance metrics.* Fractal dimension (R=0.56), but not time standing (R=0.039), appears to be correlated to distance walked. Dotted lines represent the thresholds for classifying experts and novices that correspond to the optimal tradeoff between true positives and true negatives. Subjects to the right of the vertical lines or above the horizontal lines are classified as experts. True positives are represented by experts above the threshold, false positives are represented by novices above the threshold. Time standing and fractal dimension both had four novices above the threshold, while beam walking had one. However, beam walking had four experts fall under the threshold, while time standing and fractal dimension had two.

Discussion

Metrics collected during eyes closed single-limb stance (EC-SLS) and beam walking were better able to discriminate experts from novices than metrics collected during eyes open single-limb stance (EO-SLS). While all these tasks were considered challenging and chosen to

amplify differences between experts and novices, EO-SLS was the least challenging and elicited failures less frequently than either EC-SLS or beam walking. Few other studies of either standing or walking balance have incorporated tasks challenging enough to elicit failures. Of the few studies that investigated balance under challenging conditions, failures were generally discarded. These studies leave unclear whether the observed differences in CoP behavior in experts or novices reflect differences in balance strategy or balance skill. Furthermore, few studies have gone further than reporting group differences when investigating the utility of different CoP or balance performance metrics, leaving the question of the utility of these metrics to differentiate between different skill or impairment levels essentially unanswered.

We found differences in balance performance between experts and novices that were consistent with prior literature. It is important to note than unlike other studies comparing dancers and novices, we chose balance tasks that were not specific to dance training, being performed with toes pointing forward instead of rotated out, as in ballet training. Few studies have used time standing as a measure of balance performance during challenging SLS tasks. Our findings agree with a study that reported dancers stood for longer than novices during SLS with and without visual input on either foam or firm surfaces [33]. Another study compared only EO-SLS in dancers and non-dancers and found that dancers had higher time standing on average [34]. Assessing time standing during EC-SLS may be a useful strategy in the clinic since it requires no instrumentation and had high true positive rates and area under the curve. It is likely that we could have better discriminated between groups if we had not imposed a performance ceiling at 30 seconds, however, long trials of EC-SLS run the risk of inducing fatigue and confounding the results.

Mean velocities were larger during eyes-closed conditions for both groups compared to eyes-open, as in previous studies [18]. Our results differ slightly from a previous study which observed that dancers had lower mean velocities than non-dancers in both EO-SLS and EC-SLS conditions, whereas we observed lower mean velocities for dancers only during EO-SLS.

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The differences between experts and novices in EO-SLS were not significant in our study or in Gerbino et al. [1]. A lack of significant group difference does not necessarily imply a lack of discriminatory power, but in this case, we found that mean velocity during both EO and EC-SLS was only marginally better than chance at discriminating between experts and novices. In a review of papers comparing CoP behavior in athletes and non-athletes, Kiers et al. noted that sway during quiet standing was not sensitive enough to detect differences in balance skill between healthy individuals [10]. It appears that mean velocity is not sensitive to differences in balance skill even in challenging stances and therefore is not likely to be clinically useful.

Fractal dimension has also been observed to be higher in dancers than non-dancers, although this difference was only observed in standing with feet turned out but not in challenging stances that were not specific to their dance training, such as tandem stance [27]. Doherty et al. found that fractal dimension was associated with successful task completion in EC-SLS, which agrees with the between-group differences we observed [26]. However, not all previous studies agree that higher fractal dimension is related to better balance or dance experience. Older adults that participated in a contemporary-dance based balance training intervention showed a statistically significant decrease in fractal dimension at the end of the program [25]. Interestingly, fractal dimension was not sensitive to the presence or absence of visual information. Fractal dimension may be a clinically useful metric to identify differences in balance skill since its true positive rate was 80%.

Beam walking had the highest true positive rate of any metric, however we did not find other studies that incorporated walking balance tasks in dancers. Sawers et al. previously showed that distance walked was significantly higher in experts, therefore the lack of significant between-group differences in distance walked is likely due to our reduced sample size [29]. This is a good example of why group averages alone do not provide enough information to determine if a metric is useful for identifying between-group differences. When we plotted individual subject averages for beam walking against the thresholds for discriminating experts and novices, only

one novice made it above the threshold, but four experts fell below it. Three of these experts were close to the threshold. Subjects which we labeled 'novices' may have had better-than-average balance skill even though they had no dance or gymnastics training. For example, one novice with very good performance had ten years of training in tennis. In addition, some experts did not perform as well as expected. Anecdotally, dancers that have trained almost exclusively in ballet and not in jazz or contemporary styles find it difficult to balance with their feet turned-in since they are used to balancing with their feet turned-out. This may be a contributing factor to the variability in performance within the expert group. Because of these factors, the presence of false positives or false negatives should not necessarily be interpreted as limitation of beam walking as an assessment, but rather as a limitation of how subjects were labeled. Since beam walking had a high true positive rate and area under the curve, it may be a useful tool to evaluate subtle impairments in skilled populations**.**

We were interested to see if there was overlapping information in standing and walking balance metrics with the best discriminatory power. The lack of a clear relationship between time standing and distance walked may be because we imposed an artificial performance ceiling on time standing that may have been too low. An alternative explanation could be that skill for static balance does not necessarily translate to a dynamic walking balance task. The moderate correlation between fractal dimension and distance walked makes sense if we interpret high values of fractal dimension to reflect how effectively the sensorimotor system can take advantage of the base of support [26].

Both eyes closed single limb stance and beam walking elicited failures over eighty percent of the time, and resulted in better between-group discrimination. The thresholds for between-group discrimination reported in this study should not be taken as clinical recommendations since our sample size was relatively small (n=17). Future studies should test the sensitivity of beam walking, fractal dimension, and time standing during EC-SLS to discriminate between uninjured athletes and athletes suffering from concussion or chronic ankle

instability. Another possible application of these measures would be to evaluate progress through rehabilitation, particularly in the elderly. Beam width could be increased to modify the test for subjects with more severe impairment. Simple instrumentation of the beam using load cells could automate the process of determining distance walked and render the test more user-friendly. One possible strategy for increasing the discriminatory power of standing balance tasks is investigating performance in the context of support-surface perturbations. More work is needed to determine: 1) what thresholds for these metrics are appropriate for diagnosing and assessing level of injury or impairment, 2) whether these tests should be combined for more discriminatory power, and 3) which type of task, standing or walking, yields more discriminatory power to detect a particular kind of impairment.

Acknowledgements

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