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Thinking on your feet: An analysis of movement and cognition in a sit to stand task

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ABSTRACT

The maintenance of upright posture involves constant adjustment to external and internal perturbations. This balancing act is often assumed to be an automatic process, but studies suggest that cognitive processes, particularly attention, are necessary for the control of posture. The current study examines the role of attention in balance using a dual-task paradigm. Twenty-four healthy young adults performed a sit-to-stand (STS) task on either a stable or unstable platform while performing a secondary cognitive task of counting backwards aloud. Movement of the upper and lower body was analyzed using the largest Lyapunov exponent (λ_1) and standard deviation (SD). Results replicated earlier findings (Gibbons, Amazeen, & Likens, 2018) that the transition from sit to stand was marked by increased variability and a temporary destabilization of postural control. Participants exhibited greater movement variability overall on the unstable platform (large SD), but small λ_1 indicated that movement was controlled. During second task performance, SD increased for the upper body only. Further research is necessary to understand the interaction between attention and balance in young adults.

1. Introduction

The act of balancing, though an everyday activity, is a complex motor task that requires constant adaptation. Postural balance refers to the ability to keep one's center of mass within safe limits of the base of support (Balasubramaniam & Wing, 2002) and has been traditionally considered to be an automatic or reflexive task. However, research has shown that postural control requires attentional resources, especially as the difficulty of the balance task or secondary cognitive task increases (Albertsen, Ghédira, Gracies, & Hutin, 2017; Lajoie, Richer, Jehu, & Tran, 2016; Woollacott & Shumway-Cook, 2002) or when compound postural movements are performed (e.g., sit-to-stand; Gibbons, Amazeen, & Likens, 2018). The current study tests this interaction by using a dual-task paradigm in which participants balance on a platform that varies in stability while simultaneously engaging in a cognitive task.

1.1. Variability in movement

Linear measures (e.g., standard deviation, sway area, path length) are typically used as an index of postural control or stability (Doyle, Hsiao-Wecksler, Ragan, & Rosengren, 2007). Those measures treat variation in movement as random noise or error in the system. When viewed this way, variation is assumed to be negatively correlated with stability. In support of this assumption are findings that sway variability increases as balance is challenged by a difficult standing task (e.g., standing on one foot, visual deprivation) or pathology (e.g., age, Parkinson's) compared to young and healthy individuals (Adkin, Frank, & Jog, 2003; de Haart, Geurts, Huidekoper, Fasotti, & van Limbeek, 2004; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; Vuillerme et al., 2001). The goal, then, is to reduce variation to achieve healthy or skilled movement.

In opposition to this assumption are results that demonstrate greater movement variability in more skilled performance. For example, elite triple jumpers displayed significantly larger variability in joint coordination than intermediate-level jumpers (Wilson, Simpson, van Emmerik, & Hamill, 2008) and elite basketball players demonstrated significantly larger variability in elbow trajectory compared to intermediate-level players (Button, Macleod, Sanders, & Coleman, 2003). Posture occurs in a dynamically changing environment and requires adaptation to unexpected disruptions or perturbations. Variation may indicate exploration of the environment and adaptations to perturbations rather than a loss of stability (Harbourne & Stergiou, 2009). The message, then, is that variability is negative in some contexts and positive in others. An approach that compares linear to nonlinear measures that capture the structure of a movement's variation over time

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may help to resolve the issue.

1.2. Largest Lyapunov exponent

The largest Lyapunov exponent (λ_1) is a nonlinear measure of stability that is commonly used to identify structured variation in movement and can be used to identify the presence of chaos (Rosenstein, Collins, & De Luca, 1993). Technically, λ_1 is an estimate of the exponential rate of divergence of initially nearby trajectories in a system's state space, the space in which the dynamics reside, over time. Positive λ_1 indicates divergence of trajectories, which is indicative of less stable behavior, and negative λ_1 indicates convergence of trajectories as might be expected for stable behavior (Rosenstein et al., 1993; Yamada, 1995). λ_1 has been used as a measure of stability for many different psychological phenomena, including: neural activity (λ_1 = 1.8–3.2; Röschke, Fell, & Beckmann, 1995); infant sitting (λ_1 = −0.024–0.087; Harbourne & Stergiou, 2003); posture (λ_1 = −0.371–1.45; Gibbons et al., 2018; Yamada, 1995); handwriting (λ_1 = 0.09–0.132; Longstaff & Heath, 1999); gait (λ_1 = 0.75–1.75; England & Granata, 2007); and team coordination (λ_1 = −0.03–2.80; Demir, Likens, Cooke, Amazeen, & McNeese, 2018; Gorman, Hessler, Amazeen, Cooke, & Shope, 2012).

Postural studies have reported small positive λ_1 for heathy participants (Gibbons et al., 2018; Ladislao & Fioretti, 2007; Murata & Iwase, 1998; Yamada, 1995). The general finding in assessments of postural "health" is larger λ_1 for patients with clinical conditions like Parkinson's disease (Fioretti, Guidi, Ladislao, & Ghetti, 2004), stroke (Roerdink et al., 2006), and developmental delays (Deffeyes, Harbourne, Kyvelidou, Stuberg, & Stergiou, 2009; Harbourne et al., 2007). Gibbons et al. (2018) extended the research on young healthy adults to include the sit-to-stand (STS) task, which promotes an understanding of the disruption that occurs as individuals transition from one stable posture to another. To further challenge posture, participants stood onto a platform that was either stable or unstable. That study illustrated the utility of comparing linear (SD) and nonlinear measures (λ_1) of variability. Standing posture was characterized by small positive λ_1 that did not differ significantly across platform conditions. However, participants used more movement to maintain balance on the unstable platform, as indicated by amplified movement variability, specifically, standard deviation (SD).

Gibbons et al. (2018) further challenged postural control by randomly striking a crash cymbal during the STS task, a disruption that affected head movement (away from the sound) but not overall performance stability. We anticipate that the introduction of a secondary cognitive task in the current study will disrupt posture through its mediating effect on attentional resources without introducing any extraneous movements that could occlude the effect of a perturbation.

1.3. Posture and cognition

Postural control is often a background activity for other daily tasks, for example, conversation, visual search, decision making, and reaching. Ordinarily, we think of posture as requiring little attention. However, postural stability may be compromised if concurrent tasks require the same attentional resources required to maintain postural balance. Research has shown an impact of secondary cognitive task on posture, particularly when either task is sufficiently difficult (Albertsen et al., 2017; Lajoie et al., 2016; see Woollacott & Shumway-Cook, 2002 for a review of earlier studies). The effect varies according to the nature of the secondary task (Mitra & Fraizer, 2004; Stins, Roerdink, & Beek, 2011; Teasdale, Bard, Larue, & Fleury, 1993; Woollacott & Shumway-Cook, 2002). Postural sway increases during performance of spatial and non-spatial memory tasks (Maylor, Allison, & Wing, 2001; Raymakers, Samson, & Verhaar, 2005) but decreases during visual search (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). More recent studies demonstrated that the greatest increases in movement variability result from concurrent performance of numerical counting tasks, especially backward counting (Ceyte et al., 2014; Maylor & Wing, 1996; Pellecchia, 2003).

1.4. Current study

The current study was designed to replicate and extend the findings of Gibbons et al. (2018) by introducing a dual-task paradigm to the study of postural control during the STS task. That task is particularly interesting because it requires destabilization of one stable posture (sitting) in order to transition to another, less stable posture (standing). Participants transitioned from a seated position onto a stable or unstable platform while either remaining silent (single-task condition) or counting backwards by intervals of three to 13 (dual-task condition). Postural sway of the upper and lower body was estimated using λ_1, which captures structured variation, and SD, which combines both structured and random variation. Based on previous findings (Gibbons et al., 2018), we predicted small SD for sitting and standing on the stable platform but a larger SD for the transition and standing on the unstable platform. We predicted the same pattern of results for λ_1 with one exception: Because participants were young and healthy, we expected postural variability to be controlled on the unstable platform, as revealed by small λ_1, as in Gibbons et al. (2018). Comparison of upper and lower body movements was expected to reveal amplified effects for the upper body. Previous studies have identified a negative impact of backward counting on standing (Ceyte et al., 2014; Pellecchia, 2003) and no impact of backward counting on the duration or peak velocity of the transition to the stand (Porciuncula, Rao, & McIsaac, 2016); movement variability was not measured in the latter study. Based on those previous findings, we expected an increase in variability during one or more stages of the STS task.

2. Methods

2.1. Participants

Twenty-four healthy young adults (16 women, 8 men; mean age 19.5 years; mean height 170.5 cm; mean weight 65 kg) participated in this study in exchange for course credit. Power analysis was conducted based on sample effect size from Gibbons et al. (2018) and following the methods from Anderson, Kelley, and Maxwell (2017) to reveal a target sample size of 25 to achieve 0.8 power. The power of the current study was strengthened by the use of a repeated-measures design. Informed consent was obtained prior to participation. None of the participants reported any previous injuries or disorders that would have affected performance of the tasks. The study was approved by the Institutional

Fig. 1. Marker positions along the right-side of the body.

Review Board at Arizona State University in accordance with the Declaration of Helsinki.

2.2. Apparatus

Movement was captured using an Optotrak 3D-Investigator (Northern Digital Inc., Waterloo, Canada). Participants were positioned 4.5 m from the camera with the right side of the body facing the camera. Following the precedent of Gibbons et al. (2018), four infrared markers were attached at the participant's ankle, knee, shoulder, and head along the right side of the body (Fig. 1). The shoulder and knee markers were affixed using double-sided adhesive tape, while the head and ankle markers were affixed to head- and ankle-bands worn by the participant. These markers were used to track the position of the participant in three-dimensional space to a resolution of 0.01 mm. That resolution is at a finer scale than meaningful changes in postural control (see Fig. 2C–D for comparison). The sampling frequency of each marker was registered at 250 Hz.

Participants were asked to engage in both an STS balance and a counting task. For the STS balance task, participants transitioned from sitting on a chair (seat height = 0.51 m) to standing on a Fitterfirst Professional Rocker Board (board height = 0.1 m; Fitter International Inc., Calgary, Canada). There were two stability conditions: stable, in which the board was secured with wooden blocks placed underneath so that the board could no longer tilt; and unstable, in which the wooden blocks were removed and the board tilted side-to-side, in the medial-lateral direction. An auditory cue ('click') was used as a signal to stand.

The secondary task included two conditions: non-counting and counting backwards aloud. The non-counting condition, in which participants performed only the STS task, served as the single-task condition. The counting condition, in which participants engaged simultaneously in the STS and counting task, served as the dual-task condition. In dual-task trials, participants counted backwards from a four-digit starting value (2991 to 3000) by intervals of 3, 7, 8, 9, or 13. The starting values and intervals were randomized across trials. The starting value was placed on a slip of paper that hung on the wall approximately 1.75 m directly in front of the participant at standing eye-level. During non-counting trials, a 3 × 7 ½ cm blue "control" target was placed in the same location as the starting values in the corresponding dual-task trials. Participants were instructed to fixate on the paper or control target throughout the duration of the trial.

2.3. Procedure

Before data collection began, participants stood onto the unstable platform twice so that the experimenter could confirm that they could safely perform the more challenging balance task. Participants began each trial sitting upright in a chair with their hands placed on their thighs and their feet placed shoulder-width apart on the platform. Following the precedent of previous studies (e.g., Gibbons et al., 2018; Scholz & Schöner, 1999), participants were instructed to avoid using their arms to transition from sitting to standing. A second experimenter monitored compliance to instructions, and trials were repeated if necessary. Across all participants, only one trial was repeated because the participant used the arms to rise from the chair.

On any given trial, the platform was either stable or unstable and participants were asked to remain silent (single-task) or audibly count backwards (dual-task). During dual-task trials, participants were told of the counting interval immediately prior to the start of data collection so that they could not plan their counting sequence. When participants gave an incorrect answer, they were told "incorrect" and were asked to begin counting from the starting value again. Participants were instructed to continue counting until the end of the trial. The number of counting errors made during each trial was recorded.

An auditory signal ('click') to stand was presented approximately 10 s after data collection began. Participants stood onto the platform at a comfortable speed and remained standing with the eyes fixated on the paper target in front of them for the remainder of the trial. Each trial was 30 s in duration. After each trial, participants returned to the seated position and rested before the start of the next trial. Ten trials were conducted in each of the platform conditions (stable, unstable). On five of the ten trials in each platform condition, participants engaged in the secondary counting task. Experimental sessions consisted of 20 trials (five trials per condition) and lasted approximately 35 min.

2.4. Analysis and design

The vertical movement of the shoulder marker was used to identify the sitting, transition, and standing stages of the STS task. The vertical movement of the shoulder marker was tightly coupled to the moment of lift-off from the chair, so that the transition stage was identified as the interval between the beginning and end of the upward trajectory at the shoulder marker. Identical segments of time (3.3–4.6 s, depending on the trial) were used to mark the sitting stage (before upward movement began) and the standing stage (after upward movement ended) per trial. λ_1 and SD were estimated for the mediolateral movements during these three stages. Those two measures provided estimates of postural in-stability (stability $\propto \lambda_1^{-1}$) and movement variability, respectively.

λ_1 was estimated using the time-delayed method of attractor reconstruction (Taken, 1981). That procedure requires the calculation of an appropriate time lag, τ, and embedding dimension, d_E in order to estimate λ_1. We estimated τ as the first zero-crossing of the autocorrelation function (Kaplan & Glass, 2012; Packard, Crutchfield, Farmer, & Shaw, 1980) and d_E as the number of embedding dimensions for which false nearest neighbors decreased below 10% (Rosenstein et al., 1993). The exponential divergence, quantified by λ_1, is found by measuring the Euclidean distance between pairs of initially close points (near-neighbors) over time and then estimating the least-squares slope of the averaged near-neighbor trajectories (Kantz & Schreiber, 2004). Technically, then, larger λ_1 indicates greater in-stability, and smaller λ_1 indicates greater stability.

To simplify analysis of the four marker locations across the body, a paired samples *t*-test was conducted to compare the two upper (head and shoulder) and two lower (knee and ankle) body locations on both dependent measures (λ_1 and SD). Results revealed no significant difference in λ_1 value between the head and shoulder ($t(23) = 0.36$, $p = 0.725$) and knee and ankle ($t(23) = 0.73$, $p = 0.472$) locations. Similar results for SD were found between the two upper body ($t(23) = 1.27$, $p = 0.217$) and two lower body ($t(23) = 1.74$, $p = 0.095$) marker locations. Therefore, λ_1 and SD from the two upper and two lower body locations were averaged, respectively, at each of the three task stages.

A repeated-measures analysis of variance (ANOVA) was conducted for both λ_1 and SD on four factors: body (upper, lower); stage (sit, transition, stand); platform (stable, unstable); and secondary task (counting, no counting). Although the four-way interaction was not of particular interest, the omnibus test allowed us to control for Type I error. Simple interaction analyses were used to clarify significant interactions.

3. Results

3.1. Largest Lyapunov exponent

Fig. 2 depicts mean λ_1 for the (A) upper and (B) lower body across the three stages of the STS task for both platform and secondary task conditions. From the figure, we can see an overall trend that λ_1 was larger at the transition stage than at the sitting or standing stages across both platform and secondary task conditions. In addition, λ_1 varied more across stages for the upper body than for the lower body. Results from the repeated-measures ANOVA revealed a significant two-way body × stage interaction, $F(2, 46) = 8.40, p < 0.001$, and a significant

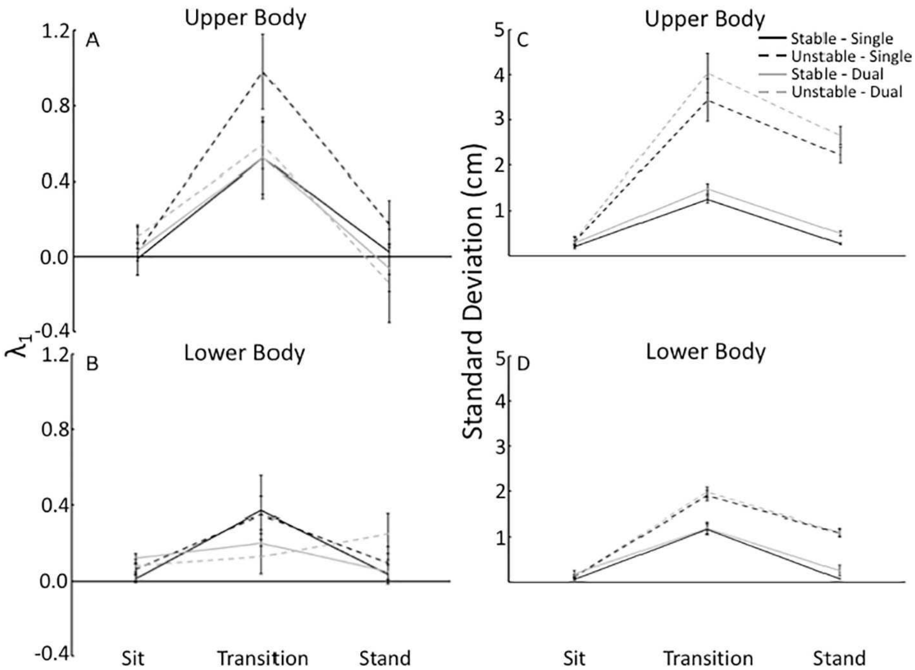

Fig. 2. Mean λ_1 and standard deviation for the (A, C) upper and (B, D) lower body as function of task stage, platform, and task condition. Error bars depict standard error of the mean.

main effect of stage, $F(2, 46) = 18.61, p < 0.001$. No other interaction or main effects were significant. Those results suggest that postural stability, as indexed by λ_1, was not affected by the platform or cognitive task.

Simple effects analyses were conducted to better interpret the body × stage interaction. Results revealed that λ_1 changed significantly across stages for both the upper ($F(2, 46) = 15.98$, $p < 0.001$) and lower ($F(2, 46) = 6.03$, $p = 0.005$) body. λ_1 was significantly larger during the transition than sitting stage (upper: $F(1, 23) = 20.01$, $p < 0.001$; lower: $F(1, 23) = 10.22$, $p = 0.004$) and decreased significantly during the standing stage (upper: $F(1, 23) = 18.77$, $p < 0.001$; lower: $F(1, 23) = 4.97$, $p = 0.036$) as participants stabilized balance. The upper and lower body differed only in that these effects were amplified for the upper body: λ_1 was significantly larger for the upper body during the transition stage ($F(1, 23) = 7.70$, $p = 0.011$). Overall, these trends in λ_1 imply that sway variability was more structured (i.e., more stable) during the sitting and standing stages as indicated by small positive λ_1, whereas the larger λ_1 at the transition stage suggest a relatively less stable (or more chaotic) state.

3.2. Standard deviation

The right panels of Fig. 2 depict mean SD for the (C) upper and (D) lower body across the three stages of the STS task for both platform and secondary task conditions. As with λ_1, SD was smallest during the sit stage and peaked during the transition stage. The SD results are different from λ_1, however, in that there is a clear distinction between the platform conditions in the stand stage: for both the upper and lower body, greater movement variability was observed when participants stood on the unstable platform in comparison to the stable platform. SD of the upper body also appeared to be elevated for the dual task trials.

A repeated-measures ANOVA revealed a significant three-way body × stage × platform interaction, $F(2, 46) = 14.40$, $p < 0.001$. Four of the two-way interactions were significant: body × stage, $F(2,46) = 11.16$, $p < 0.001$; body × platform, $F(1, 23) = 31.67$, $p < 0.001$; body × secondary task, $F(1, 23) = 6.36$, $p = 0.019$; and stage × platform, $F(2, 46) = 42.95$, $p < 0.001$. All four main effects were significant: body, $F(1,23) = 50.46$, $p < 0.001$; stage, $F(2, 46) = 135.72$, $p < 0.001$; platform, $F(1, 23) = 149.06$, $p < 0.001$; and secondary task, $F(1, 23) = 9.99$, $p = 0.004$.

Simple interaction analysis was used to reveal the source of the three-way body × stage × platform interaction: Across both body and platform conditions, SD increased significantly from the sitting stage to the transition stage and decreased significantly from the transition to standing stage, $F(1, 23) = 13.05$, $p = 0.001$. Even though SD differed across stages, differences between the unstable and stable platforms were only observed during the transition and standing stages of the task: SD was significantly greater on the unstable platform in comparison to the stable platform at both the transition ($F(1, 23) = 56.30$, $p < 0.001$) and standing ($F(1, 23) = 213.67$, $p < 0.001$) stages of the task. That stage × platform interaction was qualitatively the same for the upper and lower body but amplified for the upper body, $F(1, 23) = 21.25$, $p < 0.001$.

Based on previous findings using the same secondary cognitive task, we expected movement variability to be greater for dual-task trials than for single-task trials. However, as identified above, the secondary task only interacted significantly with body. Therefore, we cannot make any comparison across the stages of the task. Comparison of Fig. 2C and D reveals the source of the interaction: SD was significantly greater during the dual-task trials for the upper body only ($F(1, 23) = 9.69$, $p = 0.005$). There was no effect of the secondary task on the movement variability in the lower body ($p > 0.05$).

3.3. Cognitive task performance

The current study focused primarily on the effect of the additional cognitive task (backwards counting) on postural sway. We did not collect cognitive performance in a single task condition (i.e., in the absence of the STS task) and will not comment on the impact of movement on the cognitive task. Instead, we report results for performance on the counting task to contribute to the literature on this common secondary task (see Fig. 3). A one-way repeated measures ANOVA revealed no significant effect of counting interval on the number of errors, $F(4, 92) = 0.69$, $p = 0.546$.

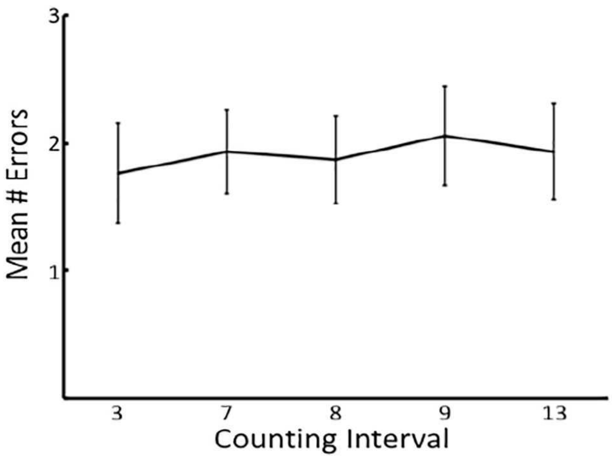

Fig. 3. Mean number of errors in the dual task condition as a function of counting interval. Error bars depict standard error of the mean.

4. Discussion

The first purpose of the current study was to replicate findings from Gibbons et al. (2018), in which the structure of variability was examined across the three stages of the STS task on both stable and unstable platforms. We used both traditional, linear (SD) and nontraditional (λ_1) measures to distinguish uncontrolled from controlled sources of variability. We replicated the overall results: small values of λ_1 and SD were observed during the sitting stage, large values were observed for the transition stage, and large SD but small λ_1 values were observed for the standing stage. The implication of the divergence of those values identifies that participants exhibited more sway during the standing stage but maintained postural stability. As in Gibbons et al. (2018), observed effects were larger for the upper body than for the lower body. The second purpose of this study was to use a dual-task paradigm to test the connection between posture and cognition. Our hypothesis that postural sway would increase when a secondary cognitive task that demanded attention was introduced was supported for the upper body. However, that increase in movement variability (large SD) did not compromise postural stability (small λ_1).

4.1. Nonlinear vs linear measures of variability

The disparity between λ_1 and SD measures is readily explained by the way in which variability is measured. Both random and structured variability are combined in the traditional SD measure, but only structured variability is captured in the nonlinear λ_1 measure (Harbourne & Stergiou, 2009; van Emmerik & van Wegen, 2002). In the current study, participants made more movements on the unstable platform, but those movements were controlled, as revealed by small, near-zero λ_1. Similar λ_1 values were reported for healthy participants in previous experiments (Gibbons et al., 2018; Ladislao & Fioretti, 2007; Murata & Iwase, 1998; Roerdink et al., 2006; Yamada, 1995). That result supports the hypothesis that healthy postural sway is characterized by small positive λ_1. This finding suggests that deviations in those values from near-zero can be used to track the disruption that occurs as individuals transition from one stable posture to another. That finding is promising for application to other transitions as well, including changes in communication patterns in teams (e.g., Gorman et al., 2012) and insight learning (e.g., Stephen, Dixon, & Isenhower, 2009).

The traditional interpretation of variability as error is challenged by a perspective that interprets variability as functional and necessary for a healthy system. Increases in movement variability may serve a functional role by enriching sensory information (visual, haptic, vestibular) used to control posture and by enhancing flexibility (Stergiou & Decker, 2011; van Emmerik & van Wegen, 2002). In one study, healthy individuals and patients with anterior cruciate ligament (ACL) injury were asked to balance on one foot (Davids, Kingsbury, George, O'Connell, & Stock, 1999). The nonintuitive result that healthy individuals demonstrated greater sway was interpreted by Davids et al. (1999) not as a lack of stability but as evidence that healthy individuals were exploring balance solutions. The pattern of large SD and small but positive λ_1 reported here and in previous studies (Gibbons et al., 2018) further supports the hypothesis by revealing the controlled nature of the amplified movement variability.

Results of the current study were consistent with other studies that have used λ_1 and other nonlinear measures to capture regularities in postural sway (Donker, Roerdink, Greven, & Beek, 2007; Riley & Clark, 2003; Roerdink et al., 2006). Riley and Clark (2003) used measures from recurrence quantification analysis as well as traditional linear measures to show changes in the temporal structure of sway as the standing conditions increased in difficulty. Healthy young adults displayed more regular (as indexed by higher percent recurrence and determinism measures) and more stable (as indexed by a longer maxline) sway behavior despite increased sway variability (as indexed by higher SD and path length measures). Donker et al. (2007) similarly reported increases in stability and movement variability. The implication is that amplification of variability does not necessarily compromise postural stability, as indexed by multiple measures.

4.2. The role of cognition in postural control

The use of a dual-task paradigm to test the connection between posture and cognition provided partial support for the hypothesis that postural sway, as indexed by movement variability (SD), would increase when a secondary cognitive task that demanded attention was introduced. The result that sway increased for the upper body supports previous findings of an increase in center of pressure movement when participants were engaged in backwards counting (Ceyte et al., 2014; Maylor & Wing, 1996; Pellecchia, 2003) and other studies that compared upper and lower body movements during the STS task (Gibbons et al., 2018). The unique addition of the current study was the use of λ_1 to show that postural stability was maintained despite the increase in movement variability during backward counting. The impact of a more challenging cognitive task on postural control is considered in the following section.

4.3. Limitations and future directions

It is clear that future research may need to challenge participants with more difficult tasks to push them beyond their physical and cognitive capacity to concurrently perform both tasks equally well. We are currently investigating two possibilities in the lab in response to the limitations of the current study: Participants in the current study were young and healthy and demonstrated no real difficulty in balancing, even on the unstable platform. Based on age effects reported in past literature (e.g., Prieto et al., 1996), it is quite possible that none of the balance conditions were sufficiently challenging. The balance task may be made more difficult by requiring participants to balance on one foot only. Murata and Iwase (1998) reported amplified λ_1 and linear sway measures (e.g., sway area) during a one-footed balance task compared to the more typical two-footed balance. Removing vision is another way to increase the difficulty of the balance task and has been extensively studied in the postural literature (Day, Steiger, Thompson, & Marsden, 1993; Donker et al., 2007; Lee & Lishman, 1975; Yeh, Cluff, & Balasubramaniam, 2014). Participants generally display increased sway variability and velocity when standing with eyes closed compared to standing with eyes open (Day et al., 1993; Yeh et al., 2014). Donker et al. (2007) found an increase in λ_1 when participants stood without vision compared to with vision.

Porciuncula et al. (2016) reported no effect of backward counting on the duration or peak velocity of the transition from a sit to a stand.

They compared cognitive-processing tasks (e.g., backward counting) to manual-dexterity tasks (e.g., carrying a filled cup of water) as well as combinations of both (e.g., backward counting while carrying a filled cup of water). The cognitive literature provides other possibilities for increasing cognitive load: The *n*-back task, commonly used in working memory experiments (e.g., Redick & Lindsey, 2013), requires participants to report whether a single item (digits or letters) they see or hear matches the item presented *n* back in the sequence. Because it places continuous demands on attention and working memory, the *n*-back task may have greater potential to disrupt postural control, particularly during challenging balance conditions.

Real-time implementation of nonlinear analyses may facilitate an understanding of changes in variability that occur immediately prior to postural transitions such as the sit-to-stand. Gorman et al. (2012) developed a real-time analysis of λ_1 to identify changes in stability of team coordination to facilitate monitoring and the timely implementation of interventions. They detected perturbations such as the loss of communication and tracked the effects as they persisted across different lengths of time by estimating λ_1 concurrently across multiple window (sample) sizes. Perturbations were revealed as disruptions to λ_1 that persisted across window sizes. In the current study, we used large samples (825–1150 samples, corresponding to 3.3–4.6 s of data) to derive stable estimates of λ_1, but data could just as easily have been divided into smaller windows for analysis purposes. Contributions to both scientific research and therapeutic application will follow from the potential for real-time monitoring and timely implementation of perturbations to probe postural stability.

4.4. Conclusions

The current study extends our understanding of the interaction between cognitive and motor processes during dual-task performance by demonstrating that increased cognitive load led to an increase in movement variability in the upper body during the standing stage of a sit-to-stand task. The addition of nonlinear methods of analysis revealed that the increased lateral movement at the transition and standing stage did not correspond to a loss of postural stability. Those findings add to previous literature that suggests that an increase in movement variability may serve a functional purpose, allowing healthy participants to find a stable balance solution. Future studies that explore additional nonlinear methods and greater challenges to the postural and cognitive systems will help to extend our understanding of the role that cognition and attention play in the control of posture and other motor processes.

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