METHODOLOGICAL CONSIDERATIONS AND CLINICAL UTILITY OF ANALYZING TRANSIENT BEHAVIOR IN QUIET STANCE POSTURAL CONTROL

by

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ABSTRACT

Postural control has been widely studied to provide insight into various health concerns. Traditionally, postural control is assessed using whole-trial analysis techniques that measure center of pressure parameters as a singular estimate for an entire trial. These whole-trial estimates may be more reliable for longer duration trials. However, longer trials and whole-trial analyses mask transient (i.e., a destabilized period followed by a transition to a more stable, quasi-steady state level) responses within center of pressure data. By only using whole-trial estimates, we may be missing out on unique information that is contained within this understudied aspect of postural control. Therefore, four experiments were conducted to better understand the clinical utility of evaluating transient postural control behavior.

The first experiment tested whether transient, epoch-based characteristics of center of pressure parameters provided unique information compared to traditional whole-trial estimate approaches. The second experiment evaluated participants in eyes open and closed conditions to test whether transient behavior was a sensory reweighting response to eye closure. The third experiment tested whether transient characteristics of postural control could distinguish between younger and older adults. Based on the results of the first three experiments, a fourth experiment was conducted to investigate the influence of cognitive perturbations on transient characteristics of postural control.

Negligible correlations were found between transient characteristic and whole-trial estimates, indicating that unique information is contained in transient measures of postural control. Although transient behavior was exaggerated during eyes closed stance, transient behavior still existed during eyes open stance. In addition, select transient characteristics distinguished between young and older adult groups, supporting the clinical relevance of transient measures. Lastly, cognitive perturbations influenced transient postural behavior, supporting the use of transient measures for analyzing dual-task scenarios.

Overall, our results support the use of epoch-based estimates to characterize transient postural behavior as a complementary assessment to traditional whole-trial analyses. Our results also indicate the need to carefully consider how postural control trials are analyzed and initiated. Moving forward, further evaluation of transient characteristics of postural control is warranted to determine their relationship to health outcomes such as falls.

CHAPTER 1

INTRODUCTION

Defining Postural Control

How do I stand? When I close my eyes, how does my body keep myself from falling over? Will I one day be unable to stand up? These are questions that we do not usually consider, yet for most of us standing and staying upright is one of the body's most basic functions. While standing is often thought of as simple and automatic, controlling our posture is actually a rather challenging and complex task. Because of how humans are structured anatomically, we are constantly balancing approximately two-thirds of our body mass (including most of our vital organs) more than half of our height from the ground above two slender limbs that provide a very small base of support [1]. Additionally, we have to perform this balancing act with a very high degree of precision in order to execute most movements safely. This challenging quiet stance balance problem is most easily simplified using the inverted pendulum model, where the whole body's center of mass (CoM) is modeled as a pendulum pivoting about the ankle joint [2]. In the model, the CoM oscillates back and forth as the destabilizing force of gravity is counteracted by the stabilizing force of the ankle musculature. Our ability to solve this model by regulating the CoM position to maintain upright stance is defined as postural control.

Successful postural control is achieved by meeting the two main goals of postural control: postural orientation and postural equilibrium. Postural orientation involves controlling body alignment with respect to gravity, the ground, and the environment, whereas postural equilibrium is the active coordination of sensory and motor systems to stabilize the body's CoM

[3]. With these two goals in mind, it is important to understand what body systems contribute to successful postural control. While there are a multitude of factors that are required for postural control, the main contributors are the sensory systems, the central nervous system (CNS), and the neuromuscular system [1,3,4]. In the simplest model, the sensory systems provide visual, vestibular, and proprioceptive input from the environment, which the CNS then processes to regulate the correct motor output to stabilize posture [1,3,4]. Although each component is individually important to maintaining balance, it is the dynamic integration of all these systems that is required for us to achieve successful postural control.

Why Study Postural Control?

Even in healthy individuals, investigating postural control can help us better understand several aspects of health and fitness. Additionally, postural control has been widely studied to provide insight into various negative health outcomes such as falls [5,6], musculoskeletal injuries [7,8], and concussions [9,10]. For example, postural stability deficits after anterior cruciate ligament (ACL) reconstruction have been reported to be predictors of a second ACL injury after return to sport [7]. Additionally, there are studies that have demonstrated the clinical relevance of using various postural control metrics as indicators of post-concussion deficits in balance and postural control [9,10]. However, the most widely researched area of postural control involves the link between postural control and fall risk, especially in older adults.

Falls are the leading cause of fatal and nonfatal injuries among individuals aged 65 years or older, and in 2014, 28.7% of older adults reported falling at least once in the past year [11]. Additionally, it is well-documented that older adults are at an increased risk of falling, compared to younger adults, due to factors such as muscle weakness, sensory deficits, cognitive impairment, and postural instability, among others [12,13]. Because of this increased risk and the severe consequences of falls among older adults, postural control has been widely investigated to better understand fall risk predictors and fall prevention strategies. Postural measures of lateral stability have been shown to predict future falling risk among older adults [5], in addition to identifying older adult fallers compared to non-fallers [6]. Measures of postural sway area have also predicted risk of future recurrent falls in a cohort of nursing-home residents [14]. While ageing is one of the most pertinent and extensively researched instances of when postural ability may deteriorate, there are numerous other compromising scenarios in which it is important to investigate postural control.

Analysis of postural control for individuals following stroke [15] or lower limb amputation [16] have shed important insight into motor control strategies used following compromising traumas. Additionally, measures of postural sway have identified deficiencies in postural stability for cancer patients undergoing taxane-based chemotherapy [17]. For patients with cognitive impairments such as Alzheimer's disease, postural control deficits were identified during cognitive dual-task scenarios compared to patients without cognitive impairment [18]. While ageing, traumas, pathologies, and cognitive impairments can all demonstrate adverse effects on postural control ability, our postural control systems can also be compromised due to sensory and cognitive perturbations, even in healthy individuals.

Sensory and cognitive perturbations represent challenging real-world scenarios that may influence postural behavior, especially among at risk groups such as older adults or individuals with cognitive impairment. For example, many postural control studies analyze postural behavior in response to visual occlusion or a perturbation in the support surface they are standing on

[5,19–21]. These represent real-world scenarios such as standing in a room when the lights are suddenly turned off or transitioning from walking on a smooth surface to a rocky surface. Under the presence of sensory conflict, we often employ a strategy of sensory reweighting (i.e., changes in the relative contributions of each sensory system based on environmental conditions) [22]. It is important to investigate postural control during these periods of sensory conflict, because worse sensory integration ability has been associated with worse balance and an increased likelihood of falling [23,24]. Postural control is also analyzed during dual-task scenarios, in which participants are usually asked to perform a secondary cognitive task such as counting backwards, memorizing a set of numbers, or reacting to a stimulus in addition to quiet standing [18,25–27]. However, there are mixed results in the literature regarding the influence of a cognitive dual-task on postural control. Some studies report decreased postural stability [26,28,29] during a simultaneous cognitive task, while other studies report increased postural stability during similar dual-task scenarios [30–33]. Overall, postural control is clinically applicable in many scenarios and can provide insight into a wide variety of health concerns.

Postural Control Analysis Techniques

While postural control can be evaluated for participants with various pathologies, for numerous different sensory and cognitive perturbation conditions, and in a range of stances (bipedal, tandem, single-leg, during gait, etc.), it is important to establish how postural control is actually measured in clinical and laboratory settings. Mostly utilized in the clinical setting, there are a number of non-instrumented tests that have been designed to evaluate participants postural ability and fall risk using a combination of patient reported outcomes, qualitative analysis, and simple calculations [34]. The most widely regarded of these non-instrumented tests are the Berg

Balance Scale and the Mini Balance Evaluation Systems Test [35]. Postural performance can also be analyzed using kinematic devices such as 3D motion capture or 3D accelerometers to asses joint movements and calculate CoM movements of the body and its segments [34]. Electromyography (EMG) is another option for evaluating postural control that measures the muscle activity required for completing specific postural tasks [34]. However, far and away the most common measurement technique for analyzing postural control is the use of force platforms.

Force platforms measure the ground reaction force and moment acting on the plate when someone is standing on it. The force and moment data are then most often used to calculate the time series of the center of pressure (i.e., the point of application of the ground reaction force vector) over the course of a postural control trial [34]. Center of pressure (CoP) parameters are commonly used as the primary outcome variable in postural control studies due to their ease of collection and their established clinical relevance [36]. While there is a vast amount of parameters that can be calculated based on raw CoP data, some of the most commonly used CoP parameters for assessing postural control are 95% confidence ellipse area, path length, CoP amplitude, CoP velocity, root-mean-squared excursion, and mean power frequency [34]. All of these parameters characterize various aspects of how the CoP moves or fluctuates throughout a postural control trial. Additionally, all these parameters can be calculated using the magnitude of the resultant and/or medial-lateral and anterior-posterior components of the CoP path.

Whole-Trial vs Transient Approach to Characterizing Postural Control

Traditionally, postural control analyses that measure CoP have outcome variables of CoP that are represented as whole-trial estimates [21,36–38]. Whole-trial estimates use CoP data from throughout a balance trial but result in one singular estimate of the CoP parameter being measured. Whole-trial estimates are frequently averages of a CoP parameter calculated over the course of the trial. Typically, whole-trial estimates are calculated for balance trials ranging from 30 seconds up to 2 minutes in length [21,36–38]. While there is no standardized trial length that has been established as best-suited for analyzing postural control, some studies have advocated for using longer trial durations (1-2 minutes) in order to increase CoP parameter reliability [37,39,40].

In a study of healthy older adults, common CoP parameters were found to be most reliable in 120-second long trials compared to 60 and 30-second trial durations [39]. In addition, for a cohort of young adults, trials of at least 60 seconds were needed to achieve acceptable levels of reliability for typical CoP parameters [40]. Lastly, a study of eyes open and eyes closed stance reported that a sample duration of at least 60 seconds should be used to optimize the stability and reliability of two commonly used CoP parameters [37]. This was due to the presence of a transient (i.e., a destabilized period followed by a transition to a more stable, quasi-steady-state level) component in the postural control CoP data. The study observed that the proportion of the sample occupied by this transient component will determine the extent to which the transient component will influence the whole-trial estimates of CoP [37]. With another study reporting similar sampling duration effects and nonstationarity in the measured CoP parameters, questions arise as to what aspects of postural control are actually being captured by whole-trial estimates [38].

While it may be advantageous to implement longer sampling durations in order to increase CoP parameter reliability, this approach ends up masking or diminishing the influence of transient postural behavior on whole-trial estimates. Still, whether this transient postural behavior contains new and unique information that is relevant to human health needs to be investigated. Instead of ignoring or minimizing transient postural behavior through longer trial lengths, it may be beneficial to explore how temporal analysis of common CoP parameters can complement existing whole-trial estimate approaches.

As previously mentioned, transient postural behavior has previously been identified during quiet stance [37,38,41–44]. However, these studies either regarded the transient behavior as a negative influence on CoP parameter reliability [37,38], or had observations in very small (n = 3) [43] or very specialized pathologic populations (Parkinson's patients [42] and diabetic neuropathy patients [44]). Interestingly, in studies where transient behavior has been observed, the transient behavior often occurs after a sensory transition such as visual occlusion [38,42–44]. Therefore, this behavior may be a result of sensory reweighting following the removal or reintegration of a sensory input. A few studies have investigated this relationship between sensory reweighting dynamics and the time course of several balance measures after a sensory transition [22,45,46]. Additionally, more complex methods such as recurrence quantification analysis [30,47,48], stabilogram-diffusion analysis [49], and the moving window standard deviation technique [50,51] have also attempted to quantify the temporal structure of CoP fluctuations. Despite these instances of observed transient postural control behavior, few studies have tried to characterize components of the transient responses and better understand the clinical relevance of this behavior. Taking a deeper look into this postural variability may prove beneficial; much like investigations into the “alleged noise” of stride-to-stride variability eventually provided valuable insight into gait physiology that was untapped through traditional, average-stride gait parameters [52].

Statement of Purpose

Because traditional CoP analysis techniques mask or do not account for transient postural responses, there is currently a limited understanding of the significance of transient postural behavior on postural control analysis. Beyond this limited understanding, an overall lack of research into transient postural behavior inhibits the ability to utilize transient postural control data clinically. This emphasizes the need for further investigation into the transient behavior of common CoP parameters, which may provide new, unique, and clinically-relevant insight into postural control analysis that complements existing methods.

Therefore, the overall purpose of this study is to better understand the clinical utility of transient characteristics of postural control during quiet stance. Three experiments were initially conducted to address the following questions: 1) Do transient characteristics of CoP estimates provide different information than traditional whole-trial estimates? 2) Is transient behavior a result of sensory reweighting following the sensory transition of eye closure? 3) Can transient characteristics of CoP estimates distinguish between young and older adults? Based on the results of the initial experiments, a fourth experiment was conducted to address the question 4) How do cognitive perturbations affect the transient behavior of quiet stance postural control?

CHAPTER 2

A NEW PERSPECTIVE ON TRANSIENT CHARACTERISTICS OF QUIET STANCE POSTURAL CONTROL

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Abstract

Postural control provides insight into health concerns such as fall risk but remains relatively untapped as a vital sign of health. One understudied aspect of postural control involves transient responses within center of pressure (CoP) data to events such as vision occlusion. Such responses are masked by common whole-trial analyses. We hypothesized that the transient behavior of postural control would yield unique and clinically-relevant information for quiet stance compared to traditionally calculated whole-trial CoP estimates. Three experiments were conducted to test different aspects of this central hypothesis.

To test whether transient, epoch-based characteristics of CoP estimates provide different information than traditional whole-trial estimates, we investigated correlations between these estimates for a population of young adults performing three 60-second trials of quiet stance with eyes closed. Next, to test if transient behavior is a result of sensory reweighting after eye closure, we compared transient characteristics between eyes closed and eyes open conditions. Finally, to test if there was an effect of age on transient behavior, we compared transient characteristics during eyes closed stance between populations of young and older adults.

Negligible correlations were found between transient characteristics and whole-trial estimates ($P > 0.08$), demonstrating limited overlap in information between them. Additionally, transient behavior was exaggerated during eyes closed stance relative to eyes open ($P < 0.044$). Lastly, we found that transient characteristics were able to distinguish between younger and older adults, supporting their clinical relevance ($P < 0.029$).

An epoch-based approach captures unique and potentially clinically-relevant postural control information compared to whole-trial estimates.

Introduction

Postural control has been widely studied to provide insight into various negative health outcomes such as falls, musculoskeletal injuries, and concussions [5,9,10]. Center of pressure (CoP) parameters are often used as the primary outcome variables to characterize postural control for clinical applications, such as predicting fall risk [5,36]. While these CoP parameters are clinically-relevant, there is significant untapped potential in using these postural control measures as an indicator of health, particularly when investigating transient responses within CoP data.

Traditionally, CoP time-series analyses result in whole-trial estimates of 30 seconds or longer (up to 2 minutes) [5,21,37,38]. However, reports of nonstationarity and sampling duration effects on CoP-based variables of interest raise questions about what aspects of postural control are represented by whole-trial estimates [38]. While longer sampling durations, of 1-2 minutes, have been proposed to increase CoP parameter reliability [37], this approach masks transient postural behavior (i.e., an initial destabilized period followed by a transition to a more stable, quasi-steady state level) that might be relevant to human health. For instance, transient postural control behavior associated with sensory transition (i.e., vision obstruction) was reported to distinguish adults with diabetes from healthy counterparts [44]. Still, a dearth of research into transient postural responses limits the ability to utilize them clinically, necessitating further study.

Although transient behavior has previously been identified during quiet stance [41–44], little research has attempted to characterize aspects of the transient response and understand the clinical relevance associated with this behavior. In experiments where transient behavior has been observed, the transient response often occurs after a sensory transition, such as eye closure, which suggests that this behavior may be a result of sensory reweighting [41–44]. Additionally, few experiments have studied transient postural behavior in older adults despite their well-documented increased risk of falling [5,12,13]. Therefore, deeper investigation into the transient behavior of common CoP parameters may yield new and unique information that complements existing whole-trial estimate approaches.

Three experiments were conducted with the overall purpose to better understand the clinical utility of transient characteristics of postural control during quiet stance. Experiment 1 tested whether transient characteristics of CoP estimates provide different information than traditional whole-trial estimates, with the hypothesis being that transient characteristics of CoP estimates would not be associated with whole-trial CoP estimates. Experiment 2 tested if transient behavior is a result of sensory reweighting after eye closure, with the hypothesis that transient behavior would only exist during eyes closed stance and not eyes open stance. Experiment 3 tested whether transient behavior could distinguish between young and older adults, with the hypothesis that older adults would demonstrate more exaggerated transient behavior than young adults.

Experiment 1: Whole-Trial Estimates vs Transient Characteristics of Postural Control

Experiment 1 Methods

Participants. Young adults (18-35 years old) were recruited from a 2017 American Society of Biomechanics (ASB) Quick Study (i.e. attendees of the 2017 ASB annual meeting in Boulder, CO, USA who volunteered to participate in a society-facilitated “quick research study”) and the Bozeman, MT community. The data from these two groups were combined. Individuals with a known neurological impairment, a prior lower-extremity joint replacement surgery, or a lower-extremity injury within the three months prior to testing were excluded.

Protocol. Before testing, all participants provided written informed consent approved by the Ohio State University Biomedical Sciences Institutional Review Board (Protocol No. 2017H0149) or the Montana State University Institutional Review Board (Protocol No. SM042618). After providing informed consent, participants completed a testing session that analyzed their postural control performance during quiet, eyes closed (QEC) stance. All tests were completed in a single visit.

Each testing session consisted of three successful, 60-second QEC trials. Participants stood without shoes and positioned the medial borders of their feet 5 cm apart [17]. A researcher instructed each participant to stand as still as possible while looking forward and keeping their arms relaxed at their sides. Whenever they felt ready, participants then counted down aloud ‘3-2-1-GO’, simultaneously closing their eyes as they said ‘GO’, which initiated the start of the 60-second trial. Prior to the collection of any official trials, participants performed a 10-second practice trial in which researchers confirmed that the participant understood the counting down and eye closure protocol. Between trials, participants were allowed a self-selected amount of rest. Any trial where a participant lost their balance was not used for analysis and an additional successful trial was then performed to obtain a total of three successful trials. During each trial, vertical force and moments about the x and y axes were recorded at 1000 Hz using a balance plate (BP5046; Bertec Corp.; Columbus, OH) and captured using custom software written in LabView (National Instruments; Austin, TX).

The resulting data were analyzed in MATLAB using custom scripts (Version 2018b; MathWorks, Inc.; Natick, MA). Medio-lateral and anterior-posterior CoP time series data were calculated from the force and moment data using Bertec guidelines. All data were 4th order Butterworth lowpass filtered at 20 Hz [17,21,53]. Traditional, whole-trial estimates and epoch-based estimates were calculated for three commonly used CoP parameters: 95% confidence ellipse area (EA), medial-lateral mean velocity (MVEL_ml), and medial-lateral root-mean-squared excursion (RMS_ml) [21] (Fig 1A). These CoP parameters were selected because they have been linked to fall risk, supporting their clinical relevance [5,6,14,54]. Increases in all CoP parameters were interpreted as worse balance (i.e. more sway). Whole-trial estimates were calculated for each CoP parameter using data from each entire 60-second trial and averaged across all three trials for each participant. In addition to the whole-trial estimates, epoch-based estimates of each CoP parameter were calculated by dividing each trial into twelve, 5-second epochs and calculating each CoP parameter for each epoch (Fig 1B). CoP data were demeaned with epoch-specific mean values, rather than a whole-trial mean, in order to isolate the sway within a given epoch.

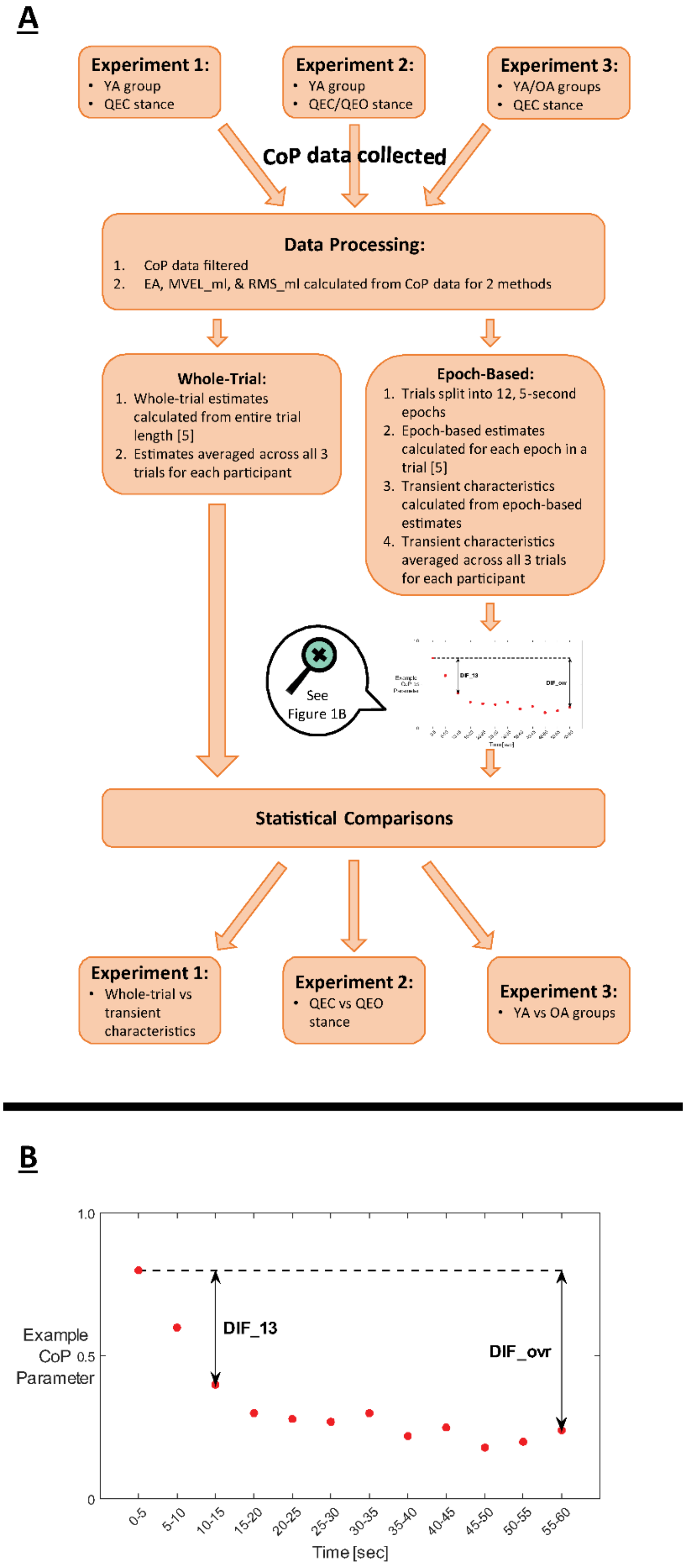

A
Experiment 1:
• YA group
• QEC stance
Experiment 2:
• YA group
• QEC/QEO stance
Experiment 3:
• YA/OA groups
• QEC stance
CoP data collected
Data Processing:
1. CoP data filtered
2. EA, MVEL_ml, & RMS_ml calculated from CoP data for 2 methods
Whole-Trial:
1. Whole-trial estimates calculated from entire trial length [5]
2. Estimates averaged across all 3 trials for each participant
Epoch-Based:
1. Trials split into 12, 5-second epochs
2. Epoch-based estimates calculated for each epoch in a trial [5]
3. Transient characteristics calculated from epoch-based estimates
4. Transient characteristics averaged across all 3 trials for each participant
See Figure 1B
Statistical Comparisons
Experiment 1:
• Whole-trial vs transient characteristics
Experiment 2:
• QEC vs QEO stance
Experiment 3:
• YA vs OA groups
B
1.0
0.5
0
Example CoP Parameter
DIF_13
DIF_ovr
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
Time [sec]

Figure 1. Study overview. (A) General study workflow. Abbreviation definitions: YA = young adult, OA = older adult, QEC = quiet eyes closed, QEO = quiet eyes open. (B) Magnified visual representation of epoch-based estimates and transient characteristics DIF_ovr and DIF_13 for a hypothetical response of an example CoP parameter (e.g., EA, MVEL_ml, or RMS_ml).

Two transient characteristics of these epoch-based estimates were calculated on their original scales to quantify features of the transient behavior of each CoP parameter (Fig 1B): the difference between the 1st and final (12th) epochs (DIF_ovr) and the difference between the 1st and 3rd epochs (DIF_13). The DIF_ovr characteristic was used to quantify the difference from the beginning of the trial to the end of the trial, while the DIF_13 characteristic was used to isolate the transient behavior early in the trial before postural control reached a quasi-steady-state. Each transient characteristic was calculated for EA, MVEL_ml, and RMS_ml parameters.

We also attempted to characterize the transient behavior with an exponential decay fit by using the exponent ‘b’, which we termed ‘DECAY’, from the exponential function equation with a constant offset ($y = a \cdot e^{bx} + c$). While the group data (i.e., averaged epoch values across all trials and participants for a given condition or group) were modeled very well with the proposed exponential fit, considerable variability in the appropriateness of the fit was observed for fitting data for individual participants for a given condition. Poor fits were most prominent when fitting epoch data from individual trials, but persisted in 0-30% of participants when fitting epoch data that were averaged across trials for a given participant and condition. Cases of poor fits were highlighted by negative R^2 values. Given the limitations of the poor fits, we elected to omit the DECAY analysis from the primary hypothesis testing for the three experiments, but have provided the associated analyses in the Supporting information for reference (S1 Table, Appendix A). In these supplemental analyses, we account for the poor fits using three approaches, 1) including all DECAY values as calculated 2) omit the data where the fits do not provide meaningful information (i.e., negative R^2) and 3) designate the DECAY values for these cases with a value of zero to indicate no observed transient behavior.

Statistical Analysis. Spearman's Rank Order correlations were performed between the whole-trial estimates and the transient characteristics DIF_ovr and DIF_13. Transient characteristics DIF_ovr and DIF_13 were averaged across all three trials for each participant. Tests were run separately for EA-, MVEL_ml-, and RMS_ml-based transient characteristics. Non-parametric tests were used because data were often not normally distributed, as assessed by the Anderson-Darling normality test. Associations were interpreted using Spearman correlation coefficients on a traditional scale (.00 to .30 = *negligible*, .30 to .50 = *low*, .50 to .70 = *moderate*, .70 to .90 = *high*, .90 to 1.00 = *very high*) [55]. Significance for all analyses was defined *a priori* at $\alpha = 0.05$. All analyses were performed in Minitab (Version 18.1; Minitab Inc., State College, PA).

Experiment 1 Results

Sixty-seven healthy, young adults (24.9 ± 3.9 years, 75.7 ± 14.7 kg, 1.77 ± 0.09 m, 42 males/25 females) participated in the study. Transient characteristics DIF_ovr and DIF_13 were not correlated to the corresponding whole-trial estimates for EA, MVEL_ml, and RMS_ml parameters (all $P > 0.08$, Table 1). Group values of transient characteristics and whole-trial estimates are provided in Table 2 for reference.

Table 1. Spearman's Rank-Order Correlations between Transient Characteristics and Whole-Trial Estimates

	DIF_ovr	**DIF_13**
EA	0.01 (0.94)	0.13 (0.31)
MVEL_ml	0.21 (0.09)	0.19 (0.12)
RMS_ml	-0.12 (0.32)	-0.02 (0.88)
Values are presented as: Spearman's ρ (*P*-value)		

Table 2. Mean Values for Transient Characteristics and Whole-Trial Estimates for all CoP Parameters

CoP Parameter	**Estimate**	**Value**
EA [mm^2]	DIF_ovr	86.0 ± 133.0
	DIF_13	78.0 ± 129.6
	Whole-Trial	398.0 ± 263.7
MVEL_ml [mm/s]	DIF_ovr	4.72 ± 2.76
	DIF_13	3.45 ± 2.99
	Whole-Trial	7.43 ± 2.60
RMS_ml [mm]	DIF_ovr	0.82 ± 1.03
	DIF_13	0.62 ± 0.96
	Whole-Trial	3.99 ± 1.30
NOTE: Mean ± SD values calculated for between-subjects.		

Experiment 2: Eyes Closed vs Eyes Open Stance

Experiment 2 Methods

Participants. For this experiment, a subset of 30 young adults (22.9 ± 2.6 years, 75.1 ± 11.6 kg, 1.77 ± 0.09 m, 18 males/12 females) that participated in Experiment 1 had additional data collected during their testing session which allowed us to look deeper into the effect of eye closure on transient postural behavior. These were the participants from the Bozeman, MT community that were not subjected to the same time constraints as the ASB Quick Study participants. The same exclusion criteria from Experiment 1 were also used in this experiment.

Protocol. The subset of participants from Experiment 1 had their postural control performance analyzed during quiet, eyes open (QEO) stance in addition to QEC stance per the protocol approved by the Montana State University Institutional Review Board (Protocol No. SM042618). QEO tests were completed during the same visit as the QEC tests from Experiment 1.

The extended testing session consisted of three, 60-second QEC trials and three, 60-second QEO trials. The first trial was randomized between QEC and QEO conditions, with all subsequent trials alternating between the two conditions. For the three QEO trials, participants followed the same protocol described in Experiment 1 and counted down aloud ‘3-2-1-GO’ as they did for QEC trials, but kept their eyes open and fixated on a target (fixation cross, 10 cm x 10 cm) placed 2 m away and 1.69 m high. Participants wore noise-canceling headphones for all QEC and QEO trials to minimize potential environment noise and audible distractions. All tests were completed in a single visit.

The same transient characteristics of epoch-based measures from Experiment 1 (i.e., DIF_ovr and DIF_13 for EA, MVEL_ml, and RMS_ml) were calculated for this experiment.

Statistical Analysis. Linear mixed models were performed for QEC and QEO conditions, separately, to test for the effect of epoch on EA, MVEL_ml, and RMS_ml. Within the models, 'Participant' was a random effect, while 'Epoch', 'Trial Number', and 'Epoch*Trial Number' interaction were fixed effects. Normality and equal variance assumptions were satisfied using the natural logarithms of all CoP parameters. Tukey post-hoc comparisons were performed with a family error rate of $\alpha = 0.05$.

Additionally, paired t-tests were performed to test for the differences in transient characteristics between QEC and QEO conditions for all CoP parameters. Transient characteristics DIF_ovr and DIF_13 were averaged across all three trials for each participant. Because EA DIF_13 were not normally distributed, a 1-Sample Sign test of within-subject differences between conditions was performed for this variable instead of the paired t-test. Normality was assessed using the Anderson-Darling normality test. Significance for all analyses was defined *a priori* at $\alpha = 0.05$. All analyses were performed in Minitab.

Experiment 2 Results

The 'Epoch' fixed effect was significant for both QEC and QEO conditions (all $P < 0.018$) for EA, MVEL_ml, and RMS_ml parameters. Post-hoc analysis identified an initial transient period that was associated with worse balance, where the 1st and 2nd epochs (0-10 seconds) generally had the highest mean values for EA, MVEL_ml, and RMS_ml measures in both QEC and QEO conditions (Fig 2), although not always statistically significant (S2 Table, Appendix A). Additionally, a significant effect of 'Trial Number' existed for all three CoP parameters in both QEC and QEO conditions (all $P < 0.018$), except EA during QEO ($P = 0.138$). Post-hoc analysis identified that in general, Trial 1 was associated with better balance compared to subsequent trials in both conditions, although not always statistically significant (S3 Table, Appendix A). No significant effect for the interaction 'Epoch*Trial Number' existed for any of the three CoP parameters for either QEC or QEO conditions (all $P > 0.059$).

Transient characteristics DIF_ovr and DIF_13 exhibited significant differences between QEC and QEO conditions for EA, MVEL_ml, and RMS_ml parameters, except for DIF_13 for RMS_ml (Table 3). The QEC condition consistently demonstrated higher DIF_ovr and DIF_13 estimates compared to the QEO condition, across all three CoP parameters (Table 3, Fig 2).

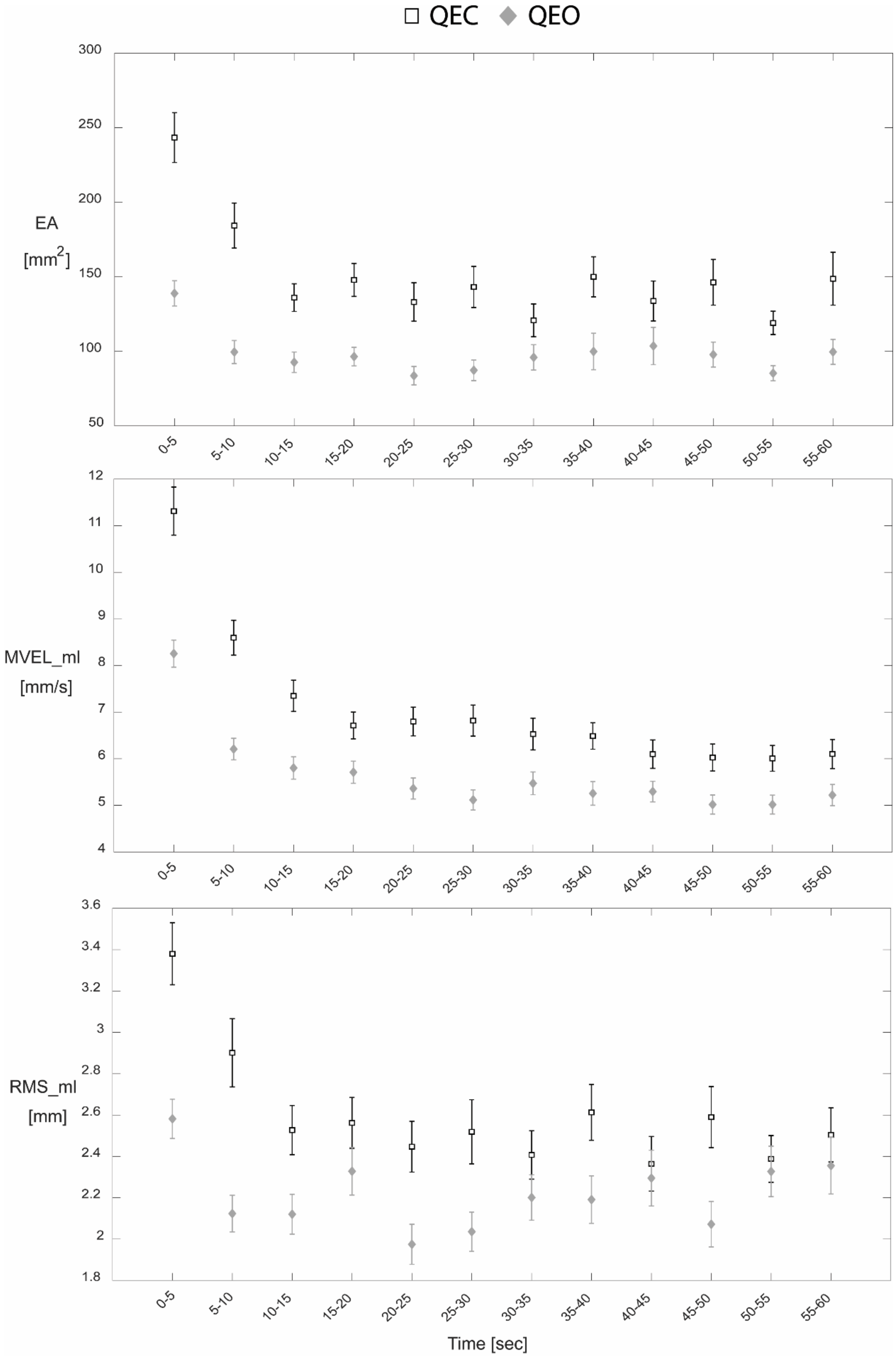

□ QEC ◆ QEO
EA
[mm²]
300
250
200
150
100
50
MVEL_ml
[mm/s]
12
11
10
9
8
7
6
5
4
RMS_ml
[mm]
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
1.8
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
Time [sec]

Figure 2. QEC and QEO transient behavior for each CoP parameter. Hollow squares and gray diamonds represent the time-series data for QEC stance and QEO stance, respectively. Values correspond to mean ± standard error of the mean for each epoch.

Table 3. Mean Values of Transient Characteristics for all CoP Parameters for Eyes Closed and Eyes Open Stance

CoP Parameter	**Transient Characteristic**	**QEC**	**QEO**	***P*-value**
EA [mm^2]	DIF_ovr	94.6 ± 126.2	39.3 ± 50.2	**0.030***
	DIF_13	107.3 ± 102.3	46.2 ± 60.8	**0.043***†
MVEL_ml [mm/s]	DIF_ovr	5.21 ± 3.00	3.04 ± 1.60	**0.001***
	DIF_13	3.96 ± 2.86	2.45 ± 1.75	**0.017***
RMS_ml [mm]	DIF_ovr	0.88 ± 0.94	0.23 ± 0.60	**0.01***
	DIF_13	0.85 ± 0.95	0.46 ± 0.74	0.118

* $P < 0.05$

† The *P*-value of DIF_13 for EA was obtained from a 1-Sample Sign test of within-subject differences between conditions because the data were not normally distributed

NOTE: Mean ± SD values calculated for between-subjects.

Experiment 3: Young vs Older Adults

Experiment 3 Methods

Participants. Older adults (OA) from the Bozeman, MT community were recruited for this experiment and had their postural control performance compared to the healthy, young adults (YA) from Experiment 1. Potential OA participants with any known neurological impairment or who could not stand for more than 5 minutes at a time without some form of assistance (e.g. cane, walker, etc.) were excluded.

Protocol. Before testing, all participants provided written informed consent, which was approved by the Montana State University Institutional Review Board (Protocol No. SM042618). After providing informed consent, all participants completed a testing session that analyzed their postural control performance during QEC stance. All tests were completed in a single visit.

QEC trials were completed following the protocol described for Experiment 1 (i.e., 60-second trial, feet 5 cm apart, participant counted down '3-2-1-GO' and closed eyes to initiate trial). The same transient characteristics of epoch-based measures from Experiment 1 (i.e., DIF_ovr and DIF_13 for EA, MVEL_ml, and RMS_ml) were calculated for this experiment.

Statistical Analysis. To determine whether both young and older adult populations exhibited transient behavior in their postural control, linear mixed models were performed. This analysis was done for each population, separately, to test for the effect of epoch on EA, MVEL_ml, and RMS_ml. Within the models, 'Participant' was a random effect, while 'Epoch', 'Trial Number', and 'Epoch*Trial Number' were fixed effects. Normality and equal variance assumptions were satisfied using the natural logarithms of all CoP parameters. Tukey post-hoc comparisons were performed with a family error rate of $\alpha = 0.05$.

Additionally, Kruskal-Wallis tests were performed to test for the differences in transient characteristics between OA and YA groups for each CoP parameter. Transient characteristics DIF_ovr and DIF_13 were averaged across all three trials for each participant. Non-parametric tests were used for these transient characteristic outcome measures because they were not normally distributed for most cases. Normality was assessed using the Anderson-Darling normality test. Significance for all analyses was defined *a priori* at $\alpha = 0.05$. All analyses were performed in Minitab.

Experiment 3 Results

Sixty-seven healthy, young adults (YA, Table 4) and forty-nine older adults participated in the study. Eleven older adults were excluded due to the following reasons: 4, failure to comply with test protocol; 4, neurological impairment; 2, technical difficulties during collection; 1, blind. The remaining 38 older adults (OA, Table 4) were included in the analyses for this experiment.

Table 4. Participant Demographics (Mean ± SD) for Younger and Older Adult Groups

Group	**Young Adults (YA)**[†]	**Older Adults (OA)**
Size (n)	67	38
Gender (m/f)	42/25	8/30
Age (years)	24.9 ± 3.9[a]	83.5 ± 8.4[a]
Mass (kg)	75.7 ± 14.7[a]	66.5 ± 12.9[a]
Height (m)	1.77 ± 0.09[a]	1.66 ± 0.09[a]

[†] Young Adults group is the same as from Experiments 1 and 2. Demographics for this group are replicated from Section 2.2. for convenience.

[a] $P < 0.05$ for difference between YA and OA.

The ‘Epoch’ fixed effect was significant for both YA and OA groups (all $P < 0.013$) for all three CoP parameters, except RMS_ml for OA ($P = 0.105$). Post-hoc analysis identified an initial transient period that was associated with worse balance, where the 1st Epoch (0-5 seconds) generally had the highest mean values for EA, MVEL_ml, and RMS_ml measures in both YA and OA groups (Fig 3), although not always statistically significant (S4 Table, Appendix A).

Additionally, a significant effect of ‘Trial Number’ existed for all three CoP parameters in both YA and OA groups (all $P < 0.006$), except EA for YA ($P = 0.058$). Post-hoc analysis identified that for OA, Trial 1 was generally associated with worse balance compared to subsequent trials, whereas for YA there was no common trend in how they performed from one trial to the next (S5 Table, Appendix A). No significant effect for the interaction ‘Epoch*Trial Number’ existed for any of the three CoP parameters in either age group (all $P > 0.225$).

Significant differences were found between the OA and YA groups for certain transient characteristics. The OA group had larger DIF_ovr for EA (Cohen’s d = 0.71, $P = 0.001$) and DIF_ovr for RMS_ml (Cohen’s d = 0.45, $P = 0.028$)(Table 5, Fig 3). No other transient characteristics exhibited significant differences between the two groups ($P > 0.05$, Table 5).

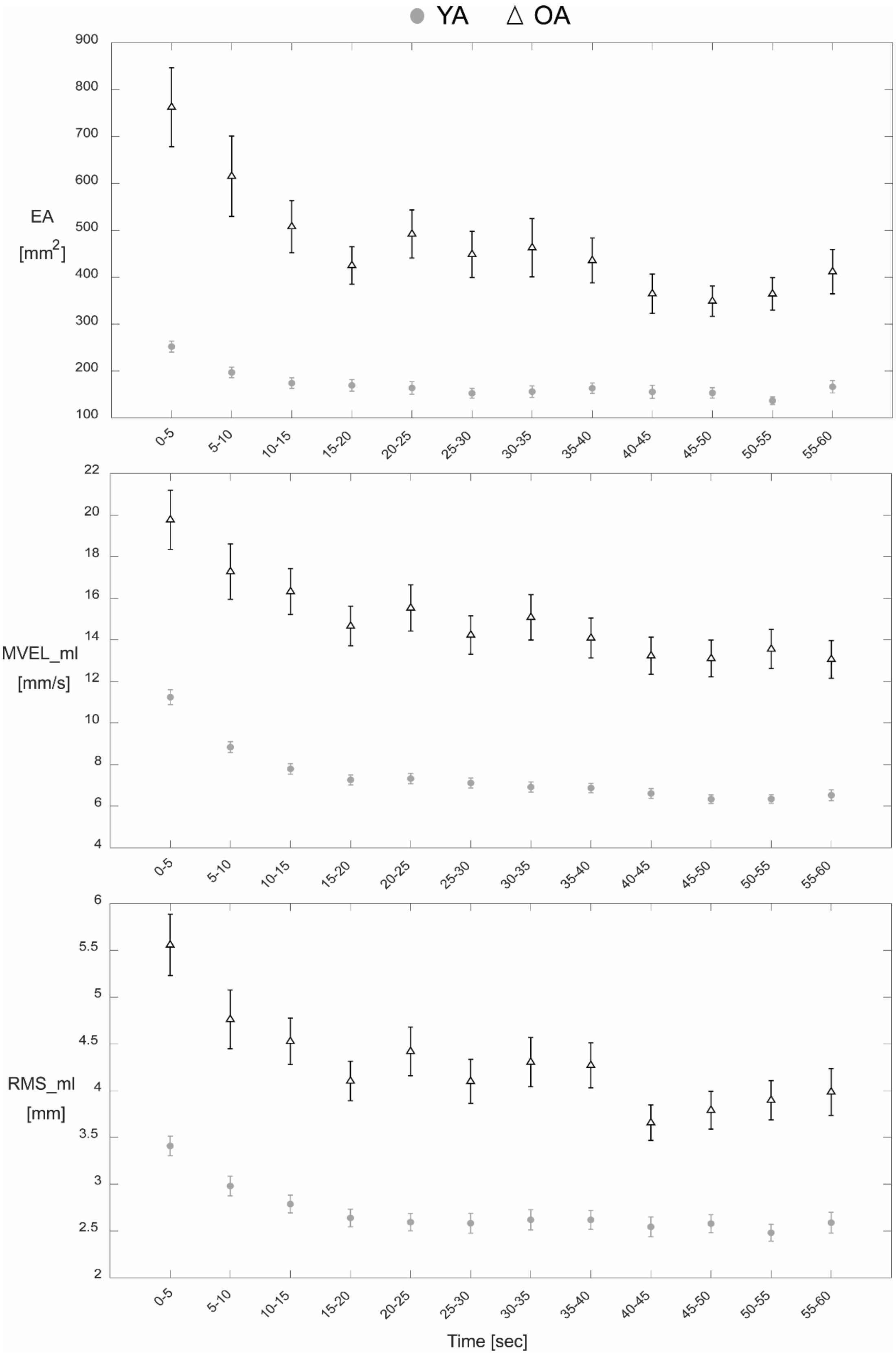

● YA
△ OA
EA
[mm^2]
900
800
700
600
500
400
300
200
100
0-5
5-10
10-15
15-20
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
MVEL_ml
[mm/s]
22
20
18
16
14
12
10
8
6
4
RMS_ml
[mm]
6
5.5
5
4.5
4
3.5
3
2.5
2
Time [sec]

Figure 3. Young and Older Adult transient behavior for each CoP parameter. Gray circles and hollow triangles represent the time-series data for the Young Adult (YA) and Older Adult (OA) groups, respectively. Values correspond to mean ± standard error of the mean for each epoch.

Table 5. Comparisons of Transient Characteristics between Younger and Older Adult Groups

CoP Parameter	Transient Characteristic	YA	OA	P-value
EA [mm^2]	DIF_ovr	86.0 ± 133.0	350.9 ± 513.6	**0.001***
	DIF_13	78.0 ± 129.6	254.8 ± 514.9	0.064
MVEL_ml [mm/s]	DIF_ovr	4.72 ± 2.76	6.71 ± 7.45	0.704
	DIF_13	3.45 ± 2.99	3.45 ± 8.35	0.246
RMS_ml [mm]	DIF_ovr	0.82 ± 1.03	1.57 ± 2.15	**0.028***
	DIF_13	0.62 ± 0.96	1.03 ± 2.09	0.496

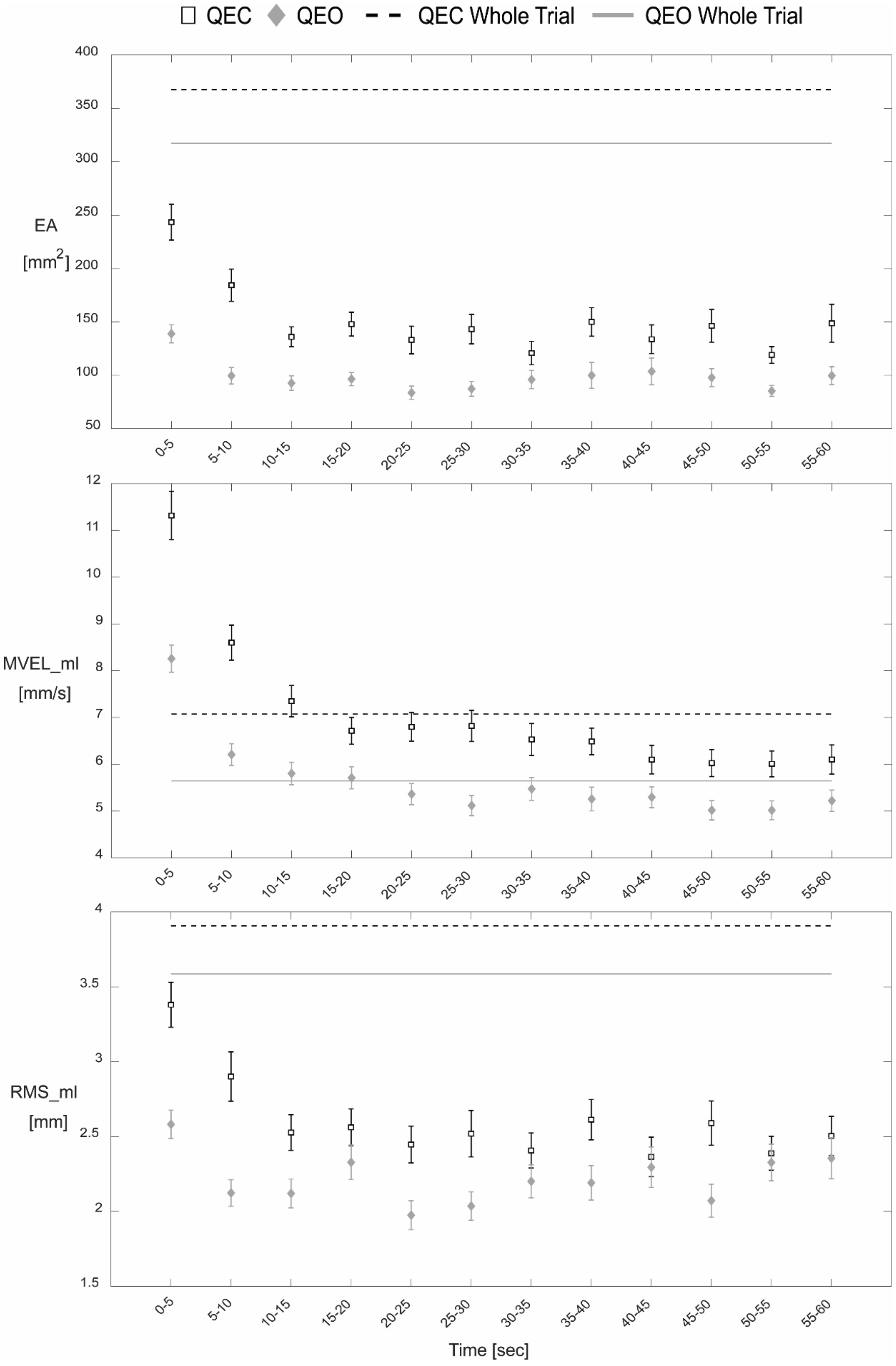
* $P < 0.05$ from Kruskal Wallis tests

NOTE: Mean ± SD values calculated for between-subjects.

Discussion

This study represents a first step toward better understanding the clinical utility of transient characteristics of postural control during quiet stance. Our hypotheses were partially supported. Transient characteristics of epoch-based CoP estimates did not generally associate with whole-trial CoP estimates, supporting the limited overlap in the information they convey. Transient behavior was found for both eyes closed and eyes open conditions, although participants demonstrated exaggerated transient behavior consistent with greater deficits during the eyes closed condition. Additionally, the initial transient behavior at the start of balance trials was observed in both YA and OA populations, with OA demonstrating worse balance and altered transient characteristics for select CoP parameters. This work supports the potential value of considering the transient responses in CoP data when assessing postural control. Notably, the analyses described for our experiments can be made, potentially even retrospectively, with the same CoP time series data that researchers analyze when using traditional whole-trial estimates as primary outcomes. These retrospective analyses should only be considered for experiments where the balance trials and any sensory alteration begin simultaneously. Nevertheless, the transient measures are accessible with little additional effort to provide a potentially more comprehensive assessment of postural control.

The current study found a lack of evidence for relationships between commonly-used whole trial estimates and transient characteristics of epoch-based estimates for the same type of outcome measure (e.g., EA, MVEL_ml, RMS_ml). These findings support the premise that unique information is contained in the initial transient responses of epoch-based CoP estimates that seems to be diminished when using CoP estimates based on entire trials. Conversely, a post-hoc analysis found that both the 1st and final (12th) epochs of EA, MVEL_ml, and RMS_ml measures exhibited moderate-to-high correlations with the whole-trial estimates (S6 Table, Appendix A). Therefore, while the epoch estimates from the beginning and end of trials may correlate to traditional whole-trial estimates, the characteristics of the transient behavior (e.g., differences between these epochs) reflect unique information (i.e., lack of correlation with whole-trial estimates). Additionally, when overlaying graphs of the whole-trial estimates and the time-series data of the same type of outcome measure (Fig 4), it can be seen that, especially for CoP parameters calculated from a central location (e.g., EA and RMS_ml), the whole-trial estimates deviate from the epoch-based estimates. While the whole-trial estimates of EA and RMS_ml correlate with the values for the 1^{st} and 12^{th} epochs, the estimates are biased due to the different method for calculating mean CoP position used to demean the CoP data prior to calculating the parameters (i.e., mean of CoP data within epoch vs. mean of CoP data for entire trial). Additionally, the correlations with whole-trial estimates largely disappear when comparing against transient characteristics that are defined by differences in epoch estimates. Collectively, these findings support that transient characteristics of postural sway may complement traditional whole-trial estimates.


☐ QEC ◆ QEO - - QEC Whole Trial — QEO Whole Trial
EA
[mm^2]
400
350
300
250
200
150
100
50
MVEL_ml
[mm/s]
12
11
10
9
8
7
6
5
4
RMS_ml
[mm]
4
3.5
3
2.5
2
1.5
0-5
5-10
10-15
15-20
20-25
25-30
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50-55
55-60
Time [sec]

Figure 4. Whole-Trial estimates vs Epoch-based estimates for each CoP parameter in QEC and QEO stance. Hollow squares and gray diamonds represent the time-series data for QEC stance and QEO stance, respectively. Dashed black lines and solid gray lines represent the whole-trial estimates for QEC stance and QEO stance, respectively. Values correspond to mean ± standard error of the mean for each epoch.

Although transient behavior in CoP measures during quiet stance have previously been discussed, prior studies have not attempted to characterize aspects of the transient response using an epoch-based approach. Previous studies have identified transient effects in CoP measures following visual deprivation, but either had very small sample sizes (3 participants) [43] or collected data from very specialized clinical populations (diabetic neuropathy [44] and Parkinson's disease [42]). Some more recent studies have investigated relationships between transient postural behavior and sensory reweighting dynamics in healthy populations, albeit using more complex protocols and analysis techniques [22,45,46]. Additionally, numerous studies have generally viewed this initial behavior as undesirable noise with regard to its effects on obtaining traditional whole-trial estimates. Research aimed at maximizing the reliability of whole-trial estimates has understandably advocated for longer quiet stance trial durations [37,39,40] . In the context of our findings, longer trials introduce greater proportions of a quasi-steady-state component (see 20-60 seconds region of Fig 2) that diminishes the influence of the initial transient portion (see 0-15 seconds region of Fig 2) on traditional whole-trial estimates. While our epoch-based approach gives insight into why longer trials are an effective strategy for increasing whole-trial estimate reliability, our findings also indicate that this strategy effectively marginalizes unique information that may be contained in this early portion of quiet stance trials. Our results indicate that particular consideration should be made regarding which aspects of postural control are most pertinent to a given hypothesis. Longer trials may improve the reliability of whole-trial estimates [37,39,40]; however, including a complementary assessment of the initial transient characteristics may provide a more comprehensive characterization of postural control by also accounting for potentially valuable information contained within initial transient responses. Further work is needed to determine if this more comprehensive approach provides advantages in terms of assessing deficiencies and predicting health outcomes.

Notably, we found significant differences between YA and OA groups in our study for the transient characteristics DIF_ovr for EA and DIF_ovr for RMS_ml. Where the OA group exhibited larger overall differences for EA and RMS_ml compared to the YA group. We speculate that the increased transient magnitude may be due to diminished sensory reweighting ability (i.e., the ability to respond to sensory conflicts or transitions) among the OA group. One potential explanation for this observation is that the OA group used a less effective strategy at the onset of the sensory transition of eye closure compared to the YA group. Previously, worse visual-somatosensory integration ability (i.e., the ability to consolidate sensory information from visual and somatosensory modalities) has been associated with worse balance and an increased likelihood of falling in older adults [23]. Although no study has investigated the direct relationship between sensory reweighting ability and fall risk [56], it may be beneficial to measure transient postural control responses to sensory transitions to understand how a person may respond to challenging real-world scenarios (e.g., lights turning off in a room). Additionally, it may be valuable to investigate if other sensory transitions (e.g. vestibular interference or peripheral sensation interference) elicit similar transient responses, as well.

Consistent with previous research that has established that older adults often exhibit diminished postural control and are at an elevated risk for falling compared to younger adults

[5,12,13], these two transient characteristics (DIF_ovr for EA and DIF_ovr for RMS_ml) may also provide clinically-relevant information when assessing an individual's fall risk. While previous research has identified numerous and sometimes contradictory CoP-based measures that are predictors of falls in older adults, there is no consensus on which CoP measures provide the best predictive ability for falls [36,57,58]. However, most of these studies used whole-trial CoP estimates and as established in this study, the transient characteristics of epoch-based CoP estimates exhibit negligible correlations with whole-trial estimates. Therefore, the transient characteristics DIF_ovr for EA and DIF_ovr for RMS_ml may offer complementary clinically-relevant information to be considered alongside whole-trial estimates for a more comprehensive assessment of postural control. Further studies that measure these transient characteristics and longitudinally track falls are necessary to assess whether transient characteristics combined with whole-trial estimates provide any improvement in the predictive ability for fall risk compared to traditional whole-trial estimates alone.

Interestingly, initial transient behavior consistently appeared during both QEC and QEO stance, although the effect on participants' balance was magnified in the eyes closed condition. These results were contrary to our original hypothesis that transient behavior would only exist during QEC stance as a response to the sensory transition that occurs when participants close their eyes and eliminate their vision from helping them control their balance. While it appears that sensory transitions do contribute to transient behavior, observing initial transient effects in the eyes open condition raises questions as to what other factors may be contributing to this behavior. Because participants were able to decide when each trial began by starting the '3-2-1-GO' countdown only after they felt comfortable and ready, we do not believe that the observed transient behavior is a result of participants adjusting to standing on a new surface or standing in the study-imposed stance. One potential contributing factor to the persisting transient effect during the eyes open condition may be a form of a cognitive perturbation that results from an individual transitioning from counting to standing still quietly. Future work is necessary to delineate additional factors that may contribute to transient behavior in postural control data.

As previously stated, during both QEC and QEO stance, we observed an initial transient period in which participants demonstrated worse balance compared to the rest of the trial. However, the transient behavior was exaggerated in the QEC condition (Fig 2), as defined by larger DIF_ovr and DIF_13 estimates compared to the QEO condition (Table 3). This result is consistent with previous work that reported transient responses associated with temporarily destabilizing effects following visual deprivation, although within diabetic neuropathy [44] and Parkinson’s disease patients [42]. In addition, decreased postural stability following the withdrawal of vision has been reported, especially among older adults [59].

While this study provides novel insight into the transient characteristics of postural control, there are several limitations that should be considered. Due to the exploratory nature of this study, we did not correct for multiple comparisons. This provided a more stringent criteria for Experiment 1 where we are more likely to detect significant relationships, although still none were found. Additionally, it allowed for potentially meaningful findings that could guide future confirmatory research to be missed (i.e., found insignificant) [60,61]. Therefore, the risk of Type I error may be inflated and caution should be taken when considering the statistical significance of findings, particularly for comparisons with marginal *P*-values. However, even if we used an overly conservative Bonferonni correction for our 9 original dependent variables (0.05/9 =

0.0056), our results would still indicate that the DIF_ovr for MVEL_ml transient characteristic can distinguish between QEC and QEO stance, while DIF_ovr for EA can distinguish between YA and OA groups. Also due to the exploratory nature of this study, future work that investigates how various processing and filtering schemes affect the transient characteristics may be necessary.

Future work may improve the ability for a DECAY coefficient approach to be used to gain insight into transient characteristics. While the exponential fit with an offset appropriately modeled the group-level epoch data, the quality of the fit for a given participant and condition (using average epoch values across trials for that participant-condition) was much more variable. In some instances, no meaningful fits were able to be obtained. Therefore, it may be beneficial to obtain more than three trials for every participant and condition in order to account for the large variability in quality of fits for epoch data based only on three trials. Adjusting the epoch length may also alter the consistency of these fits. Improving the robustness of the fits would be particularly important for applying this method for screening or longitudinal tracking individual patients. Further work would also be needed to establish the reliability of the transient characteristics for tracking within-subject changes in postural control over time.

Participants within the YA group from the Bozeman, MT community completed their testing in the Montana State University Neuromuscular Biomechanics Lab and wore noise-canceling headphones in order to ensure a quiet environment, free of audible and visual distractions. However, participants within the YA group from the 2017 ASB Quick Study and the OA group completed their testing at the 2017 ASB Annual Meeting and various senior living facilities, respectively. While steps were taken to minimize audible and visual distractions in these environments, they were not completely free of background noise due to the vibrant ASB conference being held in the same building. However, the protocols were otherwise identical and we do not believe that this introduced any confounding effects. Additionally, self-selection bias, particularly amongst the older adults that participated, may have resulted in a relatively higher performing OA group. By not having a truly representative sampling of a typical older adult population, the data may not be representative of the general older adult population. However, the large age difference between older and younger participants provides a useful starting place to understand the ability for features of transient behavior to distinguish between two groups with previously documented differences in postural control and fall risk [21].

Conclusion

This study provides insight into the transient behavior that is observed during quiet stance postural control in various age groups and under various sensory conditions. These findings indicate that using an epoch-based approach for analyzing postural control may capture unique and potentially clinically-relevant information that is marginalized when using traditional whole-trial estimates. Further evaluation is warranted to better understand the relationships between the observed transient behavior during quiet stance postural control and falls.

Acknowledgments

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CHAPTER 3

INFLUENCE OF A COGNITIVE PERTURBATION ON TRANSIENT CHARACTERISTICS OF QUIET STANCE POSTURAL CONTROL

Contribution of Authors and Co-Authors

Manuscript in Chapter 3

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Contributions: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Methodology, Writing – original draft, Writing – review & editing

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Contributions: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Resources, Software, Supervision, Writing – review & editing

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Gait & Posture

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Abstract

Although transient behavior has previously been reported following sensory transitions (e.g., eye closure), transient behavior has recently also been reported even during eyes open stance when no sensory transition was present. It was speculated that the persisting transient behavior may be a response to a cognitive perturbation that occurs when participants counted down out loud to initiate trials. Therefore, we attempted to better understand the influence of cognitive perturbations on transient aspects of postural control. We hypothesized that a cognitive perturbation would introduce transient effects in comparison to no cognitive perturbation, with the magnitudes of the transient postural response increasing as the difficulty of the cognitive perturbation task increased.

Twenty healthy, younger adults had their postural control performance assessed during eyes open quiet stance using the center of pressure parameter 95% confidence ellipse area (EA). EA was calculated for 5-second epochs throughout the trial. Participants completed three trials in three different conditions that either had no cognitive perturbation present (NO), an easy cognitive perturbation (LO), or a more difficult cognitive perturbation (HI) part of the way through the balance trials. The difference in EA from the first epoch following the cognitive perturbation to the last epoch of the trial (i.e., 55-60 seconds after perturbation) characterized transient postural control behavior and was tested for an effect of condition.

There was a significant effect of condition on transient behavior following a cognitive perturbation ($P < 0.029$), with a distinguishable difference between a difficult cognitive perturbation and no cognitive perturbation (Cohen’s d = 0.47, $P < 0.037$). Results suggest

cognitive perturbations may contribute to transient postural behavior, with more difficult cognitive tasks possibly exhibiting magnified transient effects.

Introduction

While postural control is often thought of as a simple and automatic task, it is a rather complex process that requires the integration of sensory systems, motor control, and attentional resources to maintain balance [3,4]. Postural control is often measured using parameters that characterize the movement in the center of pressure (CoP) trajectory over the course of a trial, due to their clinical significance [5,36]. Traditionally, these CoP parameters are represented as whole-trial estimates [5,21,37,38], with longer duration trials (1-2 minutes) thought to improve the reliability of the whole-trial estimates [37,39,40].

While longer trials may in fact improve whole-trial estimate reliability, recent research has determined that this approach masks unique and potentially clinically-relevant transient postural behavior (i.e., a destabilized period followed by a transition to a more stable, quasi-steady-state level) by diminishing the influence of the initial transient portion of balance trials [62]. Previous research has observed transient behavior during quiet stance postural control, generally after a sensory transition such as vision occlusion or restoration [42–44]. Due to these transient responses occurring immediately after a sensory transition, the transient behavior may be a consequence of sensory reweighting (i.e., changes in the relative contributions of each sensory system based on environmental conditions) [22,63]. Additionally, a few studies have found evidence supporting a relationship between sensory reweighting dynamics and the time course of several balance measures in response to sensory transitions [22,45,46]. Various complex methods such as recurrence quantification analysis [30,47,48], stabilogram-diffusion analysis [49], and the moving window standard deviation technique [50,51] have also attempted to quantify the temporal structure of CoP fluctuations. However, the clinical utility of these methods is still not fully understood, necessitating further study.

One recent study from our group explored transient postural control behavior using an epoch-based approach in which 60-second postural control trials were divided into twelve, 5-second epochs, with commonly used CoP parameters calculated for each epoch (Figure 5) [62]. Results indicated that initial transient behavior was present across all experiments in the study, and two characteristics of these epoch-based estimates were able to quantify features of the transient response (Figure 5) [62]. This study also revealed that transient behavior consistently appeared in both quiet, eyes closed (QEC) and quiet, eyes open (QEO) stance, although it was more prominent in the QEC condition (Figure 5) [62]. While transient behavior was expected in QEC trials, observing initial transient effects in the QEO condition raises questions as to what factors may be contributing to this behavior. One proposed theory arises from how these balance trials were initiated. In both conditions, participants initiated the start of trials by counting down aloud ‘3-2-1-GO’, with participants either closing their eyes on ‘GO’ (QEC condition) or maintaining their gaze at a fixation cross on ‘GO’ (QEO condition). Because there was no sensory transition in the eyes open condition, we believe that a cognitive perturbation that occurs when participants transition from counting down to standing quietly may contribute to this transient behavior.

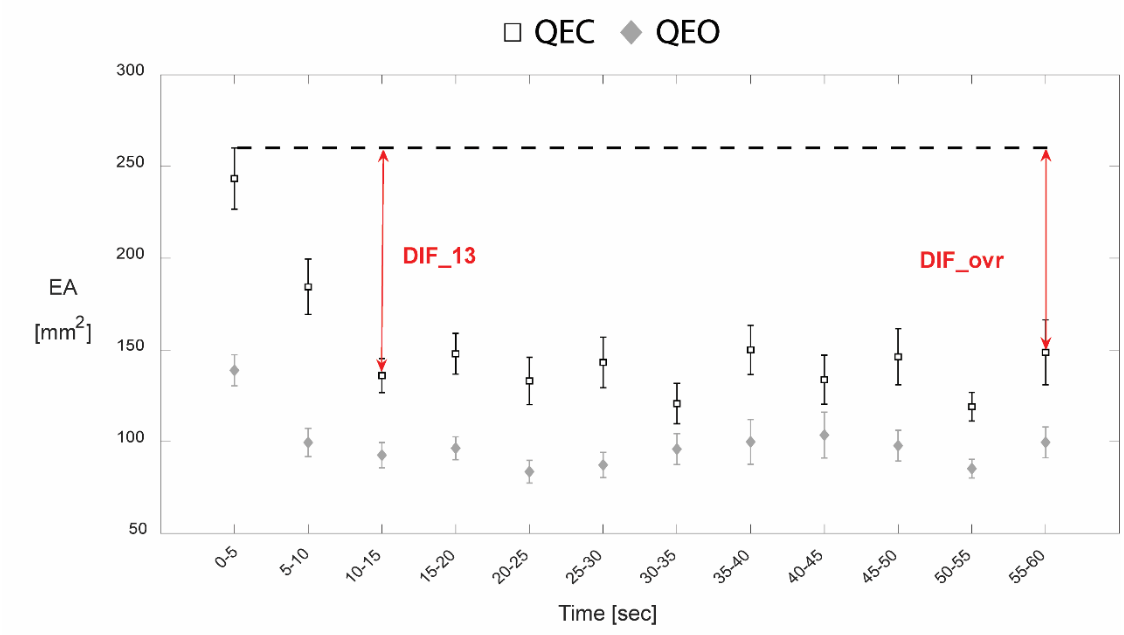

Figure 5. Transient characteristics of epoch-based estimates for postural control. Graph of 95% confidence ellipse area (EA) results for quiet, eyes closed (QEC) versus quiet, eyes open (QEO) stance. Data were calculated for twelve, 5-second epochs in the 60-second balance trials for each condition. A visual depiction of the transient characteristics representing the difference between the 1st and the last (12th) epoch (DIF_ovr) and the difference between the 1st and the 3rd epoch (DIF_13) is highlighted in red for the QEC condition.

While counting down ‘3-2-1-GO’ is an easy task, simple counting tasks have been shown to require at least some level of cognitive demand and attentional resources [64]. Additionally, many studies have shown a relationship between cognition and postural control performance through the posture-cognition dual-tasking paradigm [65]. Although this relationship has been recognized, there are mixed results on how a cognitive task impacts postural control performance. Some studies show that performing a secondary cognitive task while standing decreases postural stability [26,28,29], while others show an increase in postural stability [30–33]. Despite this well-studied link between posture and cognition, very little research has explored transient postural behavior following a cognitive dual-task perturbation. Therefore, investigating the influence of a cognitive perturbation on the transient behavior of common CoP parameters may yield new and unique insight into the posture-cognition dual-tasking paradigm.

The overall purpose of the present study was to better understand the influence of cognitive perturbations on transient postural control behavior during quiet, eyes open stance. We hypothesize that a cognitive perturbation will introduce transient responses in postural control compared to no cognitive perturbation, with an increased magnitude in transient effects as the cognitive perturbation task difficulty increases.

Methods

Participants

Young adults (18-30 years old) were recruited from Montana State University and the Bozeman, MT community. Twenty individuals (22.4 ± 2.1 years, 72.2 ± 10.7 kg, 1.80 ± 0.15 m, 13 males/7 females) participated in the study. Individuals were excluded if they had a known neurological impairment, a lower-extremity surgery within ten years prior to testing, a concussion within one year prior to testing, or a lower extremity injury within three months prior to testing.

Protocol

Prior to testing, all participants provided written informed consent approved by the Montana State University Institutional Review Board (Protocol No. SM042618). Participants then completed a testing session that analyzed their postural control performance during QEO stance, after completing various cognitive dual-task perturbations. All tests were performed in a single visit.

Each testing session consisted of three conditions that represented the difficulty level of the cognitive dual-task perturbation (i.e., NO, LO, and HI). The NO condition was our baseline and involved no cognitive perturbation throughout the trial. The LO condition involved counting backward by 1s from a random 3-digit number, whereas the HI condition involved counting backward by 7s from a random 3-digit number. These cognitive perturbations were chosen because serial subtraction tasks have frequently been used for dual-tasking [18,28,33,46], and they are the most analogous to the '3-2-1-GO' countdown procedure from our previous work [62]. For each condition, participants completed three successful, 100-second trials, resulting in a total of 9 trials.

Each 100-second long trial consisted of three phases (0-30 seconds: Calibration, 30-40 seconds: Stimulus, 40-100 seconds: Testing) (Figure 6). During the Calibration phase, participants began the trial and performed QEO stance. The Calibration phase was necessary to include for the calibration of an fNIRS (functional near-infrared spectroscopy) device (i.e., a neuroimaging device used to measure cerebral activation) that was simultaneously collecting data (not reported in the present study). During the Stimulus phase, participants completed a cognitive task while maintaining QEO stance. During the Testing phase, participants stopped performing the cognitive task and exclusively maintained QEO stance until the end of the trial. While the Calibration and Testing phases were identical across all conditions, the Stimulus phase was not (Figure 6). For the LO condition, the Stimulus phase was initiated 30 seconds into the start of the trial when a researcher said aloud a random 3-digit number (e.g., '510'). The participant was instructed to count backwards by 1s (e.g., '510-509-508-…') aloud and at a comfortable pace from the random number provided by the researcher while maintaining QEO stance. For the HI condition, the Stimulus phase was initiated in the exact same manner as the LO condition, however the participant was instructed to count backwards by 7s (e.g., ‘510-503-496-…’) while maintaining QEO stance. For the NO condition, the participant was instructed to just continue maintaining QEO stance throughout the Stimulus phase of the trial. For all conditions, the Stimulus phase was terminated and transitioned immediately into the Testing phase at 40 seconds into the start of the trial when a researcher said aloud ‘GO’ (Figure 6). This cue reminded the participants to stop performing the cognitive task (i.e., counting backwards aloud) and exclusively focus on maintaining QEO stance until the end of the trial.

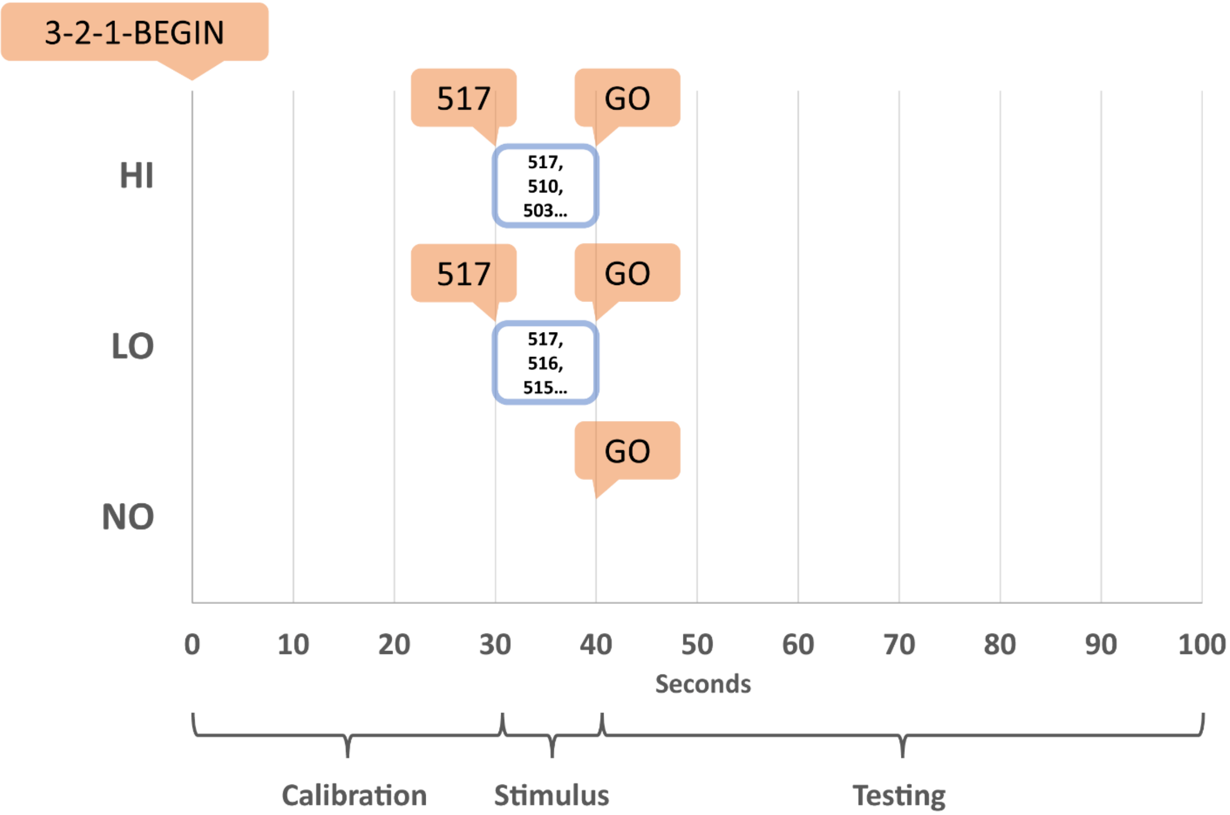

Figure 6. Diagram of researcher cues and participant responses in each cognitive perturbation condition. Visual schematic of NO, LO, and HI conditions with researcher verbal cues represented by the orange-shaded callout shapes and participant verbal responses represented by the blue-outlined boxes. All conditions were initiated by the researcher countdown '3-2-1-GO', with trials starting upon 'GO'. The separate phases of the 100-second trial are also depicted with 0-30 seconds representing the Calibration phase, 30-40 seconds representing the Stimulus phase, and 40-100 seconds representing the Testing phase.

For all trials, participants stood without shoes and positioned the medial borders of their feet 5 cm apart (Figure 7A) [17,62]. The most anterior aspect of participant's feet was marked with tape on the balance surface to ensure participants resumed a consistent foot positioning across trials. Participants were instructed to stand as still as possible with their arms relaxed at their sides, while focusing their gaze on a target (fixation cross, 10 cm x 10 cm) placed 2 m away and 1.69 m high (Figure 7B). Throughout the experiment, participants were also wearing a soft fNIRS cap, although fNIRS data are not reported in the present study (Figure 7B). Once participants confirmed they were in position and ready, the researcher counted down aloud ‘3-2-1-BEGIN’ to initiate the start of the 100-second trial as shown in Figure 6. Prior to the first recorded trial in every condition, participants performed an abbreviated practice trial in which researchers confirmed that the participant understood the instructions, verbal cues, and cognitive dual-task guidelines. Between trials, participants were allowed a self-selected amount of rest. Any trial where a participant did not comply with experimental protocol was not used for analysis and an additional successful trial was then performed to obtain a total of three successful trials in each condition (9 total, successful trials). The testing order of the conditions was block-randomized for every participant. Between conditions, participants took a mandatory break of at least 2 minutes.

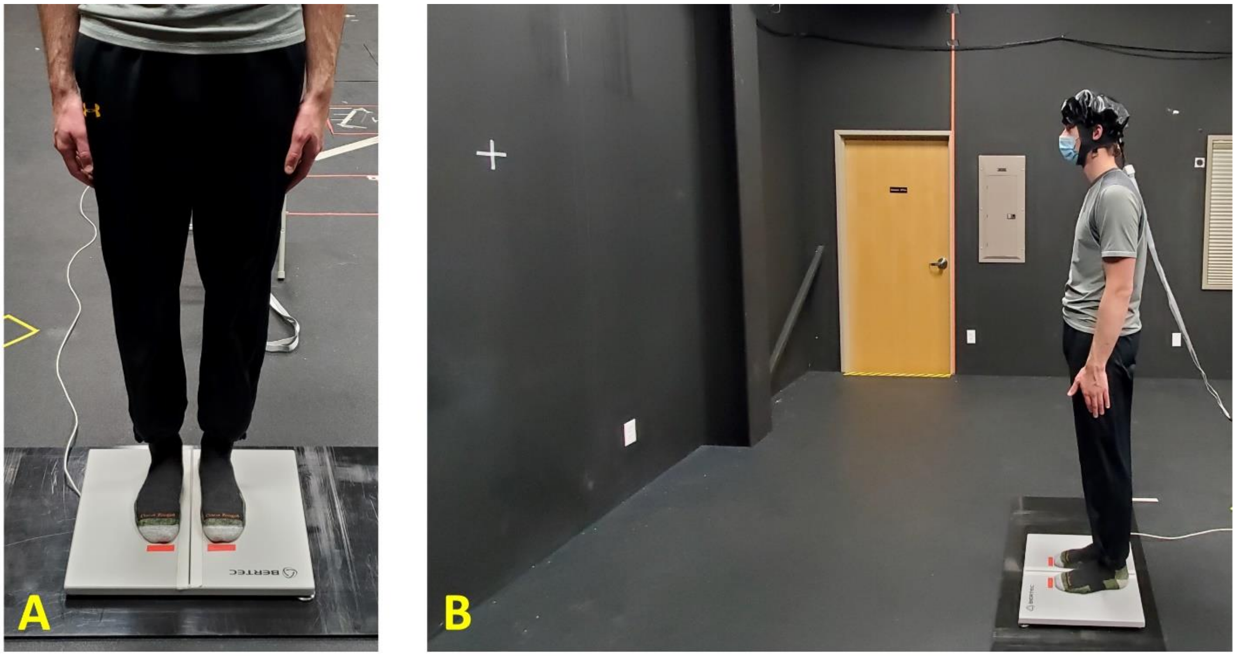

Figure 7. Balance Plate Setup. (A) Frontal plane view of participant performing a trial. (B) Sagittal plane view of participant performing a trial.

During each trial, center of pressure (CoP) data were recorded at 1000 Hz using a balance plate (BP5046; Bertec Corp.; Columbus, OH) and captured using custom software written in LabView (National Instruments; Austin, TX). Using custom MATLAB scripts (Version 2018b; MathWorks Inc.; Natick, MA), the data were 4th order Butterworth lowpass filtered at 20 Hz [17,21,53,62] and variables of interest were calculated for the Testing phase (40-100 seconds) of the 100-second trials. The CoP parameter 95% confidence ellipse area (EA) was calculated for twelve, 5-second epochs throughout the trial. The EA data were demeaned with epoch-specific mean values in order to isolate the CoP movement within a given epoch. The EA CoP parameter was specifically chosen based on its reported clinical relevance in assessing fall risk [6,14]. Additionally, in our previous work, the EA variable demonstrated the ability to distinguish between QEC and QEO stance and young and older adults [62].

In order to compare the transient behavior of EA across epochs and throughout the trial, the difference between the first epoch in the Testing phase and the last epoch (12th) in the Testing phase was calculated (DIF_ovr). The DIF_ovr characteristic was used to quantify the difference in EA from immediately after the cognitive stimulus ended to the end of the trial. The timeframe over which DIF_ovr was calculated represents a 60-second period of quiet stance following the completion of a counting down task that is analogous to the DIF_ovr characteristic of our previous study [62].

Statistical Analysis

Linear mixed models were performed for NO, LO, and HI conditions, separately, to test for the effect of epoch on EA. For the models, ‘Participant’ was a random effect, while ‘Epoch’, ‘Trial Number’, and ‘Epoch*Trial Number’ interaction were fixed effects. Normality of the data and uniform distribution of model residuals were satisfied using the natural logarithms of EA. Tukey post-hoc comparisons were performed with a familywise error rate of $\alpha = 0.05$.

In addition, a general linear model was performed to test for differences in the transient characteristic DIF_ovr for EA between NO, LO, and HI conditions. ‘Condition’ and ‘Trial Number’ were considered fixed effects. Tests were run on both the raw scale EA DIF_ovr measures and the natural logarithmic EA DIF_ovr measures, as the raw scale model residuals exhibited some deviation from normality. Significance for all analyses was defined a priori at $\alpha = 0.05$. All analyses were performed in Minitab (Version 18.1; Minitab Inc., State College, PA).

Results

‘Epoch’ was significant for the HI condition ($P = 0.004$) and the LO condition ($P = 0.012$) for EA, but was not significant for the NO condition ($P = 0.425$). Post-hoc analysis revealed that Epoch 1 had the highest point-estimate of all epochs and earlier epochs generally had higher estimates than later epochs for the HI condition (Figure 8). For the LO condition, there were no discernible trends in how the epochs differed from one another (Figure 8). The ‘Trial Number’ fixed effect was significant for the LO condition ($P = 0.002$) and the NO condition ($P = 0.008$). Post-hoc analysis did not reveal any discernible trends in how the trial numbers differed from one another in the LO and NO conditions. No significant effect for the interaction ‘Epoch*Trial Number’ existed for any of the conditions (all $P > 0.129$).

A general linear model tested for changes in the transient outcome measures between cognitive perturbation conditions. The ‘Condition’ fixed effect exhibited a significant difference for DIF_ovr for both the raw-scale analysis ($P = 0.029$) and the natural logarithmic analysis ($P = 0.006$) (Table 6). Post-hoc analysis revealed that the HI condition was significantly different from the NO condition for both the raw-scale comparisons (Cohen’s d = 0.47, adjusted *P* = 0.037) and the natural logarithmic comparisons (Cohen’s d = 0.58, adjusted *P* = 0.007) (Table 7). Post-hoc analysis also revealed that the LO condition was trending towards a significant difference from the NO condition for the raw-scale comparisons (Cohen’s d = 0.39, adjusted *P* = 0.083), whereas the LO condition exhibited a small significant difference from the NO condition for the natural logarithmic comparisons (Cohen’s d = 0.44, adjusted *P* = 0.047) (Table 7). The HI and LO conditions were not significantly different from each other for both the raw-scale comparisons (Cohen’s d = 0.06, adjusted *P* = 0.943) and the natural logarithmic comparisons (Cohen’s d = 0.13, adjusted *P* = 0.771) The ‘Trial Number’ fixed effect was not significant for the transient characteristic DIF_ovr for EA (*P* = 0.929).

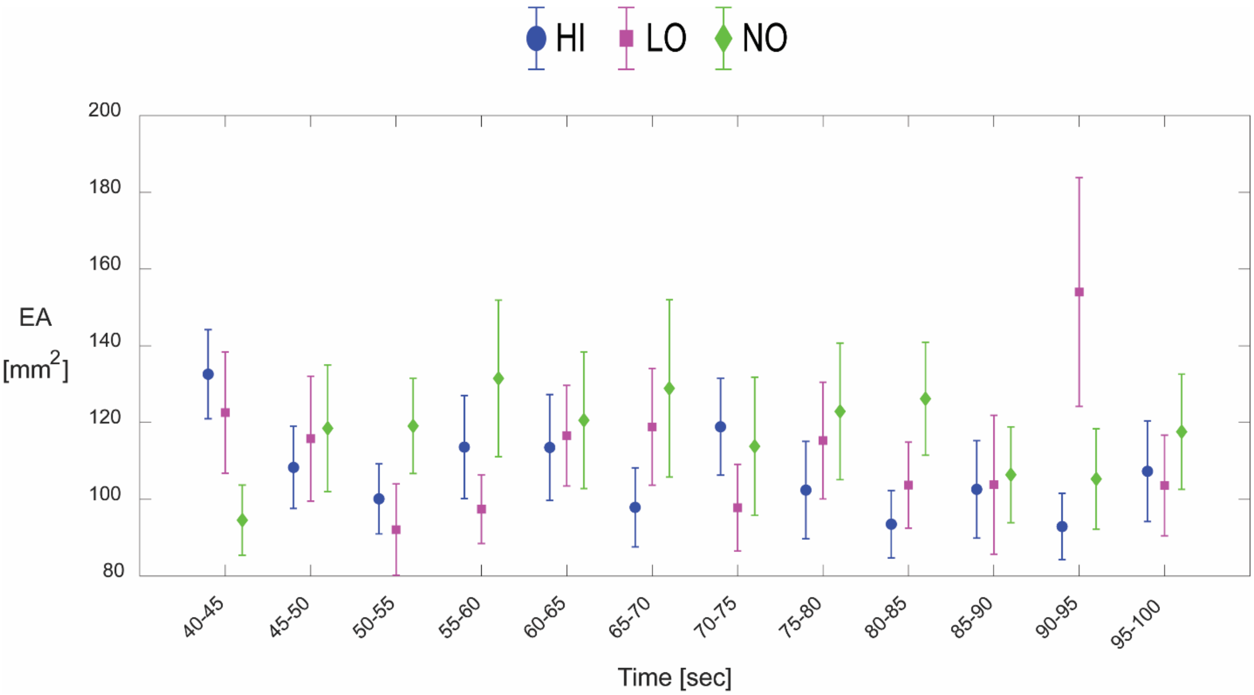

Figure 8. Transient behavior for EA across all three cognitive perturbation conditions. Blue circles, pink squares, and green diamonds represent the time-series data for the HI, LO, and NO cognitive perturbation conditions, respectively. Values correspond to mean ± standard error of the mean for each epoch.

Table 6. Mean Values of Raw Scale and Natural Logarithmic EA DIF_ovr for All Three Cognitive Perturbation Conditions

C	HI	LO	NO	*P*-value
EA DIF_ovr	25.4 ± 104.3	19.0 ± 116.2	-23.0 ± 99.8	**0.029***
LN EA DIF_ovr	0.302 ± 0.829	0.198 ± 0.875	-0.166 ± 0.780	**0.006***

* $P < 0.05$

Mean ± SD values calculated for between-subjects

Table 7. Tukey Post-Hoc Comparisons between Cognitive Perturbation Conditions for Raw Scale and Natural Logarithmic Analyses

Raw Scale		**Natural Logarithm**	
Comparison	**Cohen's d (Adjusted *P*-value)**	**Comparison**	**Cohen's d (Adjusted *P*-value)**
NO-LO	0.39 (0.083)	NO-LO	**0.44 (0.047*)**
NO-HI	**0.47 (0.037*)**	NO-HI	**0.58 (0.007*)**
LO-HI	0.06 (0.943)	LO-HI	0.13 (0.771)
* $P < 0.05$ Values are presented as: Cohen's d (Adjusted *P*-value)			

Discussion

This study represents a first step into better understanding the influence of a cognitive perturbation on transient aspects of postural control during quiet stance. Our hypothesis was partially supported. Transient behavior was present following a difficult (HI) and easy (LO) cognitive dual-task perturbation, but no transient behavior existed during quiet stance without a cognitive dual-task perturbation (NO). Additionally, the transient characteristic of DIF_ovr for EA was able to distinguish differences between the HI and NO conditions, with a small difference trending towards significance between the LO and NO conditions. While there was not a significant difference in DIF_ovr between HI and LO conditions directly, the HI (Cohen's d = 0.47) condition did exhibit a slightly larger effect size than the LO condition (Cohen's d = 0.39), relative to the NO condition. Overall, there is evidence to support that cognitive perturbations, especially more challenging tasks, can contribute to transient behavior in quiet stance postural control trials. Our findings also indicate that a form of cognitive perturbation due to participants transitioning from counting to standing quietly is a plausible explanation for the persisting transient behavior that we observed in the eyes open condition of our previous study [62]. Collectively, these results further support the use of transient characteristics in analyzing CoP responses to various types of postural perturbations.

Notably, initial transient behavior appeared in the HI and LO conditions, much like the transient behavior observed in response to sensory transitions [42–44,62]. However, when comparing the mean, raw-scale DIF_ovr for EA magnitudes from the cognitive perturbation conditions (HI and LO) to our previously collected sensory perturbation conditions (OA QEC, YA QEC) [62], noticeable differences do exist (Figure 9). The smallest mean DIF_ovr for EA was in the NO condition, where there was no cognitive or sensory perturbation present. At a slightly higher magnitude than the NO condition, the HI and LO cognitive perturbation conditions and the YA QEO condition (i.e., unintended cognitive perturbation due to '3-2-1-GO' countdown) from our previous study all exhibited similar DIF_ovr for EA values. When combining the sensory perturbation of eyes closure (YA QEC) to the unintended countdown cognitive perturbation, DIF_ovr for EA results are even higher in magnitude. Lastly, the highest magnitude DIF_ovr for EA results occur in the combined sensory and unintended countdown cognitive perturbation condition within an increased fall-risk population of older adults (OA QEC). These collective results suggest that sensory perturbations may be a larger contributor to transient postural behavior than the cognitive perturbations of the present study, but the transient effects may be compounded when sensory and cognitive perturbations are present simultaneously.

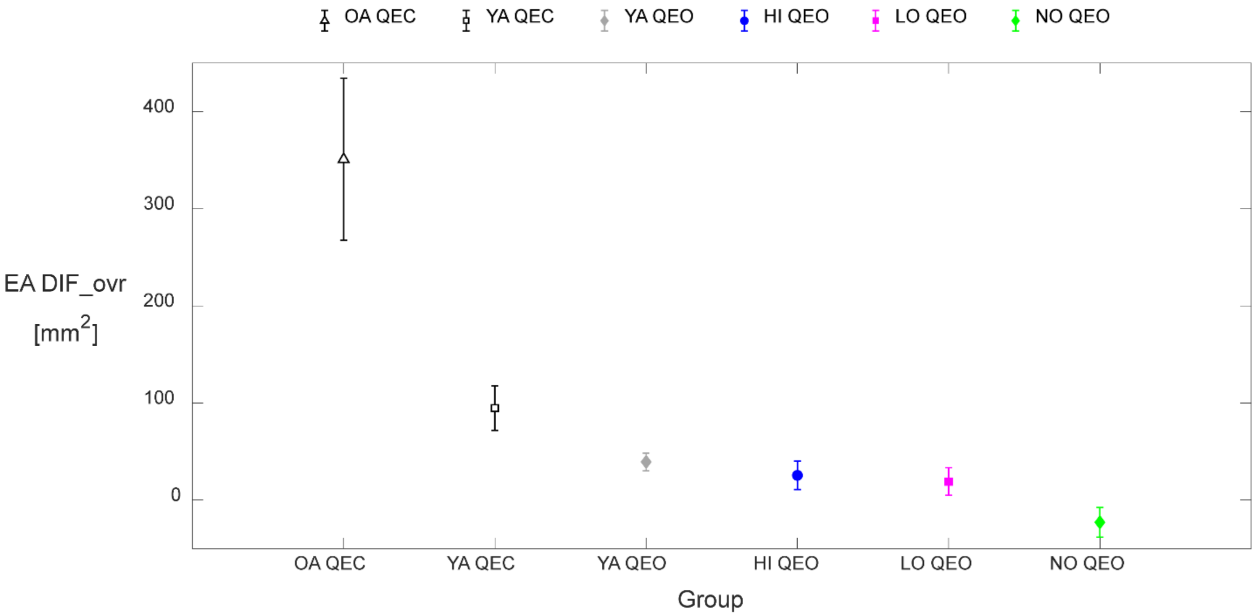

Figure 9. Mean EA DIF_ovr values across various sensory and cognitive perturbation conditions. The mean DIF_ovr for EA estimates for participant groups of various ages and under various sensory and cognitive perturbation conditions. OA QEC, YA QEC, and YA QEO data is from a previously collected study [62], while HI QEO, LO QEO, and NO QEO data is from the HI, LO, and NO conditions of the present study. Values correspond to mean ± standard error of the mean for each group.

While many studies have looked into the cognitive-postural dual-task paradigm to understand how sensory transitions and cognitive tasks influence postural control [65], few have approached this with the perspective of looking into transient responses to these transitions. Some studies have investigated temporal changes in postural control following a sensory transition while performing a cognitive task [46], but little research has investigated transient postural control performance while transitioning in or out of performing the cognitive task. Because both sensory transitions (e.g., lights turning off in a room) and cognitive perturbations (e.g., answering your phone and starting to talk) are representative of challenging real-life scenarios, investigating the transient behavior at these transition points, may provide unique and complementary insight into events where postural control is compromised. Future work into transient postural responses following cognitive, sensory, and stance perturbations is needed to better understand the interplay between various types of perturbations and their relative contributions to transient postural control behavior.

It is also important to note that transient behavior was not observed in the NO condition, as the epoch estimates were not significantly different from each other across trials when there was no cognitive perturbation (Table 6, Figure 8). This finding further supports the potential value of using transient characteristics to assess postural control, especially in response to perturbations, as transient behavior does not appear to always be present in the resulting CoP data. Another implication of this finding, is the need for researchers to carefully consider how postural control trials are initiated, depending on what aspects of postural control they are attempting to analyze. Even something as simple as a countdown procedure can introduce (potentially unintended) transient effects that may or may not be accounted for based on the analysis techniques used. When designing a postural control study, researchers may need to consider whether trials are researcher- or participant-initiated and whether or not to allow participants a period of time to assume quasi-steady state posture prior to recording data.

Although our results provide evidence that cognitive perturbations can contribute to transient postural control behavior, there may be additional factors that also influence the observed transient responses. One possible factor is the effect of articulation when a spoken mental task is being performed. A previous study found an increase in sway path when performing cognitive tasks that required articulation, compared to cognitive tasks that were performed silently [66]. They suggested that potential changes in respiration and arousal levels that occur during articulation may contribute to changes in postural control performance.

Therefore, it may be necessary to investigate transient postural responses from both spoken and silent cognitive perturbations. While there is well-documented use of silent cognitive tasks in the posture-cognition dual-task paradigm [30,33,56,67], it can be harder to confirm engagement in silent tasks compared to spoken cognitive tasks. The use of a technology that measures cerebral activation, such as fNIRS, may be needed to assess changes in brain activation to corroborate interpretations regarding attentional investment in studies that investigate how articulation affects transient postural control [68].

While this study provides new insight into the influence of cognitive perturbations on transient behavior in quiet stance postural control, there are several limitations that should be considered. During all balance trials that were collected, participants were also wearing an fNIRS cap that may have influenced postural control performance compared to typical real-world stance. Based on patient reported outcomes of comfort throughout the trial and because the fNIRS cap was worn for all balance trials, we do not believe that this introduced any confounding effects regarding our findings. Participants were also wearing masks or face coverings during all balance trials, due to the COVID-19 pandemic. While we do not believe this had any effect on postural control performance, there may have been unaccounted for effects especially when articulating the cognitive perturbation responses. Lastly, the standard deviation measures of EA for DIF_ovr were very large compared to the means of EA for DIF_ovr (Table 6). While results of our previous work had similarly large standard deviations in DIF_ovr for EA, the mean values were much smaller than the means in our previous work [62].

Conclusion

This study provides a better understanding of the influence of cognitive perturbations to transient behavior in quiet stance postural control. These findings indicate that cognitive perturbations, such as serial subtraction tasks, can contribute to transient postural behavior during quiet stance trials.

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CHAPTER 4

GENERAL CONCLUSION

Postural control is a widely studied area of research that provides significant insight into many health concerns such as concussions, musculoskeletal injuries, and falls. Within falls related research, postural control analysis has become an important tool for predicting fall risk and informing fall prevention strategies, especially among at-risk populations such as older adults and individuals with cognitive impairments [12,13]. Traditionally, analysis techniques for postural control rely on whole-trial estimates of various center of pressure (CoP) parameters, because of their proven clinical-relevance [5,36]. However, recent research into whole-trial CoP analyses has raised questions on if these traditional techniques are capturing all aspects of postural control [37,38].

Some advocates of whole-trial CoP analyses suggest that increasing postural control trial durations may improve the reliability of the resulting whole-trial CoP estimates [37,39,40]. However, whole-trial analyses and longer trial durations mask transient behavior within CoP data that are regularly present at the beginning of postural control trials [37,38,62]. While this transient behavior is often considered noise within postural control data, it may provide important information that is not captured or disregarded by traditional whole-trial analysis techniques. This potentially valuable information contained with transient postural behavior may provide a new perspective on postural control that complements existing methodologies.

Therefore, the purpose of this thesis was to better understand the clinical utility of transient characteristics of postural control during quiet stance. To address this gap in knowledge, we set out to answer four distinct questions: 1) Do transient characteristics of CoP estimates provide different information than traditional whole-trial estimates? 2) Is transient behavior a result of sensory reweighting following the sensory transition of eye closure? 3) Can transient characteristics of CoP estimates distinguish between young and older adults? 4) How do cognitive perturbations affect the transient behavior of quiet stance postural control?

Whole-Trial Estimates vs Transient Characteristics

To answer question 1, we tested for the correlations between transient characteristics of epoch-based estimates of CoP and traditional whole-trial estimates. Results indicated that epoch-based estimates of CoP did not generally associate with whole-trial CoP estimates for the CoP parameters EA, MVEL_ml, and RMS_ml. This indicates that there is limited overlap in the information that is conveyed by the transient characteristics compared to the traditional whole-trial estimates.

Eyes Closed vs Eyes Open Stance

To answer question 2, we tested if transient postural behavior was a result of sensory reweighting by comparing transient characteristics of epoch-based estimates of CoP between eyes closed and eyes open stance. Results indicated that while transient behavior was present in both eyes closed and eyes open stance, the transient effects were exaggerated in the eyes closed condition. This supports that sensory reweighting contributes to transient postural behavior, but it is not the sole factor contributing to transient responses.

Young vs Older Adults

To answer question 3, we tested for the potential clinical relevance of transient characteristics of epoch-based estimates of CoP by comparing these measures between young and older adult groups. Results indicated that while transient behavior was present in both groups, the older adults demonstrated much more exaggerated transient responses compared to the young adults. Additionally, certain transient characteristics were able to distinguish between young and older adults. This supports the potential clinical relevance of the certain transient characteristics that could distinguish between groups, due to the known differences in fall risk between young and older adults.

Cognitive Perturbation Influences

To answer question 4, we tested for the influence of various cognitive perturbations on transient postural control behavior by comparing the transient characteristic DIF_ovr for EA between three different difficulty level cognitive dual-task conditions. Results demonstrated that transient behavior was present following a cognitive perturbation, with more difficult cognitive perturbations potentially causing more exaggerated transient effects. This indicates that cognitive perturbations may also be a contributor to transient postural control behavior.

Overall Conclusions

Overall, the collective results of these four experiments provide an impactful first step towards better understanding the clinical utility of transient characteristics of postural control during quiet stance. Our findings support the premise that new and unique information truly is contained within the initial transient portions of postural control trials. Because of this, there is support for using a more comprehensive approach to analyzing postural control that includes both whole-trial and transient measures. Additionally, because whole-trial and transient analyses capture different information, there are a few methodological considerations that need to be accounted for when analyzing postural control.

While whole-trial outcomes and epoch-based transient characteristics each provide information for postural control assessment, these analyses may be most valuable when used together as a more comprehensive approach to analyzing postural control. For example, a trial where a participant exhibited very stable postural sway with one large, but immediate shift in center of pressure could benefit from this comprehensive approach. Using epoch-based techniques, if the participant exhibited a very stable CoP before and after one large shift in posture, this shift would most likely only be captured by one epoch estimate with no influence on any other epochs. Likewise, using whole-trial techniques, the one large shift in posture may dominate the outcome measure and may not capture the very stable posture exhibited outside of the one large shift. With a comprehensive approach that includes both types of analysis, a clearer and more complete picture of how that participant controlled their posture could be obtained.

Additionally, when designing a postural control study, researchers need to critically think about which aspects of postural control they are attempting to evaluate. If a researcher or clinician wants to assess the quasi-steady state component of a postural control trial, they may benefit from using longer trial durations and use whole-trial estimates to provide more reliable outcome measures [37,39,40]. However, a researcher looking into postural control responses to a sensory transition may want to capture the transient component of a postural control trial using the approach that we implemented throughout this thesis [62]. Once again, because these two approaches provide different, yet relevant information, the most comprehensive assessment of postural control may include both whole-trial and transient analyses. Still, further work is needed to determine if this comprehensive approach provides any advantages in assessing postural deficiencies and predicting health outcomes.

Researchers also need to be conscientious of how postural control trials are initiated so as not to introduce potentially confounding transient effects into the initial portions of a trial. As we discovered in this study, even participants performing a simple countdown procedure to initiate a trial may contribute to the transient response within CoP outcomes. The impact of these effects on balance outcomes is likely larger for transient characteristics than whole-trial estimates that may already water down the transient effects present during quiet stance. Therefore, when designing a postural control study with interest in transient characteristics, researchers may need to consider whether trials are participant or researcher initiated, whether or not participants have a period of time before data is collected to assume quasi-steady state posture, and when exactly participants should transition in and out of sensory or cognitive perturbations throughout a trial.

The collective results of this thesis also provide a new perspective into better understanding the concepts of sensory reweighting and sensory integration. By utilizing analysis techniques that do not mask transient components of postural control trials and characterize the transient response, researchers may be able to provide new insight into how postural control is affected by sensory transitions. These techniques may also be able to pick up on more subtle changes in posture in response to sensory transitions that are not always captured by whole-trial CoP analyses. Furthermore, since transient analyses are sensitive to postural changes in response to cognitive perturbations, these analyses may also be important to use in the postural-cognitive dual-task paradigm. Perhaps, transient analyses could be used in dual-task scenarios to delineate contributions in postural changes attributed to cognitive versus sensory perturbations. In addition to sensory and cognitive perturbations, transient techniques could be extended to analyzing postural control in response to stance perturbations such as landing from a jump or transitioning from double limb to single limb stance. Because sensory, cognitive, and stance perturbations may be more representative of real-world scenarios that challenge our postural control, it is important for further work to investigate the clinical relevance of transient analyses within fall prediction and fall prevention studies.

Additionally, transient postural control analyses may be able to provide complementary insight into postural adaptations and postural strategies that are employed during sensory and cognitive perturbations. Especially in dual-task studies, transient analyses collected in conjunction with technologies that measure brain activation (e.g., fNIRS) may be able to provide valuable understanding into the relationship between temporal postural control measures and the corresponding attentional investment during a dual-task scenario. Further work that combines these two sources of data, may be able to elicit the postural strategies that are used in response to various sensory or cognitive perturbations.

Lastly, it is important to recognize that the transient analyses implemented in this thesis can be made with the same CoP time series data that researchers collect when using whole-trial analysis techniques. This allows retrospective analysis using the proposed transient measures for previous balance studies where trials were initiated simultaneously with a balance perturbation or if a trigger marked the timepoint of the perturbation. Thus, with minimal effort previous studies may be able to perform the proposed transient analysis and provide a potentially more comprehensive assessment of postural control. Not only are these analysis techniques useful for retrospective analysis, but they are also easy to implement within a clinical setting. The CoP data needed for the proposed transient analysis can be collected using the same equipment as existing quiet stance analyses. Clinicians can then access transient responses to sensory and cognitive perturbations that are often captured using more elaborate and expensive force plate equipment.

Overall, this thesis provides a new perspective on the unique information contained within transient postural behavior and insight into important methodological considerations for researchers when designing future postural control studies.

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APPENDICES

APPENDIX A

CHAPTER 2 SUPPLEMENTAL INFORMATION

S1 Table. DECAY statistical analysis and results.

Experiment 1			Experiment 2			Experiment 3		
Case 1: Including all DECAY values as calculated								
	N	**Spearman rho (p-value)**		**N**	**p-value**		**N**	**p-value**
EA	67	0.06 (0.63)	**EA**	30	0.099	**EA**	105	0.254
MVEL_ml	67	-0.03 (0.84)	**MVEL_ml**	30	1.000	**MVEL_ml**	105	0.254
RMS_ml	67	0.24 (0.05)	**RMS_ml**	30	0.585	**RMS_ml**	105	0.222
Case 2: Omitting DECAY values that have poor fits (i.e., negative R^2)								
	N	**Spearman rho (p-value)**		**N**	**p-value**		**N**	**p-value**
EA	58	0.17 (0.20)	**EA**	23	0.093	**EA**	89	0.558
MVEL_ml	65	-0.009 (0.94)	**MVEL_ml**	30	0.585	**MVEL_ml**	101	0.154
RMS_ml	59	0.19 (0.14)	**RMS_ml**	19	1.000	**RMS_ml**	92	0.281
Case 3: Designating DECAY values that have poor fits to a value of zero								
	N	**Spearman rho (p-value)**		**N**	**p-value**		**N**	**p-value**
EA	67	-0.11 (0.39)	**EA**	30	0.265	**EA**	105	0.380
MVEL_ml	67	0.008 (0.95)	**MVEL_ml**	30	0.585	**MVEL_ml**	105	0.125
RMS_ml	67	-0.003 (0.98)	**RMS_ml**	30	0.458	**RMS_ml**	105	0.323

NOTE: The N column refers to the number of DECAY fits analyzed. In Case 1 and 3, this number matches the total number of participants for each experiment.

NOTE: Experiment 1 analyses were ran using Spearman Rank-Order correlations, Experiment 2 analyses were ran using 1-Sample Sign tests, and Experiment 3 analyses were ran using Kruskal-Wallis tests.

S2 Table. ‘Epoch’ post-hoc analysis for all CoP parameters for eyes closed and eyes open stance.

Experiment 2 Tukey Pairwise Comparisons: Epoch

Grouping Information Using the Tukey Method and 95% Confidence

QEC							**QEO**						
	Epoch	**N**	**Mean**	**Grouping**				**Epoch**	**N**	**Mean**	**Grouping**		
Natural Log of EA [mm^2]	1	90	5.551	A			**Natural Log of EA [mm^2]**	1	90	4.833	A		
	2	90	5.082	A	B			2	90	4.563	A	B	
	12	90	4.828		B	C		10	90	4.417	A	B	
	9	90	4.746		B	C		4	90	4.322		B	
	10	90	4.743		B	C		3	90	4.322		B	
	4	90	4.720		B	C		11	90	4.282		B	
	8	90	4.693		B	C		8	90	4.272		B	
	6	90	4.670		B	C		7	90	4.270		B	
	5	90	4.655		B	C		6	90	4.245		B	
	3	90	4.628		B	C		9	90	4.206		B	
	7	90	4.534			C		12	90	4.176		B	
	11	90	4.520			C		5	90	4.088		B	
	Epoch	**N**	**Mean**	**Grouping**				**Epoch**	**N**	**Mean**	**Grouping**		
Natural Log of MVEL_ml [mm/s]	1	90	2.462	A			**Natural Log of MVEL_ml [mm/s]**	1	90	2.104	A		
	2	90	2.187	A	B			2	90	1.846		B	
	3	90	1.928		B	C		3	90	1.736		B	C
	4	90	1.875			C		4	90	1.648		B	C
	7	90	1.809			C		9	90	1.617		B	C
	8	90	1.801			C		8	90	1.609		B	C
	6	90	1.791			C		6	90	1.597		B	C
	5	90	1.784			C		7	90	1.589			C
	10	90	1.735			C		5	90	1.573			C
	9	90	1.727			C		10	90	1.545			C
	12	90	1.706			C		12	90	1.530			C
	11	90	1.702			C		11	90	1.498			C
	Epoch	**N**	**Mean**	**Grouping**				**Epoch**	**N**	**Mean**	**Grouping**		
Natural Log of RMS_ml [mm]	1	90	1.244	A			**Natural Log of RMS_ml [mm]**	1	90	0.936	A		
	2	90	0.981	A	B			2	90	0.791	A	B	
	10	90	0.912	A	B			11	90	0.749	A	B	
	8	90	0.899	A	B			3	90	0.742	A	B	
	12	90	0.885	A	B			4	90	0.717	A	B	
	4	90	0.874		B			7	90	0.685	A	B	
	7	90	0.831		B			12	90	0.668	A	B	
	9	90	0.801		B			9	90	0.666	A	B	
	11	90	0.784		B			6	90	0.652	A	B	
	5	90	0.757		B			8	90	0.616	A	B	
	6	90	0.756		B			10	90	0.601	A	B	
	3	90	0.754		B			5	90	0.511		B	

NOTE: The N column refers to the number of total trials collected.
(N = 90 = 30 participants * 3 trials per participant)

* Means that do not share a letter are significantly different from each other.

S3 Table. ‘Trial Number’ post-hoc analysis for all CoP parameters for eyes closed and eyes open stance.

Experiment 2 Tukey Pairwise Comparisons: Trial Number Grouping Information Using the Tukey Method and 95% Confidence													
QEC							QEO						
Natural Log of EA [mm^2]	Trial #	N	Mean	Grouping			Natural Log of EA [mm^2]	Trial #	N	Mean	Grouping		
	5	48	4.934	A	B			4	156	4.440	A		
	4	84	4.866	A	B			5	60	4.411	A		
	2	288	4.799	A				3	264	4.403	A		
	6	12	4.727	A	B			1	312	4.302	A		
	3	312	4.699	A	B			2	228	4.294	A		
	1	336	4.659		B			6	48	4.260	A		
								8	12	4.221	A		
Natural Log of MVEL_ml [mm/s]	Trial #	N	Mean	Grouping			Natural Log of MVEL_ml [mm/s]	Trial #	N	Mean	Grouping		
	4	84	1.971	A				3	264	1.710	A		
	5	48	1.910	A	B			6	48	1.699	A	B	C
	6	12	1.886	A	B			8	12	1.688	A	B	C
	2	288	1.871	A				4	156	1.675	A	B	
	3	312	1.862	A				5	60	1.654	A	B	C
	1	336	1.753		B			2	228	1.616		B	C
								1	312	1.562			C
Natural Log of RMS_ml [mm]	Trial #	N	Mean	Grouping			Natural Log of RMS_ml [mm]	Trial #	N	Mean	Grouping		
	5	48	0.977	A				4	156	0.801	A		
	4	84	0.973	A				3	264	0.755	A		
	2	288	0.879	A				5	60	0.688	A	B	
	3	312	0.856	A				6	48	0.685	A	B	
	6	12	0.797	A	B			8	12	0.676	A	B	
	1	336	0.756		B			1	312	0.629		B	
								2	228	0.628		B	

NOTE: The protocol required 3 successful trials. The Trial # column indicates the attempt for which that particular trial was collected. Reasons for trial numbers beyond 3 include participants not adhering to protocol, technical difficulties in collecting data, or a background disruption during collection.

NOTE: The N column refers to the number of epochs collected for each trial number. Each 60-second trial consists of 12 epochs (5 seconds per epoch). (e.g. for Trial #5 for QEC, N = 48 = 4 trials * 12 epochs per trial, meaning 4 total participants required a fifth trial)

* Means that do not share a letter are significantly different from each other.

S4 Table. ‘Epoch’ post-hoc analysis for all CoP parameters for younger and older adult groups.

Experiment 3 Tukey Pairwise Comparisons: Epoch

Grouping Information Using the Tukey Method and 95% Confidence

YA							OA						
	Epoch	**N**	**Mean**	**Grouping**				**Epoch**	**N**	**Mean**	**Grouping**		
Natural Log of EA [mm^2]	1	201	5.598	A			**Natural Log of EA [mm^2]**	1	114	6.158	A		
	2	201	5.143	A	B			9	114	5.819	A	B	
	12	201	4.895		B	C		2	114	5.769	A	B	
	9	201	4.805		B	C		3	114	5.710	A	B	
	10	201	4.776		B	C		6	114	5.694	A	B	
	4	201	4.760		B	C		7	114	5.625	A	B	
	3	201	4.739		B	C		10	114	5.605	A	B	
	8	201	4.736		B	C		5	114	5.589	A	B	
	5	201	4.735		B	C		4	114	5.537	A	B	
	6	201	4.707		B	C		8	114	5.506	A	B	
	7	201	4.646		B	C		11	114	5.335		B	
	11	201	4.561			C		12	114	5.287		B	
	Epoch	**N**	**Mean**	**Grouping**				**Epoch**	**N**	**Mean**	**Grouping**		
Natural Log of MVEL_ml [mm/s]	1	201	2.486	A			**Natural Log of MVEL_ml [mm/s]**	1	114	2.762	A		
	2	201	2.228	A	B			3	114	2.518	A	B	
	3	201	1.977		B	C		2	114	2.510	A	B	
	4	201	1.930			C		6	114	2.449	A	B	
	7	201	1.865			C		7	114	2.439	A	B	
	8	201	1.848			C		9	114	2.433	A	B	
	6	201	1.834			C		4	114	2.402	A	B	
	5	201	1.833			C		10	114	2.390	A	B	
	9	201	1.787			C		8	114	2.385	A	B	
	10	201	1.780			C		5	114	2.368		B	
	12	201	1.757			C		11	114	2.324		B	
	11	201	1.746			C		12	114	2.288		B	
	Epoch	**N**	**Mean**	**Grouping**				**Epoch**	**N**	**Mean**	**Grouping**		
Natural Log of RMS_ml [mm]	1	201	1.261	A			**Natural Log of RMS_ml [mm]**	1	114	1.506	A		
	2	201	1.011	A	B			9	114	1.367	A	B	
	10	201	0.922	A	B			3	114	1.359	A	B	
	8	201	0.903		B			2	114	1.355	A	B	
	12	201	0.898		B			6	114	1.326	A	B	
	4	201	0.893		B			7	114	1.305	A	B	
	7	201	0.873		B			5	114	1.296	A	B	
	9	201	0.842		B			8	114	1.285	A	B	
	3	201	0.809		B			4	114	1.273	A	B	
	11	201	0.805		B			10	114	1.247	A	B	
	5	201	0.784		B			11	114	1.137	A	B	
	6	201	0.780		B			12	114	1.006		B	

NOTE: The N column refers to the number of total trials collected. (e.g., for the YA group, N = 201 = 67 participants * 3 trials per participant)

* Means that do not share a letter are significantly different from each other.

S5 Table. ‘Trial Number’ post-hoc analysis for all CoP parameters for younger and older adult groups.

Experiment 3 Tukey Pairwise Comparisons: Trial Number

Grouping Information Using the Tukey Method and 95% Confidence

YA							OA						
	Trial #	**N**	**Mean**	**Grouping**				**Trial #**	**N**	**Mean**	**Grouping**		
Natural Log of EA [mm^2]	5	48	5.016	A			**Natural Log of EA [mm^2]**	1	456	5.786	A		
	4	84	4.953	A				4	12	5.658	A	B	
	2	732	4.790	A				3	444	5.565		B	
	1	780	4.789	A				2	456	5.536		B	
	3	756	4.756	A									
	6	12	4.747	A									
	Trial #	**N**	**Mean**	**Grouping**				**Trial #**	**N**	**Mean**	**Grouping**		
Natural Log of MVEL_ml [mm/s]	4	84	2.036	A			**Natural Log of MVEL_ml [mm/s]**	1	456	2.571	A		
	5	48	1.975	A	B			2	456	2.429		B	
	6	12	1.896	A	B			3	444	2.414		B	
	2	732	1.884		B			4	12	2.342	A	B	
	1	780	1.876		B								
	3	756	1.870		B								
	Trial #	**N**	**Mean**	**Grouping**				**Trial #**	**N**	**Mean**	**Grouping**		
Natural Log of RMS_ml [mm]	5	48	1.020	A	B		**Natural Log of RMS_ml [mm]**	1	456	1.357	A		
	4	84	1.018	A				4	12	1.314	A	B	
	2	732	0.869		B			3	444	1.259		B	
	3	756	0.853		B			2	456	1.225		B	
	1	780	0.840		B								
	6	12	0.791	A	B								

NOTE: The protocol required 3 successful trials. The Trial # column indicates the attempt for which that particular trial was collected. Reasons for trial numbers beyond 3 include participants not adhering to protocol, technical difficulties in collecting data, or a background disruption during collection.

NOTE: The N column refers to the number of epochs collected for each trial number. Each 60-second trial consists of 12 epochs (5 seconds per epoch). (e.g. for Trial #5 for the YA group, N = 48 = 4 trials * 12 epochs per trial, meaning 4 total participants required a fifth trial)

* Means that do not share a letter are significantly different from each other.

S6 Table. Spearman's rank-order correlations between epochs 1 and 12 and whole-trial CoP estimates.

Experiment 1 Spearman's Rank-Order Correlations		
CoP Parameter	**Epoch 1**	**Epoch 12**
EA	0.72 (<0.001)	0.83 (<0.001)
MVEL_ml	0.79 (<0.001)	0.90 (<0.001)
RMS_ml	0.72 (<0.001)	0.77 (<0.001)
NOTE: Values are presented as Spearman's ρ (P-value)		