11-11-2017

Saccades Attenuate Postural Sway Despite Muscular Fatigue Negatively Influencing Proprioception

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SACCADES ATTENUATE POSTURAL SWAY DESPITE MUSCULAR FATIGUE NEGATIVELY INFLUENCING PROPRIOCEPTION

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The School of Kinesiology

by
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B.S., East Carolina University, 2014
December 2017

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Nomenclature

- FP – Fixation Point
- SAC – Saccades
- NF – Non-Fatigued State
- S – Stretched State
- F – Fatigued State
- CoP – Center of Pressure
- CoG – Center of Gravity
- PoG – Point of Gaze
- ROM – Range of Motion
- ML displacement – Average Medio-Lateral CoP Displacement
- AP displacement – Average Anterior-Posterior CoP Displacement
- MLsd – Medio-Lateral Displacement Standard Deviation
- APsd – Anterior-Posterior Displacement Standard Deviation
- PL – Path Length of CoP
- Vel – Average Velocity of CoP
- Area95 – Area of the 95% Confidence Ellipse for CoP

Abstract

Background: Muscular fatigue, which reduces force output and position sense, often leads to increased sway and potential balance impairments. In contrast, saccadic eye movements can attenuate sway more than fixating gaze on an external target. The goal of this study was to determine whether the use of saccades could compensate for the increased postural sway in a fatigued state. **Methods and Materials:** We compared the effects of gazing at a fixation point (FP) and performing saccades (SAC) on various sway measures of the center of pressure (CoP) while participants stood as still as possible on a force plate. Participants used either a Narrow or Wide base of support (BOS) and performed 3 trials for each eye movement condition (SAC, FP) in three states (non-fatigued—NF, stretched—S, and fatigued—F). Calf rises to exhaustion induced ankle fatigue. Extreme plantar- and dorsi-flexion induced stretch. **Results:** SAC significantly decreased sway compared FP. F increased sway compared to NF and S states, which were similar. **Conclusion:** Reduced force production, which accompanies muscle fatigue and stretching, did not account for increased sway associated with acute bouts of ankle muscle fatigue. Increased position sense associated with muscle stretching apparently compensated for any reduced force output for S, while the decreased position sense explained the increased sway associated with F. Use of saccadic eye movements during quiet stance can help young adults reduce sway under NF, S, and F states.

Introduction

Musculoskeletal, neural, and sensory feedback systems change as individuals age. These changes can lead to balance impairments while standing (Maki and McIlroy 1996) and can increase an older individual's likelihood of falling (Melzer et al. 2004). Falling in older adults can result in acute injuries, that affect performance of daily activities (Takacs et al. 2013), or can result in accidental death (Melzer et al. 2004). Thirty-two percent of older adult fallers will require assistance when performing daily activities after a fall occurs (Takacs et al. 2013), making studies which help identify strategies to combat age-related balance impairments of interest to researchers and clinicians alike.

While physical activity can lead to improved balance, results related to how it influences fall risks in older adults vary. For example, researchers showed that a multimodal exercise program, involving balance, resistance, and agility training, reduced the amount of injuries requiring medical attention in older women but did not reduce the incidence of falls or the amount of fractures resulting from falls (Patil et al. 2015). Aerobic, strength training, and flexibility activities lead to a decrease in the likelihood of a fall in older adults, a reduction in the amount of fractures seen in older fallers, and provided systematic physiological changes (such as muscular strength and bone density) that could help protect older adults from injury if they do fall (El-Khoury et al. 2013). Carefully designed physical activity programs, including balance rehabilitation, can lead to strength gains to improve balance (Howe et al. 2011) and changes in sensorimotor control, possibly lowering fall risk (Voelcker-Rehage et al. 2011). However, physical activity may also put older individuals at risk for a fall due to fatigue (Kamitani et al. 2017) that can occur immediately upon completion of the activity.

Muscular fatigue after moderate to vigorous bouts of physical activity in young and older healthy adults increases postural sway compared to a non-fatigued state (Thomas and Magal 2014); (Seliga et al. 1991). People, who fatigue easily during daily activities because of low fitness levels, injuries, or disease, may also experience greater postural sway when standing. Increased postural sway can lead to greater fall risk in older adults (Thomas et al. 2016), thus becoming a concern for this population.

Why does muscular fatigue negatively influence postural control? Loss of force production from a muscle or muscle group due to exercise or physical activity, the definition of muscular fatigue (Taylor and Gandevia 2008), may be a possible cause for diminished postural control in a fatigued state. Acute changes in force output may decrease proprioception and muscle activation (Behm et al. 2004). Impaired or decreased proprioception impairs balance (Patel et al. 2014) because it does not allow the central nervous system (CNS) to sense small changes in postural sway (Mohapatra et al. 2012) and engage appropriate muscle activation to correct for small deviations in the center of gravity (CoG). Decreased muscle activation on the other hand may restrict adequate responses to correct for deviations in the CoG. Understanding what mechanisms cause the balance impairments after fatiguing activities would help when developing strategies to combat balance problems.

Use of visual inputs for standing often reduces sway and improves balance compared to performances without vision available (e.g., (Tanaka and Uetake 2005). Control of human eye positioning can also play a major role in how individuals attenuate postural sway (Fox 1990; Rodrigues et al. 2015; Kim et al. 2016). Fixation of gaze on a point in the environment can decrease postural sway compared to looking into a visual field without a fixation point (Paulus et al. 1984; Strupp et al. 2003). Most evidence from previous studies reveal that saccades can

attenuate postural sway equal to (Rey et al. 2008; Thomas et al. 2016) or better than (Stoffregen et al. 2006; Rougier and Garin 2007; Ajrezo et al. 2013; Rodrigues et al. 2013; Rodrigues et al. 2015) a simple fixation point. This saccadic effect on postural sway holds true when performing slow or fast saccadic movements (Rodrigues et al. 2015). Whether saccades and fixation points affect sway similarly or differently when fatigued, remains unanswered. If true, eye positioning may lead to a short-term solution for improving balance, like acute bouts of fatigue post exercise, and possibly contribute to long-term balance training protocols.

With the recent growth of older individuals attempting to become more physically active to obtain health benefits and reduce fall risk (Nelson et al. 2007), comes the responsibility to identify possible mechanisms that may reduce fall risk during a fatigued state. The first step and main purpose of this study was to investigate how saccades and fixation points influence postural sway under a fatigued state in young adults. We also included a muscular stretching condition to better understand the mechanism underlying muscle fatigue and postural sway. Although muscular stretching can reduce force output production leading to increased static standing sway (Behm et al. 2004; Nagano et al. 2006; Hemmati et al. 2016), it assisted people to maintain a neutral position during dynamic standing on a stabilometer (Nelson et al. 2012). Authors posed that the remaining fine muscle contractions compensated for the reduced force output limited to gross muscle contractions. Together these data indicate that reductions in force output can influence balance in various ways, depending on the task performed. During static balance, stretching effects should mimic muscular fatigue effects on sway only if reduced force output is the main reason for balance impairments. However, stretching effects should oppose muscular fatiguing effects on sway if reductions in proprioception account for the main reduction in balance impairments, as current literature suggests that stretching muscles may result in an

increased (Ghaffarinejad et al. 2007; Cho and Kim 2016; Walsh 2017) or similar joint position sense (Larsen et al. 2005; Bjorklund et al. 2006). Apparently, stretching muscles may positively affect proprioception and postural sway. The results of this study helped determine whether the force output during muscular fatigue could account for the diminished postural control or if there were other mechanisms, such as proprioception, at work.

Materials and Methods

Participants

Thirty-one healthy individuals, 18-30 years old, gave written informed consent on procedures approved by the Louisiana State University's IRB before participating in this study. Seven participants were excluded due to methodological issues, leaving 18 female and 6 male college students. Remaining participants possessed no protective plantar sensation deficiencies, determined by the following protocol. Participants closed their eyes while an investigator touched a Semmes-Weinstein monofilament (5.07 monofilament) perpendicular to the plantar surface of each foot in five locations: hallux, first metatarsal head, fifth metatarsal head, lateral midfoot, and calcaneus. The monofilament was held in a bowed position at each location three times for up to one second. Participants provided verbal responses after feeling each randomly placed touch. Two or more responses at each site were needed to qualify for the study. A test of visual acuity made sure participants had no major visual deficiencies; each participant scored 20/30 or better (the score needed to read U.S. road signs from far enough away to be able to make adequate decisions and perform proper responses (Owsley and McGwin 2010)) and no difficulties viewing targets 1 m away.

Setup and Procedure

Participants were directed to stand as still as possible during each trial. One condition consisted of standing still while performing horizontal saccadic eye movements (SAC) to targets, presented at 1 Hz with twenty degrees of separation. A control condition involved standing still while looking at a centrally located fixation point (FP). In each case the target was a red dot (2 cm in diameter) on a white background, presented on a computer screen (22-inch screen) 1 m directly in front of the eyes at eye-level of the participant.

Barefoot participants started standing either with their feet side-by-side shoulder width apart, determined as the distance between their left and right acromion processes (Wide base of support, BOS) or 3 cm apart (Narrow BOS) with feet parallel to one another. Participants stood on a AMTI force plate for each trial (AMTI, Watertown, MA), and collected data at 100 Hz. Feet were marked in this position by outlining them so starting position remained consistent for every trial. Participants were then asked to perform saccadic eye movements several times. Once they became comfortable with the movements, the trials began. Participants performed the eye movements for about 5 seconds before the data collection began, to help ensure more constant eye movements or fixation effects on static balance throughout the trial. Each data collection, thus trial, lasted 50 seconds.

Postural sway for the FP and SAC conditions were assessed in three different states. These included the non-fatigued state (NF), stretched state (S), and the fatigued state (F).

Characterization of NF included not exercising (a workout) 24 hours before the experimental procedure began. Three trials randomly presented for FP and SAC offered a baseline of natural static standing balance for each eye movement condition.

After completing NF trials, participants performed the static stance task following passive stretching of the ankle musculature (S). Each stretching round involved 30 seconds of dorsiflexion followed by a 15 second rest, then 30 seconds of plantarflexion followed by a 15 second rest. After four rounds of stretching participants completed two trials, comprised of a randomly determined FP and SAC condition. Only 2 rounds of stretching were performed before the next two trials, to help maintain a stretched state. This was repeated until participants completed 3 FP and 3 SAC trials.

A 10-minute break was given to the participant's to ensure that their muscles had time to recover from their stretched state, as stretching effects can last 10 minutes or less, depending upon the type of stretch (Skarabot et al. 2015). Participants achieved a fatigued state (F) by performing calf raises before each trial. Participants were instructed to perform the bilateral calf raises on a raised platform as fast as they could while maintaining at least 75% of their maximum range of motion (ROM) until they could no longer continue or until they could no longer achieve the measured ROM. ROM was measured for each participant based on full plantar- and dorsi-flexion on the raised surface and marked on a flat vertical stick attached to the surface for easy visual inspection. Two to three practice trials oriented participants to the protocol. Keeping full ROM was encouraged during the fatiguing process through visual observations and the investigator stopped participants when s/he missed the 75% ROM cutoff twice, either during dorsiflexion or plantar flexion, which was considered adequately fatigued. ROM was videotaped for the first 3 participants to ensure the observing investigator (same person for all participants) gave adequate feedback to participants regarding ROM. Participants completed 1 trial in F, comprised of a randomly determined FP or SAC condition. After a 5-minute break participants completed the next fatiguing round and a trial comprised of a randomly determined FP or SAC condition. This process continued until 3 FP and 3 SAC trials were completed. The breaks gave the participant's muscles a chance to recover similar to protocols used elsewhere (Ledin et al. 2004).

Use of a 60 Hz mobile Eye Tracker (SMI, Teltow, Germany) ensured that gaze was directed appropriately for each trial. Visual inspection of the video involving the point of gaze (PoG) on the computer screen and the PoG x- and y-plots simultaneously using B-Gaze software (SMI, Teltow, Germany) provided clear evidence of gaze during task performance (see Figure 2

in results). The following measures of sway were determined using Balance Clinic software (version 2.03.00): average CoP medial-lateral (ML) displacement and its standard deviation (MLsd), average CoP anterior-posterior (AP) displacement and its standard deviation (APsd), path length of the CoP, average velocity of the CoP (Vel), and the area of the 95% confidence ellipse of the CoP (Area95). ML displacement was determined as the average x displacement of the CoP from the platform center and MLsd was the standard deviation of this average x displacement. AP and APsd values were calculated in the same manner as the ML and MLsd values but for the y direction. The PL was determined to be the entire path length of the CoP for the duration of a trial. Vel was determined to be the CoP path length per second. Area95 was determined to be the area of the 95th percentile ellipse during a trial. Variables were reported in cm, cm/s, or cm^2.

Data Analyses

Data were averaged for each eye movement condition (FP, SAC), state (NF, S, F), and participant and tested for normal distribution using Shapiro-Wilk test. Mixed model ANOVAs determined whether each normally distributed variable of interest varied according to eye movement condition, state, or the randomly assigned BOS group (Wide, Narrow). Within subject factors included eye movement condition and state with a between subject factor of group. Greenhouse-Geisser adjustments were reported for violations of sphericity. Tukey's HSD tests were used for post-hoc analyses, where appropriate. Friedman ANOVAs determined whether each non-normally distributed variable of interest varied according to eye movement condition or state. Wilcoxon Matched Pairs Tests with Bonferroni corrections determined whether paired comparisons within each eye movement and across each state differed for each non-normally distributed variable. Mann-Whitney U Tests determined group effects for these variables

between each eye movement and state pairing. Significance was determined for $p < .05$ unless corrected.

Results

Raw Data

Raw data shown in Figure 1 illustrates the differences and similarities between state and eye movement conditions, specifically showing CoP results from subject #9 (Wide BOS). The figure shows that SAC resulted in less sway compared to that of a FP for states.

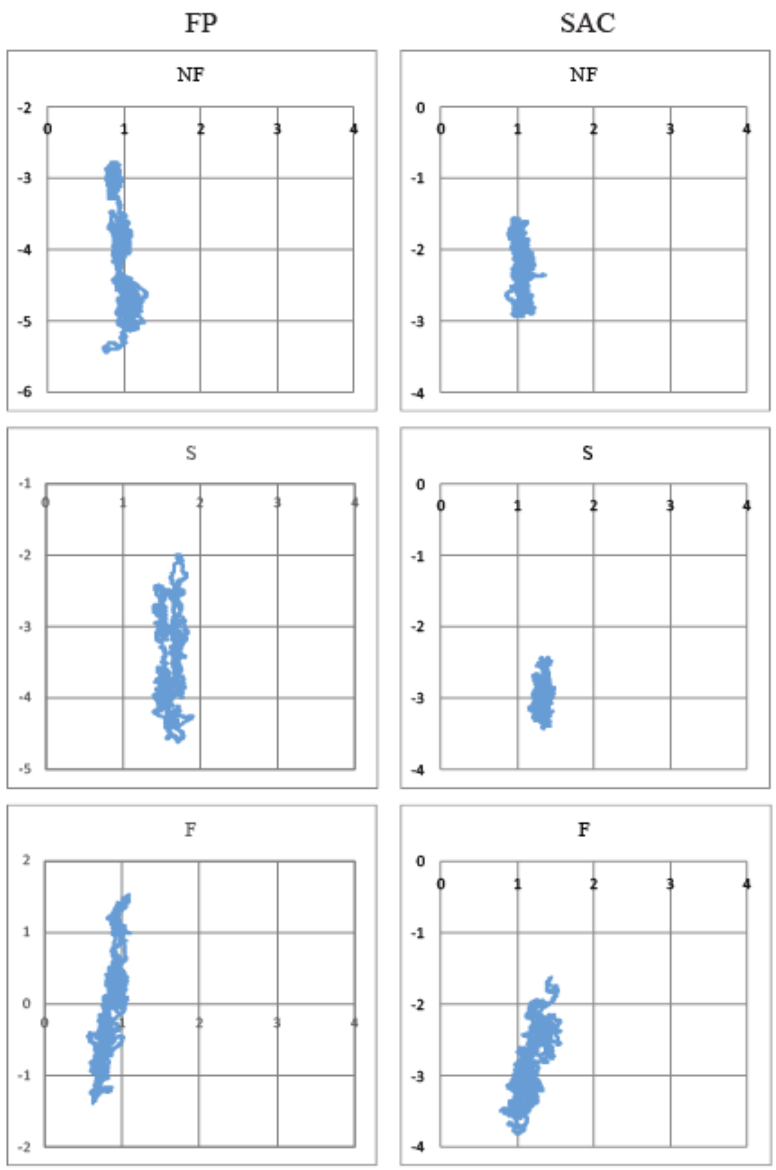

Figure 1. Plots of CoP are shown for one trial for one subject (#9) in each eye movement condition and state pair. Data for x CoP (x-axis) and y CoP (y-axis) are in cm.

Participants were able to complete the saccade task using different strategies. Figure 2 shows that participants could respond to or anticipate target appearance using eye movements as well as use corrective saccades to reposition their gaze on a target.

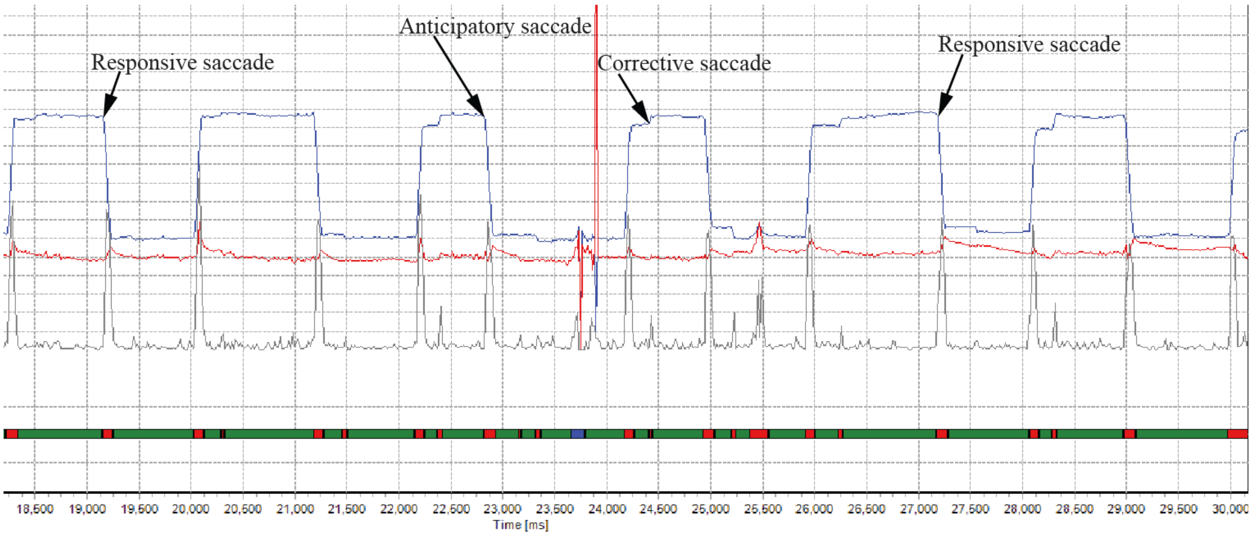

Figure 2. Plots of gaze position for lateral eye movements (blue) and vertical eye movements (red) and eye movement velocity (gray) are shown for participant #4 for part of one trial.

Displacements

Significant results of Mixed model ANOVAs on AP displacement and APsd are reported in Tables 1 and 2, respectively. Main effects of group, state, and eye movement conditions revealed the following. People in the Wide group produced less AP displacement with less variability compared to the Narrow group (Figure 3). Being fatigued increased AP displacement and its variability compared to the other two states (Figure 4). SAC during static standing significantly decreased AP displacement and its variability compared to FP (Figure 5).

Table 1. Mixed model ANOVA results for AP displacement

Main Effect	**F value**	**df**	***P* value**	**Effect Size**
Group	7.36	(1,22)	0.01	0.25
State	27.36	(1.48,32.46)	< .0001	0.55
Eye movement	46.65	(1,22)	< .0001	0.68

Table 2. Mixed model ANOVA results for APsd

Main Effect	**F value**	**df**	***P* value**	**Effect Size**
Group	7.37	(1,22)	0.01	0.25
State	29.02	(1.41,31.06)	< .0001	0.57
Eye	48.96	(1,22)	< .0001	0.69

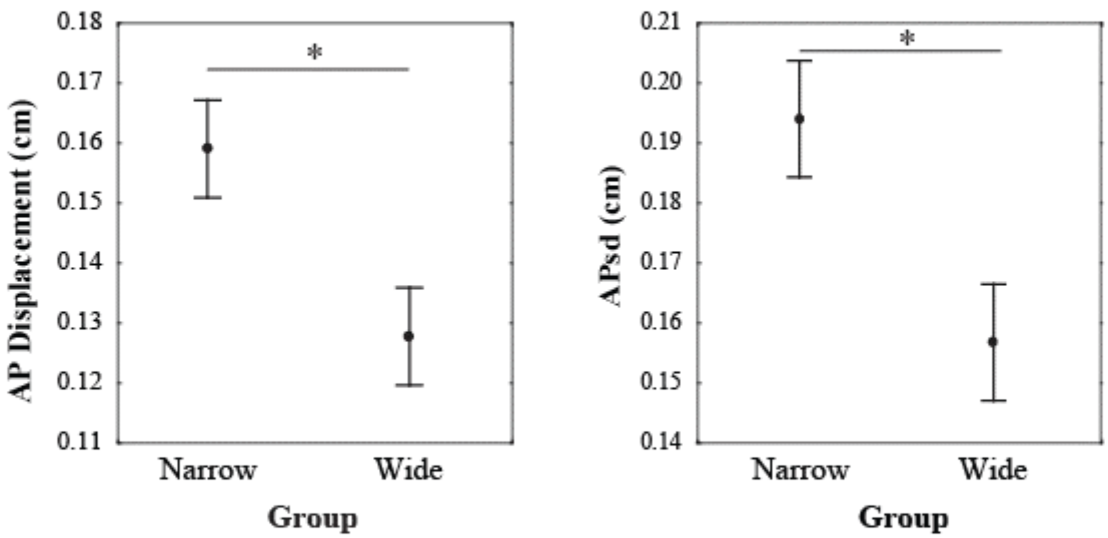

Figure 3. Shows the AP and APsd mean differences between stances. Each significant difference at the line ends is marked by an asterisk.

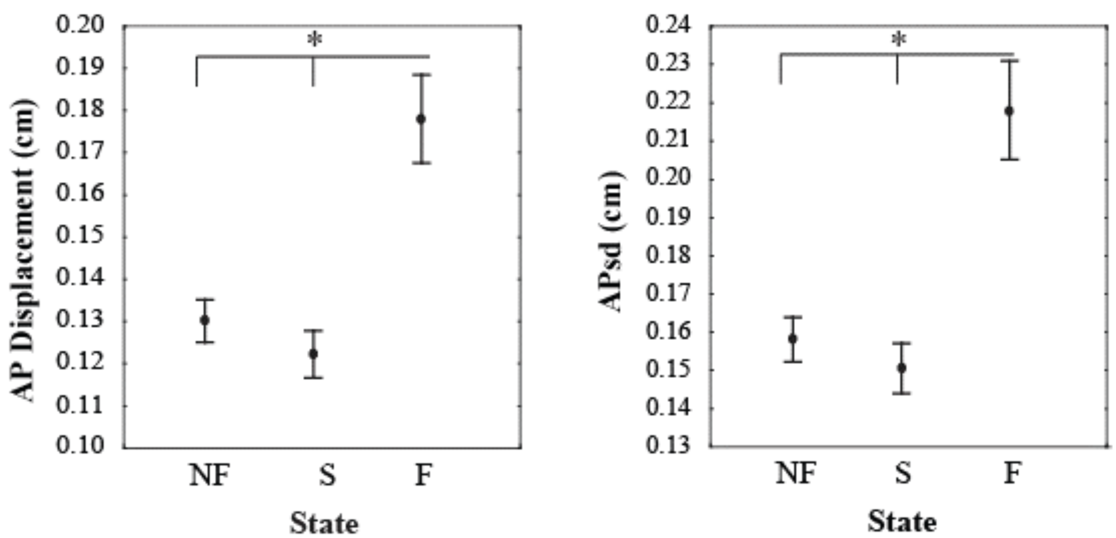

Figure 4. Shows the AP and APsd mean differences between each state. Each significant difference from F is marked accordingly.

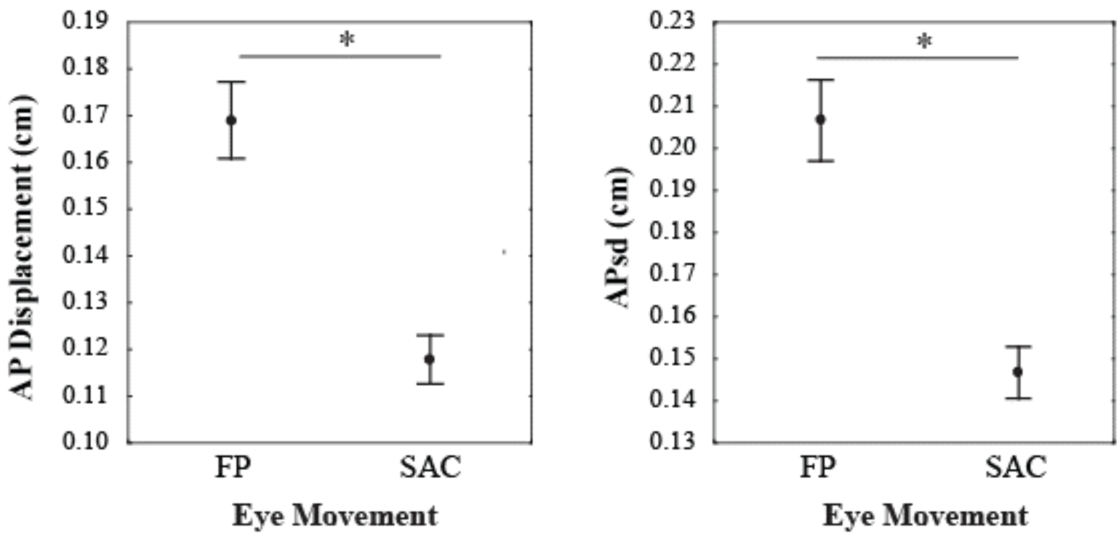

Figure 5. Shows the AP and APsd mean differences between eye movement conditions. Each significant difference at the line ends is marked by an asterisk.

Friedman ANOVAs revealed significant differences among various state and eye movement combinations for ML ($\chi^2(5) = 25.3$, $P < .001$) and MLsd ($\chi^2(5) = 27.5$, $P < .0001$). SAC significantly decreased ML displacement and its variability compared to FP for NF (ML displacement: Z = 3.94, $P < .0055$; MLsd: Z = 3.91, $P < .0055$) and S (ML displacement: Z = 3.29, $P < .0055$; MLsd: Z = 3.10, $P < .0055$) states. Mann-Whitney U test results revealed group differences between each eye movement and state pairing such that those in the Narrow group produced greater ML displacement and MLsd than those in the Wide group ($P < .05$).

COP Path Length, Velocity, and Area

Friedman ANOVAs revealed significant differences among various state and eye movement combinations for path length ($\chi^2(5) = 27.5$, $P < .0001$) and Vel ($\chi^2(5) = 27.5$, $P < .0001$), similarly. SAC in S state produced lower values compared to F state for path length (Z = 2.91, $P < .0055$) and Vel (Z = 2.91, $P < .0055$). Significant differences among the various state and eye movement combinations also existed for Area95 ($\chi^2(5) = 68.95$, $P < .00001$) as observed in Figure 6. Significant differences in Area95 existed between SAC and FP for NF (Z = 4.14, $P <$

.0055) and S (Z = 3.83, $P < .0055$) states as with other variables, but also for F (Z = 2.97, $P < .0055$), so that values for SAC produced lower values than FP. Post-hoc testing revealed substantial influences between states. FP and SAC for the F state produced significantly higher Area95 values when compared to the corresponding NF and S states ($P < 0.0055$). Mann-Whitney U test results revealed group differences between each eye movement and state pairing such that those in the Narrow group produced greater Area95 than those in the Wide group ($P < .05$).

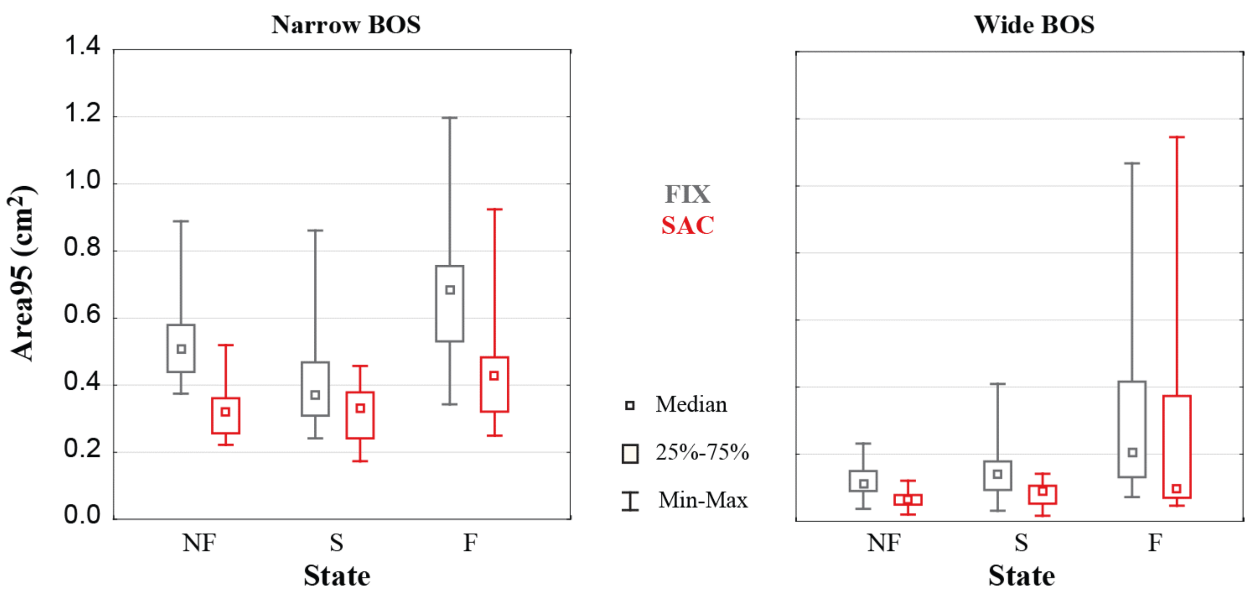

Figure 6. Shows the Area95 differences between eye movement conditions and states for each BOS group (left panel, Narrow; right panel, Wide).

Discussion

In the current study, SAC that led to a reduction in multiple CoP variables. The associated reduction in sway was observed across different states for each group. A Wide BOS was shown to be more stable than a Narrow BOS across eye movement conditions and states. The F state was shown to significantly increase sway compared to NF and S, regardless of eye movements or group.

Group Effects on Sway

As expected, narrowing the BOS consistently demonstrated more sway than placing feet shoulder width apart. Group differences for displacement and variability of displacement in the AP and ML directions and for Area95 revealed an overall increase in sway, not limited to ML direction as might be expected (e.g., (Rodrigues et al. 2013). The present outcomes not only add to the evidence that a wider BOS helps individuals reduce sway but it also indicates that a wider BOS can help with stability under various conditions shown to decrease sway such as saccades (Stoffregen et al. 2006) and under various states known to increase sway such as fatigue (Thomas and Magal 2014).

Eye Movements Effects on Sway

Data from the present study support the outcomes that performing SAC movements can further decrease postural sway compared FP (Ajrezo et al. 2013; Rodrigues et al. 2013); (Stoffregen et al. 2006; Rougier and Garin 2007; Rodrigues et al. 2015). Performing SAC consistently produced less sway when compared to FP for displacement and variability of displacement in the AP and ML directions and for Area95 for NF and S states. Interestingly, differences between eye movements only existed for fatigued participants when considering Area95 as well as AP displacement and its variability. It appears that the higher attentional

demands of SAC over FP (Rey et al. 2008) have limitations that do not improve medio-lateral sway in the F state. SAC yielded the greatest influence over postural sway in the anterior-posterior direction, which associated with the fatigued muscles needed to control these movements. Therefore, we reasoned that the attentional demand of SAC likely yield the greatest influence over control of the fatigued muscles and acknowledge that this hypothesis requires further testing.

States Effects on Sway

Being fatigued delivered the greatest values in postural sway regardless of eye movement condition. Fatiguing the ankle musculature directly influenced how individuals could control postural sway in the anterior-posterior direction and for Area95, revealing increased sway comparable to elsewhere (Thomas and Magal 2014). Similarities between the sway measures for NF and S states contradict research showing that stretching can increase static standing sway (Behm et al. 2004; Nagano et al. 2006; Hemmati et al. 2016) compared to non-stretched states. This contradiction could result from differences in methodology; specifically, stretching opposing versus single muscles, the degree of the stretch, and the stretch duration.

Although mean values for AP displacement and its variability for NF exceeded those for S (Figure 4), this was only true for 18/24 participants for AP displacement and 16/24 participants for APsd across states and eye movements, suggesting possible idiosyncratic differences among participants. Regardless, the sway differences among states provided vital information about control mechanism used to maintain static balance when fatigued.

Control Changes due to Acute Fatigue

Acute bouts of muscular fatigue result in reduced force output (Taylor and Gandevia 2008) and proprioception (Behm et al. 2004), both of which can increase sway and impair

balance. Although muscular stretching can also result in reduced force output production leading to increased static standing sway (Behm et al. 2004; Nagano et al. 2006; Hemmati et al. 2016), it can improve position sense (Ghaffarinejad et al. 2007; Cho and Kim 2016; Walsh 2017), potentially counteracting some or all the effects of reduced force output. Because S and F contribute to reduced force output, the different results between these states in this study may result from something other than a reduction in force output. While stretching does not always positively enhance proprioception, it apparently does not diminish it (Larsen et al. 2005; Bjorklund et al. 2006). Together these results indicate proprioception differences likely account for the differences between states.

Various fatigue states link to a decrease in joint position sense (Seliga et al. 1991; Bottoni et al. 2015). Researchers found that this negative affect on proprioception was a result of damaged muscle fibers, which led to the alteration of important muscle receptors (Bottoni et al. 2015). Two muscle receptors associated with proprioception are golgi tendon organs and muscle spindles. These receptors may be altered in a manner that diminishes their ability to provide appropriate proprioception information. However, researchers also noted that general fatigue probably influences how proprioceptive information is processed (Bottoni et al. 2015). Muscle receptor alteration, processing deficiencies, or a combination of the two, may lead to decreased proprioception and increased instability at the joint of a fatigued extremity.

Conclusion

In conclusion, this study provided evidence that saccades may be a viable tool for decreasing postural sway under various states and BOS stances. In contrast, being fatigued negatively influenced postural sway. The present results support that this increased sway due to muscular fatigue resulted from decreased proprioception.

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