The effect of light touch on standing sway when the stability of the external touch reference becomes unreliable.

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Abstract

Lightly touching a stable reference is associated with sway reduction during standing. Unexpected displacement of the touch reference results in a false-positive balance reaction in some participants, but only with the first such disturbance. This study investigated whether light touch reduces standing sway 1) after the touch reference becomes unreliable, and 2) when participants are aware the touch reference is unreliable. Forty healthy adults, twenty that were naïve to the possibility of a touch reference displacement and twenty that were made aware prior to testing, were asked to stand while lightly touching (<1 N) a reference with normal vision or vision occluded. Motion of the center of pressure was used to estimate standing sway before and after a single displacement, and then multiple displacements, of a touch reference. Sway area was always reduced while touching the reference, compared to standing with vision occluded without touch, even when the reference was known to be unreliable. In addition, sway area was further reduced following a single touch displacement in Naïve participants when vision was occluded. These results suggest that tactile cues from the finger interact with postural control in a complex manner, depending upon the expectation and experience of the characteristics of the touched object. Taken together, light touch can 1) be used as a spatial reference that assists in sway stabilization, 2) be a source of movement variability that impacts the performance of a skilled task, or 3) introduce noise in the sensory channels impacting fidelity.

Keywords: Posture, touch, standing, human, sway

Introduction

Visual, vestibular, and somatosensory feedback provide essential afferent information to the central nervous system (CNS) to sense body orientation within the environment and to select and initiate appropriate muscular corrective responses to prevent loss of balance (Peterka 2002). This involves the dynamic interaction of sensorimotor processes to properly weight and re-weight relative contributions of each source of sensory feedback based on the changing task demands; therefore, the postural strategy adopted will be context-dependent, based on the goals of the task, characteristics of the external environment, and prior experience (Horak 2006). For example, in the absence of vision, lightly touching external supports can potently reduce standing postural sway amplitude and velocities in healthy adults (Jeka and Lackner 1994; Kouzaki and Masani 2008), even when the force applied is insufficient to provide mechanical support (<1 N). Shear forces from the fingertip have been suggested to improve postural stability by increasing the somatosensory inflow to the central nervous system by detecting the direction, amplitude and speed of body sway (Clapp and Wing 1999; Jeka et al. 1997). When the difficulty of the postural task is further increased by standing on a foam surface and vision is occluded, stabilization of posture can be enhanced with the addition of light touch by favoring cutaneous signals from the hand to compensate for the increased instability, and down-weighting unreliable feedback from the plantar surface of the feet (Dickstein et al. 2001). Taken together, the addition of light touch input from the hand has the ability to augment sensory feedback and facilitate balance control by providing supplemental spatial reference and orientation information, which is enhanced when other sensory sources become unreliable or impaired, or when the task becomes more challenging (Bove et al. 2006; Honeine et al. 2015; Huang et al. 2009; Jeka and Lackner 1994, 1995; Jeka et al. 1996; Schieppati and Nardone 1995; Sozzi et al. 2011, 2012).

Previous investigations have shown that standing sway becomes entrained to the position and velocity of subliminal movements of a touch reference (Jeka et al 1998; Misiaszek et al. 2016; Wing et al. 2011). This entrainment reflects the active use of the haptic cues arising from the touch reference to control the amplitude and direction of body sway by participants. Therefore, even when the touch reference provides feedback regarding body position in conflict with other somatosensory and vestibular inputs, tactile feedback remains a potent source for the regulation of postural sway if an individual is unaware of its motion and unable to discern the proprioceptive conflict. Recently, we observed that unexpected rapid displacements of a fingertip touch reference resulted in a "false positive" balance reaction in most participants (Misiaszek et al. 2016; Misiaszek and Vander Meulen 2017). Blind-folded participants inaccurately interpreted a forward slip of the touch reference as a backward fall, activating tibialis anterior and generating an inappropriate forward sway correction. Interestingly, this "false-positive" balance reaction was only observed after the first exposure to the disturbance with participants adopting an "arm-tracking" strategy for subsequent trials. The change in response behavior that was observed with repeated exposure to the touch displacement suggests that the role and interpretation of the sensory feedback from the fingertip is also modified. It is unclear if cutaneous feedback from the finger continues to provide meaningful information regarding body sway afterwards, or if the haptic contributions to balance control would be down-weighted, re-purposed, or abandoned altogether. Therefore, the primary objective of this study was to determine whether light touch continues to be a relevant sensory cue when the touch reference is no longer a reliable and stable spatial reference. In a first experiment, we compared the standing sway of participants touching a stable reference and after the touch reference was no longer reliable in conditions with the eyes open and with vision occluded.

The results from the first experiment demonstrated that sway area was further reduced and the direction of sway became biased towards the touch reference after a single, unexpected displacement of the touch reference with vision occluded. However, these effects were eliminated after repeated exposure to the touch displacements. Moreover, participants that had vision available showed an increase in sway area, but only after repeated exposures to the touch displacement. We speculated that seeing the touch reference move allowed participants to gain awareness of the events. Expectation of impending postural perturbations has been shown to influence control strategies and influence the contribution of sensory feedback to the regulation of balance (Caudron et al. 2008; Maki and Whitelaw 1993; McChesney et al. 1996). Therefore, in a second experiment our goal was to determine if participants utilized touch to stabilize sway when they were aware that the touch reference will move.

Methods

Participants

Forty healthy adults (18 to 29 years of age; 22 female) volunteered to participate in this investigation. Participants reported no history of neurologic, musculoskeletal, metabolic or cardiovascular disease, and had not experienced musculoskeletal injury or concussion in the past 6 months. Four participants self-reported as left-hand dominant. Participants provided written informed consent. Participants in Experiment 1 were naïve to the true nature of the study as the displacement of the touch plate was not disclosed prior to testing. Participants in Experiment 1 were provided full disclosure of the study after the testing was completed and were given the opportunity to withdraw their consent. The study was approved by the University of Alberta Research Ethics Board in accordance with the Declaration of Helsinki.

Set-up and Data Acquisition

Participants stood barefoot on a foam pad (5 cm thick ethylene-vinyl acetate (EVA)) atop a 6-component force plate (AMTI OR6-7-1000, Advanced Mechanical Technology, Inc., Watertown, MA, USA) in a normal bipedal stance with the feet shoulder width apart, or what was deemed comfortable by the participant (Fig. 1a). Participants were instructed to stand quietly, as they would normally, and to look directly ahead. When standing with eyes open a visual reference was located on the wall approximately 5 m in front of participants to direct their gaze. When standing with vision occluded, participants were asked to maintain a similar posture of the head and neck, but with their vision occluded by the use of darkened goggles.

In some tasks participants were asked to lightly touch a 3.75-cm wide x 7.5-cm long brushed aluminum plate positioned so that the pad of the right index finger was centered on the plate. A raised dimple was located at the center of the aluminum plate to provide a reference. The index finger was angled such that only the pad of the finger was in contact with the plate. The other fingers of the right hand were curled into the palm to prevent inadvertently contacting the touch plate. The right arm was positioned such that the upper arm was aligned vertically and the forearm was horizontal, with the elbow at approximately 90°. Participants were asked to maintain the same arm and hand posture during the no touch condition, but with the touch plate lowered. The touch plate was located in front of and to the right of the participants, laterally aligned with the right arm, and was visible to the participants during the eyes open conditions.

The touch plate was mounted on a square rail acme screw drive positioning stage (LinTech 130 Series, LinTech Positioning Systems, Monrovia, CA, USA), driven by a two-phase stepper motor (Applied Motion Products 5023-124 2-phase hybrid stepper motor, Watsonville, CA, USA), to produce linear displacements in fore/aft direction. Touch plate displacements were 12.5 mm with a peak velocity of 124 mm/s. Stage position was measured using a linear displacement sensor (Penny & Giles SLS130, Curtis-Wright Industrial Group, Christchurch, UK). The entire touch plate positioning apparatus was mounted on a 6-component force transducer (AMTI MC3A-100, Advanced Mechanical Technology, Inc., Watertown, MA, USA) to measure the vertical load applied by the participant when touching the touch plate. Participants were asked to maintain a light touch of < 1 N during conditions involving touch and were provided practice prior to testing. During testing, the applied force was monitored and auditory feedback was provided when the touch force exceeded 1 N. The relatively mild noise generated by the operation of the motor and the positioning stage was masked by white noise delivered through a pair of over-the-ear headphones. The participants wore the headphones and received white noise during all test conditions. A spotter stood adjacent the participants during testing. A safety harness was not used. Forces and moments from the standing force plate, vertical force of the touch plate, and position of the touch plate were digitized at a sampling rate 2000 Hz using a National Instruments data acquisition card (PCI-MIO-16E-4, National Instruments, Austin, TX, USA) and a custom-written LabView v8.2 (National Instruments, Austin, TX, USA) routine.

Protocol

Experiment 1: Naïve

Twenty participants naïve to the study hypothesis and protocol, and who had not participated in previous studies involving touch plate displacements, were pseudo-randomly allocated into two groups of ten. One group completed all testing with their eyes open (EO), while the second group were asked to wear darkened goggles to occlude vision (eyes closed, EC) during the experimental conditions. The EO group stood while 1) not touching the spatial reference (NT), 2) lightly touching the spatial reference (T), 3) lightly touching the spatial reference that was unexpectedly displaced forward once (P), and 4) lightly touching the spatial reference that was unexpectedly displaced forwards and returned backwards 3 times, with random inter-disturbance intervals of between 3 and 12 s (PP). The EC group first completed a trial of quiet standing with eyes open, before completing the same 4 trials as the EO group, but with vision occluded. For each trial, participants were asked to stand still for 120 s. For trials that included one or more touch plate perturbations the touch plate was stable for at least the first 10 s of the trial, with the subsequent perturbation or perturbations completed within the next 30 s. As the perturbations were unexpected, no specific instructions were provided to participants with respect to maintaining contact with the touch plate during the perturbation trials. The order of the trials was consistent across all participants as it was not possible to randomize the unexpected occurrence of the perturbations. Participants were asked to rest, seated on a chair, 2-3 min between trials.

Experiment 2: Aware

In the second experiment, we replicated the protocol of Experiment 1 with twenty additional participants. These participants were instructed prior to testing that the touch plate could move and the movement was demonstrated. Participants were not informed in which trials the touch plate might move or the number or frequency of any displacements. No cues or warnings were provided for the impending displacements. Several of the participants had participated in previous studies involving touch plate displacements. However, none were previous members of the Naïve cohort for this study.

Data Analysis and Statistics

Prior to analysis the data signals were digitally low-pass filtered at 20 Hz (4th order zero-lag Butterworth filter). The last 60 s of each trial was then used to calculate the center of pressure (COP) from the force and moment signals from the force plate (Fig. 1b). Sway area was estimated by calculating the 95% confidence ellipse, using principal component analysis to extract the major (1st principal component) and minor (2nd principal component) axes from the COP sway pattern (Oliveira et al. 1996). Sway orientation was estimated as the angle of rotation of the major axis of the 95% confidence ellipse, with 0^{o} aligned to the x-axis and 90^{o} aligned to the y-axis. Sway velocity was also calculated. Sway area and velocity were then expressed as a percentage of the eyes open, without touch condition to normalize across participants.

For each experiment, sway area and sway velocity were compared across conditions using mixed model analyses of variance (ANOVA) with Vision (eyes open vs. eyes closed) as the between-participants factor and Condition (touch vs. single perturbation vs. multiple perturbation) as the repeated-measures factor. Pairwise comparisons, with Bonferroni adjustments applied, were used to discern differences identified by the ANOVAs. Sway orientation was compared using circular statistics. Given that the angle of the major axis represents bidirectional sway (i.e. 90^{o} represents sway in the anterior-posterior direction), the data must be regarded as arising from two unimodal components with the same variance but with modes 180 degrees apart. Therefore, a doubling of angles was first required and from this, group directional means (∠) were calculated, as well as the mean vector length (***r***), which is a measure of angular dispersion (***r*** varies between 0 and 1 where a value near 1 implies little variation in angles). To test if a significant directional mean was present for each group, a *Rayleigh z* test was performed for all touch conditions. *Watson's Two-Sample U^2* tests were used to test for significant difference between conditions for each group (T vs. P; T vs. PP; P vs. PP). Circular statistics were performed using Oriana v4 statistical software package (Kovach Computing Services, Anglesey, Wales), while SPSS v25 (IBM, Armonk, NY, USA) was used to perform linear statistical analyses. All comparisons were made with $\alpha = 0.05$.

Results

Experiment 1: Naïve

Data from one participant in the Naïve EC group are displayed in Fig. 2 for all 5 conditions tested. For this participant, removing vision resulted in a large increase in sway area, increasing to 761.1 mm^2, a 253% increase over the 300.1 mm^2 observed during standing with EO. This was typical of standing with EC without touch with sway area increasing between 200-450% across participants. However, with the addition of touch, sway area was reduced in this participant to 276.4 mm^2, comparable to that observed when standing with EO. With the introduction of a single, unexpected displacement of the touch reference the sway area was further reduced to 116.8 mm^2. Thereafter, following the presentation of multiple touch displacements, the sway area increased to 248.8 mm^2, similar to the EO no touch condition.

The impact of condition on sway area in the Naïve participants is summarized in Fig. 3a for both the EC and EO groups. The data for the EC group are consistent with the single participant's data described in Fig. 2. During the ECP condition, mean sway area was 72.4 ± 39.5% EO (mean ± standard deviation), which was reduced compared to the ECT condition with a sway area of 117.2 ± 45.2% EO. Sway area then increased to 103.4 ± 27.8% EO during the ECPP condition. In contrast, with the eyes open the addition of light touch reduced sway area, compared to EO without touch in all conditions with sway areas of 40.5 ± 10.5% EO, 45.8 ± 14.8% EO, and 68.6 ± 21.9% EO for EOT, EOP, and EOPP, respectively. A significant Vision x Condition interaction was identified by the ANOVA (F=6.159, p=0.005). Subsequent pairwise comparisons indicated the decrease in sway area during ECP was significantly reduced compared to ECT in the EC group. In addition, sway area during EOPP was significantly greater than both EOT and EOP in the EO group.

Shown in Fig. 3b are the sway velocity data for both the EC and EO groups. Sway velocity during the EC conditions was 118.6 ± 36.8% EO, 103.1 ± 34.7% EO, and 104.4 ± 32.3% EO for ECT, ECP, and ECPP, respectively. In general, sway velocity was reduced in the EO group across all conditions with velocities of 68.9 ± 9.6% EO, 69.1 ± 12.3% EO, and 69.8 ± 9.9% EO for EOT, EOP, and EOPP, respectively. The ANOVA identified a significant main effect of Vision (F=13.95, p=0.002), without a significant interaction (F=2.65, p=0.085) or main effect of Condition (F=2.28, p=0.117).

The data in Fig. 2 also suggest that the orientation of the dominant sway direction is impacted by the touch conditions. For this participant, the dominant sway direction when standing with EC without touching was primarily in the anterior-posterior direction. However, when touching with EC the dominant sway direction was primarily oriented in the medial-lateral direction. Following a single displacement of the touch reference, the major axis of the sway ellipse for this participant was then oriented in approximation with the location of the touch reference. Whereas, following repeated touch displacements, the dominant sway direction appeared to be similar to that of the EO condition.

We compared the orientation of the major axis for each participant to determine if these behaviors were consistent across participants. The top row of Fig 4 depicts the orientation of the major axis of the 95% confidence ellipses for all Naïve participants in the EC conditions. As can be seen, when standing with EC and not touching, the dominant sway direction for all participants was predominantly in the anterior-posterior direction, with $\angle = 88.9^{\circ}$ and $\boldsymbol{r} = 0.95$, representing a significant group directional mean (*Rayleigh z* = 9.10, p<0.001). However, when participants touched the stable reference (ECT) the group of sway axes appeared to become more medial-lateral dominant, with $\angle = 4.2^{\circ}$ and $\boldsymbol{r} = 0.48$, although this failed to reach significance (*Rayleigh z* = 2.32, p=0.097). With the introduction of a single touch plate perturbation (ECP), the group of sway axes appeared to rotate, achieving $\angle = 41.97^{\circ}$ and $\boldsymbol{r} = 0.60$, representing a significant group directional mean (*Rayleigh z* = 3.55, p = 0.02). In contrast, following multiple touch displacements there appeared to be no consistent trend in the sway orientation across the 10 participants with a mean vector length ***r*** = 0.14, which is close to a completely uniform spread, therefore the directional mean (∠) of 11.0º was not significant (*Rayleigh z* = 0.19, p=0.83). Watson's two-sample U^2 tests revealed significant differences in the uniformity of dominant sway directions between EC and all three touch conditions: EC vs. ECT, U^2 = 0.425 (p<0.001); EC vs. ECP, U^2 = 0.253 (p<0.02); EC vs. ECPP, U^2 = 0.505 (p<0.001). In contrast, the dominant sway directions were not found to be different between the three touch conditions: ECT vs ECP, U^2 = 0.105 (p>0.2); ECT vs. ECPP, U^2 = 0.057 (p>0.5); ECP vs. ECPP, U^2 = 0.105 (p>0.2).

The bottom row of Fig. 4 depicts the orientation of the major axis of the 95% confidence ellipses for all Naïve participants in the EO conditions. The dominant sway direction for all participants standing with EO and not touching was in the anterior-posterior direction, ∠ = 83.3º and ***r*** = 0.77, representing a significant group directional mean (*Rayleigh z* = 5.91, p<0.001). With the application of light touch, the dominant sway direction became less consistent across participants with a general clustering along a diagonal toward the upper right quadrant. However, the directional mean (∠) of 23.4º, with an ***r*** = 0.36, did not reach significance (*Rayleigh z* = 1.33, p=0.27). Following a single touch displacement, sway direction was consistently dominated by the medial-lateral direction across all participants, with ∠ = 5.0º and ***r*** = 0.69 (*Rayleigh z* = 4.81, p=0.005). In contrast, the dominant sway direction following multiple touch displacements showed little consistency across participants with ***r*** = 0.18, which is close to a uniform spread, rendering the directional mean (∠) of 141.5º not significant (*Rayleigh z* = 0.31, p=0.74). Watson's two-sample U^2 tests revealed significant differences in the uniformity of the dominant sway directions between EO vs. EOT (U^2 = 0.195, p<0.05) and EO vs. EOP (U^2 = 0.385, p<0.001). In contrast, the dominant sway directions were not different between EO vs. EOPP (U^2 = 0.175, p>0.05), or between any of the touch conditions: EOT vs. EOP (U^2 = 0.167, p>0.05); EOT vs. EOPP (U^2 = 0.097, p>0.5); EOP vs. EOPP (U^2 = 0.123, p>0.2).

Experiment 2: Aware

In the second experiment, participants were instructed prior to testing that the touch reference could move, but were not informed for which trials or when the touch reference would be displaced. As with the Naïve participants, closing the eyes resulted in large increases in the sway area in the absence of touching the reference. As can be seen in Fig. 5a, touching the reference reduced the sway area close to the EO no touch values with an average sway area for ECT of 94.3 ± 66.9% EO. Introduction of a single touch displacement (ECP) yielded an average sway area of 94.0 ± 47.5% EO. In contrast, the average sway area increased to 155.6 ± 76.8% EO following multiple displacements of the touch reference (ECPP). With EO the addition of light touch reduced sway area in all conditions, compared to EO without touch, with sway areas of 48.0 ± 13.1% EO, 60.6 ± 29.6% EO, and 56.5 ± 16.5% EO for EOT, EOP, and EOPP, respectively. The ANOVA identified a significant Vision x Condition interaction ($F=8.75$; $p=0.001$). Subsequent pairwise comparisons indicated that sway area during ECPP was significantly larger than during both ECT and ECP. No differences between touch conditions were identified for the EO group.

Shown in Fig. 5b are the mean sway velocity data for both the EC and EO groups. Sway velocity during the EC conditions was 118.2 ± 24.2% EO, 102.3 ± 19.0% EO, and 110.5 ± 27.2% EO for ECT, ECP, and ECPP, respectively. In general, sway velocity was reduced in the EO group across all conditions with velocities of 65.3 ± 8.4% EO, 63.3 ± 9.7% EO, and 66.3 ± 11.1% EO for EOT, EOP, and EOPP, respectively. The ANOVA revealed a significant main effect of Vision ($F=39.7$; $p<0.001$) and Condition ($F=3.80$; $p=0.032$), with no significant interaction ($F=2.32$; $p=0.115$). Subsequent pairwise comparisons indicated that sway velocity during the P conditions was significantly reduced compared to the T conditions ($p=0.024$) and that sway velocity during the EO conditions was significantly reduced compared to the EC conditions ($p<0.001$).

As shown in Fig. 6, participants standing without touch and with eyes open (EC) or closed (EO) typically had dominant sway directions in the anterior-posterior direction, with ∠ = 87.3° (***r*** = 0.95) and ∠ = 83.5° (***r*** = 0.83) respectively, both of which were significant directional means (p<0.001). Participants that were aware the touch device could move rotated their dominant sway direction to align approximately with the location of the touch reference during the T condition, regardless of whether their vision was occluded (ECT, ∠ = 37.5°, ***r*** = 0.64) or not (EOT ∠ = 37.3°, ***r*** = 0.76), resulting in significant directional means (p=0.012 and 0.001, respectively). A consistent orientation of the dominant sway direction was not observed across participants following the introduction of a single displacement (ECP, ***r*** = 0.43; EOP, ***r*** = 0.18), or following multiple displacements (ECPP, ***r*** = 0.48; EOPP, ***r*** = 0.32). Watson's two-sample U^2 tests indicated that the uniformity of sway orientation during EC was significantly different from all three touch conditions: EC vs. ECT (U^2 = 0.425, p<0.001); EC vs. ECP (U^2 = 0.331, p<0.002); EC vs. ECPP (U^2 = 0.203, p<0.05). Uniformity of the sway orientation was not significantly different across the three touch conditions: ECT vs. ECP (U^2 = 0.051, p>0.5); ECT vs. ECPP (U^2 = 0.183, p>0.05); ECP vs. ECPP (U^2 = 0.165, p>0.05). With eyes open, the uniformity of sway orientation during EOT was significantly different from EO (U^2 = 0.297, p<0.005). No other comparisons revealed significantly different uniformity in sway orientation between conditions with the eyes open: EO vs. EOP (U^2 = 0.173, p>0.05); EO vs. EOPP (U^2 = 0.173, p>0.05); EOT vs. EOP (U^2 = 0.133, p>0.1); EOT vs. EOPP (U^2 = 0.135, p>0.1); EOP vs. EOPP (U^2 = 0.077, p>0.2).

Discussion

It is well established that postural sway is reduced when lightly touching a stable reference point. This effect is most pronounced when standing with eyes closed as the tactile cues are argued to provide supplementary spatial information for the absent visual inputs. We recently demonstrated that unexpected displacement of a light touch reference often evokes a postural response when participants expect that the touch reference is stable and reliable (Misiaszek et al. 2016; Misiaszek and Vander Meulen 2017). However, with repeated displacements of the touch reference participants forego the postural response in favor of tracking the displacement with isolated arm movements. The aim of the present study was to determine if light touch sensory cues continue to be effective in reducing postural sway when the touch reference is unreliable. The primary result of our study is that light touch continues to influence sway when the touch reference is unreliable. Indeed, sway area while touching the reference was always much less than the sway area observed when standing with the eyes closed in the absence of a touch reference (cf. Fig. 2). Therefore, touching the spatial reference, even when it was unreliable, impacted the extent to which a person swayed. Additionally, our results also demonstrated for some groups (e.g. Naïve EO, Aware EC) that when the touch reference was known to be unreliable the sway area increased, relative to other touch conditions, indicating the integration of this sensory cue in standing balance control was adapted. Conversely, there is also evidence from the Naïve EC group that sway area became further constrained when there was uncertainty about the reliability of the touch reference. In the following two sections we will 1) elaborate on the discussion of the adaptation of the contribution of tactile cues to standing balance, and 2) consider the functional relevance of these observations.

Sensory reweighting of the tactile cues

When standing with the eyes closed without a touch reference, sway area increased to 200 – 450% of the control, eyes open no touch condition. In contrast, touch of the reference reduced sway area, regardless of the touch condition and, therefore, regardless of the reliability of the touch reference. Nevertheless, increases in sway area were often observed when the touch reference became unreliable, relative to the stable touch reference condition. This is most evident for the Naïve group of participants with eyes open and the Aware group of participants with eyes closed. Data from both of these cohorts showed significant increases in sway following the multiple touch perturbations, when participants were now certain that the touch reference was unreliable. It is also worth noting that for the Naïve EC cohort we observed an increase in sway area following multiple touch perturbations, when compared to the single touch perturbation data. However, this increase was not statistically significant with this relatively small sample size. Regardless, the increase in sway area following multiple touch perturbations in the

Naïve EO and Aware EC cohorts indicates a diminished contribution of touch to regulating sway, suggesting a reweighting of the sensory contribution from tactile cues. This is consistent with previous reports demonstrating that the influence on balance control of discordant sensory information from visual (Barela et al. 2009; Jeka et al. 2008) or somatosensory (Tjernström et al. 2010) stimuli, including light touch (Assländer et al. 2018), is down-weighted.

Sensory reweighting has been described as a means to regulate the relative importance of the various possible sensory inputs to the regulation of balance (Peterka 2002). In the context of this study, when vision is occluded and a presumed stable touch reference is provided, the tactile information from the fingers can provide important spatial cues about the sway of the body. However, in many instances, the fingers and hand will interact with contacts that might be moving, unstable, or unpredictable. In these instances, the contribution of tactile information from the hands presumably assumes a different role and will be weighted, or integrated, into control processes as needed (Assländer et al. 2018; Mergner 2010). The contribution of sensory feedback to motor control is argued to be subject to sensorimotor set, or the selective gating and amplification of sensory information based upon the anticipated or expected requirements of a movement within a given context (Prochazka 1989). The adaptations to sway area demonstrated in the present study indicate that the contribution of tactile information to balance control had adapted with changes in environmental context (stability of the touch reference) and contextual awareness. Moreover, we previously demonstrated that most Naïve participants typically respond to the first occurrence of a touch displacement with a postural response, but immediately switch to an "arm-tracking" behavior with subsequent exposures (Misiaszek et al. 2016; Misiaszek and Vander Meulen 2017). In other words, when the touch reference became unreliable, the contribution of the sensory channel to balance control was not merely down-weighted in favor of other, more reliable sensory sources. Rather, the same sensory signal was quickly repurposed to generate a different motor response, one which incorporated an altogether different balance behavior to stabilize against the forward displacement of the mass of the arm (Misiaszek and Vander Meulen 2017).

Sway as noise

It is interesting that sway area during the touch conditions never reached the extremes observed in the ECNT conditions, even when the touch reference was unreliable. This suggests that the touch reference was still influencing sway control to a degree. Barela et al. (2014) made a similar observation with the use of incongruent visual stimuli, remarking that participants were unable to avoid incorporating the inaccurate sensory channel into the control of balance. In our study, it is possible that the participants learned the extent to which the touch reference would move, and coupled with their knowledge of the size of the touch plate, were able to extract sufficient spatial information to assist with sway control. Alternatively, it is also possible that the participants were controlling their sway in an effort to maintain touch with the touch plate. For example, it has been argued that sway is stabilized when touching an unstable curtain (Riley et al. 1999) or performing a skilled manual tasks (Morioka et al. 2005; Wulf et al. 2004) as a means of facilitating task performance. This mechanism might also explain why sway area remains reduced in the EOT condition for both the Naïve and Aware cohorts, relative to the EONT control condition, even after receiving multiple touch perturbations. With the eyes open, stable balance is readily achieved in the absence of touch. Therefore, the decrease in sway area might serve to facilitate the task of maintaining touch with an object that is anticipated to move. Although participants were not explicitly instructed to maintain touch with the *moving* touch plate, participants were instructed to maintain light touch of no more than 1 N. The tacit instruction of maintaining touch with the moving plate is thus obvious.

The interpretation that the sway area is reduced to facilitate the task of maintaining touch is further supported by the surprising finding that Naïve participants reduced sway further after a single touch displacement, compared with the touch condition. This reduction in sway area was paired with a consistent orientation of the primary sway direction with an average sway angle of about 42^{o}, which approximates the location of the touch reference relative to the participant's body. We suggest that following a single displacement of the touch reference the participants were uncertain as to what they had experienced. Previously, it has been shown that explicit (by instruction set) and implicit (by experience of a disturbance without instruction) knowledge of a disturbance to visual stimuli impacts the weighting of the visual sensory channel within balance control (Barela et al. 2014), consistent with our results following the multiple touch displacements when both the Naïve and Aware cohorts had knowledge of the disturbance. However, we speculate that with the uncertainty created with the *single* touch displacement, participants reduced sway area and directed their sway orientation towards the touch reference as a means to enhance the sensory acuity from the finger by minimizing the sway-induced stimulation at the fingertip. This interpretation is corroborated by the findings in the Aware group of participants as both the EC and EO cohort tended to align their primary sway orientation towards the touch plate during the touch condition, as though in anticipation of its eventual movement. This is somewhat in conflict with the finding that anticipation of an impending postural threat leads to increased sway amplitude (Shaw et al. 2012), which is mitigated in part with prior experience of the disturbance (Johnson et al. 2017). However, in our study, the displacement of the light touch reference does not create a postural disturbance per se and therefore does not constitute an overt postural threat. Presumably, this lack of an overt threat to stability allowed participants to direct attentional resources (Johnson et al. 2017) towards differentiating the suspicious events that occurred at the finger. Taken together, we argue that purposely reducing sway may serve the function of enhancing the sensory signal from the fingertip by reducing the background noise associated with sway-induced activation of the tactile receptors.

Conclusion

Light touch sensory cues provide a potentially rich source of information regarding the interface of the hand with external objects. In the present study, contact of a fingertip with an external object was shown to have a complex effect on postural sway, depending upon the expectation and experience of the characteristics of the object being touched. This complex interaction between touch and postural control highlights the flexibility and responsiveness required within the sensorimotor integration processes. Inaccurate weighting of a sensory channel can lead to an inappropriate selection of a motor response to a stimulus, such as the automatic postural response often seen with the unexpected displacement of a touch reference (Misiaszek et al. 2016; Misiaszek and Vander Meulen 2017). In addition, postural sway may impact upon the performance of a skilled task (Riley et al. 1999; Teixeira et al. 2018) or introduce noise in the sensory channels, confounding the contribution of touch to balance control.

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Conflict of Interest:

The authors declare that they have no conflict of interest.

Figure Legends

Fig. 1 a) Depiction of the experimental set-up for the EC conditions with touch. Participants stood on a foam pad atop a 6-axis force plate while contacting a touch plate that was capable of moving, driven by a stepper motor. The height of the touch plate was adjusted to accommodate each participant. **b)** Center of pressure (grey line) was plotted in the x and y directions for a 60 s period of standing during each condition. The 95% confidence ellipse (black oval) was calculated and the angle of the dominant sway direction was taken as the angle of the major axis relative to horizontal.

Fig. 2 Example center of pressure plots (grey lines) with their respective 95% confidence ellipses (black ovals) for each trial from a single Naïve participant in the EC cohort.

Fig. 3 Naïve participant group data. **a)** Mean sway area and **b)** mean sway velocity, expressed as %EONT condition for both the EC and EO cohorts. Error bars are standard deviations. Horizontal lines connect significantly different pairwise comparisons ($p<0.05$) between touch conditions.

Fig. 4 Naïve participant directional data. Each line represents the orientation of the major axis of the 95% confidence ellipse from a single participant for each trial for both the EC (top row) and EO (bottom row) cohorts.

Fig. 5 Aware participant group data. **a)** Mean sway area and **b)** mean sway velocity, expressed as %EONT condition for both the EC and EO cohorts. Error bars are standard deviations. Horizontal lines connect significantly different pairwise comparisons ($p<0.05$) between touch conditions.

Fig. 6 Aware participant directional data. Each line represents the orientation of the major axis of the 95% confidence ellipse from a single participant for each trial for both the EC (top row) and EO (bottom row) cohorts.

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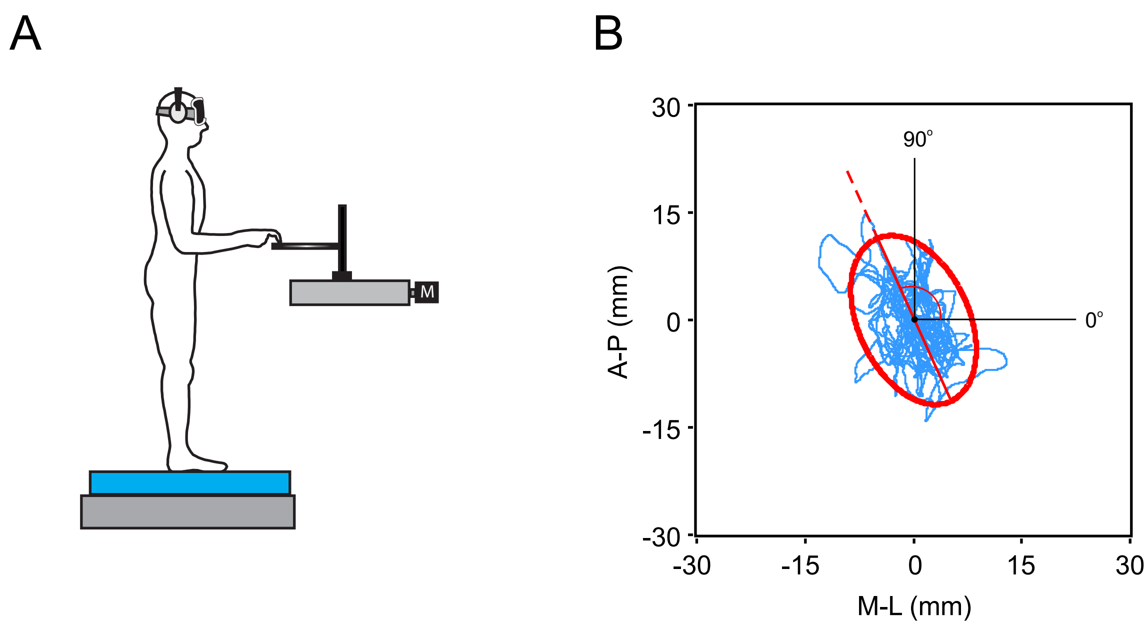

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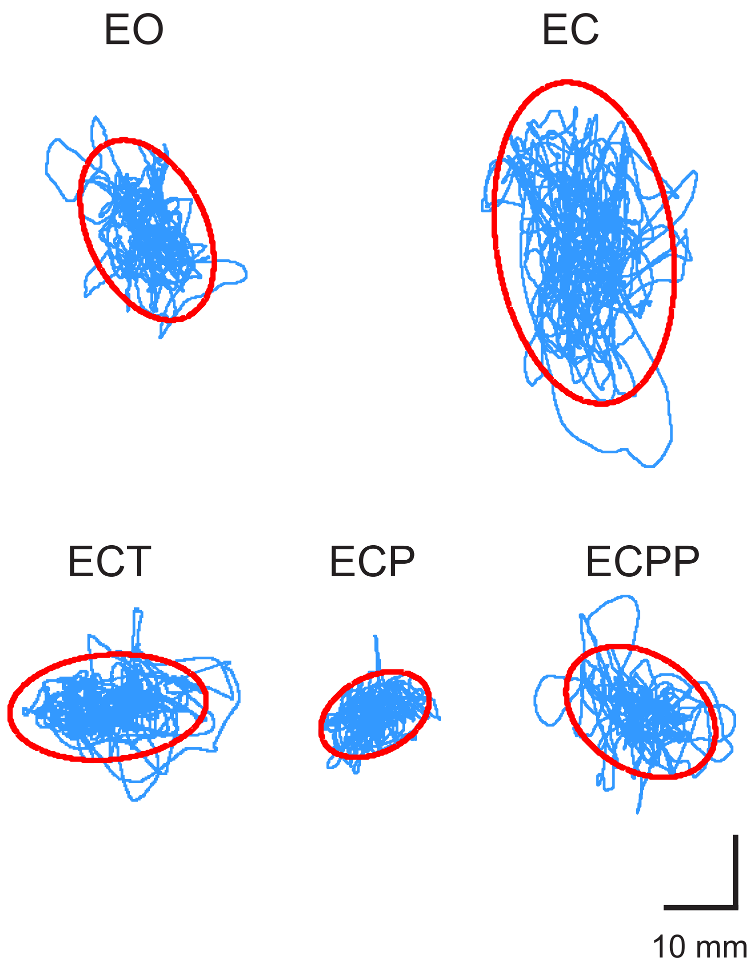
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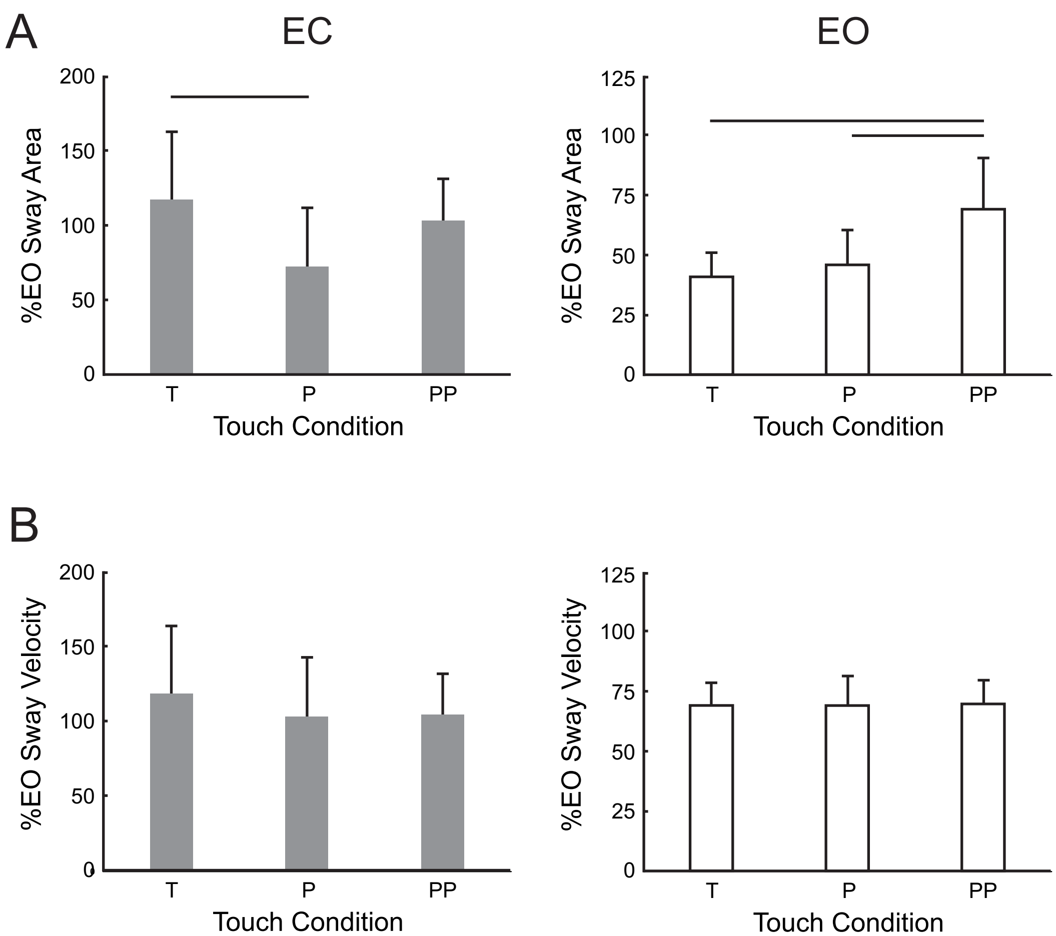
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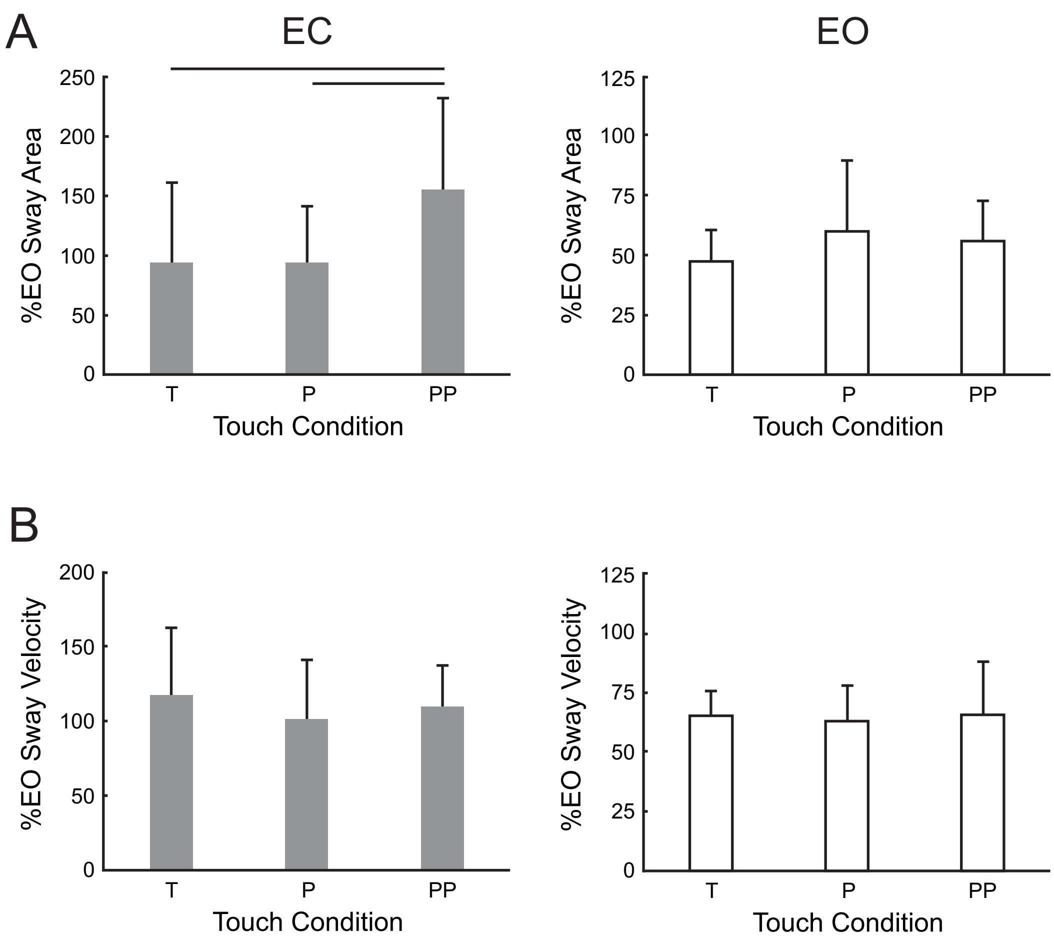
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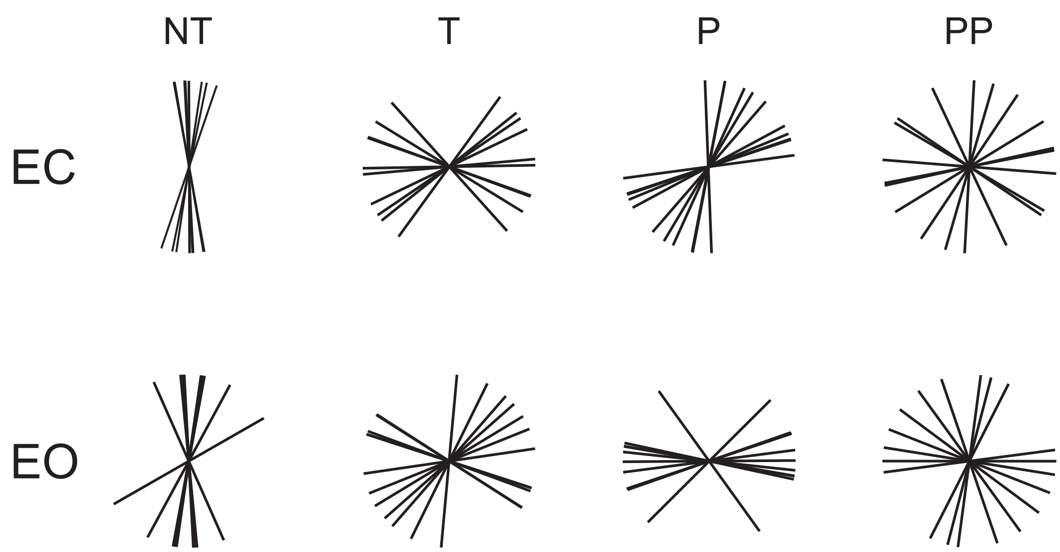
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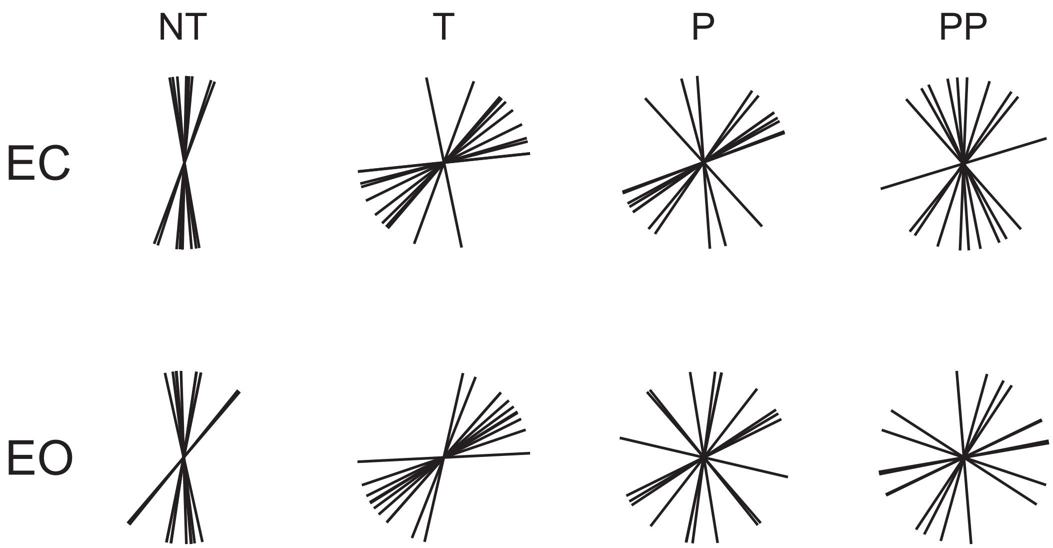
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