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Balancing sensory inputs: Sensory reweighting of ankle proprioception and vision during a bipedal posture task

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ABSTRACT

During multisensory integration, it has been proposed that the central nervous system (CNS) assigns a weight to each sensory input through a process called sensory reweighting. The outcome of this integration process is a single percept that is used to control posture. The main objective of this study was to determine the interaction between ankle proprioception and vision during sensory integration when the two inputs provide conflicting sensory information pertaining to direction of body sway. Sensory conflict was created by using bilateral Achilles tendon vibration and contracting visual flow and produced body sway in opposing directions when applied independently. Vibration was applied at 80 Hz, 1 mm amplitude and the visual flow consisted of a virtual reality scene with concentric rings retreating at 3m/s. Body sway elicited by the stimuli individually and in combination was evaluated in 10 healthy young adults by analyzing center of pressure (COP) displacement and lower limb kinematics. The magnitude of COP displacement produced when vibration and visual flow were combined was found to be lesser than the algebraic sum of COP displacement produced by the stimuli when applied individually. This suggests that multisensory integration is not merely an algebraic summation of individual cues. Instead the observed response might be a result of a weighted combination process with the weight attached to each cue being directly proportional to the relative reliability of the cues. The moderating effect of visual flow on postural instability produced by vibration points to the potential use of controlled visual flow for balance training.

1. Introduction

The control of bipedal human posture requires accurate information from various sensory systems. Information related to change in body orientation either due to self-motion or external influences is obtained from these sensory systems and integrated in the central nervous system (CNS).

Many theories and models have been proposed to explain the mechanism by which the CNS processes multisensory information [1–4]. It has been suggested that the information carried by individual sensory channels is combined and a 'weight' is assigned to the various input sources depending upon the current functional state of a particular sensory system, the postural task itself, and the context in which task is being performed. During this process the most reliable inputs are given more emphasis i.e. upweighted by the CNS, and the less reliable sensory inputs are given less emphasis i.e. downweighted. A dependency on one type of input over others can increase the risk of falls under circumstances where the continually upweighted input is unavailable or unreliable. For example, returning astronauts and elderly are reported to be visually dependent [5–7]. Treatment regimens to address this problem should focus on training these individuals to effectively weight the sensory systems and use the one that is most appropriate in a given situation. To develop such treatment plans it is important to understand how various sources of feedback interact to influence postural control.

The aim of the current investigation was to determine how ankle proprioception and vision interact to maintain postural equilibrium, when the two inputs provide conflicting information about the direction of body sway. Sensory conflict was created by

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simultaneously providing Achilles tendon vibration, resulting in backward sway [8–10], with a pattern of visual stimulation resulting in forward sway [11,12].

Simultaneously combining the two stimuli and measuring the resulting magnitude and direction of body sway was expected to provide insight into the relative weighting of the two inputs during sensory integration. It was hypothesized that the addition of contracting visual flow would moderate the extent of corrective backward COP displacement and angular displacement about the lower limb joints produced by tendon vibration.

2. Methods

Ten healthy adults (M ± SD = 26.3 ± 4.1 years old) participated in this study. They were screened using a Modified Physical Activity Readiness Questionnaire which has questions designed to assess for any history of neurological or vestibular disorders that might affect balance. The participants were also screened for their responsiveness to tendon vibration as reflected in backward COP displacement of at least 5 mm in response to bilateral Achilles vibration. The study was conducted in accordance with the Helsinki Declaration and approved by the institutional Committee for the Protection of Human Participants and each participant provided informed consent.

2.1. Vibratory stimulus

The Achilles tendons were stimulated bilaterally by using continuous 80 Hz, 1 mm amplitude vibration using cylindrical shaped vibrators (VB 115, Techno-Concept, Cereste, FR) [13].

2.2. Visual stimulus

This stimulus consisted of a visual flow pattern created using virtual reality software (WorldViz, Santa Barbara, CA) and viewed through a head mounted visual display (Oculus Rift DK2, Oculus VR, Irvine, CA). The virtual environment consisted of circular rings made up of small white spheres equally placed around them as shown in Fig. 1A. Each ring of spheres moved as one entity in the forward direction at a constant linear speed of 3 m/s and appeared smaller in radii as it approached the farthest end. This created an illusionary backward motion through an infinite number of circular rings that resulted in a corrective response of forward sway.

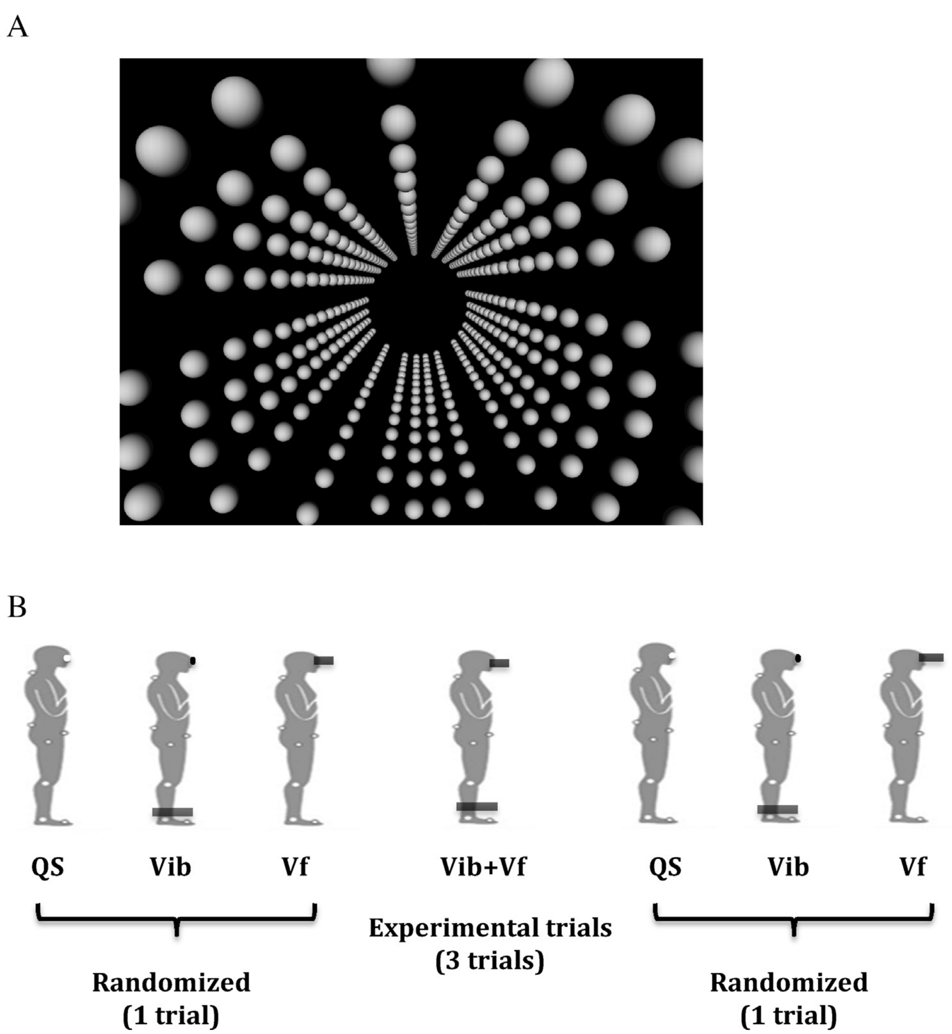

Fig. 1. A) Visual scene consisting of concentric circular rings of white spheres, with each ring moving away from the observer at a constant linear speed of 3m/s. B)An illustration of the experimental design.

2.3. Experimental procedure

The participants' postural sway was assessed under four conditions. The baseline conditions consisted of one trial each of eyes open quiet stance (QS), eyes closed with Achilles tendons vibration (Vib) and eyes open with visual flow (Vf). The experimental condition simultaneously combined vibration and visual flow (Vib + Vf) and was tested three times. QS, Vib and Vf were repeated after the experimental condition (post-test trials). The experimental design is illustrated in Fig. 1B. All trials lasted five seconds and for the stimulation trials, the stimuli were activated after one second. Stimulation periods of four seconds were used because the corrective postural responses to both vibration and visual flow emerge within the first second of stimulation [14,15]. A safety harness was used to prevent potential falls. The participants wore the Oculus Rift and the vibrators during all the trials (except QS) but they were naïve to the stimulus they were to receive prior to a particular trial.

2.4. Data recordings

The kinetic data associated with balance was measured using a force plate system (NeuroCom EquiTest, NeuroCom Intl, Clackamas OR) equipped with four sensors. The data from the force plate were collected at 100 HZ and used to compute COP. Kinematic data were recorded at a rate of 30 Hz using wireless inertial measurement units (MTw system, Xsens Technologies, NL) placed on the pelvis (close to the sacral bone, between the left and the right iliac spine), upper legs (on the tibial tract, between the iliac crest and lateral condyle of the tibia), lower legs (lower third of the medial surface of the tibia) and feet, and secured with Velcro® straps. Each IMU consists of a 3D gyroscope, 3D magnetometer and 3D accelerometer. The XSens software was used for data acquisition and to compute hip, knee and ankle joint angles. This software uses a Kalman filter based sensory fusion algorithm that fuses the data of accelerometers, gyroscopes and magnetometers to calculate segment orientations [16].

2.5. Data analysis

Analyses were performed using Matlab (Mathworks, Natick, MA). The COP data were low pass filtered at 5 Hz and amplitude normalized [17]. This was done by subtracting the data from the average of the data obtained from the initial second of the trial [8]. A positive value of the COP indicated a forward sway and a negative value indicated a backward sway with respect to the first second of the trial. The angular joint displacements were also normalized by following the same procedure as described above. Positive values of the ankle indicated dorsiflexion while negative values indicated plantar flexion. Similarly positive values of knee and hip angles indicated extension and negative values indicated flexion.

Each trial was divided into three time intervals for analyzing mean COP and mean angular joint displacement. The first second was the pre stimulation period (T_0) and the next two 2-s periods comprised the stimulation period (T_1 (1–3 s) and T_2 (3–5 s)). The mean COP position and joint angular displacements were calculated separately for the three intervals. For all conditions the root mean square (RMS) and peak displacement of COP and joint angles were computed for the entire stimulation period to capture the overall variability and the maximum displacement produced by the stimuli. Peak displacement was identified as the maximum absolute value during the stimulation period.

2.6. Statistical analysis

Statistical analyses were performed using SPSS V.20 (IBM Corp, Somers, NY). Normality tests were performed on all of the variables before conducting any statistical analysis. We performed *t*-tests on COP and joint angle data between baseline and post-test trials and between the three experimental trials and found no significant differences. Hence the data were averaged across trials for further analysis. We verified that joints motions were symmetrical about the sagittal plane and pooled the left and right joint angles.

Two-way repeated measures analysis of variance (RANOVA) was performed separately on mean COP and angular displacement of each joint. Additionally, a second two-way RANOVA was performed to test if the mean COP displacement produced in Vib + Vf condition was statistically different from the sum of the mean COP displacement produced by Vib and Vf independently. The two factors in the first analysis were time interval (T_0, T_1, T_2) and condition (QS, Vib, Vf, Vib + Vf) and the two factors in the second analysis were time interval (T_0, T_1, T_2) and condition (Vib + Vf, Vib + $Vf_{predicted}$). Where Vib + $Vf_{predicted}$ was the arithmetic sum of mean COP produced by Vib and Vf independently. Finally, a two-way RANOVA was performed on RMS and peak displacement measures of COP and joint angle of the stimulation phase. The two factors were vibration (Vib Off vs Vib On) and visual flow (Vf Off vs Vf On). Bonferroni post hoc analyses were performed as needed.

3. Results

All variables met the tests of normality for all conditions. Independent application of Achilles vibration and visual flow stimuli significantly affected participants' COP displacement and joint kinematics relative to quiet stance. No fall or loss of balance events were observed in any of the conditions, though the participants reported to have the most difficulty to balance in Vib condition. There was a significant main effect of condition (COP: $F(1.37,12.35) = 32.54$, $p < 0.01$, $\eta^2_p = 0.78$; Ankle: $F(1.58,14.25) = 27.5$, $p < 0.01$, $\eta^2_p = 0.74$; Hip: $F(3,27) = 7.83$, $p < 0.01$, $\eta^2_p = 0.47$) and time interval (COP: $F(1.38,12.39) = 16.97$, $p < 0.01$, $\eta^2_p = 0.65$; Ankle: $F(1.12,10.07) = 8.72$, $p < 0.01$, $\eta^2_p = 0.45$; Hip: $F(1.10,9.90) = 12.04$, $p < 0.01$, $\eta^2_p = 0.59$) on mean COP displacement and mean angular displacement of all joints except knee. There was a significant interaction effect (COP: $F(1.58,14.22) = 20.86$, $p < 0.01$, $\eta^2_p = 0.70$; Ankle: $F(1.38,12.37) = 16.25$, $p < 0.01$, $\eta^2_p = 0.64$; Hip: $F(3.28,29.48) = 6.87$, $p < 0.01$, $\eta^2_p = 0.44$). Pairwise comparisons indicated that at T_1, the mean COP and ankle displacement of Vib was significantly greater than QS. At T_2, the mean COP displacement of Vib, Vf and Vib + Vf was significantly greater than QS ($p < 0.05$). The ankle displacement at T_2 for Vib was significantly greater than QS. Between Vib and Vib + Vf, Vib had significantly greater mean COP and ankle displacement. Between mean COP displacement of Vib + $Vf_{predicted}$ and Vib + Vf, the former was significantly greater than the COP produced in Vib + Vf at both T_1 and T_2 ($p < 0.05$). The mean COP, ankle, knee and hip joint displacements are summarized in Table 1 and Fig. 2.

3.1. Peak COP displacement and RMS of COP displacement

There was a significant main effect of vibration (RMS: $F(1,9) = 24.37$, $p < 0.01$, $\eta^2_p = 0.73$; Peak: $F(1,9) = 19.68$, $p < 0.01$, $\eta^2_p = 0.69$) and visual flow (RMS: $F(1,9) = 12.75$, $p < 0.01$, $\eta^2_p = 0.59$; Peak: $F(1,9) = 7.9$, $p < 0.05$, $\eta^2_p = 0.47$) and a significant interaction (RMS: $F(1,9) = 18.34$, $p < 0.01$, $\eta^2_p = 0.67$; Peak: $F(1,9) = 14.84$, $p < 0.01$, $\eta^2_p = 0.62$) on RMS and peak of COP displacement. Pairwise comparisons indicated that RMS and peak COP

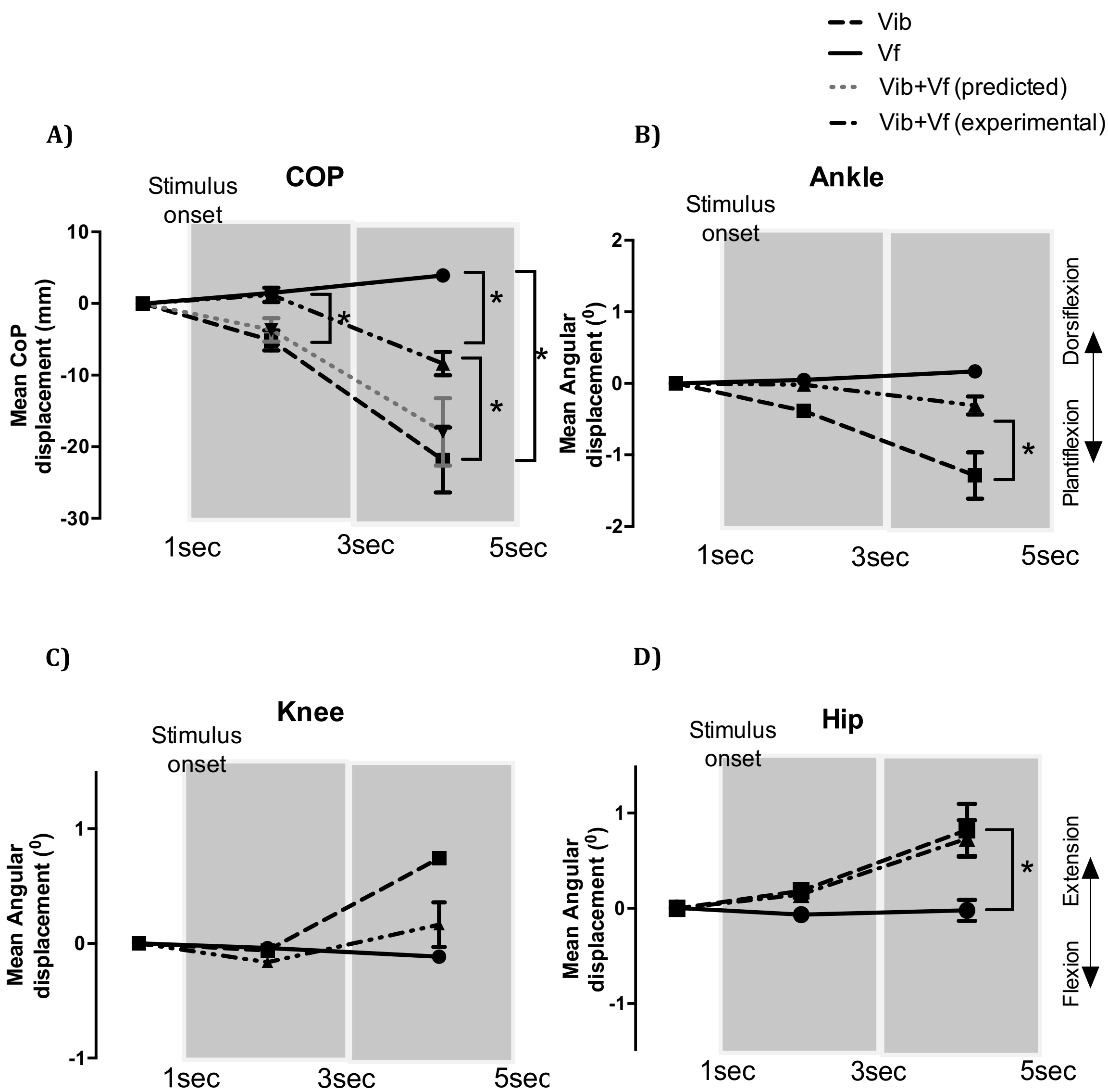

Fig. 2. A) Mean COP displacement (±1SEM) and B–D) Mean angular position of ankle, knee and hip joints (±1SEM) of the three time intervals (T_0,T_1,T_2) of the Vib, Vf and Vib + Vf conditions. Vib + Vf(predicted) represents the algebraic sum of mean displacement produced in Vib and Vf conditions. The region in white represents the baseline time interval (T_0) before the onset of the stimulus and the region in grey represents the stimulation phase following the onset of stimulus. Asterisks (*) indicate statistical significance with corresponding p value <0.05.

displacement of Vf were significantly greater than QS (Table 1 and Fig. 3A and B). These measures for Vib + Vf were significantly lesser when compared to Vib ($p < 0.05$). This indicates that the effect of vibration was significantly reduced when it was combined with visual flow than when it was applied by itself.

3.2. Peak and RMS of angular displacement of lower limb joints

There was a significant main effect of vibration (RMS: $F(1,9) = 20.08$, $p < 0.01$, $\eta^2_p = 0.69$; Peak: $F(1,9) = 15.40$, $p < 0.01$, $\eta^2_p = 0.63$) and visual flow (RMS: $F(1,9) = 25.41$, $p < 0.01$, $\eta^2_p = 0.65$; Peak: $F(1,9) = 18.58$, $p < 0.01$, $\eta^2_p = 0.67$) and a significant interaction (RMS: $F(1,9) = 25.41$, $p < 0.01$, $\eta^2_p = 0.74$; Peak: $F(1,9) = 26.24$, $p < 0.01$, $\eta^2_p = 0.75$) on RMS and peak ankle angular displacement. Pairwise comparisons indicated that peak ankle angular displacement was significantly greater for Vf when compared to QS. Between Vib and Vib + Vf, both RMS and peak ankle angular displacement measures were significantly greater in Vib when compared to Vib + Vf (Fig. 4A and B and Table 1). For knee and hip joint displacement, only RMS had a significant main effect of vibration (Knee: $F(1,9) = 4.75$, $p < 0.05$, $\eta^2_p = 0.40$; Hip: $F(1,9) = 9.06$, $p < 0.05$, $\eta^2_p = 0.50$). There was a main effect of vibration on hip peak angular displacement ($F(1,9) = 10.13$, $p < 0.05$, $\eta^2_p = 0.53$), but not for the knee.

4. Discussion

This study examined how sensory stimuli from two different sensory systems interact to affect postural control when the stimuli provide conflicting information about the direction of body sway. When there was a conflict in the perception of direction of body sway produced by visual flow and vibration, visual flow moderated the extent of backward COP displacement and angular displacement about lower limb joints produced by vibration. This can be explained as an outcome of a sensory reweighting process in which the disruptive proprioceptive cues from the ankle may have been downweighted in the presence of a visual input that by itself results in body sway in the opposite direction of Achilles vibration.

Table 1
Summary of mean values of all measures (±1 SE) for each condition. * indicates significant differences from QS and ** indicates significant differences from Vib condition at an adjusted p value after accounting for multiple comparisons.

Variable	Vib	Vf	Vib + Vf
Mean COP displacement			
T_0	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
T_1	$-5.17 \pm 1.41^{*}$	$1.48 \pm 0.48^{*,**}$	$1.21 \pm 1.00^{*,**}$
T_2	$-21.84 \pm 4.55^{*}$	$3.92 \pm 0.52^{*,**}$	$-8.38 \pm 1.62^{*,**}$
Mean ankle displacement			
T_0	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
T_1	$-0.39 \pm 0.07^{*}$	$0.05 \pm 0.03^{**}$	$-0.19 \pm 0.06^{**}$
T_2	$-1.29 \pm 0.33^{*}$	$0.17 \pm 0.05^{**}$	$-0.31 \pm 0.13^{**}$
Mean hip displacement			
T_0	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
T_1	0.18 ± 0.07	-0.07 ± 0.07	0.15 ± 0.06
T_2	0.82 ± 0.27	-0.02 ± 0.11	0.73 ± 0.19
RMS and Peak COP displacement (mm)	19.12 ± 3.12	$5.17 \pm 0.31^{*}$	$9.91 \pm 1.13^{**}$
	33.07 ± 6.28	$8.62 \pm 0.64^{*}$	$15.91 \pm 2.08^{**}$
RMS and Peak of Ankle joint angular displacement (°)	1.18 ± 0.23	0.23 ± 0.02,	$0.44 \pm 0.08^{**}$
	2.05 ± 0.42	$0.33 \pm 0.03^{*}$	$0.55 \pm 0.13^{**}$
RMS and Peak of knee joint angular displacement (°)	1.11 ± 0.48	$1.12 \pm 0.48^{*}$	0.62 ± 0.19
	2.42 ± 1.38	$0.32 \pm 0.05^{*}$	0.73 ± 0.19
RMS and Peak of hip joint angular displacement (°)	0.69 ± 0.19	0.28 ± 0.08	0.61 ± 0.14
	1.22 ± 0.34	0.41 ± 0.09	0.92 ± 0.23

When applied independently or simultaneously, vibration and visual flow significantly increased COP and lower limb angular displacements. The backward and forward shift in mean COP displacement with Vib and Vf respectively can be explained by significant modifications in ankle angular displacement. There was significant plantar flexion and dorsiflexion of ankle with Vib and Vf respectively during stimulation. Similarly there was extension and flexion of hip with Vib and Vf. In the Vib + Vf, the significant backward shift in COP displacement during stimulation reflected of the significant ankle plantar flexion and hip extension. Plantar flexion of ankle and hip joint extension was lower in the Vib + Vf condition when compared to Vib.

Brain imaging and neurophysiological studies have identified several regions in the brain that contain multimodal neurons that respond to more than one type of sensory stimulus and are presumed to be associated with the integration of multiple sensory inputs [18–25]. These multimodal neurons combine sensory inputs received from different cortical sensory regions and produce a single percept. Researchers have shown that the relative strength as well as the relative reliability of the sensory cues influences the percept resulting from multimodal integration.

Stanford and colleagues have explored how relative strength of the stimuli affects multisensory integration [19]. They found that when two different stimuli are simultaneously applied to a multimodal neuron, the resulting response could either be greater, equal or less than the algebraic sum of the unimodal responses generated if the stimuli were applied individually. Specifically, when a strong stimulus was simultaneously applied with a weak stimulus, the resulting neural response was found to be less than the algebraic summation of the responses produced by the individually applied stimuli applied individually. Though these results were observed at the neural level, the postural response to the combination of vibration and visual flow observed in the current study follows the same response pattern. That is, when a strong vibratory stimulus was simultaneously applied with weak visual flow stimulus, the magnitude of the mean COP displacement

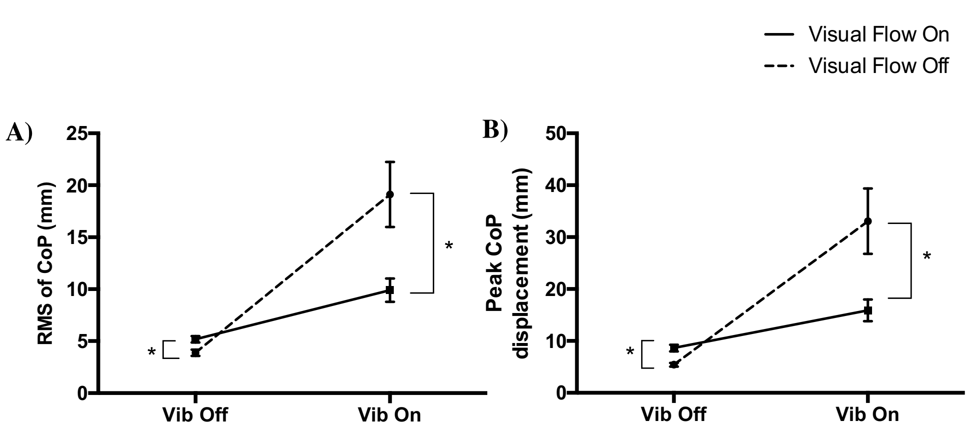

Fig. 3. A) Average peak COP displacement (±1SEM) and B) Average RMS of COP (±1SEM) along AP during the stimulation phase for all the conditions. Asterisks (*) indicate statistical significance with corresponding p value < 0.05.

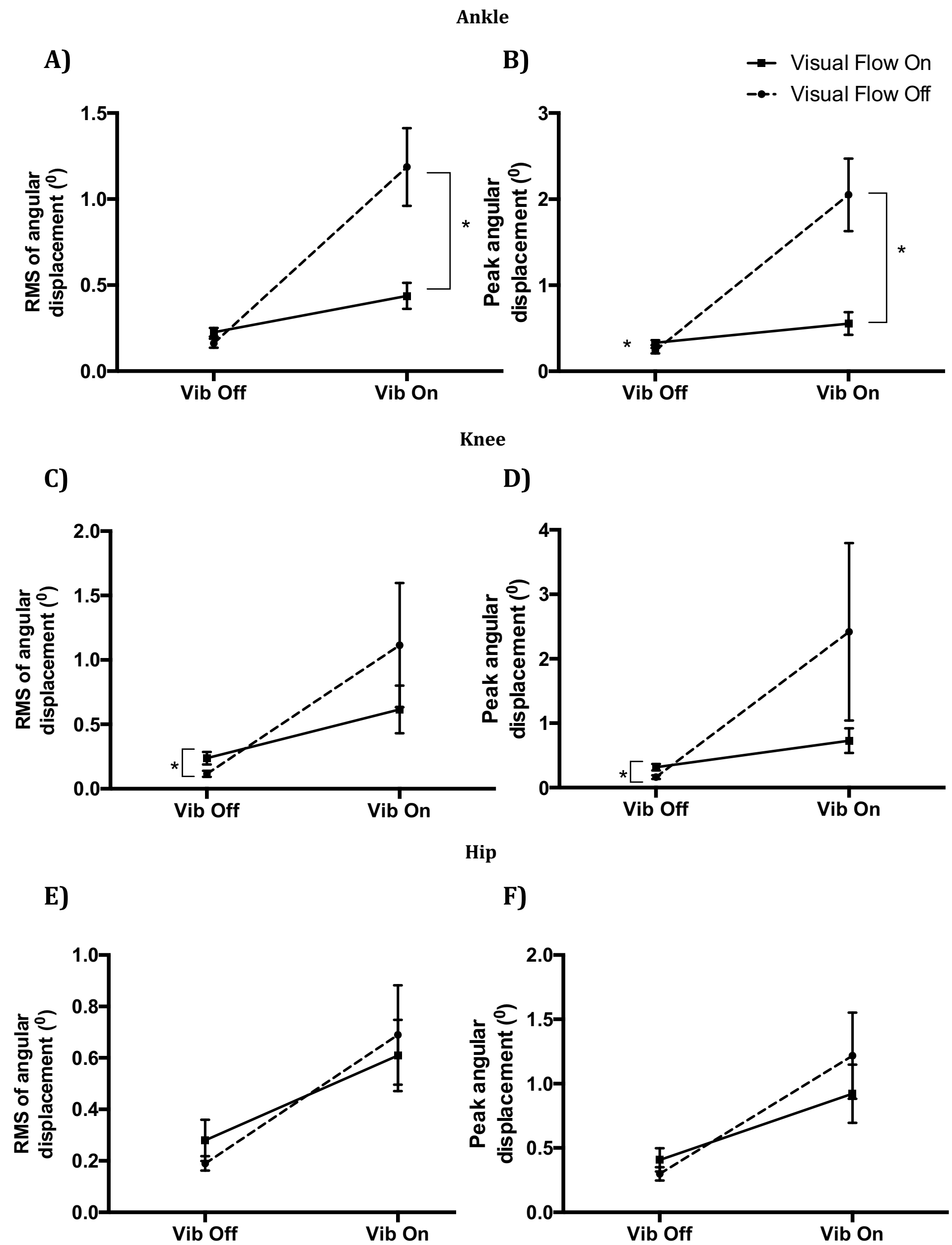

Fig. 4. A,C and E) Average peak angular displacement (±1 SEM) and B,D and F) RMS of angular displacement (±1 SEM) of ankle, knee and hip joints during the stimulation phase for quiet stance, vibration, visual flow and vibration + visual flow conditions. Asterisks (*) indicate statistical significance with corresponding p value < 0.05.

produced in Vib + Vf was less than the algebraic sum of the mean COP displacement produced by the independent application of vibration and visual flow.

The difference between the mean COP displacement produced in Vib + Vf and the algebraic sum of the mean COP displacement produced by the independent application of vibration and visual flow could be due to the specific combination of sensory cues. This combination rule is provided by the Bayes optimal cue integration model or the "weighted" linear integration model [1,26,27]. It states that humans combine cues in a statistically optimal manner that reduces the overall perceptual uncertainty and thereby improves performance. This occurs by combining the estimates of the individual stimulus cues in a weighted linear fashion, with the weight attached to each cue being directly proportional to the relative reliability of the cues. Successful predictions using this model have been tested in a variety of many psychophysical experiments using different research paradigms [1,22,23,28].

The current results can be explained based on the predictions of the weighted linear integration model. As predicted by the model, when vibration and visual flow were combined, the more reliable cue would have been upweighted. To determine the relative reliability of the two cues, we can compare the RMS, which is a measure of variance, of the COP displacement in Vib and Vf conditions. As seen in Fig. 3, the RMS of COP displacement produced by vibration was significantly greater than that of visual flow. This result can be interpreted as indicative of large uncertainty in the processing of vibration induced by proprioceptive cues when compared to visual cues. Thus when vibration and visual flow were applied simultaneously, the less reliable of the two i.e. ankle proprioception, may have received lesser weight in Vib + Vf when compared to visual cues. This resulted in a response that was less than a response that would have been predicted if the two cues were equally weighted (the algebraic sum of the individual responses). Additionally, smaller mean and RMS of

COP displacement in Vib + Vf when compared to Vib suggests that the effective weighting of the cues caused the overall uncertainty in processing of sensory cues as well as the overall instability to be reduced as predicted by the weighted linear integration model.

These results show that the combination of two conflicting sensory cues pertaining to the direction of perceived motion is more beneficial in supporting postural stability than a single sensory cue that is highly unreliable. More specifically, the combination of a weak but reliable visual flow stimulus with a stronger and less reliable vibratory stimulus, caused a reduction in COP displacement produced by vibration alone. This combination of sensory inputs helped in maintenance of COP well within the stability boundary. This demonstrates how a visual stimulus of appropriate strength and reliability can be used in moderating the instability produced by disrupted proprioception. The finding of specific changes in multisegmental motion patterns produced by visual flow point to the potential use of controlled visual flow in balance training of elders and patients with balance disorders.

Two issues serve to limit the generalizability of the current findings. One is the limited sample size and the other issue is that the postural responses to combinations of stimuli with reversed sway direction were not tested. This leaves open the question as to whether the current findings are specific to the tested combination of vibration and visual flow.

5. Conclusion

The primary finding of this study was that the magnitude of COP displacement elicited in response to a sensory conflict produced by simultaneous application of visual flow and Achilles vibration is lesser than the algebraic sum of COP displacement produced by the stimuli when applied individually. This suggests that multisensory integration does not involve a mere algebraic summation of individual cues. Instead the observed response could be a result of downweighting of vibration induced proprioceptive cues due to its lesser reliability than the visual cues even though the former was of greater strength. Moreover, this effective weighting influences the segmental motion patterns used to maintain balance. By using carefully controlled visual stimuli, visual flow can be used as a potential rehabilitation tool for postural training in certain patient populations and the elderly as suggested by previous researchers [29].

Conflict of interest

All the authors declare no conflicts of interest, financial or others.

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