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The Effect of Stroboscopic Vision on Dynamic Postural Stability in Uninjured Individuals

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Rapid adjustment and adaptation to multisensory cues are crucial for maintaining posture. The role of vision in static postural control was assessed by comparing eyes-open and eyes-closed performance; however, the impact of progressive visual occlusion during dynamic balance remains unclear. This study examined the effect of progressive visual occlusion with stroboscopic goggles on dynamic postural stability during jump landing. Sixteen uninjured, physically active adults participated in this study. Participants performed three single-leg landing trials at 50% of their maximum jump height, starting 70 cm away from the center of the force plate, while wearing stroboscopic vision goggles under three conditions: no-, low-, and high-occlusion. Ground reaction force data were analyzed using the dynamic postural stability index (DPSI). A one-way repeated-measure ANOVA and Hedges' g effect sizes were employed to assess differences among conditions in DPSI measures. Postural stability indices significantly increased (p = 0.026) with higher visual occlusion levels, indicating worse balance. However, the main effect of vision was only significant in the Medial-Lateral Stability Index (p = 0.009), specifically between no- and low-occlusion (p = 0.004, g= 0.81), resulting in a large effect size. With these results in mind, stroboscopic vision goggles, inducing progressive visual occlusion, impacted postural stability in uninjured individuals during jump landing. The findings suggest that the low-occlusion condition may introduce greater perturbations to postural stability during jump landing tasks compared to the no- and high-occlusion conditions. SV can offer unique challenges, particularly under low-occlusion conditions, and has the potential to serve as a valuable tool for training or sensory reweighting assessments in healthy individuals.

Keywords: strobe goggles, sensory reweighting, jump landing, dynamic balance

Maintaining postural stability requires integrating afferent information from proprioceptive, visual, and vestibular systems (Diener & Dichgans, 1988). This centrally mediated sensory integration must rapidly adjust to environmental and task constraints, employing "down-weighting" or "up-weighting" sensory cues to maintain postural equilibrium (Hwang et al., 2014). The capability to adapt and modulate the contribution of sensory input is defined as sensory reweighting (Nashner & Berthoz, 1978; Peterka, 2018).

Reweighting sensory information facilitates postural adaptations to interact with the surrounding environment successfully (Cenciarini & Peterka, 2006). For example, sudden changes in ambient light levels or deviating from a fixed surface, such as a transition to a moving walkway, necessitate rapid adjustments of sensory weights to react appropriately based on the most accurate information (Teasdale et al., 1991). In maintaining postural stability, the visual system assumes a dominant role (Paulus et al., 1984), providing information on object recognition and spatial orientation relative to the surroundings, thereby offering context for postural balance (Wade & Jones, 1997). When other systems are compromised, individuals often increase reliance on visual input. For example, those with vestibular or proprioceptive impairments tend to depend more on the visual system during postural tasks (Fukuoka et al., 1999). While heightened reliance on visual input may be beneficial temporarily, an increased dependency on the visual system can elevate the risk of injury during vigorous activities due to the excessive information the central nervous system may struggle to process (Peterka, 2018). Most studies assessed visual reliance by eliminating vision from the sensory equation. However, this approach is unsuitable for evaluating movements resembling real-world

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activities. Therefore, an alternative method is necessary to examine further the adaptive utilization of sensory information from reduced visual input during dynamic tasks.

Several studies have indicated that visual occlusion worsens balance (Abrahamova & Hlavacka, 2008; McKeon & Hertel, 2008); however, they typically employ a single level of visual occlusion. Common methods like eye-open (EO) and eyes-closed (EC) trials were used to investigate the role of visual input in reweighting during postural balance (Hazime et al., 2012; Springer et al., 2007). However, EO and EC trials hold two limitations: 1) they only allow static balance measures as individuals experience extreme conditions of visual occlusion due to limited methods for partial visual restriction (Kim et al., 2017), and 2) the EO/EC method results in inconsistent values during quiet stance, which questions the reliability of the technique to examine sensory reweighting abilities (Tjernstrom et al., 2015). Both issues inhibit the evaluation of a person's sensory reweighting through systematic visual perturbations during dynamic postural control assessments, which may better simulate real-world demands (D. Grooms et al., 2015). To better understand sensory reweighting dynamics, it is essential to determine whether high or low visual occlusion results in more significant tradeoffs in motor performance.

Stroboscopic vision (SV) goggles have recently enabled the systematic disruption of vision while performing dynamic tasks in the field (Kim et al., 2017). These goggles feature special lenses that alternate between transparency and opacity, producing intermittent visual occlusion conditions with a conveniently adjustable rate through a connected application on a phone or tablet. Previous studies by Kim et al. suggested that SV can be utilized to evaluate visual dependency, offering an alternative to the Sensory Organization Test(Kim et al., 2017, 2020). SV has also been suggested to interfere with visual information, prompting an adaptive strategy that forces sensory reweighting toward other sensory systems (D. Grooms et al., 2015).

Dynamic balance assessments, such as jump-landing, are necessary for challenging postural control and evaluating sensory reweighting during dynamic tasks (Kim et al., 2020; Wikstrom et al., 2006). Previous studies have highlighted single-leg jump landing as challenging for assessing dynamic postural stability(Brown et al., 2010; Ross et al., 2005). Adding SV goggles during jump-landing tasks can enhance our understanding of sensory reweighting. D. R. Grooms et al. (2018) investigated SV goggles during drop-landing, observing altered landing kinematics indicative of SV goggles influencing motor output through visual sensory contribution to neuromuscular control. However, drop-landing involved less force generation and adaptive neuromuscular motor strategies than forward jump-landing tasks (Kotsifaki et al., 2021). Further investigation using SV goggles during jump landing balance is necessary to identify visual contribution and subsequent sensory reweighting ability.

Therefore, the primary purpose of this study is to assess the effect of progressive visual occlusion on dynamic balance in uninjured individuals and identify its effect on postural stability during jump-landing. For this study, it was hypothesized that increasing visual occlusion during the jump-landing task would worsen all of the dynamic postural stability indices.

Methods

Participants

A total of 16 participants (Table 1), selected as a convenience sample from the university community, were included in the study. The study was supported by funds from the Graduate Research and Creative Activity of the University of Nebraska at Omaha. The authors declare no conflict of interest. Participants met the criteria of being free from lower extremity musculoskeletal injuries and were considered physically active, defined as those who participated in >90 minutes of physical activity per week. Exclusion criteria applied to individuals with 1) a history of surgical intervention or fracture in the lower extremity; 2) recent injury to the musculoskeletal structures of the lower extremity affecting the function of the joint and limiting their physical activity for at least one day within the previous three months; 3) history of neurological, neuromuscular, and/or chronic health conditions. Additionally, self-reported questionnaires, including the Foot and Ankle Ability Measure and the Cumberland Ankle Instability Tool, were utilized to assess the physical function of the ankle and foot (Hiller et al., 2006; Martin et al., 2005). All participants were required to have a score of >90% on both questionnaires to ensure the absence of functional ankle instability. The study protocol received approval from the Institutional Review Board at the University of Nebraska at Omaha (IRB# 201911-157).

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Table 1: *Participant Characteristics (n = 16)*

Characteristic	*M*	*SD*
Age (years)	23.5	4.6
Height (cm)	173.8	7.9
Mass (kg)	73.8	14.9
FAAM ADL (%)	100	0
FAAM Sports (%)	100	0
CAIT (score)	30	0
Gender (n): Male = 9, Female = 7		

Note. FAAM ADL = Foot and Ankle Ability Measure Activities of Daily Living; CAIT = Cumberland Ankle Instability Tool. Values are mean (*M*) and standard deviation (*SD*) unless otherwise indicated.

Procedures

Participants provided signed informed consent on documents approved by the local Institutional Review Board. Subsequently, the participant's maximal jump height was measured from a standing position using a Vertec jump trainer (Sports Import, Columbus, OH). The measurement was taken to determine the 50% maximal jump height, ensuring consistency in each jump during the test session (Ross & Guskiewicz, 2004). Maximum jump height was assessed without the SV goggles. Also, participants were asked which leg they use to kick a ball to determine the dominant leg and were asked to only land with the dominant leg.

The level of occlusion can be adjusted to 8 levels, with a constant 100ms interval of transparency and a 67ms to 900ms interval of opacity. A previous study reported that visual occlusion lasting longer than 250 ms resulted in a complete loss of vision, impairing the ability to perform dynamic activities (D. R. Grooms et al., 2018). Therefore, three conditions were selected to provide sufficient visual perturbation while ensuring the task could be completed without significantly increasing the risk of injury: no-occlusion (NO), low-occlusion (LO: 100ms interval of opacity and transparency; level 2), and high-occlusion (HO: 233ms interval of opacity and then a 100ms interval of transparency; level 4). Then, participants underwent two practice jump-landing trials while wearing SV goggles (Senaptec Inc, Beaverton, OR) under three conditions. These practice trials aimed to identify any potential risk factors during the study. During these trials, participants were instructed to perform a double-legged jump and land on a single leg. Additionally, participants were instructed to focus on an arbitrary spot on the wall in front of them throughout the trial.

During data collection, the participant stood 70cm from the force platform in a double-limb-supported position (Ross & Guskiewicz, 2004). Visual conditions were applied at the start and turned off after each trial. The level of visual occlusion was applied in the order of LO, NO, and HO. The participant initiated the trial by jumping to their targeted height of 50% of the maximal vertical jump, reaching for the Vertec trainer target adjusted to that height, and landing on the force platform. After landing, the participants were asked to maintain balance as quickly as possible on their dominant leg for at least 10 seconds.

Nine recorded trials were obtained for each data collection, three per condition. Participants were asked to take a one-minute break after every three trials to reduce inconsistency due to fatigue. Successful trial was defined as 1) reaching the 50% max jump height by touching the tartget marker, 2) maintaining the base of the foot on the force plate without moving or sliding for 10 seconds immediately after landing, 3) no contact with the ground by the uninvolved limb, and 4) no supporting the wieght of the uninvolved limb on the involved limb after landing. A failed trials were noted for each condition and discarded and repeated after adequate rest.

Outcome Measure

The recorded ground reaction force (GRF) data were collected using the AccuPower force plate (AMTI Inc, Watertown, MA) at a sampling rate of 1000Hz. The analysis of GRF data followed the calculation method for postural stability indices described by Wikstrom et al. (2005). These postural stability indices measure the stability and dynamic balance during the landing task by computing the stability indices (SI) from anterior-posterior (AP), medial-lateral (ML), and vertical (V) directions along with a composite measure of dynamic postural stability index (DPSI). APSI and MLSI represent the fluctuations around a 0 point along the AP and ML axes of the force plate, respectively. VSI represents the fluctuation around the vertical axes of the force plate after normalization by the participant's body weight. All four stability indices were calculated for each trial and condition.

Statistical Analysis

Statistical analysis was conducted using the Statistical Package for Social Sciences software (IBM Corp. Released 2016. IBM SPSS Statistics for Windows, Version 24.0 Armonk, NY: IBM Corp.). The independent variable was the level of visual occlusion (NO, LO, and HO). In contrast, the dependent variables comprised the postural stability indices (APSI, MLSI, VSI, and DPSI)—a one-way repeated-measures ANOVA was employed to assess the effect of visual occlusion on jump landing performance. The previous study (Kim et al., 2017) reported a large range of Cohen's d effect sizes from 1.05 to 2.61 between EO and SV conditions, which indicates a significant effect of SV during balance. Applying the average effect size of 0.6 to the calculation performed utilizing the G*power at an alpha of 0.05, and a beta of 0.95 showed that to meet the scientific objectives of this research,

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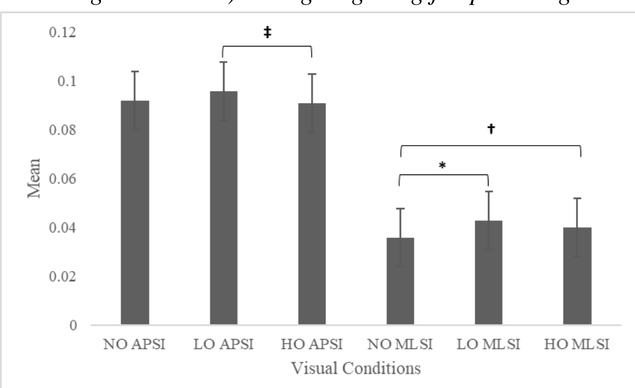
this study requires approximately 10 participants. The significance level was set at p ≤ 0.05, and Hedges' g effect size was interpreted as follows: 0.2 as a "small" effect size, 0.5 as a "medium" effect size, and 0.8 as a "large" effect size for the analysis.

Results

The results in Figures 1 and 2 represent the mean score of the postural stability indices for all participants during NO, LO, and HO conditions. As indicated in the figures, there were significant differences in postural stability indices as the level of visual occlusion progressed from NO to HO conditions. In a multivariate analysis, significant differences were observed in the within-subjects effect on the postural stability based on the levels of visual occlusion, $F(8,54)=2.428$, $p = 0.026$. The MLSI ($F(2,30)=5.474$, $p = 0.009$) was the only value to demonstrate a significant main effect on vision (Table 2). The LO condition demonstrated worse MLSI than the NO condition ($p = 0.004$) regarding postural stability indices (Table 3). Also, the largest effect size was observed for the NO-LO comparison in MLSI, with a value of 0.81 (0.09, 1.53) (Table 4).

Figure 1: *Mean values of APSI and MLSI under visual occlusion conditions (NO = no-occlusion, LO = low-occlusion, HO = high-occlusion) during single-leg jump landing.*

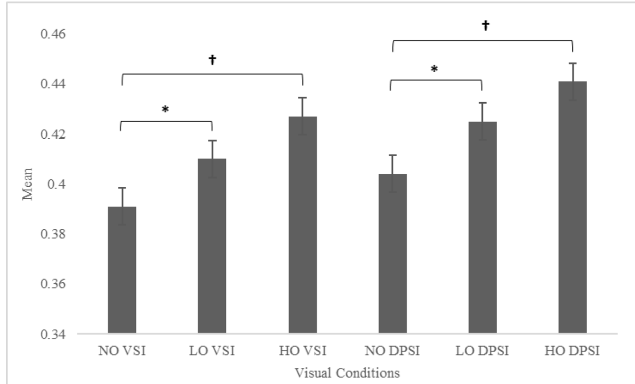


Note. Significant differences in APSI were observed between LO and HO, while significant differences in MLSI were found between NO and LO and between NO and HO. * indicates a significant pairwise difference from NO to LO; † indicates a significant pairwise difference from NO to HO; ‡ indicates a significant pairwise difference from LO to HO.

Discussion

Our study aimed to assess the effect of progressive visual occlusion on postural stability during a jump-landing task. Our findings indicate a significant effect of visual occlusion levels (NO, LO, and HO) on postural stability indices when vision was occluded during the jump-landing task. The hypothesis that the postural stability indices would demonstrate

Figure 2: *Mean values of VSI and DPSI on visual occlusion (NO, LO, HO) during jump landing.*



Note. Significant differences in VSI and DPSI were found between NO and LO and between NO and HO. * Indicates a significant pairwise difference from NO to LO; † Indicates a significant pairwise difference from NO to HO.

Table 2: *Repeated-Measures ANOVA Results for Postural Stability Indices*

Measure	*F*	*p*	Observed Power
APSI	1.368	0.269	0.241
MLSI	5.474	**0.009**	0.811
VSI	3.058	0.081	0.460
DPSI	3.106	0.078	0.465

Note. APSI = Anterior-Posterior Stability Index; MLSI = Medial-Lateral Stability Index; VSI = Vertical Stability Index; DPSI = Dynamic Postural Stability Index. Bolded p value indicates statistical significance at $p \leq 0.05$.

increased values with progressive visual occlusion during the jump landing task was only partially supported. Our main finding demonstrated significantly worse MLSI values during jump landing, specifically between the NO and LO conditions ($p = 0.004$). The effect of systematic visual occlusion achieved by the SV and the subsequent decline in balance quality aligns with findings from previous studies (Kim et al., 2017; VanDeMark et al., 2021). The compromised balance post-landing can be attributed not only to the significant role of the visual system on postural stability (Redfern et al., 2001) but also to the decreased ability to perceive vertical cues during the landing phase. Previous research suggests that visual cues aligned with gravity enhance postural control (Balestrucci et al., 2017; Goodworth & Peterka, 2012; Peterka, 2002). Goodworth and Peterka (2012) reported increased reliance on visual cues for feedback aligned with the earth's vertical to maintain lower extremity balance. Thus, it is possible that the conditions created by the SV reduced the visual system's capacity to detect vertical cues and maintain balance.

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Table 3: *Descriptive Statistics for Postural Stability Indices by Visual Condition*

Measure	NO	LO	HO
APSI	0.092±0.016	0.096±0.021	0.091±0.024‡
MLSI*	0.036±0.007	0.043±0.010†	0.040±0.012
VSI	0.391±0.130	0.410±0.128†	0.427±0.173‡
DPSI	0.404±0.128	0.425±0.126†	0.441±0.170‡

Note. NO = no-occlusion; LO = low-occlusion; HO = high-occlusion. APSI = Anterior-Posterior Stability Index; MLSI = Medial-Lateral Stability Index; VSI = Vertical Stability Index; DPSI = Dynamic Postural Stability Index. Values are mean ± standard deviation. * indicates a significant univariate effect of vision ($p \le 0.05$). † indicates a significant effect on vision compared with the NO condition ($p \le 0.05$). ‡ indicates a significant effect on vision compared to LO condition ($p \le 0.05$).

The findings are interesting, as MLSI was the only direction demonstrating a significant difference. Previous research has indicated that single-leg jump landing can increase hip adduction, hip internal rotation, and knee internal rotation, contributing to greater frontal plane instability (Taylor et al., 2016). The mechanical characteristics of the ankle and potential slight lateral deviation in the jump path might have specifically influenced the MLSI value (Wikstrom et al., 2008). Additionally, in this forward jump-landing task, where horizontal distance and jump height were consistent for each visual condition, the similarity in the AP jump direction and subsequent post-landing recovery of balance may stem from preplanned motor strategies in the AP direction, aimed at minimizing propulsion force and maintain balance. Conversely, stability in the ML direction may have needed to be addressed due to the perceived lesser threat to task completion and potentially greater variability in each jump landing trial. The increased difficulty in maintaining balance might have elicited the hip strategy for postural equilibrium, generating horizontal force against the surface and causing a greater ML motion (Horak & Nashner, 1986). However, further investigation, including kinematic variables, is warranted to better comprehend the altered motor patterns during dynamic landing under SV conditions.

The large effect size observed from the transition between NO to LO conditions may be attributed to asymmetric sensory reweighting during sudden sensory perturbation (Jeka et al., 2008). The authors reported a more rapid reweighting of sensory cues by participants to maintain postural stability from low-to-high visual perturbation compared to the high-to-low condition. The authors interpreted this as participants recognizing the sudden alteration in sensory information as a greater threat to instability, resulting in an asymmetrical dynamic reweighting of sensory cues to maintain stability. For example, encountering an unexpected loss of visual input, such as changes in ambient brightness when entering a tunnel, prompts the brain to perceive this sudden change as a heightened threat to stability and swiftly reweight sensory inputs to maintain postural stability, in contrast to emerging from the tunnel and regaining visual acuity. This mechanism might explain the substantial differences observed in our study between NO and LO conditions, which are attributable to increased visual perturbation. However, asymmetric sensory reweighting does not explain our result of decreased values in the HO condition compared to the LO condition. In summary, the significant difference between NO and LO conditions may stem from our natural reaction of recognizing greater threats in LO conditions compared to NO conditions, leading to rapid asymmetric sensory reweighting.

We considered two plausible explanations for the occurrences during the HO condition: 1) forced sensory reweighting might have resulted in less disruption in postural stability, enabling adaptation to environmental constraints, and 2) a potentially induced practice effect due to the testing protocol might have contributed to the improvement in balance.

Forced Sensory Reweighting

The forced sensory reweighting could explain the stability during the HO condition due to the excessive perturbation applied to the visual system. In prior studies, an increase in perturbation amplitude to sensory input was perceived as less reliable information about self-motion (Logan et al., 2014; Peterka, 2002). Consequently, the postural control system tends to down-weight its influence to maintain stability (Logan et al., 2014; Peterka, 2002). This concept can explain our findings of increased stability in the HO condition compared to the LO condition. SV is suggested to force adaptive sensory reweighting strategies by engaging proprioceptive or vestibular functions to compensate for decreased visual feedback (D. Grooms et al., 2015; Kim et al., 2017). The substantially increased perturbation amplitude during the HO condition may have forced the reweighting of sensory input toward proprioceptive and vestibular functions, allowing adaptation to overcome environmental constraints.

However, the LO condition might have needed to provide a sufficient perturbation level, leading participants to continuously focus on visual input rather than adjusting the weight of sensory information to other modalities, resulting in a worse balance. Thus, the LO condition could introduce additional challenges to the visual system during a dynamic balance training regimen. If the HO condition with SV can induce forced sensory reweighting, extended training with SV might reduce the reliance on visual information and enhance the utilization of lost proprioceptive function during dynamic postural control. However, further investigation is warranted to explore the dynamics of forced sensory reweighting and the impact of prolonged training with SV on improved balance.

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Table 4: *Hedges' g Effect Size Calculations for Pairwise Comparisons*

Condition	Correlation	Hedges' g	CI for Effect Size	
			Lower Bound	Upper Bound
NO-LO APSI	0.89	0.32	-0.4	1.02
NO-HO APSI	0.84	-0.11	-0.8	0.59
LO-HO APSI	0.94	-0.51	-1.2	0.2
NO-LO MLSI	0.62	0.81	0.09	1.53
NO-HO MLSI	0.66	0.50	-0.2	1.2
LO-HO MLSI	0.71	-0.28	-1	0.42
NO-LO VSI	0.97	0.52	-0.2	1.22
NO-HO VSI	0.94	0.63	-0.1	1.34
LO-HO VSI	0.93	0.28	-0.4	0.98
NO-LO DPSI	0.97	0.55	-0.2	1.26
NO-HO DPSI	0.94	0.64	-0.1	1.35
LO-HO DPSI	0.93	0.27	-0.4	0.96

Note. NO = no-occlusion; LO = low-occlusion; HO = high-occlusion. APSI = Anterior-Posterior Stability Index; MLSI = Medial-Lateral Stability Index; VSI = Vertical Stability Index; DPSI = Dynamic Postural Stability Index. CI = Confidence Interval.

Testing Protocol

Our testing protocol may have induced a practice effect, improving balance during the HO condition trials. Visual occlusion levels were ordered during data collection as LO, NO, and HO. We recorded error trials for each condition per participant (total count: LO:44; NO:12; HO:28; mean: 2.75, 0.75, and 1.75, respectively), observing a higher number of error trials during the LO condition, which were excluded. Participants, anecdotally, mentioned that NO condition trials were notably easier after LO condition trials. This suggests that participants adjusted to intermittent visual disruption during LO condition trials, potentially resulting in improved balance during subsequent NO and HO trials. Multiple familiarization trials and prior experience with the LO condition experiences contributed to a practice effect, enhancing performance during the HO condition. Alternatively, this could indicate forced sensory reweighting from visual input to proprioceptive and/or vestibular functions to maintain postural stability (Logan et al., 2014).

Based on our results, the SV can introduce novel challenges to the sensorimotor system, especially under LO conditions. SV may serve as a training or sensory reweighting assessment tool in healthy individuals (Kim et al., 2020). The utilization of SV might overcome the current limitations of EO/EC methods by enabling dynamic movements while still providing challenges similar to the EC conditions (Kim et al., 2017, 2020), offering a closer representation of the real-world environment. However, future studies should investigate whether SV promotes sensory reweighting ability and reduce visual dependency. Additionally, exploring the effects of SV on individuals with musculoskeletal injuries during dynamic tasks, such as those with anterior cruciate ligament injuries or chronic ankle instability, requires further examination.

We must acknowledge several limitations, including 1) the absence of a comparison group, 2) the lack of kinematic and extensive kinetic data, and 3) the non-randomization order of visual occlusion applied to the participants. Future investigations aiming to compare the effect of SV on sensory reweighting should consider recruiting patient groups, such as chronic ankle instability or anterior crucial ligament reconstruction, to detect group differences and assess the potential application of SV in rehabilitation. Additionally, for a more comprehensive understanding of balance strategies and muscular output during balance maintenance, kinematic and/or further kinetic data are recommended for future studies. Lastly, the testing order was arbitrarily chosen based on consistent results in previous studies (Kim et al., 2017; VanDeMark et al., 2021), regardless of randomization. To mitigate the potential practice effect, randomizing the order of visual occlusion applied to participants would benefit future investigations.

Conclusions

This study found significant differences in postural sway during the jump-landing task under progressive visual occlusion by SV goggles. Specifically, significant differences were observed in MLSI values during the transition from NO to LO condition. The LO condition may provide greater perturbation during dynamic postural control in uninjured individuals. Therefore, further studies should examine the effect of utilizing the LO condition during jump landing tasks as a training or rehabilitation method to identify its potential effectiveness.

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