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Head Stabilization during Walking in People with Unilateral Vestibular Disorder

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ABSTRACT

Background
Head stabilization plays a crucial role in locomotive tasks such as walking, but it can be impaired in individuals with unilateral vestibular disorder (UVD). This study aimed to evaluate the impact of UVD, environmental lighting, and gait speed on head stabilization during walking. The hypothesis was that people with UVD (PwUVD) restrict their head movements while walking, and faster walking speeds and darker environments would worsen head stabilization.

Methods
Eight PwUVD and nine healthy individuals were asked to walk along a 6-meter walkway at their preferred pace, as well as at 25% slower and 25% faster paces, either in normal or in dark environments. Motion analysis was utilized to measure head movement and calculate variability, range, and approximate entropy of the head kinematic data.

Results
Healthy individuals exhibited higher variability of head acceleration compared to patients in the forward (p=.020), lateral (p=.042), and vertical (p=.001) directions. The lighting conditions had a significant impact on the variability of the vertical component of head acceleration (p=.009). Gait speed also significantly influenced the variability of head acceleration in all directions (p<.001). Furthermore, the range of head acceleration was greater in healthy individuals than in patients, particularly in the forward (p=.006) and vertical (p<.001) directions. PwUVD exhibited significantly higher approximate entropy of head displacement and velocity (p<.033). Conclusion.

Conclusion
The findings suggest that head stabilization serves as a compensatory mechanism in PwUVD, particularly at higher gait speeds. However, walking in a dark environment limited the effectiveness of this strategy.

Keywords: Unilateral Vestibular Disorder, Head Stabilization, Gait, Vision, Kinematics

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1- Introduction

Unilateral vestibular deficit (UVD) has a negative impact on dynamic balance during postural control and walking [1,2]. The vestibular system, along with the visual and somatosensory systems, is one of the primary sources of sensory feedback for maintaining posture. When the vestibular system is dysfunctional, there is an increased risk of falls. However, the central nervous system (CNS) can employ compensatory mechanisms to mitigate the detrimental effects of UVD. Two main strategies used by the CNS are the re-weighting of the role of vision and somatosensory systems [3,4], and restricting head movements to a fixed spatial reference of visual feedback [5]. These strategies help reduce the reliance on the impaired side of the vestibular system for maintaining balance.

Research has demonstrated the impact of UVD on the manifestation of gait abnormalities. In a very recent study, Boutabla et al. (2025) showed that gait impairments are common in patients with bilateral vestibulopathy and chronic unilateral vestibulopathy, affecting their quality of life and increasing fall risk [6]. Liu et al. (2017) also demonstrated that UVD leads to increased posture variability and gait instability, with kinematic parameters showing potential for quantifying the severity of vestibular functional asymmetry [7]. Study of Chae et al. (2020) indicated gait function and mediolateral stability improvement after acute unilateral vestibular neuritis, suggesting rehabilitation intervention should continue after symptom resolution [8]. Stabilizing the head is crucial for people with UVD as it enables them to maintain a stable gaze during walking. The loss of vestibular function impairs the vestibulo-ocular reflex, resulting in symptoms such as dizziness, oscillopsia, and blurring [9,10]. The lighting conditions and walking speed can also play a significant role in head stabilization for patients with UVD. Individuals with UVD have more difficulty controlling head and trunk accelerations during gait without visual sensory information than healthy individuals [11]. Pozzo et al. (1990) found that the movement of the head in healthy individuals remained unchanged after darkening the walking environment. However, they observed that people with bilateral vestibular deficit had faster head movements in a darkened environment [12]. Individuals with UVD may also experience increased sensitivity to light, particularly in low or uneven lighting conditions [13]. On the other hand, Mijovic et al. (2014) demonstrated no difference in head velocity during walking between people with vestibular disorders and healthy individuals [14]. Additionally, studies have shown that individuals with UVD or other vestibular disorders exhibit slower gait speeds and take shorter steps compared to their healthy counterparts [15,16].

The researchers conducting this study found that there was no agreement among experts regarding the impact of vestibular deficits, environmental lighting, and walking speed on the stabilization of the head while walking. Therefore, the objective of this study was to evaluate how UVD, changes in environmental lighting, and variations in gait speed affect the stability of the head during walking. The hypothesis was that individuals with UVD restrict their head movements while walking, and that faster walking speeds and darker environments would worsen head stabilization.

2- Methods

2-1- Participants

In this cross-sectional study conducted between March 2021 and February 2022, a total of eight people with UVD (3 males, 5 females) and nine healthy age-matched individuals (4 males, 5 females) participated. The selection of patients was based on the identification of UVD through video head impulse, vestibular evoked myogenic potentials, and subjective visual vertical tests. In addition to having an age between 20 and 65, a body mass index between 20 and 30, and the ability to walk without assistance, patients were also required to meet other inclusion criteria. These criteria included the absence of musculoskeletal disorders such as arthritis, flat foot, arthroplasty, or any joint pain, as well as the absence of cognitive, psychological, or neurological disorders, metabolic disorders like diabetes, visual disorders like anisocoria, diplopia, binocular vision, and strabismus, and the non-consumption of sleeping or vertigo drugs. The same criteria were applied to the healthy control group, with the exception of having UVD. The study received approval from the university committee for ethics in medical research, and all participants were provided with detailed explanations of the test conditions before signing the informed consent form. This study was also approved by a local ethical committee (IR.MODARES.REC.1399.227).

2-2- Protocols

The study involved a group of participants who were instructed to walk along a 6-meter walkway at their preferred speed. Subsequently, slower and faster walking speeds were determined by calculating a 25% decrease and increase, respectively, from the measured preferred speed. To ensure consistency, an electronic metronome was used to enforce the three different walking speeds in a randomized sequence. Additionally, the impact of environmental lighting was taken into account, with two levels of light intensity: normal lighting at 700 Lux and a darkened setting with a maximum of 125 Lux. Each of the six test conditions (comprising the three speeds and two lighting conditions) was repeated three times to ensure reliability. To prevent any abnormal head movements, a large landscape image measuring 1.5 x 2 meters, devoid of any specific focal point or abstract concept, was affixed to the wall in front of the participants.

2-3- Data Acquisition

The head movements during walking were recorded using the motion analysis system (Vicon Inc., Oxford, UK). The kinematic evaluation focused on the translations of the head segment's local coordinate system origin in relation to that of the torso segment. To establish these coordinate systems, four markers were placed on a headband at the right back, right forehead, left forehead, and left back positions. Additionally, three markers were attached to the right and left acromion processes and the jugular notch. The marker locations on the head and torso segments can be seen in Figure 1.

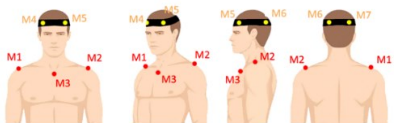

Fig. 1 Marker locations on torso and head of participants. M1: right acromion, M2: left acromion, M3: jugular notch, and using a headband M4: right forward head, M5: left forward head, M6: left backward head, and M7: right backward head.

2-4- Data Analysis

The anatomical kinematics of the head were determined by comparing the displacement, velocity, and acceleration of the head with that of the torso segment. To obtain the head motion data, three consecutive cycles of gait were selected based on the peak values of the lateral head motion signals. In order to make the data comparable between different trials and subjects, an interpolation technique was employed to normalize the data, ranging from 0 to 100% of the three gait cycles (equivalent to 300% in total). Subsequently, the variability, range, and approximate entropy of the head motion data in three spatial directions (forward, lateral, and vertical) were calculated as metrics of head stability. The computational formulas for these metrics have been extensively described in previous studies [17]. To assess the impact of UVD, environmental lighting, and gait speed on the head kinematic metrics, a one-way analysis of variance (ANOVA) was conducted. The statistical tests were performed with a confidence interval of 95%.

3- Results

The demographic data of healthy individuals and those with UVD showed that the age, weight, height, and body mass index are not different between the study groups (see Table 1).

Table 1 Demographic data of participants in healthy and people with UVD

	Healthy (n = 9)	UVD (n = 8)	p-value
Age (year)	36 ± 13	42 ± 13	.354
Height (cm)	168 ± 10	165 ± 9	.513
Weight (kg)	70.5 ± 11.2	70.8 ± 14.6	.976
BMI (kg/m^2)	24.9 ± 4.1	25.6 ± 3.9	.711
DHI score	-	30.0 ± 13.9	-
Diagnosis (year)	-	23.3 ± 7.1	-

Table 2 Metrics related to the displacement of head in forward, lateral, and vertical directions

	Healthy						**UVD**					
	Light			Dark			Light			Dark		
	Slow	Pref.	Fast	Slow	Pref.	Fast	Slow	Pref.	Fast	Slow	Pref.	Fast
Variability												
Forward	4.5 ± 1.6	4.7 ± 1.5	3.7 ± 1.0	3.7 ± 1.4	4.0 ± 1.6	4.5 ± 1.3	3.2 ± 1.0	2.8 ± 0.5	2.7 ± 0.8	3.3 ± 1.4	2.7 ± 1.3	2.7 ± 1.4
Lateral	5.4 ± 3.0	4.6 ± 1.9	4.0 ± 2.3	5.6 ± 2.7	3.9 ± 2.3	4.0 ± 2.8	4.4 ± 2.7	3.8 ± 1.9	3.4 ± 2.0	4.9 ± 2.5	3.6 ± 1.9	3.7 ± 2.7
Vertical	0.9 ± 0.4	1.2 ± 0.3	1.1 ± 0.4	1.0 ± 0.2	1.0 ± 0.3	1.3 ± 0.5	0.7 ± 0.2	0.8 ± 0.2	1.0 ± 0.4	0.8 ± 0.3	0.9 ± 0.3	0.8 ± 0.3
Range												
Forward	19.8 ± 8.4	18.8 ± 5.9	13.0 ± 3.3	14.9 ± 5.1	15.2 ± 5.7	17.1 ± 10.3	12.4 ± 4.9	11.1 ± 2.3	13.0 ± 9.4	13.6 ± 5.3	10.6 ± 4.4	11.3 ± 5.9
Lateral	20.3 ± 11.1	16.3 ± 6.3	14.1 ± 6.7	20.6 ± 10.7	14.2 ± 6.7	14.2 ± 8.7	17.4 ± 8.7	14.2 ± 6.2	12.7 ± 6.9	18.9 ± 10.2	12.9 ± 6.4	12.9 ± 8.9
Vertical	4.0 ± 1.5	4.3 ± 0.7	4.4 ± 1.5	4.0 ± 0.6	4.2 ± 1.5	4.9 ± 2.1	3.6 ± 1.5	3.6 ± 0.8	5.0 ± 3.5	3.4 ± 1.3	3.5 ± 1.3	3.6 ± 1.5
Entropy x 10^3												
Forward	40 ± 24	37 ± 35	53 ± 30	50 ± 42	49 ± 45	67 ± 38	67 ± 32	74 ± 30	78 ± 33	63 ± 25	75 ± 63	99 ± 51
Lateral	38 ± 42	40 ± 38	44 ± 40	28 ± 39	50 ± 47	59 ± 52	54 ± 36	56 ± 43	73 ± 43	45 ± 36	43 ± 42	80 ± 60
Vertical	242 ± 72	202 ± 58	175 ± 59	217 ± 91	205 ± 68	202 ± 62	305 ± 68	280 ± 67	225 ± 78	285 ± 58	232 ± 81	264 ± 56

Table 3 Metrics related to the velocities of head in forward, lateral, and vertical directions

	Healthy						**UVD**					
	Light			Dark			Light			Light		
	Slow	Pref.	Fast	Slow	Pref.	Fast	Slow	Pref.	Fast	Slow	Pref.	Fast
Variability												
Forward	23.0 ± 6.8	36.1 ± 14.3	*Forward*	23.0 ± 6.8	36.1 ± 14.3	*Forward*	23.0 ± 6.8	36.1 ± 14.3	*Forward*	23.0 ± 6.8	36.1 ± 14.3	*Forward*
Lateral	20.4 ± 8.1	30.5 ± 10.1	*Lateral*	20.4 ± 8.1	30.5 ± 10.1	*Lateral*	20.4 ± 8.1	30.5 ± 10.1	*Lateral*	20.4 ± 8.1	30.5 ± 10.1	*Lateral*
Vertical	11.8 ± 2.1	14.6 ± 1.8	*Vertical*	11.8 ± 2.1	14.6 ± 1.8	*Vertical*	11.8 ± 2.1	14.6 ± 1.8	*Vertical*	11.8 ± 2.1	14.6 ± 1.8	*Vertical*
Range												
Forward	112.4 ± 51.3	238.9 ± 321.7	*Forward*	112.4 ± 51.3	238.9 ± 321.7	*Forward*	112.4 ± 51.3	238.9 ± 321.7	*Forward*	112.4 ± 51.3	238.9 ± 321.7	*Forward*
Lateral	91.6 ± 60.4	125.9 ± 47.1	*Lateral*	91.6 ± 60.4	125.9 ± 47.1	*Lateral*	91.6 ± 60.4	125.9 ± 47.1	*Lateral*	91.6 ± 60.4	125.9 ± 47.1	*Lateral*
Vertical	65.8 ± 12.6	91.0 ± 36.3	*Vertical*	65.8 ± 12.6	91.0 ± 36.3	*Vertical*	65.8 ± 12.6	91.0 ± 36.3	*Vertical*	65.8 ± 12.6	91.0 ± 36.3	*Vertical*
Entropy x 10^3												
Forward	4 ± 2	5 ± 2	*Forward*	4 ± 2	5 ± 2	*Forward*	4 ± 2	5 ± 2	*Forward*	4 ± 2	5 ± 2	*Forward*
Lateral	4 ± 2	5 ± 2	*Lateral*	4 ± 2	5 ± 2	*Lateral*	4 ± 2	5 ± 2	*Lateral*	4 ± 2	5 ± 2	*Lateral*
Vertical	4 ± 2	5 ± 2	*Vertical*	4 ± 2	5 ± 2	*Vertical*	4 ± 2	5 ± 2	*Vertical*	4 ± 2	5 ± 2	*Vertical*

Table 4 Metrics related to the acceleration of head in forward, lateral, and vertical directions

	Healthy						**UVD**					
	Light			Dark				Light		Light		
	Slow	Pref.	Fast	Slow	Pref.	Fast	Slow	Pref.	Fast	Slow	Pref.	Fast
Variability												
Forward	0.08 ± 0.02	0.12 ± 0.05	*Forward*	0.08 ± 0.02	0.12 ± 0.05	*Forward*	0.08 ± 0.02	0.12 ± 0.05	*Forward*	0.08 ± 0.02	0.12 ± 0.05	*Forward*
Lateral	0.09 ± 0.03	0.11 ± 0.04	*Lateral*	0.09 ± 0.03	0.11 ± 0.04	*Lateral*	0.09 ± 0.03	0.11 ± 0.04	*Lateral*	0.09 ± 0.03	0.11 ± 0.04	*Lateral*
Vertical	0.10 ± 0.05	0.14 ± 0.04	*Vertical*	0.10 ± 0.05	0.14 ± 0.04	*Vertical*	0.10 ± 0.05	0.14 ± 0.04	*Vertical*	0.10 ± 0.05	0.14 ± 0.04	*Vertical*
Range												
Forward	0.39 ± 0.07	0.64 ± 0.32	*Forward*	0.39 ± 0.07	0.64 ± 0.32	*Forward*	0.39 ± 0.07	0.64 ± 0.32	*Forward*	0.39 ± 0.07	0.64 ± 0.32	*Forward*
Lateral	0.44 ± 0.17	0.56 ± 0.16	*Lateral*	0.44 ± 0.17	0.56 ± 0.16	*Lateral*	0.44 ± 0.17	0.56 ± 0.16	*Lateral*	0.44 ± 0.17	0.56 ± 0.16	*Lateral*
Vertical	0.50 ± 0.22	0.73 ± 0.21	*Vertical*	0.50 ± 0.22	0.73 ± 0.21	*Vertical*	0.50 ± 0.22	0.73 ± 0.21	*Vertical*	0.50 ± 0.22	0.73 ± 0.21	*Vertical*
Entropy x 10^3												
Forward	442 ± 120	573 ± 106	*Forward*	442 ± 120	573 ± 106	*Forward*	442 ± 120	573 ± 106	*Forward*	442 ± 120	573 ± 106	*Forward*
Lateral	443 ± 87	479 ± 76	*Lateral*	443 ± 87	479 ± 76	*Lateral*	443 ± 87	479 ± 76	*Lateral*	443 ± 87	479 ± 76	*Lateral*
Vertical	489 ± 51	551 ± 94	*Vertical*	489 ± 51	551 ± 94	*Vertical*	489 ± 51	551 ± 94	*Vertical*	489 ± 51	551 ± 94	*Vertical*

Table 5 Results of statistical analyses

	Displacement			Velocity			Acceleration		
	Forward	Lateral	Vertical	Forward	Lateral	Vertical	Forward	Lateral	Vertical
Variability									
Group	.139	.625	.890	.773	.827	.890	**.020**	**.042**	**.001**
Environment	.308	.396	.265	.105	.248	.265	.195	.174	**.009**
Gait Speed	.706	.253	.154	.851	.110	.154	**< .001**	**< .001**	**< .001**
Range									
Group	.208	.793	.231	.258	.407	.231	**.006**	.080	**< .001**
Environment	.286	.212	.830	.284	.358	.830	.258	.314	.054
Gait Speed	.580	.121	.954	.847	.424	.954	**< .001**	**< .001**	**< .001**
Entropy									
Group	**< .001**	**.032**	**.007**	**.012**	.361	**.007**	.637	**.008**	.512
Environment	**.033**	.406	.758	.436	.488	.758	.126	.502	.579
Gait Speed	**.009**	.065	.934	.794	.953	.934	**.003**	**.015**	.067

No meaningful correlation was observed between the DHI score and diagnosis of disease in patients with UVD ($r^2 = 0.307$, $p = 0.154$). The metrics related to the displacement of the head and its first and second time derivatives i.e. velocity and acceleration showed different behaviors during walking between groups, visual conditions, and walking speed (see Tables 2 through 4).

3-1- Displacement Measures

No significant Group x Environment x Gait Speed interaction effect was found for variability, range, and approximate entropy of the head displacement in all directions ($p > .05$). P-value of the forward range of head displacement

Variability and range of the head displacement and velocity was not different between healthy and patients with UVD. Elimination of the environment lights also had no effect on the variability and range of the head displacement and velocity. Walking with three different speeds caused no change in displacement and velocity of the head of the participants. Variability of the head acceleration, on the other hand, was higher in healthy individuals rather than patients in forward ($F = 5.6$, $p = .020$, $\eta^2 = 5.3\%$), lateral ($F = 4.3$, $p = .042$, $\eta^2 = 3.9\%$), and vertical ($F = 11.1$, $p = .001$, $\eta^2 = 10.1\%$) directions. Lightening of the environment only had a significant effect on variability of vertical component of the head acceleration ($F = 7.2$, $p = .009$, $\eta^2 = 6.8\%$), but gait speed significantly affected forward ($F = 15.6$, $p < .001$, $\eta^2 = 23.9\%$), lateral ($F = 11.3$, $p < .001$, $\eta^2 = 18.3\%$), and vertical ($F = 10.0$, $p < .001$, $\eta^2 = 16.9\%$) head acceleration variability. The range of head acceleration was not different between healthy and patients in the lateral direction, but forward ($F = 7.9$, $p = .006$, $\eta^2 = 7.3\%$) and vertical ($F = 16.4$, $p < .001$, $\eta^2 = 14.1\%$) accelerations were significantly greater in the healthy individuals. Environment lightening had no effect on the range of head acceleration during walking. Nevertheless, slower or faster gait speed than the preferred speed significantly reduced head acceleration range in all directions ($F > 10.7$, $p < .001$, $\eta^2 > 17.8\%$).

Approximate entropy demonstrated different trends against the kinematics of the head. Entropy the head displacement was significantly greater in patients with UVD than healthy people. This difference was observed in forward ($F = 13.8$, $p < .001$, $\eta^2 = 11.9\%$), lateral ($F = 4.7$, $p = .032$, $\eta^2 = 4.5\%$), and vertical ($F = 18.5$, $p = .007$, $\eta^2 = 15.6\%$) directions. Entropy of the head velocity in forward ($F = 6.5$, $p = .012$, $\eta^2 = 6.1\%$) and vertical ($F = 7.7$, $p = .007$, $\eta^2 = 7.0\%$) components was also significantly greater in patient group, but the head lateral velocity had similar approximate entropy in comparison to the healthy participants. Entropy of the forward head displacement has been significantly increased by elimination of the environment lightening ($F = 4.7$, $p = .033$, $\eta^2 = 4.2\%$) and by 25% enhancement of the gait speed ($F = 4.9$, $p = .009$, $\eta^2 = 8.9\%$). The main effects of the group, environment, and gait speed have been gathered in Table 2 for all kinematic outcomes.

4- Discussion

The aim of this research was to examine head stability during walking in individuals with UVD compared to healthy age-matched controls, while assessing the effects of environmental lighting and walking speed on head movement.

4-1- Demographic and Functional Correlations

No significant differences were observed in age, weight, height, or BMI between groups, minimizing confounding effects. Notably, the Dizziness Handicap Inventory (DHI) score did not correlate with UVD diagnosis, though higher scores reflected worse symptoms. Disease duration, however, did not predict symptom severity. This aligns with prior work showing that DHI scores only correlate with functional impairment (e.g., Dynamic Gait Index) when exceeding 60 [18], a threshold not met in our cohort. This discrepancy underscores the complex relationship between self-reported disability and objective gait dysfunction in UVD, which may depend on task demands and compensation mechanisms [6-8]. Mijovic et al. similarly found no link between perceived dizziness and daily task performance [14], while Sprenger et al. observed that postural fluctuations worsened with vestibular severity but not disease duration [19].

4-2- Head Stabilization Strategies in UVD

Our findings indicate that UVD patients actively stabilize their heads during walking, particularly during low-effort tasks. This aligns with broader gait adaptations in UVD, such as slower speeds, shorter steps, and wider strides—strategies thought to reduce instability [6-8]. While Mijovic et al. reported slower task completion in UVD, head movements were not consistently slower, suggesting prioritization of stability over speed [14]. Zobeiri et al. further demonstrated reduced high-frequency head movements during speed transitions, consistent with our observation of limited head motion during less demanding tasks [20]. Such stabilization may compensate for impaired vestibulo-ocular reflexes, minimizing retinal slip [5,21] and leveraging visual cues to offset vestibular deficits [11,22]. However, literature remains conflicted: some studies report increased head/trunk variability in UVD [23], while others note reduced stabilization [24,25]. These discrepancies may reflect heterogeneity in patient adaptation or task-specific demands.

4-3- Lighting and Sensory Compensation

Environmental lighting significantly influenced vertical head acceleration, with greater irregularity in forward displacement under dark conditions. This mirrors findings that UVD patients rely heavily on visual input, as gait stability and head control deteriorate without it [11,22]. Roberts et al. showed heightened sensitivity to horizontal visual cues in vestibular disorders [26], while Pozzo et al. noted darkness-induced reductions in sagittal head motion in healthy individuals but increases in vestibular patients [12,27]. Sprenger et al. attributed this to otolith dysfunction, prompting backward head shifts in the dark [19]. Our results support the idea that UVD patients depend on multisensory integration, with vision compensating for vestibular loss at higher frequencies [25,28,29].

4-4- Gait Speed and Dynamic Control

Faster walking improved head stabilization in UVD, particularly sagittally. This parallels reports that UVD patients adopt more stable head-trunk coordination at higher speeds, likely to mitigate mediolateral instability [8,20,22]. Herdman et al. found poorer head stabilization in UVD across all speeds, though differences diminished at slower paces [30]. Notably, instrumented gait analyses reveal chronic UVD deficits in stride length and turning velocity [22], suggesting that speed-dependent head stabilization may reflect compensatory neuromuscular adjustments rather than full recovery.

4-5- Nonlinear Kinematics and Entropy

UVD patients exhibited higher approximate entropy in head displacement (all directions) and velocity (forward/vertical), indicating irregular movement patterns. This aligns with studies linking vestibular dysfunction to increased entropy in head/trunk dynamics [31], reflecting unstable sensorimotor control. Despite reduced kinematic variability, elevated entropy suggests the CNS prioritizes head stability via intermittent neck muscle co-contractions. Such strategies may explain why gait variability (e.g., step width, hip roll) and local dynamic stability remain impaired in UVD [6-8]. Future work should investigate neck muscle fatigue to clarify its role in long-term adaptation. Linear metrics (e.g., acceleration) were more sensitive to UVD-related changes than displacement or velocity, while nonlinear entropy captured subtle kinematic irregularities. These findings support the use of wearable sensors and machine learning for objective UVD assessment [7,32], as traditional clinical measures often miss nuanced deficits. Quantifying head stabilization could enhance rehabilitation monitoring, particularly for interventions targeting visual-vestibular integration [11,22,33].

4-6- Limitations

This study had some limitations. The primary constraint was that participant recruitment and experimentation occurred entirely during the COVID-19 pandemic, which restricted the number of eligible volunteers. Adherence to COVID-19 safety protocols also reduced patients' testing time and proximity, making full-body motion analysis unfeasible—only head kinematics were measured. Importantly, expanding the sample size after the pandemic was not possible because COVID-19 itself affects vestibular function [34], and including post-pandemic participants would introduce confounding factors, compromising comparability.

5- Conclusions

This study concluded that:

- People with UVD exhibited a tendency to stabilize their heads during walking, particularly in low-effort tasks, limiting head movements.
- Environmental lighting significantly influenced vertical head acceleration, with greater irregularity in forward head displacement observed in dark conditions.
- Gait speed affected head stabilization, as UVD patients demonstrated improved head control at faster speeds, especially in the sagittal plane.
- Subtle differences in head stabilization between UVD patients and healthy individuals, warranting further investigation, particularly regarding neck muscle fatigue.
- From a technical perspective, head acceleration provides more comprehensive kinematic insights than displacement or velocity.

Ethics Approval:
The content of this manuscript is original, based on the authors' research, and has not been published or submitted elsewhere, either in Iranian or international journals.
Conflict of Interest:
The Authors declare that there is no conflict of interest.

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