A Virtual Reality Four-Square Step Test for Quantifying Dynamic Balance Performance in People with Persistent Postural Perceptual Dizziness

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***Abstract*— Persistent-postural perceptual dizziness (PPPD) is a recently-defined diagnosis of chronic vestibular symptoms, which is exacerbated by exposure to moving objects and self-motion but is typically undetectable by clinical tests. The current work evaluates the feasibility of a novel paradigm for evaluation of dynamic balance within complex visual environments in people with PPPD – the Virtual Reality Four Step Square Test (FSST-VR). The FSST-VR measures spatiotemporal head kinematics while subjects perform the FSST pattern of 8 steps in a predefined sequence in a virtual environment of varying levels of visual complexity. Eight healthy individuals and 3 people diagnosed with PPPD were asked to perform the FSST-VR while spatiotemporal head kinematics and heartrate were measured. Additionally, participants reported their anxiety levels and cybersickness. Results indicated that performance of the FSST-VR is feasible and did not aggravate symptoms for people with PPPD. Descriptive statistics further may suggest that people with PPPD move less smoothly and perform smaller steps in anteroposterior direction, corresponding with the visual stimuli flow in the virtual environment. Data collection is ongoing and may provide further evidence as to dynamic balance in people with PPPD within complex virtual environments that mimic visual load in daily living.**

Keywords—sensory integration, HTC Vive, head-mounted display, visual stimuli, dynamic balance

I. INTRODUCTION

Persistent-postural perceptual dizziness (PPPD) is a common cause of chronic vestibular symptoms [1]. Recently added to the International Statistical Classification of Diseases and Related Health Problems index [2], its diagnostic criteria (Box 1) rely mainly on patient history while laboratory, physical and imaging tests remain normal. To date, no agreed biomarker for PPPD exists, even though functional MRI studies of PPPD do show differences in brain functioning relative to controls [3], [4].

BOX I. PPPD DIAGNOSTIC CRITERIA [5]
A. Dizziness, unsteadiness, or non-spinning vertigo present on most days for at least 3 months. Symptoms: 1. Last for prolonged periods of time but may change in severity. 2. Aren't continuous throughout the whole day. B. Symptoms are exacerbated by: 1. Upright posture 2. Non-specific active or passive motion 3. Moving visual stimuli/complex visual patterns C. The disorder is precipitated by conditions causing vertigo, unsteadiness, dizziness, or balance problems such as vestibular syndromes, other neurologic or medical illnesses, or psychological distress. 1. Acute/episodic precipitants – as they resolve, symptoms appear as in criterion A but may occur intermittently first, consolidating later as persistent symptoms. 2. Chronic syndrome precipitants – symptoms may develop slowly and gradually worsen. D. Significant distress or functional impairment is present E. No other disease/disorder better explains the symptoms

An exacerbating factor of PPPD is exposure to complex full-field visual stimuli, including large or small moving objects, viewed at various distances [5]. In addition, upright self-motion worsens the sense of imbalance in individuals with PPPD [5]–[7] as individuals with chronic dizziness display impaired walking characteristics, specifically when visual input is absent [8]. However, evidence is lacking regarding dynamic balance in people with PPPD in complex visual environments.

Visual stimuli from wide image designs, projections or virtual reality systems, can affect static balance and spatial

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orientation in healthy individuals as well as in individuals with persistent dizziness [9]–[12]. Recently, with advances in virtual reality technology, virtual reality head mounted devices (HMDs) have been adopted for studying individuals with dizziness and balance impairments [11], [13]–[15]. These affordable, portable and easy to use HMDs are suited for measuring head kinematics while controlling visual flow, and generate data that can help characterize posture, movement and dynamic balance in changing, complex virtual environments [16], [17]. This is particularly important for people with PPPD whose symptoms are known to be aggravated by complex visual stimuli [5]. The HTC Vive (HTC Corporation, Taoyuan City, Taiwan) is an accessible HMD that can project semi-realistic immersive visual experiences [18]. Following a short built-in calibration, the Vive can effectively track head position with excellent accuracy and low jitter, using external sensors ("light-houses") placed in opposite room corners, covering a large working area and range [19].

In order to evaluate dynamic balance in people with PPPD, we developed a virtual reality version of a standard tool used for dynamic balance and vestibular assessment – the Four-square step test (FSST) [20], [21]. Originally developed as a measure of dynamic balance for older adults, the FSST measures time for completion of a rapid sequential square-shaped stepping task clockwise and counterclockwise while avoiding stepping on low obstacles (canes). The rapid stepping task requires changes in direction, and challenges motor planning and coordination more than straight-line walking. Indeed, the FSST has been validated for various clinical populations such as people with Parkinson's disease, stroke or vestibular disorders [22]. For people with vestibular disorders, a cutoff of 12 seconds was shown to implicate a balance deficit leading to fall risk [20]. The Four-Square Step Test Virtual Reality (FSST-VR) requires the participant to perform the FSST task, but also enables the introduction of different levels of visual stimulus complexity during task performance - which can provoke symptoms in individuals with PPPD following the diagnostic criteria [5].

Objectives

Using the FSST-VR, our long-term goals are to quantify dynamic balance in individuals with PPPD in various levels of visual complexity, compared with controls. Thus, the aims of the current preliminary study are twofold: (1) to evaluate the feasibility of a virtual reality assessment protocol of dynamic balance (FSST-VR) in individuals with PPPD, and (2) to evaluate spatiotemporal kinematic parameters of FSST-VR in people with PPPD and healthy individuals in different visual complexity conditions. Given the known relationship between PPPD symptoms and complex visual environments, we hypothesized that people with PPPD will modify their FSST movement pattern such that they will make smaller and less smooth movements as the virtual environment becomes more complex. A secondary objective of this study is to evaluate the effect of personal factors (e.g. age, gender and levels of state and trait anxiety) on dynamic balance of people with PPPD. The current work presents preliminary results of an ongoing study.

II. Methods

A. Participants

Participants aged 18-85 are being recruited. Participants in the PPPD group are clinically diagnosed with PPPD according to the ICD-11/Bárány Society diagnostic criteria [5]. These criteria are confirmed via a phone interview. Participants in both groups are required to have independent ambulation and sufficient understanding of Hebrew to sign an informed consent. Exclusion criteria are: a history of drug/alcohol abuse; active neuro-otologic disorders other than PPPD; new medication use or recent change in dosage less than one month prior to participation; pregnancy; neurological conditions affecting balance; musculoskeletal pain affecting gait or standing; impaired cognition; peripheral neuropathy and uncorrected visual impairments. Written informed consent was obtained before study participation. The study was approved by University of Haifa institutional review board.

B. Instruments

FSST-VR: An HTC Vive commercially-available system (HTC Corporation, Taoyuan City, Taiwan) was used for projecting the virtual environment and measuring head kinematics as part of the FSST-VR paradigm. The system was supported by a laptop PC (ASUS GL502VM-i7-7700H, NVIDIA GeForce GTX1070 graphic card and 32GB DRAM DDR4 memory). The virtual environments (programmed in Unity version 5.2.1f; ©Unity Technologies, San Francisco, California) include three levels of visual stimuli (Figure 1):

1) a "simple" visual level, that simulates an empty subway platform environment;

2) a "complex" visual level that includes additional human avatars walking on the platform towards and away from the participant (in anteroposterior direction, speed 2m/s), representing a busier environment;

3) a "complex+" visual level, adding to the previous level additional trains passing by every 16-21 seconds on both sides of the platform (speed random at 10.5m/s-14m/s), representing additional linear visual stimuli, relatively peripheral to the participant.

Within each virtual environment, participants were verbally instructed to perform eight steps within a square (formed by a virtual cross mark on the floor, Figure 1) on the floor of the virtual environment, as fast as they can. Just as instructed in the overground FSST [21], four steps were to be performed in a clockwise direction followed by four counterclockwise steps back to the starting point. Participants were instructed to look straight ahead. Head kinematics weremeasured using the Vive HMD at 90Hz.

C. Additional assessments

Prior to performing the virtual reality version, participants completed a "traditional" FSST (with no HMD). Level of impairment due to dizziness was assessed using the Hebrew version of the Dizziness Handicap Inventory (HDHI) [23] – a reliable adaptation of the original questionnaire widely used among individuals with dizziness.

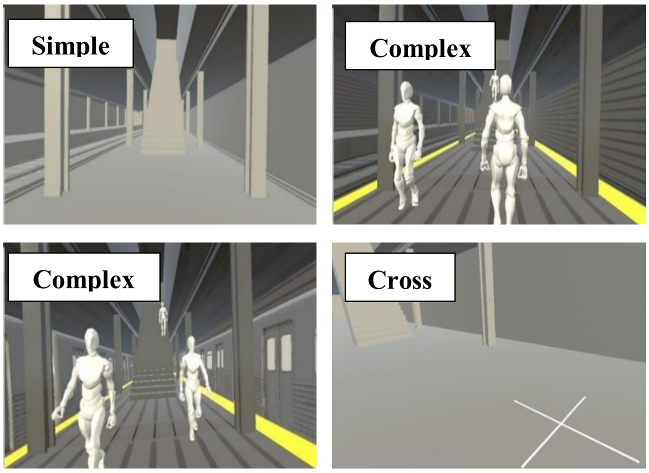

Fig. 1. The three visual stimulus conditions (Simple: an empty subway platform; Complex: People moving in the AP direction; Complex+: people and trains entering and leaving the platform). The bottom right panel depicts the cross on the floor of the platform; participants are required to look forward and not down).

For assessing anxiety levels, we used the State-Trait Anxiety Inventory (STAI). The STAI [24] is a well-established, reliable, valid and widely used questionnaire for measuring state anxiety (temporary fearful arousal reacting to a transient threat) and trait anxiety (a personality characteristic of general inherent reactivity to threat) in individuals with persistent vestibular symptoms [6]. The STAI includes two self-reporting questionnaires (Y1 state; Y2 trait) containing 40 items. In addition, average heart rate was measured during each task to assess level of physiological arousal (H10, Polar, Finland). Surface-electrode sensors were attached to a flexible strap placed anteriorly over the participant's chest, and mean value of heart rate was extracted using software (Polar Flow, Polar, Finland) and averaged for each trial. Finally, the Simulator Sickness Questionnaire (SSQ) [25] was used to assess various physical symptoms due to exposure to virtual environments (i.e., cybersickness). The SSQ contains 16 items rated on a scale between 0 to 3 (max score of 48).

D. Procedure

Participants attended a single session of ~1 hour. After signing an informed consent and filling out a demographic questionnaire and the HDHI questionnaire, a heart rate sensor was strapped over each participant's chest. The participants then completed the STAI questionnaires (Y1+Y2). The experimental session began by performing three trials of the overground FSST (practice + two measurements). Next, the researcher instructed the participants to perform the FSST-VR with the HMD: first, a training trial within the "simple" environment was performed, followed by a measured trial (3 repetitions) and three repetitions of each remaining condition ("complex", "complex+") in a randomized order. Each repetition lasted 5-20 seconds while the participant was guarded by a researcher. Standing or seated rest breaks without the HMD were provided as needed between trials. The participants verbally reported simulator sickness symptoms using the SSQ (before and immediately after the experimental tasks). Finally, at the end of the session, the STAI (Y1) was completed again while seated.

E. Data analysis

Spatiotemporal head kinematics were extracted using custom-written Matlab code (Mathworks, Natick, MA). Tangential velocity of the head was computed as the square root of the sum of squares of velocity in the anteroposterior (AP) and mediolateral (ML) directions. A 20Hz, dual-pass low-pass Butterworth filter was applied to the tangential velocity profile. Time to complete the FSST was identified automatically from tangential velocity profiles; following visual inspection of the trials, onset and offset times of each FSST-VR repetitions were determined as the first and last moment when tangential velocity profile exceeded 10% of peak velocity. Spatial outcome measures from the FSST-VR included range of movement in the Anteroposterior direction (proxy to indicate forward and backward steps) and in Mediolateral direction proxy to indicate side stepping). Finally, a measure of movement smoothness was obtained by counting the number of peaks in the tangential velocity profile for each repetition; for the FSST, maximally smooth movement is expected to contain 8 peaks (one for each step). A larger number of peaks indicates movement which is less smooth and jerkier [26]. Due to the small sample size, only descriptive statistics (median, inter-quartile range (IQR)) were computed for FSST-VR and other assessments.

III. Results

To date, 8 healthy individuals (4 Male; age median (IQR) 44 (35-58)) and 3 individuals with PPPD (2 male; age 33 (28-39)) participated in the study. Participant characteristics are detailed in Table 1. Participants with PPPD reported varying levels of disability due to dizziness in everyday life (HDHI 38 (34-84); for control group – 0.

Scores on the STAI trait subscale were 38.5 (28.5-41.5) for controls and 44 (44-50) for PPPD. The STAI state subscale score prior to the experimental session was 30.5 (28.5-41) and 38 (31-42) for controls and PPPD respectively and following the experiment: 31.5 (25.5-39) and 37 (35-46), i.e. no augmentation of anxiety was noted for people with PPPD. For controls, SSQ increased from 0 to 1.5 (1-11) and for people with PPPD from 1(0-6) to 12 (11-14).

The overground FSST was performed by control participants at a median time of 6.71 (IQR 5.93-7.1), and people in the PPPD group at a median time of 6.52 (6.15-8.0).

An example of performing the FSST-VR by a control participant and a person with PPPD is provided in Figures 2 and 3. In the AP direction, decreased range of motion is demonstrated in the person with PPPD (Figure 2). Furthermore, jerkier movements are demonstrated by an increased number of peaks (Figure 3, A vs. B) and an increasing heartrate pattern throughout the trial (Figure 3, C vs. D).

TABLE I. SUBJECT CHARACTERISTICS AND FSST-VR PERFORMANCE FOR CONTROLS AND PEOPLE WITH PPPD, POOLED ACROSS CONDITIONS OF VISUAL COMPLEXITY. DATA ARE MEDIAN [INTER QUARTILE RANGE].

Outcomes	**Group**		
	Controls (n=8)	***Younger controls (n=5)[a]***	***PPPD (n=3)***
Age	44 [35 58]	37 [33 42]	33 [30.5 36]
Height	170 [160.5 176.5]	173 [160 175]	176 [167 176]
Weight (kg)	70.5 [63 73.5]	66 [60 72]	74 [61.5 86]
FSST-VR			
Time (s)	8.15 [7.43 9.10]	7.45 [7.42 8.04]	8.02 [6.85 8.46]
Number of peaks (N)	10.33 [9.72 11.89]	9.78 [9.78 10.89]	10.89 [10.44 13.5]
Anteroposterior ROM (m)	0.41 [0.4 0.53]	0.4 [0.4 0.43]	0.3 [0.28 0.35]
Mediolateral ROM (m)	0.33 [0.3 0.36]	0.34 [0.31 0.35]	0.3 [0.24 0.34]
Heart rate (BPM)	90.96 [82.93 102.48]	86.95 [84.57 103.09]	101.69 [95.7 107.0]

[a.] A subgroup of younger controls (N=5; 2 male) is presented since the two groups (PPPD, controls) were not individually matched for age.

A summary of spatiotemporal outcomes for the group is depicted in Figure 4 and Table 1. It is unclear whether differences associated with level of complexity exist in this preliminary data set. However, the descriptive statistics suggest that people with PPPD in this group seem to make smaller head movements specifically in the AP direction.

Finally, heartrate during performance of the FSST-VR task for both groups and conditions is depicted in Figure 5 and Table 1. Again, these preliminary results may support higher heartrate in the PPPD group for all complexity conditions.

IV. Discussion

This study presents a novel virtual reality paradigm for assessment of dynamic balance in people with PPPD and provides preliminary results as to the ability of this paradigm to distinguish between people with PPPD and controls. The FSST-VR uses affordable technology to present various levels of visual complexity stimuli while performing a measured dynamic balance task. Compared with previous studies, this controlled combination may better address the specific functional complaints that characterize people with PPPD, as triggered by vision and head movement. This approach might help further characterizing people with PPPD based on those specific triggers as data collection continues.

Our preliminary results support the feasibility of this paradigm. Participants with PPPD demonstrated no changes in state anxiety and minimal changes in SSQ scores, indicating good tolerance to the FSST-VR. In addition, the FSST-VR offers the opportunity to collect spatiotemporal measures of head kinematics beyond task duration parameters. Descriptive statistics may suggest that patients in this sample perform smaller movements especially in the AP direction, which are also less smooth, possibly indicating increased reliance on visual input. This finding will be examined as the study continues.

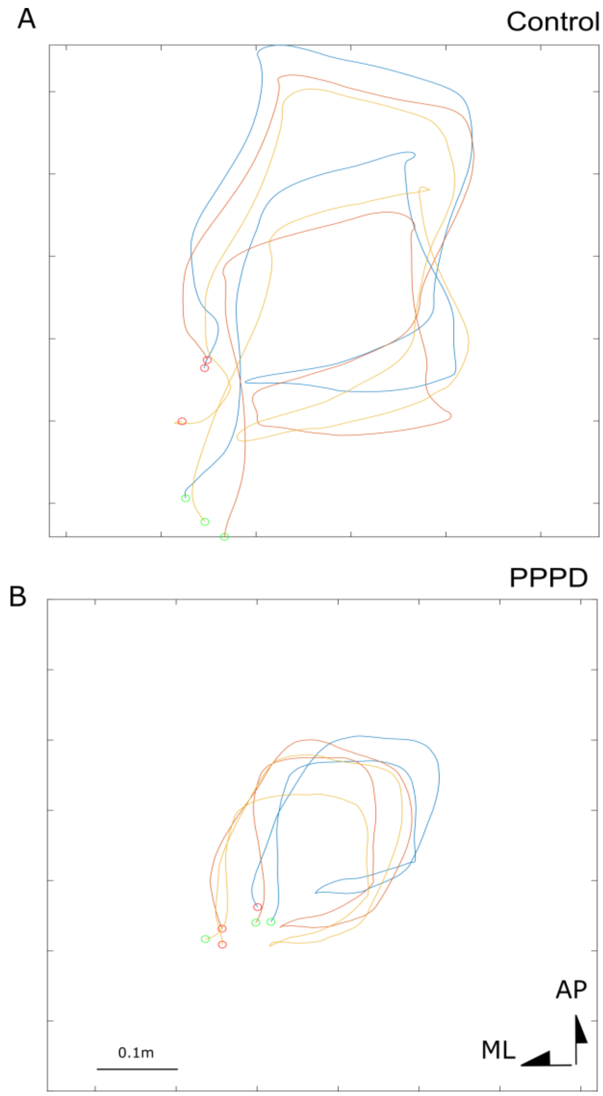

Fig. 2. An example of a control participant (A) and a person with PPPD (B) performing three repetitions of the FSST-VR in the "complex" virtual environment. Colors denote different repetitions, with green circles marking onset and red circles marking offset of movement.

The FSST-VR is a multi-directional balance task which requires less room space relative to straight walking tasks (approximately 1.8*1.8 meters). Unlike the clinically-used FSST, the FSST-VR uses high-frequency head kinematics measured by HTC Vive to provide objective spatiotemporal markers of performance which may better distinguish between people with and without PPPD and provide direction-specific information on dynamic balance. Enrichment of clinical tests to provide more information regarding clinical populations was performed for the Timed Up and Go [27]. In a virtual reality setting, Plotnik et al. recently evaluated the Trail Making Test [28]. In the latter case, the virtual reality version of the test was associated with larger durations but similar psychometric properties as the non-VR version. Similar results of longer durations of the VR version are suggested here (see text and Table 1). Importantly, the duration of FSST performance may not be different between people with PPPD and controls. In this case, it is suggested here that relying only on this outcome, as in the clinical FSST, may suggest lower sensitivity of the test in this population.

A clear limitation of this work is the small sample size, as data collection is currently ongoing. This sample consisted of healthy individuals which were older than the PPPD group. However, a subgroup analysis of younger individuals within this group suggests that differences are not attributed to age. Our operational assumption that the translational head movement relate to step size in a certain direction (AP or ML) will be tested in a future study using feet markers. As the study continues, we will also compare head rotation patterns between the groups.

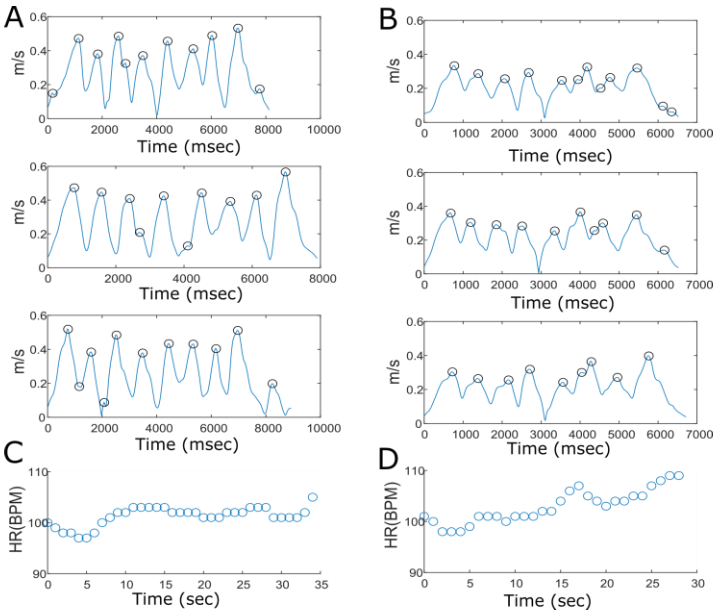

Fig. 3. Tangential velocity profiles of a healthy ocntrol (A) and a person with PPPD (B) performing three repetitions (a single trial) of the FSST-VR in the "complex" environment. Panels C and D depict the heartrate profiles associated with the same three repetitions.

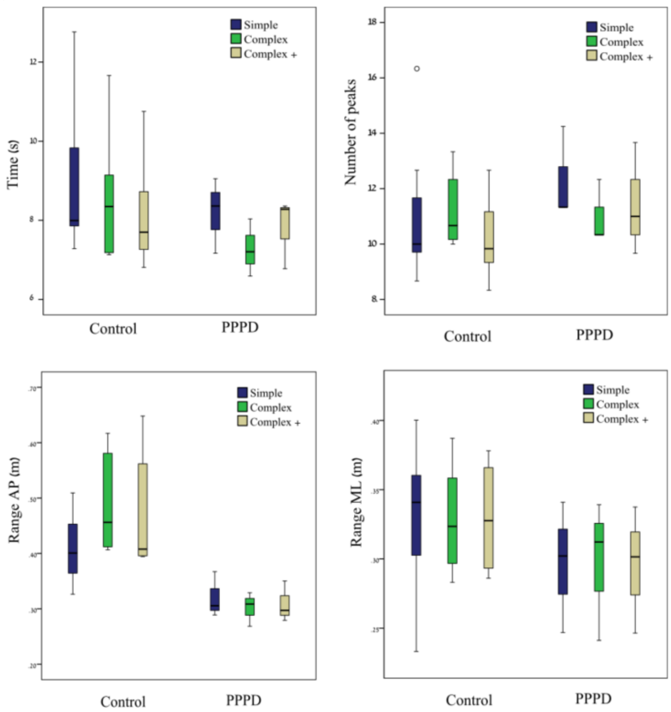

Fig. 4. Box plots of spatiotemporal variables for both groups and conditions of visual stimulus complexity (simple, complex, complex+).

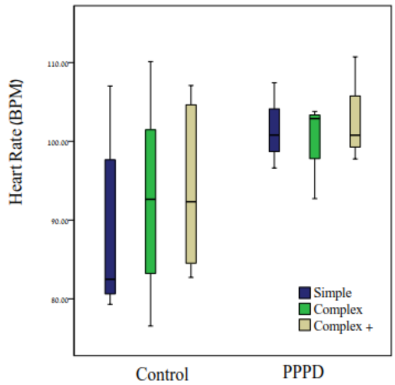

Fig. 5. Box plots of mean heartrate for both groups and conditions of visual stimulus complexity (simple, complex, complex+)

V. CONCLUSION

Developing a sensitive clinical paradigm to quantify functional limitations of individuals with PPPD is essential in order to provide a better understanding of the pathophysiology underlying PPPD [5] and promote further recognition of this diagnosis and its effects. The FSST-VR provides additional information to the clinical FSST, specifically in measuring spatial and temporal parameters which indeed may distinguish between people with PPPD and healthy individuals, when the time to complete the overground FSST does not. Furthermore, the FSST-VR can provide objective performance quantifications of dynamic balance in different visual complexity conditions.

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