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Head mounted displays for capturing head kinematics in postural tasks

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ABSTRACT

Tracking head motion in a simple, portable and accurate manner during performance of postural tasks in a virtual reality environment could have important implications for investigating normal and pathological head kinematics. We investigated concurrent validity of head tracking of two Head Mounted Displays (HMDs), Oculus Rift and HTC Vive, vs. a gold-standard motion capture system (Qualisys). Head kinematics of N = 20 healthy young adults was quantified during static and dynamic postural tasks. While wearing the Oculus Rift or HTC Vive, participants observed moving stars (static tasks) or a flying ball (dynamic task). Head kinematics were recorded simultaneously by the Rift or Vive and Qualisys camera system. We calculated head directional path, acceleration in 6 directions and volume of translation movement. Intra-Class Correlations (ICC) and 95% Limits of agreement were calculated. Most ICC values were around 0.9 with several at 0.99 indicating excellent agreement between the HMDs and Qualisys. Weaker agreement was observed for vertical displacement during a static task and moderate agreement was observed pitch and yaw displacement during a dynamic task. A negative bias of a small magnitude (indicating more movement in VR) was observed for most variables in static tasks, while a positive bias was observed for most variables in the dynamic task (indicating less movement in VR). Our results generally support the concurrent validity of Oculus Rift and HTC Vive head tracking during static and dynamic standing tasks in healthy young adults. Specific task- and direction-dependent differences should be considered when planning measurement studies using these novel tools.

1. Introduction

Commercially available virtual reality (VR) head mounted display (HMD) systems such as the HTC Vive (HTC Corporation, Taoyuan City, Taiwan) and Oculus Rift (Oculus VR, Irvine, CA) support room-scale tracking of human motion in sitting, standing and to some extent walking. These portable systems carry great promise for research, with costs being lower than laboratory-grade motion capture systems. Tracking head motion in a simple yet accurate manner could have important clinical implications for the understanding of concussion (Beckwith et al., 2012), chronic neck pain or whiplash injuries (Sarig Bahat et al., 2010; Vikne et al., 2013; Williams et al., 2017), and vestibular dysfunction (Keshner et al., 2004).

Several research groups investigated the accuracy of the Oculus (primarily the Development-Kit 2) to measure cervical range of motion (ROM) (Sarig Bahat et al., 2016; Williams et al., 2017; Xu et al., 2015), and head rotation (Quinlivan et al., 2016). Xu et al. (2015) tested the accuracy of Oculus Rift to measure cervical kinematics in 10 healthy adults seated with back support. Average full ROM was close to that measured by a reference motion tracking system, with a mean difference of under 10 degrees. They hypothesized that the error results from drifting of the Oculus inertial sensor and thus may be affected by magnitude of angular velocity and suggested that larger and faster head movements should be tested. Sarig Bahat et al. (2016) found moderate to good inter-rater reliability of cervical kinematics measured using an HMD during a VR game. Their protocol required fast movements, but evaluated instantaneous measures of velocity (peak velocity, time to peak, smoothness, etc.) rather than ROM. Recently, the ability of Oculus Rift to differentiate between patients with vestibular dysfunction and healthy individuals was demonstrated by Lubetzky and Hujsak (in press) who showed significant differences in head directional path (defined as length of the position curve in a given direction) during standing in a tandem position (standing one foot in front of the other, toes of back foot touching the heal of the front

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foot) for 20 s and observing a scene of moving stars. Lubetzky et al. also found significant between-group differences in head directional path, head acceleration and peak frequency during a dynamic ball-avoidance task, with good to excellent reliability (Lubetzky et al., 2018a).

The HTC Vive, also an advanced HMD, is similar in specifications to those of Oculus Rift, but the Vive allows more movement in space (Vive: 4.5 * 4.5 m Rift: 1.5 * 1.5 m). Niehorster et al. (2017) evaluated accuracy and precision of the Vive's position and orientation during static measurement (with no person wearing the HMD) and demonstrated jitter of <0.01 cm for all three directions of translation. However, they observed variations in vertical axis measurements across the tracking space resulting from a reference plane that was tilted away from the true ground plane. This systematic error varied from system to system when two Vive systems were compared, however could be corrected using calibration. Borrego et al. (2018) compared the Vive to the Rift in terms of static precision and accuracy and similarly found jitter of under 1 mm in both systems. They, however, identified differences of 0.58 to 1.22 cm between actual and reported height of the HMDs, with no systematic tilt in reference plane.

The aforementioned studies form an important first step in validating these head-mounted displays for use in human biomechanics research. However, accuracy and precision of a novel measurement tool must be assessed in the tasks which will be used with the outcomes to be extracted. We therefore aimed to evaluate the head tracking capabilities of the Oculus Rift and HTC Vive during postural tasks which require both small and large-scale fast movements in dynamic VR environments. We quantified head kinematics and compared both systems to a gold-standard motion capture system (Qualisys AB, Göteborg, Sweden).

2. Methods

2.1. Experimental setup

This study was approved by the New York University Committee on Activities Involving Human Subjects. Twenty healthy young adults (ages 18–39) participated in a single 45-minute session. After signing informed consent, the participants wore an OptiTrack MoCap Beanie (©2018 NaturalPoint, Inc. DBA OptiTrack) and 3 Qualisys reflective markers were placed in a triangle over the frontal, parietal and occipital lobes (see Fig. 1B&C). To maintain within-subject marker placements between Rift and Vive trials, the cap remained on the participant's head when the headset was replaced.

We used the first customer-version of the Oculus Rift which included a single head-tracking sensor. The Rift sensor was placed on an adjustable tripod 1.4 m in front of the participant (yellow arrow, Fig. 1A). The Vive uses 2 laser emitters called "lighthouses". They were placed 3.66 m from each other (length of diagonal, white arrows, Fig. 1A) with the participant positioned along this line about 2 m away from 1 lighthouse (red cross, Fig. 1A). The lighthouses were connected to each other with the sync cable provided by the manufacturer. All tripod positions were marked for consistency between participants.

We chose 3 tasks that target postural control responses to visual input during static balance (at two levels of difficulty) as well as dynamic balance activities. Expanding the work of Borrego et al. (2018) and Niehorster et al. (2017), we chose functional tasks of varying durations (from 20 to 60 s) to be able to study the effects of possible drift (e.g. Xu et al., 2015) over time. Participants performed each task once via the Oculus and once via the Vive.

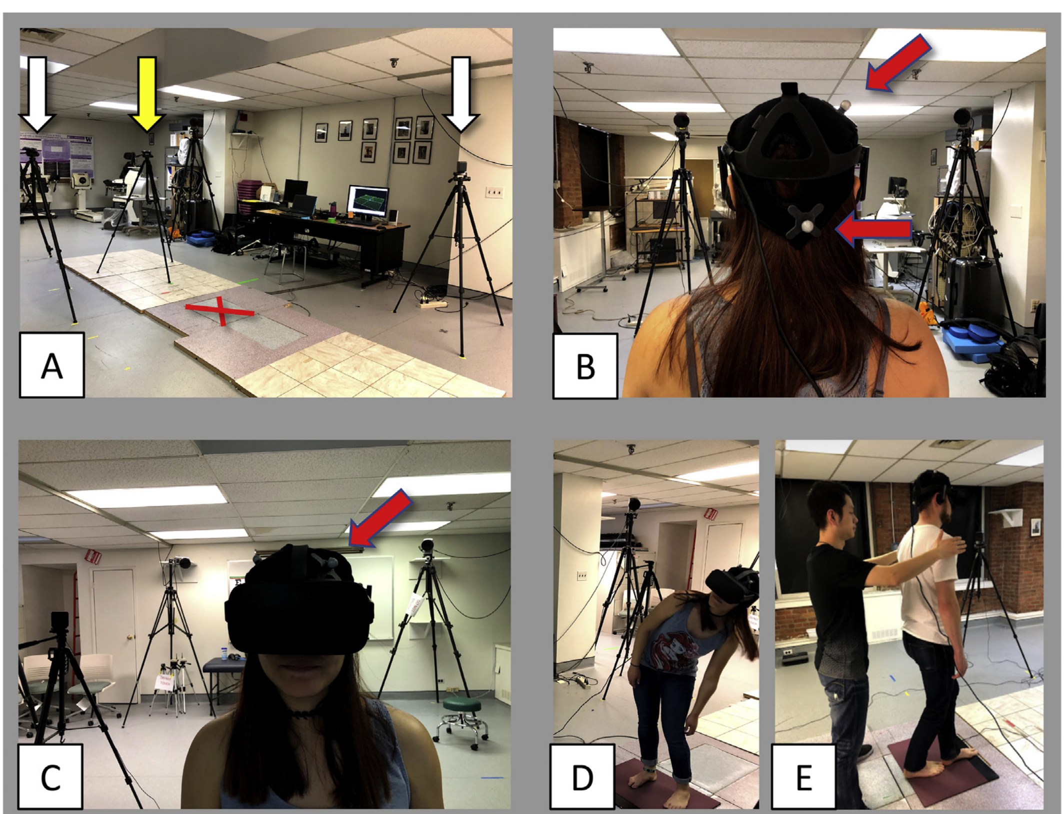

Fig. 1. (A) Our laboratory arrangement of tripods (yellow arrow: Oculus Rift sensor, white arrows: HTC Vive lighthouses), (B and C) marker arrangement on a participant's head (red arrows), (D) a participant avoiding a ball in the BALL_AVOID scene, and (E) a participant standing in tandem position during the STARS_TAN task. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the first scene, STARS (Lubetzky et al., 2017), the participant is standing within a 3-wall 'moving room' (Polastri and Barela, 2013) displaying randomly distributed white spheres (diameter 0.02 m) on a black background. The display is viewed as 1.63 m away from the participant, each wall was 6.16 m by 3.2 m. The spheres move at a frequency of 0.2 Hz and an amplitude of 32 mm (See Supplementary Video file). The participant is asked to stand hip-width apart and do whatever feels natural to them to maintain their balance for 60 s. The 3-wall display of stars was originally designed to assess visual dependence via the visual weighting paradigm (Logan et al., 2014; Peterka, 2002; Polastri and Barela, 2013). Typically, in this paradigm, patterns in postural sway are tested with respect to changes in amplitude and frequency of moving dots (Lubetzky et al., 2018a). Head kinematics could further shed light on mechanisms of weighting and reweighting of visual input. Indeed, in previous unpublished work, average head directional path was significantly higher in 16 patients with vestibular dysfunction compared with 16 age-matched controls on all 3 directions of rotation, and in mediolateral and anteroposterior translations, whereas vertical translation was similar between groups.

The second scene, STARS_TAN, displays the same scene as above, but the participant is asked to stand in a tandem position (Fig. 1E), dominant leg in the back, and stay steady for 20 s. It was previously found (Lubetzky and Hujsak, in press) that this scene of mild visual disturbance was more sensitive to differences between people with and without vestibular dysfunction than traditional 'eyes closed' tasks in a tandem position. Specifically, we found significant between-group differences on 5 out of 6 head movement directions (all except vertical movement). Furthermore, standing in tandem position is feasible for people with vestibular dysfunction (unlike single-leg stance, for example) and minimizes ceiling effects compared with standing with feet together.

In the third scene, BALL_AVOID, the participant is standing within an abstract park (See Supplementary Video file and Fig. 1D). Balls (diameter 0.1 m, speed 15 m/s) are flying towards the person's head in a straight line or with slight inclination to either side randomly every 2–4 s. The scene was 2 min long, but only the first 60 s were used for analysis. Participants were asked to stand hips-width apart and avoid the ball (Lubetzky et al., 2018c). Eikema et al. used a virtual tennis ball avoidance task to study sensory reweighting in young and older adults (Eikema et al., 2013). They found that older adults had significantly less center-of-pressure displacement when avoiding the ball and slower upper trunk velocity compared with healthy young adults. Adapting Eikema's paradigm to an Oculus Rift environment we previously found significant differences in head acceleration between 16 individuals with vestibular dysfunction and 16 age-matched controls on mediolateral and vertical translation movements when avoiding the ball with average values of 127 cm/s^2 (SD = 37) vs. 108 cm/s^2 (SD = 35) and 110 cm/s^2 (SD = 67.6) vs. 172.4 cm/s^2 (SD = 110.5) respectively. Patients had significantly larger directional path on yaw rotation (looking away): 122.04° (51.56°) vs. 97.4° (28.65°) over 30 s (Lubetzky et al., 2018a).

The order of the devices and the scenes per device was randomized for each participant but kept constant between devices. Participants' head kinematics were recorded simultaneously via the HMD and Qualisys motion capture system (Qualisys AB, Göteborg, Sweden) with 6 motion capture cameras (Oqus 300) sampling head position at 100 Hz. At the beginning of each recording, participants were asked to perform a brisk trunk flexion movement such that temporal synchrony between the systems could be maintained.

2.2. Instrumentation

The scenes were designed in C# language using standard Unity Engine version 5.2.1f (©Unity Technologies, San Francisco, California). Both HMDs were controlled by the same application via an Alienware GPU laptop 15 R3 (Windows 10) with 8 GB RAM, Intel i7 CPU, and Nvidia 1080 Max-Q model. Calibration for height was done before each testing session using the SteamVR calibration software. Both the Rift and the Vive have a resolution of 1080 × 1200 pixels per eye and use accelerometers and gyroscopes to monitor head position with a refresh rate of 90 Hz. The Rift has a field of view of 80° horizontal and 90° vertical, and the Vive 100° horizontal and about 110° vertical. For further specifications of both HMDs see Borrego et al. (2018).

2.3. Outcome measures

All outcome measures were calculated in Matlab version R2018a (The Mathworks, Inc.). The primary outcome measure for all 3 scenes was head Directional Path (DP) (Quatman-Yates et al., 2013), defined as the length of the position curve for a selected direction: X (medio-lateral), Y (up and down/height change), and Z (anterior-posterior) translation (in cm) and pitch (looking side-to-side), yaw (looking down and up) and roll (side-flexion) rotations (in degrees). To calculate DP, the absolute value of the change in position for each direction across each trial was summed. DP is a common and reliable measure of postural steadiness when measuring postural sway (Lubetzky et al., 2018a,b,c; Quatman-Yates et al., 2013). We previously showed the utility of postural sway DP to quantify static and dynamic balance; shorter DP on the STARS scene and longer DP on the BALL_AVOID scene were associated with increased balance confidence with individuals with vestibular dysfunction (Lubetzky et al., 2018b). Calculating DP of head movements will allow for future assessment of head to center-of-pressure ratio as a potential indication of individuals' balance performance. Pitch, yaw and roll angles for the HMDs were obtained directly from the HMD and for Qualisys - computed from the rotation matrix provided by Qualisys's 6DOF rigid body.

The secondary outcome was 95% confidence ellipsoid: the smallest ellipse that covers 95% of the points of the head diagram in translation (cm^3). This outcome combines the amount of movement performed in the X, Y, and Z planes into a single number.

For the BALL_AVOID scene, which included a dynamic movement outside of the base of support, we also calculated Root Mean Square Acceleration (RMSA, cm/s^2 or rad/s^2): The square root of the average of the square of the acceleration over time in all 6 directions.

2.4. Statistical analysis

The data were inspected independently by authors AL and TK in order to verify appropriate initial processing of motion capture data and appropriate recording by the HMD systems. Concurrent validity was assessed with a fully-crossed design (all systems measure all subjects) via the following: an absolute agreement, two-way random effects model Intraclass Correlation Coefficient ($ICC_{3,2}$) (Koo and Li, 2016) was selected (Hallgren, 2012) and the mean bias between Oculus/Vive and Qualisys motion capture was assessed using Bland-Altman plots and 95% limits of agreement (Bland and Altman, 1999). Analyses were done in IBM SPSS Statistics for Windows Version 23.0 (Armonk, NY: IBM Corp.).

A post-hoc sample size analysis was performed for ICCs, specifying a null-hypothesis ICC value of 0.6. To identify whether an ICC of 0.9 is significantly higher than the null hypothesis with a significance level of 0.05 and 95% power, 20 subjects were required.

Sample size analysis was performed using WinPepi (version 3.59, copyright J. H. Abramson 2003–2016).

3. Results

The sample included 10 men and 10 women, age range 24–39 (mean 26.67, SD = 4.5) with an average height of 171.5 cm (SD = 7.8) and average weight of 69.4 kg (SD = 9.7).

Following data inspection, a total of 10 trials (8.4%) were removed from further analysis, due to problems in either motion capture recording (7 trials) or in Oculus/Vive data recording (3 trials).

A summary of results for all DP's (6 DOF) and the 95% confidence ellipsoid for each device and each scene is provided in Table 1. ICCs$_{3,2}$ for all variables appear in Fig. 2. We observed excellent concurrent validity (ICC > 0.8) for 17 out of the 21 ICCs calculated for both Oculus and Vive. For Oculus, in the STARS scene, a lower ICC was found for vertical translation ($ICC_{3,2}$ = 0.36, 95% CI [−0.1,0.69]), whereas for Vive, this ICC was higher at $ICC_{3,2}$ = 0.78 95% CI [0.53,0.91]). In the BALL_AVOID scene, where a larger amplitude of movement was expected, ICCs lower than 0.8 were demonstrated only for Pitch and Yaw rotations (Oculus) and Yaw rotations (Vive). RMSA ICCs in the BALL_AVOID were calculated for Oculus and Vive for all directions (a total of 12 ICCs). For Oculus, ICCs were shown to be above 0.98 for all directions except Pitch ($ICC_{3,2}$ = 0.84 [0.60,0.94]) and Yaw ($ICC_{3,2}$ = 0.74 [0.39,0.91]). For Vive, RMSA ICCs were shown to be above 0.93 except for Yaw ($ICC_{3,2}$ = 0.59 [0.45,0.71]).

Limits of agreement between Qualisys and Oculus/Vive are described in Table 2. For most DP measures, the mean bias was negative, indicating a larger amplitude of movement measured by the VR (both Oculus and Vive) as compared to Qualisys. An example for this is provided in Fig. 3 (compare panels A – top center, B – top center). Apparent differences in movement amplitude were demonstrated mainly in vertical translation, with a mean negative bias of under 4 cm for both STARS and STARS_TAN scenes in Oculus and Vive, and under 28 cm for the BALL_AVOID scene. This bias in the vertical direction may further depend on amount of movement (Fig. 4A vs. B) where larger values of DP generated a larger difference between the systems. For the BALL_AVOID scene, a difference in movement amplitude was apparent for Pitch, with positive mean bias for both Oculus and Vive (indicating decreased movement amplitude of both systems vs. Qualisys) as well as in Yaw, with a positive mean bias for Oculus (decreased movement amplitude compared to Qualisys) and a negative mean bias for Vive (increased movement amplitude compared to Qualisys). In both cases, ICCs were between 0.6 and 0.8.

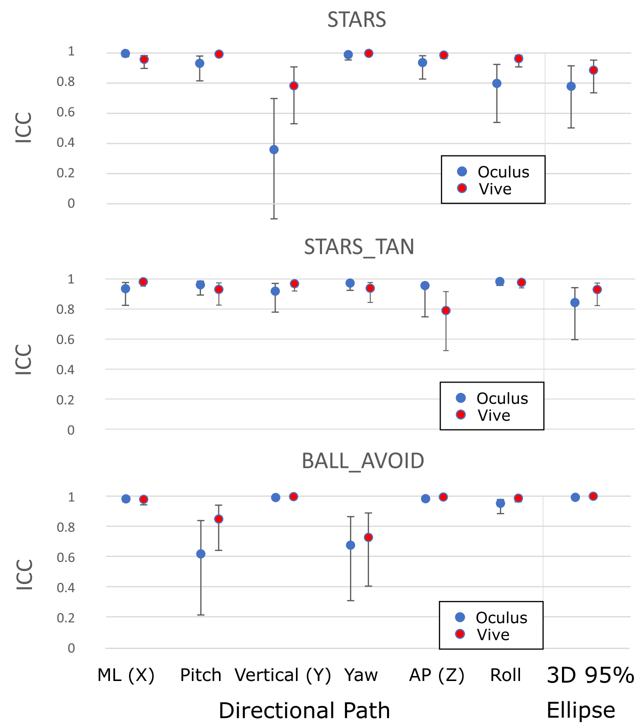

Fig. 2. Average Intraclass Correlation coefficients for 6 directional path measures (3 axes of translation and 3 axes of rotation) and a 3-dimensional 95% confidence ellipsoid for Oculus Rift (blue) and HTC Vive (red). Whiskers denote 95% confidence interval for the mean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1. Discussion

In this study, 20 healthy young adults completed static and dynamic postural tasks within virtual environments while their head motion was captured simultaneously by a gold standard motion capture system (Qualisys), and an HMD system (Oculus Rift or HTC Vive). Head path, volume and acceleration were compared between the systems. Most ICC values were around 0.9 indicating excellent agreement between the HMDs and Qualisys. Weaker agreement was observed for vertical displacement during a static task (STARS), accompanied by larger movement amplitudes in the HMDs. Moderate agreement was observed for pitch and yaw displacement during a dynamic task. A negative bias of a small magnitude was observed for most variables in static tasks, while a positive bias was observed for most variables in the dynamic task.

Table 1
Directional path and 95% ellipse values for Oculus and Vive in the three scenes; Mean [95% CI].

		STARS	STARS_TAN	BALL_AVOID
Oculus	Directional path			
	Mediolateral (cm)	17.66 [13.52 21.80]	22.39 [16.37 28.40]	1134.35 [989.10 1279.61]
	Vertical (cm)	6.68 [5.71 7.66]	4.37 [3.08 5.66]	914.24 [563.57 1264.91]
	Anteroposterior (cm)	34.04 [29.20 38.89]	12.85 [10.28 15.42]	342.72 [228.32 457.11]
	Pitch (degrees)	34.60 [29.23 39.96]	15.82 [11.37 20.26]	393.32 [282.05 504.58]
	Yaw (degrees)	28.43 [22.14 34.73]	21.39 [14.53 28.25]	521.98 [415.72 628.24]
	Roll (degrees)	22.64 [18.74 26.54]	17.23 [9.14 25.33]	1073.12 [850.87 1295.37]
	95% Ellipse (cm^3)	2.33 [0.73 3.92]	4.75 [0.15 9.35]	13517.44 [3574.40 23460.47]
Vive	Directional path	18.09 [13.87 22.31]	22.85 [13.91 31.79]	1237.24 [1106.30 1368.18]
	Mediolateral (cm)	6.56 [4.86 8.27]	4.55 [2.46 6.64]	936.14 [583.49 1288.79]
	Vertical (cm)	33.52 [28.78 38.25]	13.07 [10.80 15.33]	362.63 [247.39 477.86]
	Anteroposterior (cm)	36.03 [26.89 45.16]	15.46 [12.27 18.64]	419.00 [312.39 525.62]
	Pitch (degrees)	36.07 [17.43 54.72]	24.49 [13.30 35.67]	617.60 [502.26 732.94]
	Yaw (degrees)	22.28 [18.36 26.21]	16.70 [7.26 26.14]	1125.51 [949.24 1301.79]
	Roll (degrees)	2.23 [0.67 3.78]	5.86 [0.6 11.12]	11211.90 [6103.67 16320.12]
	95% Ellipse (cm^3)	17.66 [13.52 21.80]	22.39 [16.37 28.40]	1134.35 [989.10 1279.61]

Table 2
Limits of agreement between Qualisys-Oculus/Vive. Negative values for bias denote larger values in the VR.

	Outcome	STARS Mean Bias	STARS 95% Limits of agreement		STARS_TAN Mean Bias	STARS_TAN 95% Limits of agreement		BALL_AVOID Mean Bias	BALL_AVOID 95% Limits of agreement	
Oculus	Directional path		Low	High		Low	High			
	Mediolateral (cm)	0.09	−2.71	2.89	−0.72	−9.11	7.67	25.83	−53.85	105.51
	Vertical (cm)	−3.91	−7.63	−0.19	−1.72	−3.32	−0.12	−16.73	−99.30	65.85
	Anteroposterior (cm)	0.32	−2.49	3.13	−0.80	−4.88	3.27	22.91	−42.06	87.89
	Pitch (degrees)	−1.15	−9.17	7.45	−1.72	−5.73	2.29	155.84	−297.94	609.63
	Yaw (degrees)	0.57	−4.58	5.73	−2.29	−8.02	3.44	15.47	−352.37	383.31
	Roll (degrees)	2.86	−8.59	14.90	−1.15	−5.73	4.01	−26.36	−264.13	211.42
	95% Ellipse (cm^3)	−1.07	−4.63	2.48	−2.05	−9.43	5.33	145.11	−1559.28	1849.49
Vive	Directional path									
	Mediolateral (cm)	−2.00	−6.67	2.67	−1.12	−8.33	6.10	23.85	−83.38	131.08
	Vertical (cm)	−3.91	−7.67	−0.16	−1.76	−3.66	0.15	−27.99	−155.05	99.07
	Anteroposterior (cm)	0.06	−3.39	3.51	−0.96	−6.66	4.74	10.83	−38.82	60.48
	Pitch (degrees)	−2.29	−6.88	2.29	−2.29	−6.88	2.29	68.75	−161.00	298.51
	Yaw (degrees)	−0.57	−4.58	3.44	−1.72	−16.62	13.75	−30.94	−345.49	283.61
	Roll (degrees)	−0.57	−4.58	3.44	−0.57	−8.59	6.88	−39.53	−158.14	79.07
	95% Ellipse (cm^3)	−0.49	−4.00	3.03	0.24	−9.17	9.65	188.23	−1020.30	1396.76

The current study follows the work of Borrego et al. (2018). However, a direct comparison between these studies is difficult due to the different methodology and outcomes employed (static positioning of the HMD in space in the case of Borrego et al.). The accuracy found by Borrego et al. while standing (1.22 ± 1.18 cm for Vive, 0.61 ± 0.55 cm for Oculus) is similar to our results from longer, 20 s recordings of a static balance task (Table 2). Separating the movement directions indicated that most of the error is vertical rather than anteroposterior or mediolateral. Unlike Borrego's finding of better accuracy of the Rift compared to Vive at standing height, we observed several cases of lower agreement of Rift with Qualisys (Fig. 2). For example, low agreement (ICC < 0.4) was found between the Rift and Qualisys in vertical displacement during a static 60-seconds scene (STARS) but better agreement (>0.9) during a shorter scene (20 s) or a dynamic avoidance scene. Borrego et al. (2018) suggested that some error existed in estimation of standing height with both the Vive and the Rift. Our results support this finding and further suggest that this error (e.g. drift) may increase with longer durations of measurement in static tasks (60 vs. 20 s). Note, however, that during static postural tasks there is very little variability in vertical displacement and the verticality is primarily determined by a person's height. This was observed in the current study as well as in previous work with patients with vestibular dysfunction and age-matched controls that, during static tasks, differed on all head movement directions except for vertical (Lubetzky and Hujsak, in press). Specifically, during the 60-seconds STARS, we observed differences of 7.3CM to 18.4CM in mediolateral and anteroposterior directions DP between patients and controls, with angular differences of 7.40° to 13.26° for the three orientations. Vertical deviation, however, was not significantly different between patients and controls (average 6 cm in controls (SD = 3) and 10 cm in patients (SD = 7.5). Since a person's height can easily be measured without any HMD, the deviation reported in the current study (with a mean accumulated difference of under 4 cm for 60 s) may be of low importance for kinematic assessment of postural tasks. However, once the participants performed larger movements in the vertical plane (i.e, moving up and down to avoid a flying ball), agreement between the systems improved (Fig. 2). Note that although we report values for 60 s, ICC's stayed the same when calculated for the full 120 s period. We therefore believe that Vive and Rift have adequate ability to estimate vertical movements during dynamic tasks with large vertical movements but perhaps should not be used to evaluate vertical movement during static tasks.

Interestingly, while differences in vertical translation were minimized with larger and faster head movements, differences in estimation of pitch and yaw that were not observed during the static scenes, emerged in the dynamic BALL_AVOID scene. This finding is consistent with Xu et al.'s (2015) observation that the Rift provided better estimate of full cervical ROM than unilateral rotation (note that turning the head to avoid a ball is closer to a unilateral rotation than to full range). They suggested that a drifting error of the inertial sensor may have led to these deviations. We extend these findings to include also the HTC Vive, and further show that the two systems may be dealing differently with this error, resulting in either positive or negative bias in yaw compared to Qualisys. Differences in estimation of pitch and yaw movements should be investigated in future research with controlled amounts of head rotation (beyond a self-selected avoidance task), to estimate if there is a specific range where the deviation occurs and the reason to possible discrepancies.

The Rift and Vive have similar technical specifications (same resolution and refresh rate, similar field of view). Our findings show that they are comparable for standing tasks despite different tracking mechanisms. The Rift uses a system called Constellation which utilizes cameras to track IR-LED markers on the headset and controllers. The Vive's lighthouse tracking system is a laser-based scanning technology. The lighthouse system generates reference points for photosensor-attached headset and controllers to locate their positions in 3D space by flooding the tracking area with non-visible light. Importantly, objective system performance and subjective experience of users may mismatch for different populations, specifically in the clinic (Lloréns et al., 2015). From a user stand point, no cybersickness was reported with either system and the image quality was perceived as similar. A few participants reported that the Vive felt a little heavier on the head (indeed, the Vive weights 563 g while the Rift weighs 470 g (Borrego et al., 2018)), which theoretically could affect head movements. This should be taken into consideration in future studies testing clinical samples.

This study included a small sample of healthy young adults; hence our findings should be replicated in larger, clinical samples. We did not control for movement between the headset and the head which may have occurred, particularly in the dynamic task. However, since the bias between Qualisys and VR was mostly positive in the dynamic task (indicating more movement of the Qualisys markers) we believe that this does not explain the identified differences. Finally, we compared head kinematics during

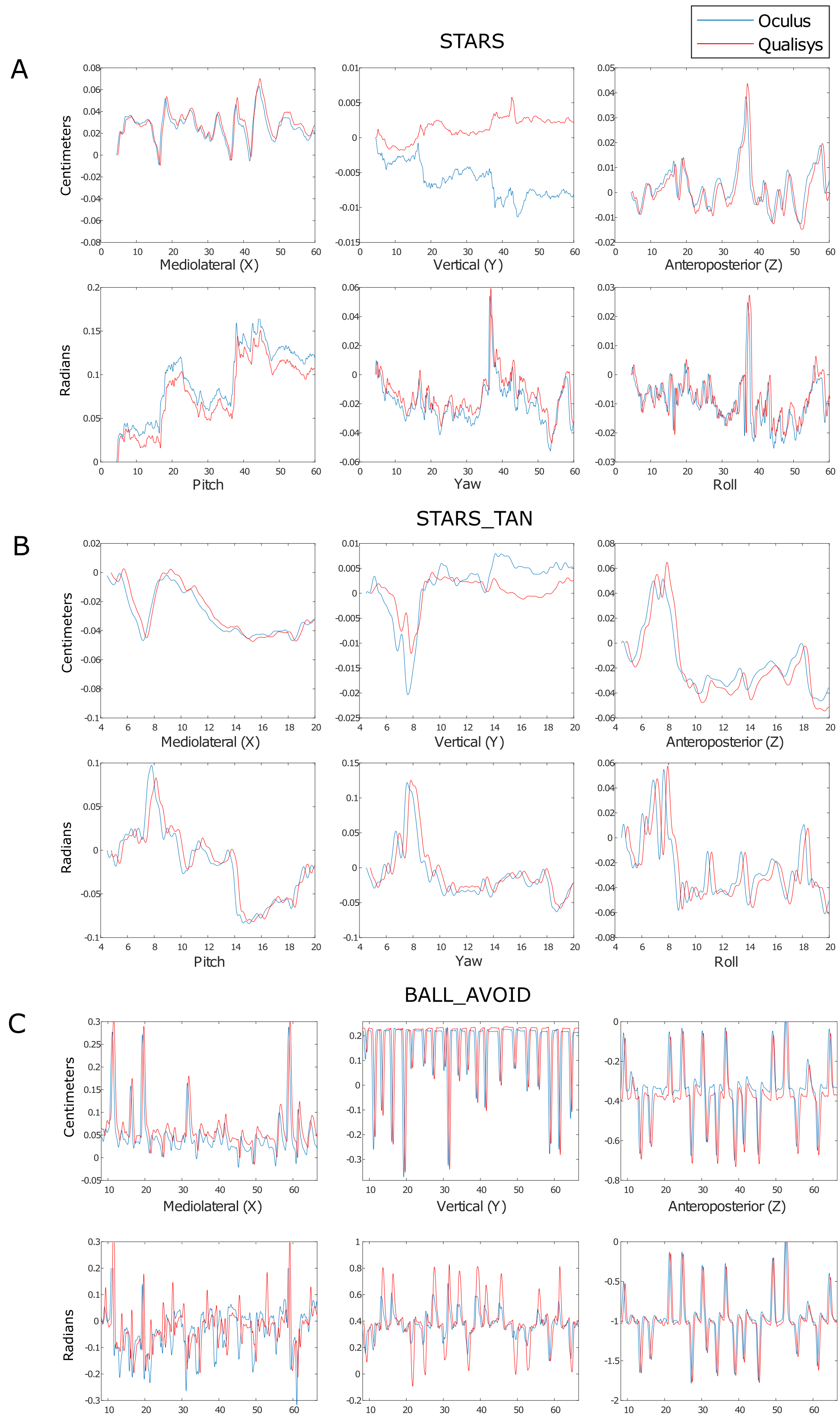

Fig. 3. Head kinematics measured by Oculus Rift (blue) and Qualisys motion capture (red) in 6 degrees of freedom (3 axes of translation and 3 axes of rotation) for (A) A static postural task where the participant watches a 'moving room' with randomly distributed white spheres moving at a frequency of 0.2 Hz and an amplitude of 32 mm (STARS), (B) A similar task where the participant is asked to stand in a tandem leg position (STARS_TAN), and (C) A dynamic task where the participant is required to avoid a ball moving towards them (BALL_AVOID). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

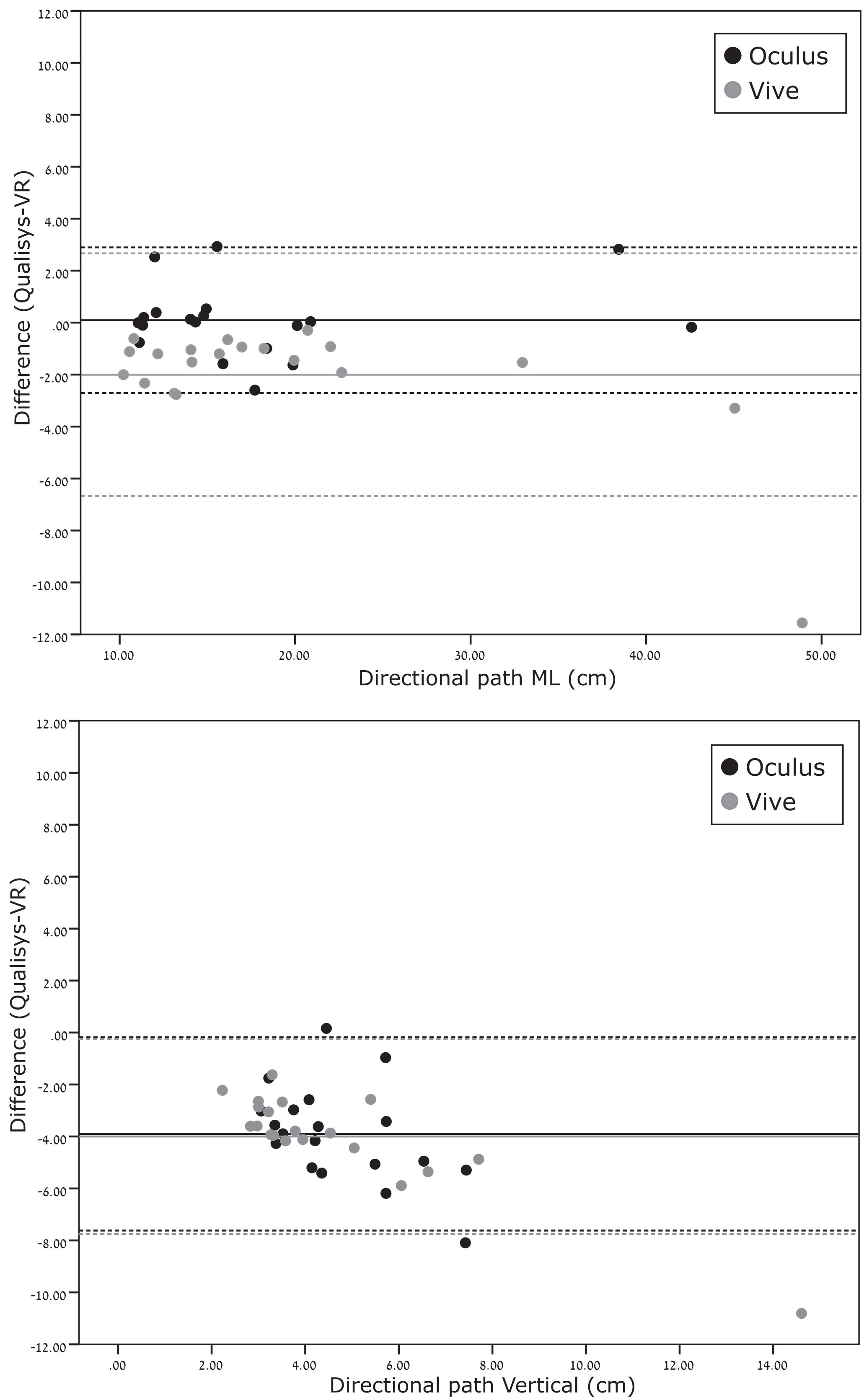

Fig. 4. Examples of Bland and Altman plots demonstrating the bias between Oculus (black) and Vive (grey) with Qualisys motion capture in the STARS task (see text). Solid lines denote the mean bias in directional path (DP) between Oculus/Vive and Qualisys, dashed lines denote 1.96 standard deviations from the mean. The top panel demonstrates bias in mediolateral directional path, while the bottom demonstrates bias in vertical direction, where increased DP values for Oculus and Vive generate a negative bias in both VR systems.

standing tasks and these findings cannot be extrapolated to walking tasks. Previous studies showed differences in accuracy of the HMDs in different locations throughout the workspace (Borrego et al., 2018; Niehorster et al., 2017) which may implicate on their suitability for more dynamic tasks such as walking. However, since neither Rift nor Vive can fully accommodate walking beyond 2 or 3 steps with existing tracking barriers, such examination should be conducted when walking is feasible within an immersive VR environment.

There is immense clinical potential in the use of HMDs for tracking head movement. For example, HMDs can shed light on coordination of head to center of mass (Pozzo et al., 1991), strategies of head stability in response to visual perturbations (Keshner et al., 2007) and spontaneous neck movement within a virtual environment (Williams et al., 2017). Establishing concurrent validity is essential prior to the acceptance of HMDs into wide use in research and clinical applications. While future research needs to address potential differences identified here, this study supports the concurrent validity of the Oculus Rift and HTC Vive as compared with standard motion capture during static and dynamic postural tasks in healthy young adults.

4. Supplementary Video File

https://docs.google.com/presentation/d/1uOb4HezSiG5gQtwE-Uc_36HlJARXdTALTL1cLUqtTek/edit?usp=sharing.

5. Conflict of interest statement

The authors declare no financial and personal relationships with other people or organizations that could inappropriately influence this work.

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