A quantitative method for evaluation of 6 degree of freedom virtual reality systems

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ABSTRACT

Modern virtual reality systems such as the HTC Vive enable users to be immersed in a virtual world. Validation of the HTC Vive and other contemporaneous systems for use in clinic, research, and industry applications will assure users and developers that games and applications made for these systems are accurate representations of the real world. The purpose of this study was to develop a standardized method for testing the translational and rotational capabilities of VR systems such as the HTC Vive. The translational and rotational capabilities of the HTC Vive were investigated using an industry grade robot arm and a gold standard motion capture system. It was found that the average difference between reported translational distances traveled was 0.74 ± 0.42 mm for all room-scale calibration trials and 0.63 ± 0.27 mm for all standing calibration trials. The mean difference in angle rotated was $0.46 \pm 0.46°$ for all room-scale calibration trials and $0.66 \pm 0.40°$ for all standing calibration trials. When tested using human movement, the average difference in distance traveled was 3.97 ± 3.37 mm. Overall, the HTC Vive shows promise as a tool for clinic, research, and industry and its controllers can be accurately tracked in a variety of situations. The methodology used for this study can easily be replicated for other VR systems so that direct comparisons can be made as new systems become available.

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1. Introduction

Virtual reality systems provide tools to develop dynamic environments capable of providing real-time feedback to a user and have the ability to track the spatial movement of the user during gameplay. As a result, human movement reports can be developed while the user is immersed in games used for physical therapy, participating in simulations that might otherwise be dangerous or expensive to develop, or interacting with virtual products. These movement reports provided a quantitative analysis that can then be used to evaluate the health, efficiency, or ergonomic needs of the user. Modern VR systems allow users to rotate and move around in their environment, which is a departure from previous systems such as the Microsoft Kinect. The HTC Vive is a virtual reality game system that was released in 2016 which immerses its player within a 3D environment. Evaluation of its motion tracking ability under controlled situations will give insight into its ability to evaluate human movement in clinical, research, and industrial applications.

Exergaming uses games to promote, encourage, and/or monitor physical objectives (Bonetti et al., 2010). Video game consoles which track motion have been increasingly studied to analyze their efficacy in tracking the movement of children (Levac et al., 2010), the elderly (Nawaz et al., 2016), and those who have physical disabilities (Burke et al., 2009; Darcy Fehlings, 2013; Harris et al., 2015) with encouraging results. Most notably, the Microsoft Kinect systems received large amounts of attention as research tools which could output kinematic data using markerless motion capture (Galna et al., 2014; Mentiplay et al., 2015; Vernon et al., 2015; Wang et al., 2015). For example, Galna et al. investigated the use of the Kinect for patients with cerebral palsy, while Vernon et al. quantified a functional assessment of stroke patients (Galna et al., 2014; Vernon et al., 2015). Commercially available exergaming systems intended for clinical rehabilitation applications, such as VERA (San Diego, CA), rely on low-cost motion tracking technology, such as the Microsoft Kinect, and have received FDA clearance (Komatireddy, 2014; "Virtual Physical Therapist," n.d.). The HTC Vive represents a new direction for exergaming which has the potential to expand on the motion tracking capabilities of previous systems while adding the new element of immersion into a 3D environment.

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Clinical adoption of the HTC Vive has many important implications. From an exergaming perspective, video games could be developed which output a detailed report on the range of motion achieved by the patient during physical therapy, increasing not only compliance from patients but ensuring more correct exercise form. Patients participating in at-home therapy could play games which provide real time assessment of movement. Physical therapists could customize a routine of exercises which are unique to each patient or define new exercises based on movement that they control. The HTC Vive has a rich development environment which can be accessed freely, meaning early adopters and savvy users could create their own software to meet specific needs. Additionally, virtual reality has the ability to create novel environments which are easy to control and manipulate while still being realistic (Rosa and Breidt, 2018), giving it the potential to impact multiple fields within psychology. Experiments made with virtual reality are highly repeatable and can have complex stimuli, both of which can greatly improve the rigor and quality of experiments (Pan and Hamilton, 2018). The subject's physical interactions with the environment could then be recorded and analyzed. Finally, industry applications for virtual reality enable companies to make interactive training and simulation software. This can allow for companies to demonstrate products to consumers, or provide training simulation for difficult, dangerous, or technical procedures. By evaluating where subjects' hands are, companies could better improve products or simulations to address shortcomings.

Prior to implementing a VR system such as the HTC Vive in a research, clinical, or industrial application, it must be demonstrated that it can output consistent and reliable movement measurements. Therefore, the objective of this study was to develop a methodology for validating 6 degree of freedom (DOF) virtual reality systems and use this framework to find the tracking accuracy and precision of the HTC Vive for use in clinic, research, and industry applications.

2. Methods

In order to validate the Vive for accurate and precise translational and rotational movements in different directions and orientations, a systematic approach was followed that used an industrial robot to physically move the controllers from the game system. Movements were simultaneously measured using a gold standard marker-based motion tracking system (referred to as the "world" coordinate system) (Windolf et al., 2008) and the Vive. Straight out of the box, the HTC Vive has three primary components: two controllers which are used to manipulate the games, a headset which displays the game, and two base stations which communicate with the controllers and headset. Translation and rotation accuracy and precision of the Vive controllers were tested in different movement directions, movement speeds, and within different calibration collection volumes.

2.1. Movement of controller

The controller was moved in a repeatable fashion by using the Universal Robots UR5 (Universal Robots, Odense, Denmark). Robot arms are effective tools for use in motion tracking system validation studies since they can provide consistent, repeatable motion. The UR5 has a precision of ±0.1 mm (Universal Robots, n.d.) which allows for the study of not only the accuracy of the HTC Vive, but also its error variance in a controlled study.

2.2. Collection of gold standard world data

The positional data was collected from the controllers using a 14 camera optoelectronic motion capture system (Vantage cameras, Vicon Motion Systems LTD, Oxford, UK) at 250 Hz. This system was selected to serve as the gold standard since it is capable of a sub-millimeter calibration accuracy (Windolf et al., 2008) and since marker-based motion tracking systems are now fairly commonplace in biomechanics laboratories. Therefore, the methodology described and followed in this study could be repeated by other research groups so long as they have access to a robotic arm or another system that can perform isolated translation and rotation movements. Four reflective markers were placed on the circular portion of a single Vive controller without blocking any sensors to track its location and orientation (Fig. 1). Marker trajectories were filtered using a Woltring filter (Woltring, 1986) using General Cross Validation with a smoothing factor of 20 in order to ensure smooth trajectories for analysis.

2.3. Collection of Vive data

Prior to any data collection with the HTC Vive, the system was recalibrated using the console's setup procedure. The two calibration methods were tested: room-scale and standing. These configurations are options provided by the Vive and have different requirements for calibration. For room scale, the base stations were 18.5 feet apart, and for standing the base stations were 8.5 feet apart. In both configurations, the base stations were raised above 6.5 feet. Finally, they were angled down between 30 and 45°. To extract position and orientation data, Python bindings were used to access Valve's OpenVR virtual reality SDK (Bruns, 2018). A modified wrapper was used to facilitate data extraction (TriadSemi, 2018). This allowed for extraction of a rotation matrix and positional X, Y, and Z coordinates. In practice, data were collected at 230 Hz.

2.4. Translation difference between Vive and world

The robot moved the controller 400 mm in either the X, Y, or Z directions as determined by the robot's local coordinate system at either 500 mm/s or 1000 mm/s for a total of 6 movement types. Each direction at each speed was taken 30 times. Directions and speeds were chosen to reflect a typical movement taken from prior human data. The total Euclidean distance moved by the controller

Fig. 1. The HTC Vive controller positioned in the UR5 robot arm.

from the start of the movement to the end of the movement was then calculated from each system's output. The absolute difference of the HTC Vive's travel distance and world travel distance was then calculated. This protocol was repeated for both the standing and room-scale calibrations for a total of 360 trials.

2.5. Orientation difference of Vive and world

Rotation matrices were obtained from reflective markers placed on the controller and the Vive's internal report and then compared. Four markers were placed on each Vive controller to form a plane and calculate a local coordinate system with a rotation matrix R_W. The plane was defined from three of the points: α, β, and γ. First, two unit vectors ($\overrightarrow{n_{\alpha\beta}}$ and $\overrightarrow{n_{\alpha\gamma}}$) were defined from a central marker α to the two other points.

$$\overrightarrow{n_{\alpha\beta}} = \frac{x_\beta - x_\alpha}{\|x_\beta - x_\alpha\|} \tag{2}$$

$$\overrightarrow{n_{\alpha\gamma}} = \frac{x_\gamma - x_\alpha}{\|x_\gamma - x_\alpha\|} \tag{3}$$

The first plane vector is arbitrarily set as one of the above ($\overrightarrow{n_1}$) and crossed with the remaining vector to form $\overrightarrow{n_2}$. The two vectors are then crossed to form a final perpendicular plane vector ($\overrightarrow{n_3}$).

$$\overrightarrow{n_1} = \overrightarrow{n_{\alpha\gamma}} \tag{4}$$

$$\overrightarrow{n_2} = \overrightarrow{n_{\alpha\beta}} \times \overrightarrow{n_1} \tag{5}$$

$$\overrightarrow{n_3} = \overrightarrow{n_1} \times \overrightarrow{n_2} \tag{6}$$

Finally, two of the vectors are normalized to become unit vectors.

$$\overrightarrow{n_1} = \frac{\overrightarrow{n_1}}{\|\overrightarrow{n_1}\|} \tag{7}$$

$$\overrightarrow{n_3} = \frac{\overrightarrow{n_3}}{\|\overrightarrow{n_3}\|} \tag{8}$$

A rotation matrix can then be established.

$$R = \begin{bmatrix} \overrightarrow{n_{11}} & \overrightarrow{n_{12}} & \overrightarrow{n_{13}} \\ \overrightarrow{n_{21}} & \overrightarrow{n_{22}} & \overrightarrow{n_{23}} \\ \overrightarrow{n_{31}} & \overrightarrow{n_{32}} & \overrightarrow{n_{33}} \end{bmatrix} \tag{9}$$

The HTC Vive controller directly reports a rotation matrix. Two rotation matrices from the beginning of the trial to the end of the trial can then be defined as R_1 and R_2. The total rotation angle θ can then be found between the two rotation matrices (Belousov, 2016). The rotation matrix Q, which relates R_1 and R_2 was found using the following steps:

Let:

$$Q \triangleq R_1 R_2^T \tag{10}$$

where:

$$tr(Q) = 1 + 2\cos(\theta) \tag{11}$$

Finally θ, the overall angle rotated, can be extracted as:

$$\theta = \cos^{-1}\left(\frac{tr(Q) - 1}{2}\right) \tag{12}$$

The controller was rotated so that it performed three orthogonal rotations (yaw, pitch, and roll) about three orthogonal axes (X, Y, and Z), allowing for 9 total configurations. A small 3D-printed holder was constructed so that the controller could be con-

sistently re-oriented 90° in each direction (Fig. 2). For each of the 9 configurations, the robot rotated its arm 90°. Each configuration was repeated 30 times at 1000 mm/s. This was repeated for standing and room-scale calibration methods. Therefore, a total of 540 rotation trials were recorded (yaw, pitch, and roll × 3 orthogonal axes × 2 calibration settings × 30 trials for each configuration). All code used to collect the HTC Vive data and compare it to real world coordinates can be found at https://github.com/Baylor-Biomotion-Lab/ViveAcquisition.

2.6. Functional movement

After data were collected analyzing the Vive during controlled movement, several on-person exercises were performed and analyzed using the HTC Vive controller to serve as a point of comparison against the controlled robot movements. The first exercise was a front raise, where the subject raised the controller from a neutral position at their side through shoulder flexion. The second exercise was a lateral raise, where the subject raised the controller from a neutral position at their side through shoulder abduction. Each exercise was performed by a single participant 30 times. Performing functional movements gives greater insight into how well the Vive will perform under movements that are less controlled as compared to the robotic arm.

3. Results

Through a series of experiments, it was verified that the Vive outputs position in meters, allowing for these values to be converted and compared to the Vicon system in millimeters. The average difference between reported translational distances traveled was 0.74 ± 0.42 mm for all room-scale calibration trials and 0.63 ± 0.27 mm for all standing calibration trials (Fig. 3) when the controller was moved using the robotic arm.

The mean difference in angle rotated was $0.46 \pm 0.42°$ for all room-scale calibration trials and $0.66 \pm 0.40°$ for all standing calibration trials (Fig. 4) when the controller was moved by the robotic arm.

The front raise exercise had an average difference of 3.68 mm ± 2.92 mm. The average distance in the lateral raise exercise was 4.27 mm ± 3.81 mm (Fig. 5).

4. Discussion

This study details a systematic methodology that can be used to evaluate the tracking accuracy and precision of 6 DOF virtual reality based motion tracking systems such as the HTC Vive. An industrial-grade robot arm was used to ensure precise and accurate movements in multiple directions for both translations and rotations. In order to verify that the HTC Vive would operate properly in a diverse set of situations, repeated testing was done where the calibration types, speeds, and directions were systematically altered. A motion tracking system (Vicon) was used as the gold standard for evaluation so that the Vive and other systems like it can be easily compared in typical biomechanics labs where these marker-based motion tracking systems are common. The methodology described and used in this study can serve as a standard way to compare multiple motion tracking systems moving forward and would allow for standard error values to be generated so that end-users can make an informed decision about the most appropriate system for their application.

Using this rigorous approach, results were obtained that suggest the HTC Vive has acceptable accuracy and precision to track both translational and rotational movements for use in most clinical, research, and industry applications. The results from this
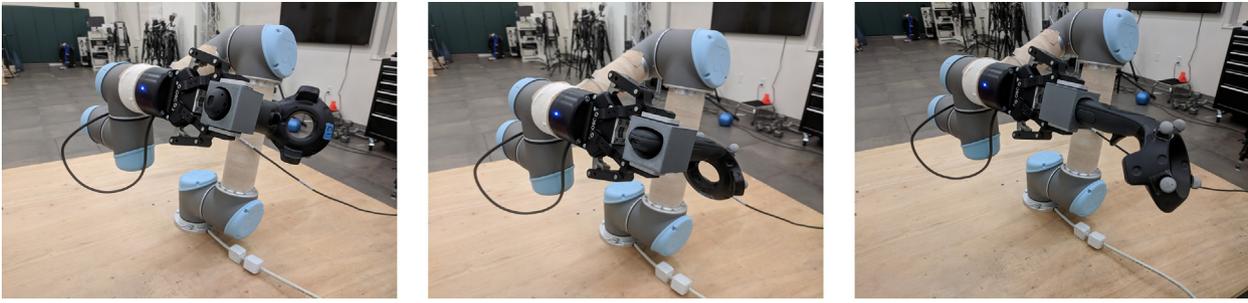
Fig. 2. The customized cubic controller base allowed for easy and repeatable 90° offset orientations of the controller in the robot hand. Therefore, yaw, pitch, and roll could be obtained about a single axis.
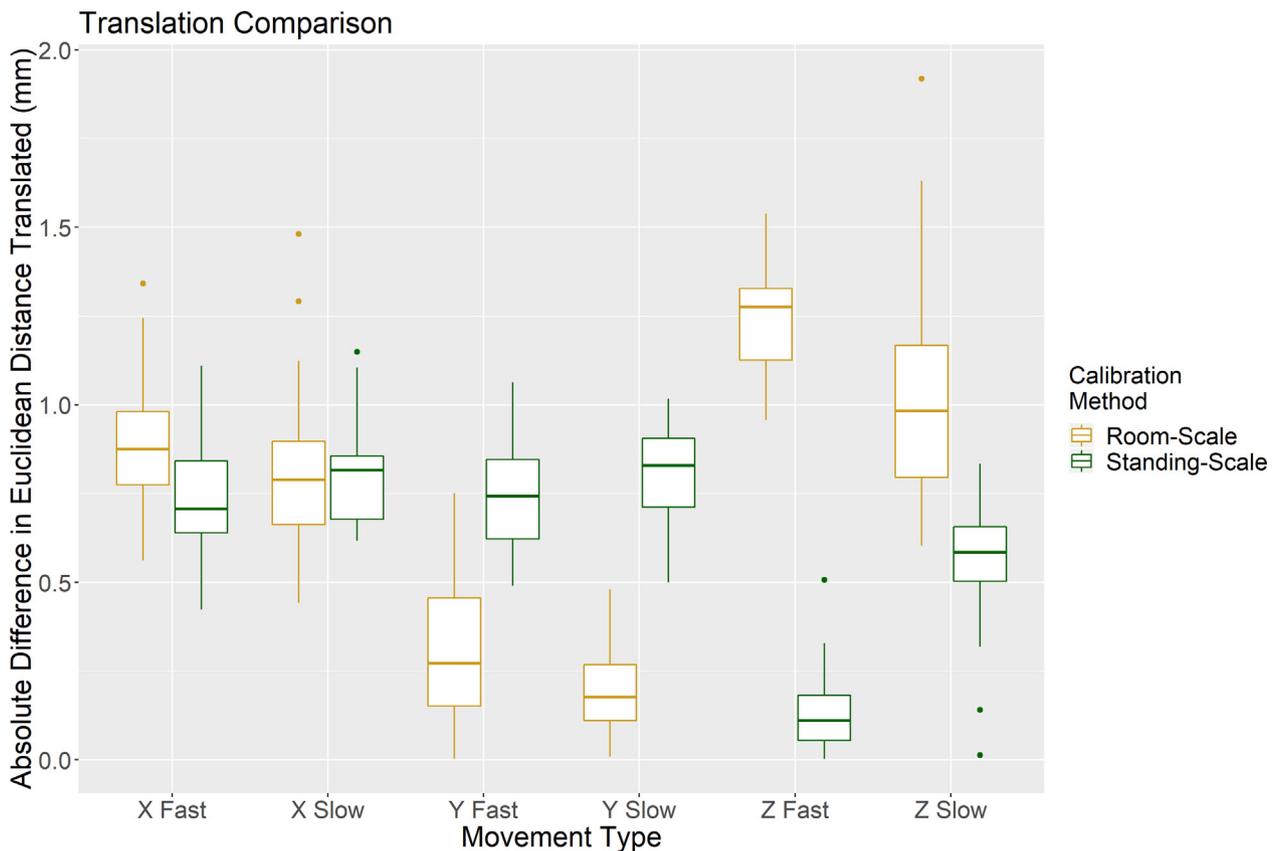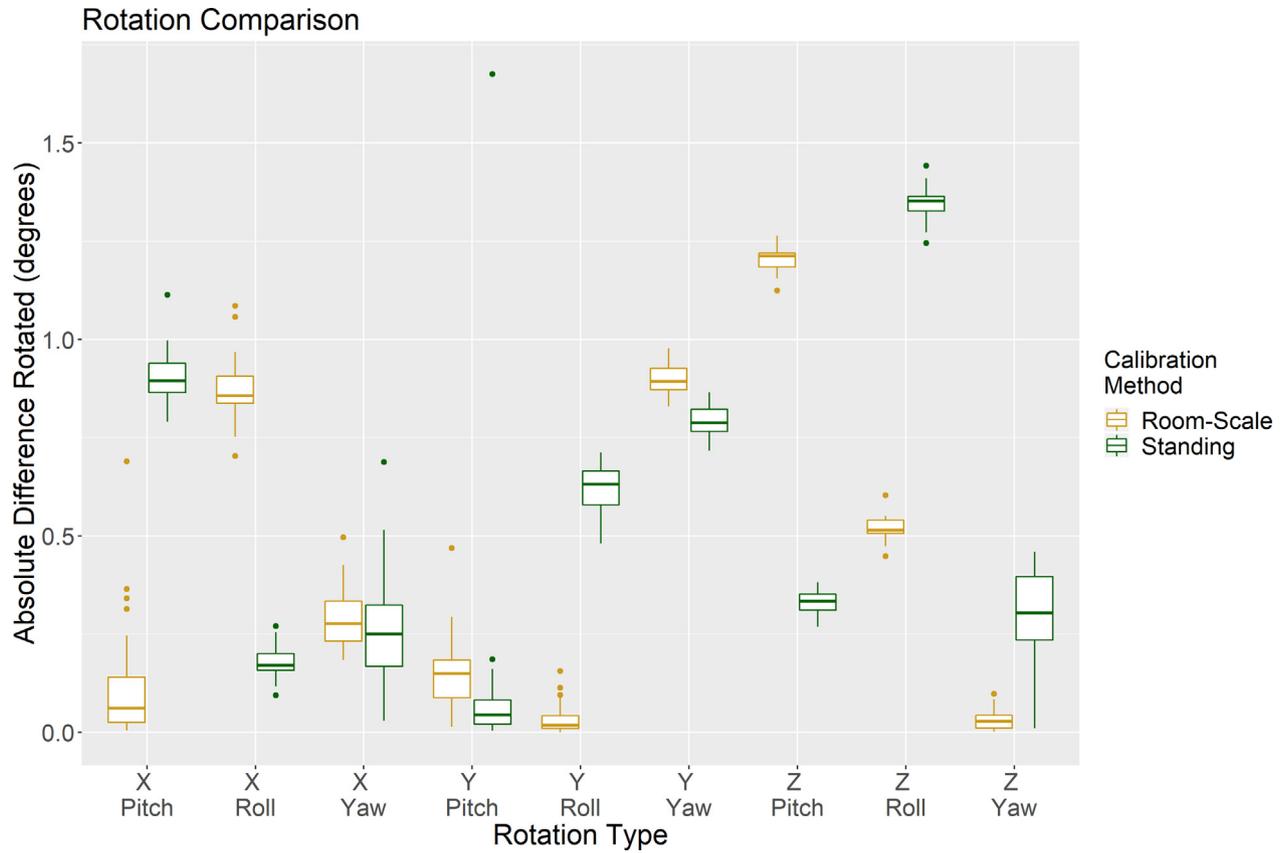

Fig. 3. Difference in distance translated by the controller as reported by the HTC Vive and Vicon Nexus (World) systems under all conditions, where fast corresponds to 1000 mm/s and slow corresponds to 500 mm/s. Coordinate directions (X, Y, Z) were in relation to the robot's coordinate system.

study indicate an accuracy of less than 1 mm of translational tracking and less than 1 degree of rotational tracking during controlled movement in all directions, speeds, and tower configurations that were tested. Overall, the Vive system never experienced more than 2 mm of translational error and 2 degrees of rotational error. The data demonstrates that for both rotation and position tracking, both room-scale and standing calibration volumes displayed excellent tracking capability, indicating that the Vive can be used in a variety of settings. Likewise, slow and fast movements did not show any consistent differences, and no direction proved to be superior when rotating or translating the controller. When the Vive was tested tracking functional movement, its level of error was increased. However, this increase is expected because the human movement is a combination of translation and rotation, and human movement will have small fluctuations (due to soft tissue, a loose grip, and other minor adjustments made by an arm holding a con-

troller) which are smaller than the Vive is able to quantify. In spite of this, the average error shows promise in tracking subjects in activities that mimic a real world use case scenario. Furthermore, the low variance demonstrated by the Vive indicates that it is consistently able to provide accurate tracking. Provided the controller does not lose tracking or become occluded for an extended period of time, it will give accurate and precise estimates of position.

Providing an immersive virtual environment and ensuring that the movement of the person in that environment is tracked accurately is important. The information provided in this study can serve as validation evidence for those who want to use the Vive for applications in medicine, research, and industry during which the tracking of human movement is important. For example, the Vive can be used in the clinic to provide immersive and interactive environments for patients recovering from stroke. Games can be made in such a way as to allow clinicians the ability to match

Rotation Comparison

Fig. 4. Difference in angle rotated as reported by HTC Vive and Vicon Nexus (World) systems under all conditions. Coordinate directions (X, Y, Z) were in relation to the robot's coordinate system.

Translation Comparison from Human Data
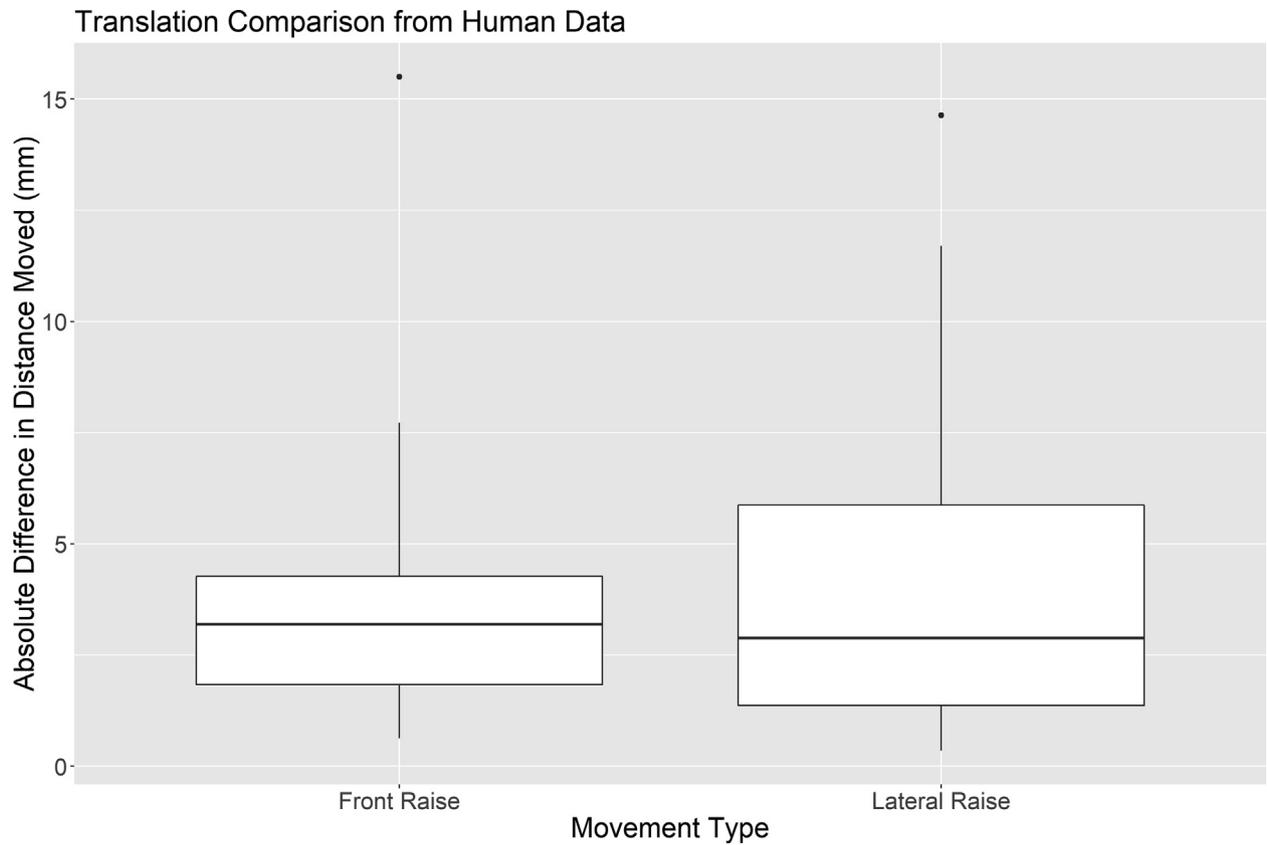
Fig. 5. Difference in distance translated by the controller by the HTC Vive and Vicon Nexus (World) systems during two functional movements.

the task difficulty, such as depth and accuracy of reaching, with the capability of the patient. The patient's reaching ability can be tracked for accuracy, speed, path, and precision and quantitative feedback can be provided back to the therapist. Similarly, researchers working in different fields can be more confident that their experiments closely mimic real life and the movements their subjects make are tracked appropriately. The findings from this paper indicate that tracked motion in this virtual world is accurate to within a few millimeters. Finally, industry developers can be reassured that any simulations they develop are true-to-life representations of their products. For example, OssoVR (Palo Alto, CA) is a new virtual reality tool aimed to train orthopedic surgeons without use of a cadaver. Validation of the HTC Vive gives credence to using virtual reality simulations such as OssoVR as preliminary training tools because users can be confident that the movements of the controllers are being tracked accurately.

The closest quantitatively evaluated comparison to the HTC Vive's capabilities are the multiple iterations of the Microsoft Kinect. The most recent iteration of the Kinect, the KinectOne, was able to calculate arm angles with a precision of $3.9 \pm 4.0°$, and trunk angles of $0.1 \pm 3.8°$ (Kuster et al., 2016). Prior Kinect models were able to track objects with promising results, although the depth sensor did reach errors of up to 4 cm at its maximum range of 5 m (Khoshelham, 2012). Mobini et al. used similar methods to those presented within this paper by constructing a physical model and tracking its accuracy using the Kinect (Mobini et al., 2014). They found errors in tracking ranging from 28 to 38 mm. The advantage in using the Kinect systems is that they are markerless motion tracking systems, but the tradeoff is that they must make guesses about the location of limbs (Nixon et al., 2013) and rotation centers, especially when they become occluded. In practice, the HTC Vive reported few occlusions, but these were easy to spot because the HTC Vive makes no attempts to "guess" as to the location of the controller and instead reports its values as being 0.

To date there have only been a few prior journal articles investigating the quantitative accuracy and precision of commercial virtual reality systems. Different elements of the HTC Vive have received attention from researchers attempting to quantify their precision and accuracy (Groves et al., 2019; Lubetzky et al., 2019; Niehorster et al., 2017; Peer et al., 2018; Spitzley and Karduna, 2019). Papers which used motion tracking (Groves; Lubetzky; and Spitzley and Karduna) to examine the Vive while moving yielded similar results to the ones presented in this paper. For example, Groves et al. found that the Vive had an average positional error of 2.63 mm, and an average rotational error of 0.45°. Papers which examined the Vive under static conditions (Niehorster and Peer) yielded less positive results about the validity of the system's tracking. Anecdotally, placing a controller in a completely static position would cause the controller to track inaccurately and move erratically.

This study had a capture volume with a distance of 18.5 feet between base stations for the room-scale calibration. This is beyond the official recommendation ("Tips for setting up the base stations," n.d.), but did not trip the normal warnings given by the base stations when they are too far apart. Researchers should be cautious when setting their capture volume, and should pay attention to any warnings given by the software. Capture volumes which are significantly larger than the recommended size will degrade the signal being received by the controller and might increase the likelihood of inaccurate tracking. Additional error could have potentially arisen in this study due to the amount of occluding material in the Vicon system's capture volume. The base station tripods and the robot arm both surrounded the controller, which could have led to errors from the markers being occluded. However, no markers attached to the robot were ever gap-filled,

indicating that at least three cameras were able to see every marker for each frame of data.

Several steps were taken to ensure that the Vive performed as optimally as possible, despite some possible sources of interference from the motion tracking system and robotic arm. Both the Vive and Vicon systems operate using 850 nm IR ("Re," 2017), which could cause the two systems to interfere with one another. Within the Baylor Biomotion Laboratory (which has 1600 ft² of space), there was no noticeable difference in controller operation when the cameras were on or off. However, controllers did lose tracking in another, smaller laboratory where the IR was more closely concentrated. Furthermore, multiple studies (Groves et al., 2019; Lubetzky et al., 2019) have used the HTC Vive in conjunction with an optical motion tracking system. Thus, it is possible that the motion capture cameras diminished the tracking ability of the controllers, but not in a way that a user would visibly be able to notice. Because the controller uses optical sensors, it was positioned in a way that these would be occluded as little as possible (Fig. 1). However, the controllers are able to track with some occlusion using the IMU, as this would be common during commercial use. While it is possible that the IMU was affected by components of the robot, the researchers were unable to determine a distinct visual difference in movement quality when the robot was in use. The optical motion tracking and robotic arm could have potentially interfered with the tracking capability of the Vive, but nevertheless, the overall accuracy and precision values obtained in this study for the Vive were very impressive and arguably would only improve if these potential sources of interference were eliminated. In this case, the benefits of using a robotic arm to precisely control movement and a fairly standard optical motion tracking system to serve as the gold standard movement measurement system seem to outweigh the potential drawbacks associated with potential interference effects. This combination of devices is a good choice for conducting standard validation protocols for 6 DOF motion tracking systems such as the Vive.

A primary goal for this study was to establish a methodology which was able to test 6 DOF virtual reality systems. A strong motivation for this is the wide body of research examining the Microsoft Kinect in which conflicting results are presented. Many papers report widely conflicting values, and their conclusions primarily come from completely novel procedures (Galna et al., 2014; Mobini et al., 2014; Nixon et al., 2013). By attempting to establish a methodology for 6 DOF systems such as the Vive, the researchers hope to develop a methodology which allows others to analyze virtual reality systems in a homogeneous way. As previously stated, several papers have been published which examine the motion tracking accuracy of the Vive's components (Groves et al., 2019; Lubetzky et al., 2019; Spitzley and Karduna, 2019). Although these papers give similar results, it is difficult to compare them because their differing methodologies vary in types of movement, tracking method, and method of movement. The methodology presented in this paper utilizes a common motion tracking method (optoelectronic motion tracking), and tests the system in a way that is repeatable and thorough in examining multiple controlled scenarios. Additionally, this methodology is particularly useful for validating 6 DOF VR systems for clinical use because it incorporates movements which reflect potential speeds and distances that subjects may use in clinical environments. Adoption of this method will allow researchers to compare their results to the ones in this paper, compare their results to concurrent systems, and compare their results to future systems.

This study demonstrates the HTC Vive's capabilities under extremely controlled situations. Future studies will measure movement accuracy of the system during actual gameplay and in other less controlled situations. The most direct application will be tracking of basic upper-body functional movement in the form of clinical movements such as arm raising and reaching tasks. However, it is possible

to apply the controllers to the legs in order to test lower body function to gain insight into knee flexion and extension angles. Subjects undergoing rehabilitation or those with motor disabilities will be of particular interest because of their unique motion patterns. While the Vive performed well under controller robotic and clinical movements, exercises and movements with sudden or irregular movement may not track as well. Further investigation is necessary to determine whether or not the Vive and other VR systems are viable options for more impaired subject populations or for exercises that involve more rapid changes of direction.

5. Conclusion

The results of this study indicate that the HTC Vive has great potential to accurately track human movement while providing an immersive environment for the user, making it a great tool for applications in biomechanical research and physical therapy. This study helped establish an easily repeatable validation methodology that can be used to compare the rotational and translational tracking capabilities of low-cost 6 DOF motion tracking technologies, such as the rapidly increasing number of available VR systems. Further studies should focus on expanding this validation methodology into testing the accuracy of these systems during typical human movements. The HTC Vive represents a new era, particularly in exergaming and physical therapy, because of its ability to transport users into completely novel environments. Future studies should leverage the combined motion tracking and immersive environment strengths of this and other systems to develop novel research experiments and clinical rehabilitation and training protocols.

Author statement

All authors listed were fully involved in this study and the preparation of this manuscript and its contents have not and will not be submitted for publication elsewhere.

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Declaration of Competing Interest

There are no conflict of interest to disclose.

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