# Portable Virtual Reality: Inertial Measurements and Biomechanics


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**ABSTRACT**

This paper presents a portable virtual reality (VR) system that affords full-body tracking by using inertial measurement units (IMUs) and several aspects of human biomechanics. The current implementation uses a commercial IMU-based full-body tracking system that only reports the orientations of body segments. We have developed an anthropometry-based method that uses this orientation data to derive accurate body-segment positions. In turn, we use kinematics and heel-based translations to provide a theoretically infinite tracking space. A head-mounted display (HMD) is used to provide visual feedback of the user's full-body avatar and to convey physical locomotion through the virtual environment. We discuss key challenges to making this system usable in everyday environments, including calibration, ergonomics, drift, and collision avoidance.



**Keywords**: Portable virtual reality, biomechanics, body tracking.

**Index Terms**: I.3.7 [Three-Dimensional Graphics and Realism]: Virtual Reality; H.5.2 [User Interfaces]: Input devices and strategies


## 1 INTRODUCTION

Historically, immersive VR has rarely been seen outside of the lab. This is primarily due to the expensive and stationary devices required to implement these interfaces. Precise tracking systems, such as Intersense or Vicon, cost several thousands of dollars and are not feasible to move due to potentially damaging the expensive devices and needing major recalibration. The Animazoo Gypsy 7 system allows for mobile tracking, but its rigid exoskeleton design limits the user's range of movements. Newer devices, such as the Microsoft Kinect and Oculus Rift, have enabled VR outside of the lab by being portable, but are normally limited in one of two ways.

The first common limitation of newer portable tracking systems is a restricted field of regard (FOR)—the total size of the visual field in degrees surrounding the user. This is normally due to using an optical tracking approach with a single camera device, such as the Microsoft Kinect. With a narrow optical field of view (FOV), the Kinect requires a direct line of sight to track the user and even then has difficulty when the user turns around due to the nature of computer vision techniques. In order to create a full 360° FOR with tracking, multiple Kinects are required. Interference between multiple Kinects can cause problems due to multiple infrared sources for depth recognition. While there are methods to work around the problem, such as a shuttering approach [1], they still require a lengthy period of time to set up and calibrate, which diminishes their portable qualities.


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The second common limitation of newer portable systems is a lack of full-body tracking capabilities. While both versions of the Oculus Rift HMD provide a full 360° FOR, neither is capable of tracking more than the user's head. The upcoming Sixense STEM system uses electromagnetic tracking to offer five tracked objects, but it still will not provide full-body tracking capabilities, which have been shown to increase presence [2] and improve depth estimations [3] through avatars.

We have developed a portable full-body tracking system with an unrestricted FOR and a theoretically infinite tracking area. We have combined this tracking system with an Oculus Rift Development Kit 1 (DK1) HMD to provide a portable VR system that can be used outside of the lab and in everyday environments, such as living rooms and office spaces. Unlike other portable VR systems, our system affords full-body avatars and 360 degrees of full-body interactions.

The heart of our portable VR system is our full-body tracking system, which relies on IMUs to measure inertia and relative orientations while a biomechanics-based algorithm tracks global positions of the user's body segments. Our system's current implementation uses the YEI 3-Space motion capture system. While this commercial system reports accurate body-segment orientations, it does not measure or track any global translations of the user. Hence, any physical locomotion techniques are impossible to implement with the 3-Space system's application programming interface (API).

To circumvent the limitations of the 3-Space system's API, we have developed a biomechanics-based method to afford a tracking area for physical locomotion that is theoretically infinite in size. First, we use anthropometrics to accurately measure the user's body segments, which we represent with a rigid-body skeleton. By applying the orientations reported by the 3-Space system to each respective skeleton segment, we derive body-segment positions that are more accurate than those reported by the system's API. Next, we use principles of human kinematics to track the user's global position by defining heel-based translations in accordance with the user's current direction of movement.

In this paper, we describe the details of our portable full-body tracking system and the biomechanics-based algorithm that drives it. We also present a preliminary informal study of our portable VR system to determine its feasibility and usability. We discuss issues that we have identified as key challenges to making our portable VR system usable in everyday environments. These include more-accurate calibrations, improved ergonomics for wearing the IMU sensors, improving tracking accuracy by addressing drift (i.e., error accumulation), and helping the user to avoid collisions with real-world objects. We conclude with our current efforts and planned future work.

## 2 RELATED WORK

Since our portable VR system relies on IMUs, we first cover related works on inertial tracking systems. We then discuss other VR systems that are portable or offer low-cost full-body tracking.

### 2.1 Inertial Tracking Systems

Previous work in inertial tracking has shown viability for motion capture. In a paper on an IMU-based motion capture system [4], Prayudi et al. have shown the ability to capture the motion of an arm through a serial-chain network of IMUs and microcontrollers. Further research by Prayudi and Kim [5] has shown feasibility of using a pre-defined pose to calibrate sensors and create offsets for frame calibration. This allows for a calibration method that can be used for any user and is simple to define.

Other research in IMU-based tracking done by Mannesson et al. [6] relies on radio triangulation to derive position while using orientation derived from IMUs. This method utilizes existing radio infrastructure, but involves an issue with signal scattering when indoors. The researchers are unsure of the exact limits and imperfections of the system, but it does allow low-cost IMUs to be used with the aid of radio signal information.

Recently, Jung et al. [7] have published similar research in creating a mobile tracking system based on IMUs. Their system requires a special setup to determine tracking states with smart shoes that sense ground reaction forces. The system allows for full-body tracking and obtains human posture by combining the vectors that correspond to body segments. This creates a system that can approximate positions through orientation tracking.

While researchers have made much progress with developing IMU-based tracking systems, there has been little consideration to how IMU-based tracking affects users in VR systems. Also, while researchers have taken advantage of some aspects of human biomechanics, such as kinetics, other aspects of biomechanics, such as anthropometry, have yet to be leveraged.

### 2.2 Portable Virtual Reality

Commercial products are not the only foray into portable VR, as researchers have also been investigating such systems.

Basu et al. have created a demo of a system that allows for a portable and untethered configuration [8]. This system utilizes an electromagnetic tracker on a wearable belt to track the user's hands. A smartphone HMD is used as the primary display with the phone's internal IMU providing orientation. A handheld device is used for navigation, as the system only supports rotational head tracking and not translational movements, such as walking.

Bachmann et al. [9] have been working with a portable immersive virtual environment system that utilizes IMUs placed on the feet and head. They use zero-velocity updates to derive nearly accurate positions and orientations of the sensors. In outdoor applications, a GPS is used for position tracking, and an ultrasonic transducer is used to plot the landscape in front of the user to create redirected walking paths and prevent the user from walking into obstacles.

While these systems provide portable VR experiences, neither system supports full-body tracking capabilities.

### 2.3 Low-Cost Full-Body Virtual Reality

While there are many VR systems with full-body tracking, only a few systems are relatively inexpensive.

Livingston et al. [10] have worked with the Kinect to determine if it is suitable for full-body gestural recognition. They found that it could function for that goal, but that its latency for a VR system could be as long as 500ms, which is too lengthy and may cause user discomfort. This can be a major problem if using the derived skeletal structure from the Kinect to drive head tracking, as simulator sickness will likely onset.

One way to increase the capabilities of the Kinect is to increase the number of Kinects in a given space and have them track a user in a calibrated space. Research by Satyavolu and others has shown this is a viable option for low-cost tracking in VR applications [1]. There are issues with using multiple Kinects in a single space though due to infrared interference. Additionally, occlusion can cause discrepancies in tracking because some portions of the body may be hidden from view.

Researchers have also investigated full-body interactions within VR environments with off-the-shelf hardware. A recent demo by Takala and Matyeinen [11] has shown a working and affordable system is possible with a Microsoft Kinect, Playstation Move, Razer Hydra, and Oculus Rift. The researchers demonstrated that the interactions afforded by the system can be very robust. Ladder climbing and simulated physics interactions are two examples, but locomotion is still accomplished virtually through a controller.

Kinect-based systems have been demonstrated as promising inexpensive solutions to full-body VR. However, these systems are still limited to small tracking volumes due to the Kinect's FOV and are often not very portable due to complex setups.

## 3 Portable Full-Body Tracking System

The centerpiece of our portable VR system is our portable full-body tracking system. It relies on IMU sensors to determine the orientations of the user's body segments. A calibration process is used to synchronize the sensors and the body segments. Our biomechanics-based approach uses anthropometrics to define accurate body-segment positions through rigid-body dynamics and human kinematics to track the user's global position based on heel strikes and the current direction of movement.

### 3.1 Inertial Measurement Units

Our current implementation uses 17 wireless YEI 3-Space sensors as IMUs for determining the orientations of the user's body segments. Each sensor consists of a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer. The 3-Space API provides direct access to each of these nine data values. Additionally, the API will report a relative orientation for each sensor based on an initial orientation. Orientations are determined by sensor fusion, with the accelerometer's gravity vector and the magnetometer's compass vector used to correct the gyroscope's angular velocity.

With the sensors attached to the user's hands, arms, upper arms, shoulders, feet, calves, thighs, waist, chest, and head, the 3-Space system accurately reports the orientation of each body segment. However, it does not report or measure any global translations of the segments. Hence, it cannot be used to track any of the user's physical locomotions or movements through the real world. Our biomechanics-based approach, described below, manages this.

### 3.2 Sensor Calibrations

Because we use a rigid-body skeleton to drive our biomechanics-based approach, it is necessary that the initial orientations of the sensors and user's body segments match the initial orientations of the skeleton's segments. Hence, the sensors must be calibrated before our approach can be applied. Currently, this process involves the user standing in a T-pose in order to define an orientation offset for each sensor. The orientation offset conforms the reported sensor orientations to the orientations of the skeleton's joints.

### 3.3 Anthropometric Rigid-Body Dynamics

Many IMU-based tracking systems use rigid-body dynamics to track the movements of the user's body segments relative to the user's pelvis. These systems use the orientations of the sensors as the orientations of a skeleton's joints. Due to forward kinematics and rigid-body dynamics, the positions of the skeleton's segments roughly conform to the positions of the user's body segments. The absolute accuracy of these positions depends on how closely the user matches the skeleton in terms of height and other measures of body-segment lengths. If the user's measurements are drastically different from the skeleton's, these positions will be inaccurate.

To improve the accuracy of this approach, we have integrated anthropometrics (the study of human measurements) into our rigid-body dynamics. Our base skeleton model is sized to be six feet tall with average body segment proportions as laid out by Drillis, Contini, and Bluestein [12]. In our current system, we input the user's total height and hip height to scale the body segments of the skeleton according to the body proportions surveyed by Drillis, Contini, and Bluestein. This creates a one-to-one, full-body mapping between the skeleton and the user. In turn, this mapping results in more-accurate body segment tracking for the measured user. For future work, we plan to investigate additional measurements, such as knee height, shoulder width, and arm lengths, to further improve this body segment mappings.

### 3.4 Heel-Based Kinematics and Global Tracking

While IMU sensors and rigid-body dynamics can be used to track the user's body segments, these segments are tracked relatively to the user's pelvis. This is apparent when users crouch down, as their skeleton counterparts appear to levitate off the ground with their knees above the waist. To provide absolute tracking of the user's body segments and to afford global positioning, we have developed a heel-based kinematic approach.

Our approach translates the pelvis origin of the skeleton based on the frame-to-frame changes in position of an active heel anchor point relative to the pelvis. For example, assume the right heel is the current anchor point and the user's gait cycle is in the single-limb stance period, just before the left foot strike. During this period, we calculate the difference between the pelvis position and the right heel position every frame. We then subtract the previous frame's pelvis-heel difference from the current frame's pelvis-heel difference and translate the pelvis by that amount. This in turn translates the entire skeleton forward relative to the heel, essentially turning the active anchor point into the skeleton's transformation origin (see Figure 1).

Our current implementation uses the left and right heels as potential anchor points. Each frame both points are compared to determine which is closest to the ground. The lower heel is then defined as the active anchor and remains in a static position within the tracking space while all other body segments move relative to it. At the time of the opposite foot strike, the other heel becomes the active anchor, which allows the skeleton to perpetually move forward. This affords a theoretically infinite tracking area.

Our heel-based algorithm affords tracking during walking, crouching, strafing, and even stepping backwards. There are some issues currently for any action that requires both feet to leave the ground, such as jumping. If a user jumps with the current system, then the skeleton will still keep one foot on the ground as an anchor point, which breaks the one-to-one mapping between the user's position and the skeleton's. For future work, we plan to use the accelerometer data to develop predictive algorithms for these types of cases to improve tracking accuracy.

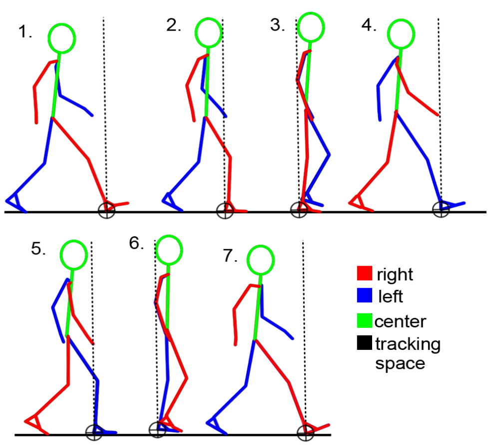


Figure 1: Definition of the skeleton's transformation origin based on the active heel anchor point.

Figure 2: Our portable virtual reality system includes 17 3-Space IMU sensors, an Oculus Rift DK1 HMD, two Nintendo Wii Remotes, and a backpack with wireless HDMI capabilities.

## 4 Portable Virtual Reality System

Using the portable full-body tracking system described above, we have created a portable VR system (see Figure 2). Our current implementation uses an Oculus Rift DK1 HMD for visual output and Nintendo Wii Remotes for wireless bimanual input. A Dell Precision Mobile Workstation laptop runs our biomechanics-based tracking system, processes input from the Wii Remotes, and renders graphics to the DK1 using the Unity game engine. Due to our anthropometric-based approach, the user's viewpoint in the virtual environment matches his or her real-world height.

Our VR system supports two modes of usage: portable and completely mobile. In the portable mode, we use a backpack to carry a wireless HDMI receiver, the Oculus Rift control box, and an external battery that powers both the receiver and the control box. A wireless HDMI transmitter is then used to push video to the Rift from the laptop sitting on a table within 30 ft. This mode is fairly easy to set up and avoids weighing the user down with equipment. In the completely mobile mode, we place the laptop in the backpack and remove the HDMI transmitter/receiver pair. In this mode, the VR system is only bounded by the real-world environment, but can quickly fatigue the user due to the weight.

## 5 Preliminary Informal Study

To judge the feasibility and usability of our portable VR system, we conducted a preliminary informal study of the system. Four male participants from our laboratory volunteered for this study. All of the participants had several prior VR experiences.

At the start of the study, each participant was measured for total height and hip height to scale the tracked skeleton proportionately. After equipping our portable VR system, participants stood in the T-pose to calibrate the sensors. Each participant then performed locomotion and interaction tasks within a testing environment to observe how well the system tracked the participant's movements. The testing environment consisted of a 4m x 4m virtual space with boundaries that corresponded to the testing room to avoid running out of physical space. Within the boundaries, a green box, a red pillar with a blue sphere on top, and an orange wall were spaced out. The participants maneuvered around the objects while walking, crouching, and reaching. The participants were also asked to perform some calisthenics and observe the movements of the virtual avatar as it corresponded to their own physical movements. After the testing environment, the participants filled out a usability questionnaire, the Slater-Usoh-Steed Presence Questionnaire, and the Simulator Sickness Questionnaire.

The results of our informal study were promising. The usability questionnaire showed that the avatar moved nearly as expected for users, though physical locomotion and the point of view need some minor improvements. Participants reported low simulator sickness ratings with only two of the four reporting slight general discomfort and fullness of head. Presence questionnaire results showed moderate levels of presence for three of the participants with a mean score of 4.33. However, one participant reported a mean score of 1.5. We believe this was due to a poor calibration.

## 6 Key Challenges for Everyday Environments

### 6.1 More-Accurate Sensor Calibrations

During our informal study, we observed that the quality of the VR experience and the full-body tracking was majorly dependent upon the user's T-pose during sensor calibrations. One participant in particular complained of the avatar's virtual hands not aligning when physically clapping their real hands together. During the calibration phase, the participant likely let one arm rest lower during the T-pose, causing the corresponding virtual arm to appear higher than the physical arm during the VR experience. To address this issue, we are investigating different poses and postures for sensor calibrations. We expect that a standing pose with the arms down by the sides may produce the best result.

### 6.2 Improved Ergonomics for Wearing Sensors

In our current system, the YEI 3-Space sensors are secured to the user's body segments with Velcro straps. In practice, it requires approximately 5 minutes to put on and strap all 17 sensors. We consider this setup time to be too long for an everyday system. As future work, we plan to integrate the sensors directly into articles of clothing for rapid donning and doffing. Instead of donning 17 sensor straps, users will put on overalls and a jacket. This should significantly reduce setup time.

### 6.3 Eliminating Drift

While we have not yet evaluated the degree of drift (i.e., error accumulation) in our current implementation, we are certain that drift will be a major issue for the system to maintain a high degree of tracking accuracy over long periods of time. We have already experienced some drift during testing due to interfering magnetic fields. We have not yet measured the drift as we are currently working on improvements to our sensor fusion algorithms. One potential method for eliminating or at least reducing drift is to use computer vision techniques to occasionally recalibrate the tracking system. With mobile HMDs, such as the Samsung Gear VR, the outward-facing camera can be used to determine absolute movement by tracking visible landmarks and observing optical flow. Also, as users bring their hands and other body segments within view of the camera, corrections can be made to any body segment drift.

### 6.4 Real-World Collision Avoidance

Assuming that HMDs with outward-facing cameras will be used anyway to eliminate drift, simultaneous localization and mapping (SLAM) techniques can be used to avoid real-world collisions. SLAM techniques can be used to recognize objects within the near physical environment. The size and other qualities of the displayed virtual environment can then be dynamically updated to help the user avoid colliding with these real-world objects. For example, redirected walking can be used to steer the user away from tripping over a chair. Additionally, if the user maintains a collision path with an object, the outward view of the physical environment can be faded in over the virtual environment view to notify the user of the upcoming collision.

## 7 Conclusion and Future Work

We have developed a portable VR system capable of full-body tracking with an unrestricted FOR and a theoretically infinite tracking area. It relies on IMU sensors, anthropometric rigid-body dynamics, and heel-based kinematics to track the user's global position and body segments. This system has shown itself to be easily usable in spaces not traditionally considered for immersive VR, such as small rooms and office spaces.

Currently, we are in the process of evaluating the tracking accuracy of our portable full-body tracking system by comparing it to an optical Vicon tracking system. We are investigating ways to make the biomechanics-based algorithm more robust for atypical movements. We are also creating a new environment for testing based on an office space to facilitate tests of distance perception and interactions using the hands. In the near future, we plan to begin development of clothing articles with the sensors sewn in for better ergonomics and faster donning and doffing. We are collaborating with electrical engineers to reduce sensor costs.

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