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A four-wall virtual reality visualization of patient-specific anatomy: Creating full user immersive experience from computed tomography scans

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Abstract
Virtual reality is the future of medical imaging diagnosis. Previous studies have introduced virtual reality rendering of anatomical models while others have mentioned processes to extract 3D models from Computed Tomography (CT) images. In this study, we provide a detailed workflow to transforming patient-specific two-dimensional (2D) CT dicom format imaging files to three-dimensional (3D) immersive, dynamic and interactive anatomical assembly models while incorporating them into a four-wall virtual reality environment system. Our study implemented 3D CAD and virtual reality capacities through software and engineering design tools to transform 2D medical images into interactive 3D models in our system. In doing so, the user was able to gain a sense of depth, scale, and dimensionality while immersed in the environment and while implementing interactive tools to investigate patient- specific hip-femur dynamics. At the same time, users were able to identify key anatomical landmarks in the patients' hip joints. Applications of the VR system to the medical field and orthopedics, in particular, were discussed.

1. Introduction

In this paper, we present the unique set-up we developed to visualize and produce medical imaging into the VR environment. The difference between our 4-wall VR system and head mounted displays HMD VR experience is demonstrated. The presented 4-wall virtual environment is a fully immersive virtual reality (VR) environment that consists for a collection of screens with rear projection of content visualized in space through the use of head mounted devices or 3D glasses, an integration system of software, and multiple projector-screen apparatuses. The presented 4-wall VR system submerses the viewer in the constructed virtual world allowing for interaction, body/head tracking, haptic feedback and visualization capabilities unlike any other. In addition, the presented system systems give users room to move physically and further experience the immersive environment compared to head-mounted display (HMD) virtual reality systems. The 4-wall VR system presented in this paper is also a collaboration environment. Since the 3D LCD shutter glasses used do not block the room view of the user, collaboration and group visualization are possible. Efforts have been made to immerse surgeons and patients in renderings of abdominal CT scan data using HMD VR capabilities through their desktop display system were difficult for surgeons. Tcha-Tokey et al., [1] concluded that CAVE VR experiences, similar to our 4-wall VR environment, presented significantly greater user experience (UX) based on both subjective questionnaires and completion time test data that measured presence, engagement, flow, skill, and judgement compared to HMD systems. Another advantage to the 4-wall VR system compared to the HMD setup is the wand, an interactive tool with six degrees-of-freedom, that allows the user to move in space with full tracking and haptic feedback capability during VR simulation person-object interactions as mentioned in [2].

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2. The case for immersive visualization

Until recently, virtual reality applications have not been used to simulate medical procedure nor conduct medical research to further our understanding of human anatomy and physiology, let alone introduce patient-specific technological capabilities in the world of medicine. Sigitov et al., [3] mention in their work that although most medical professionals use modern three-dimensional (3D) imaging equipment like Computed Tomography (CT) and magnetic resonance imaging (MRI) scanners, most of the information reviewed is in a "slice-wise manner" on a "2D medium" which does not give medical professionals the, sometimes, necessary opportunity to immerse themselves nor interact with the data in an informative manner. While some efforts have been made to immerse users in 3D anatomical structures like blood vessels, Long et al., [4] chose only to provide volume rendering to stop depth perception from being lost and disorienting the user.

Witkowski et al., [5] present work on patient-specific musculoskeletal models of lower limbs for surgical planning interventions with a semi-immersive system, not fully-immersive as with the 4-wall VR system presented, and planning functionality using 2-D display and standard mouse, as opposed to a haptic feedback capable VR wand with full-motion tracking demonstrated in our work. Finally, Al-khalifah et al., [6] present a CAVE experience navigating volumetric medical datasets, yet based on their results, visualization was conducted with only one wall. In our work, we provide a 4-wall immersive and active VR system with head tracking for improved 3D stereoscopic vision capabilities as well as motion tracking to enhance the user's sense of movement and floating models in space with SolidWorks computer-aided design (CAD) implementation to create joints between members for user interaction. The 4-wall VR demonstrated here provides multi-user interactive and collaborative environment. This is expected to be useful for medical staff collaboration as well as surgeon-patient review of planned procedures. The following paragraph describes the term "Patient-specific personalized medicine" according to the US National Institute of Health, NIH.

As technological advancements in the field of medical data visualization expand, in 2015, all of US research programs known as the Precision Medicine Initiative cohort program were created and are geared on making advancements in individualized treatment plans. The general idea behind precision medicine is the utilization of multiple data streams in analytical work in order to develop better treatments for individuals. This is not to say that certain patients will receive special treatment, rather technological innovation will allow medical professionals to tailor treatment plans to an individual of interest seeking medical attention [7]. Arnold et al., [8] express the fact that there exists little literature on the subject of patient- specific procedure planning and practice, especially efforts aimed at improving patient outcomes. Our work provides a novel step-by-step procedure to creating patient-specific 3D anatomical models from CT scan information and visualizing these models in a fully immersive 4-wall active VR environment.

3. Methods

In approaching this project, a system of integration mapping out the processes involved in creating the intended virtual reality experience was produced and is shown in Figure 1. Each process is elaborated on in this paper with feedback loops and their justification for incorporation is detailed. In the end, this apparatus allows health care workers and medical professionals to translate vital medical imaging information in virtual reality experiences to extract more information from obtained images.

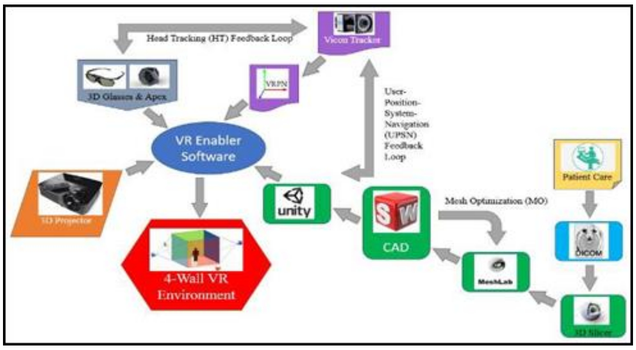

Figure 1. Data and software system integration flowchart for the 4-Wall VR environment.

4. CT Scan Segmentation and Model Development

Publicly available CT scans of patient donors at the University of Iowa Carver College (UICC) of Medicine "Visible Female CT Dataset" was used. With that dataset, CT scans of hip and pelvis body parts were utilized in hopes to recreate the human (female) hip joint, creating an assembly of the two components and utilizing 3D measurement tools to create a coordinate system and point of origin to locate the necessary data points to create a "mate" or 3D connection between the two parts (pelvis and head of femur). More on this matter is discussed further in the document.

For an accurate, high-resolution model to be constructed through 3D slicing software, CT scan files with a larger quantity of slices were of interest. As part of the Magnetic Resonance Research Facility at the UICC,

400 CT scan (.dcm) files were utilized for a female individual hip while 150 CT scan (.dcm) files were obtained which was a total of 550 CT slices that were used in the creation of the 3D model.

3D Slicer® is an open-source software used for bio-imaging informatics, imaging processing, and 3D visualization applications. Through the support of the National Institutes of Health (NIH) and other worldwide developers, the 3D slicer was made possible. The 4.10.2 version was used. The following steps were taken to translate the 2D CT scan (.dcm) scan files to create a 3D model, which was taken to other software platforms for further analysis and adjustment while preserving the integrity of anatomical features of the UICC female hip joint:

1. After launching 3D Slicer, load DICOM files from desktop (after saving the files from UICC website).
2. Go to the Segment Editor module and add a segment
3. Under Effects, select "Threshold" and adjust the intensity range using the slide bar until only human bone is highlighted in the sagittal, coronal and axial views, then click Apply
4. Click "Show 3D" to see the highlighted portions of the CT scan put together into a 3D model shown in the program
5. Next, click "Islands" and under Edit Islands select "Keep largest island", this will delete all volumes smaller than the largest volume that is intact in the newly created 3D model. As a result, the 3D model now only includes the two-femur head and the pelvis.
6. Add a new segment in order to highlight the femur bone and segment it from the main pelvic structure
7. In order to separate the ball from the socket in this hip-femur joint, the "Paint" tool under "Effects" in the Segment Editor module must be used.
8. Under "Paint", select the "Sphere brush" and use the shift key and wheel button on the mouse to increase or decrease the diameter of the sphere brush that will be used in the sagittal, coronal, and axial views of 3D Slicer
9. Use the scroll button on the mouse in all three views to find the section where the diameter of the femur head is largest, place the cursor with the sphere brush tool selected, and click to highlight that spherical area in the 3D view
10. Next, select the "Islands" feature under effects and select "Add selected island" and select in any of the three views any part of the femur bone that is highlighted in designated color. The software will add the rest of the femur bone to the isolated femur head
11. The above procedure can be done to the other femur head and bone in add yet another part to the assembly
12. Export the parts individually using the "Export to files" feature in the Segmentations module. The default file format is STL which works well with SolidWorks and MeshLab, two software that will be elaborated on later in the document.
13. In addition to exporting individual parts, export the entire assembly which will be used as one solid model to retrieve necessary dimensions to establish ball and socket joint in SolidWorks Assembly.

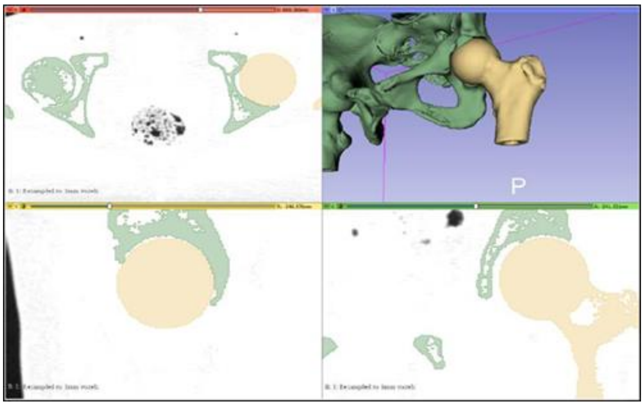

Figure 2. 3D Slicer top-side-front panels and 3D rendering of hip-joint post segmentation process.

STL models exported from 3D Slicer having been created from 550 slides has a high mesh resolution that causes the file size to be anywhere from 30-40 Mb in size. This can burden the user with time waiting for the software to handle such a high- resolution mesh. In order to decrease the file size, re- mesh works and filtering processes must go underway through the MeshLab software, another open-source software designed to edit mesh models along with other capabilities.

In MeshLab, complete the following steps:

A. Go to File and click on "Import Mesh"
B. Find the STL file that was created from 3D Slicer
C. Post-Open Processing window will pop up, click OK to "Unify Duplicated Vertices"
D. On the top of the menu program, click on the "Wireframe" icon to display the import part as wireframe with the mesh in full display.
E. Next, go to "Filters" at the top of the window and expand the "Re-meshing, Simplification, and Reconstruction" tab, then select the "Simplification: Quadric Edge Collapse Decimation" option. This option will make polygonal reduction or mesh decimation to decrease the number of faces that complies the model, in order to decrease the total amount of data needed to operate with such model Under "Percentage reduction", type 0.5 (or 50%) and click Apply. This will tell the software to cut down the total number of faces that complies the model by 50% which preserving the overall geometry of the pelvis or hip, thus keeping the models anatomically accurate and fairly easier to use in other software
F. Step 6 can be repeated several times until an optimal face count and overall geometrical appearance is met
G. Export the mesh by going to File and Export mesh. Use STL as the file type to be used in the last software in this integrated CT scan to 3D assembly process: SolidWorks.

5. The Solid-modeling CAD Joint Assembly

Before mating the femur head with the pelvic acetabulum can occur, three-dimensional coordinates and measurements relative to the fixed point of origin must first be established for the assembly of the two to result in an anatomically accurate manner. In order to set up a coordinate system, three planes must be assembled using the 3-2-1 rule of fixturing.

The non-segmented pelvis and femur whole body was imported into SolidWorks. Three points on the top surface of the L4 vertebrae was used to create the Top Plane (z-axis). For the Right Plane (x-axis), the first reference was a perpendicular callout when the Right Plane and the Top Plane. Two additional vertices were chosen along the entire span of the cross-section plane (created by Cropping in 3D Slicer) were used in additional to the perpendicular callout to fix and define the Right Plane. Next, an axis was created from the two above planes. The last plane (Front Plane, y axis) was created using a perpendicularity callout relative to the newly created Axis and a vertex point created on the superior and anterior portions of the L4 vertebrae. Then, a point was created from the intersection of the Axis line and Front Plane. This point will be used to define the point of origin in the model. Finally, the coordinate system was defined using the three planes mentioned previously and the point of origin previously defined.

Before measurements can be conducted, a uniform spherical surface of the femoral head must be constructed. A handful of triangular faces on the surface of the femoral head mesh were selected to define the new “perfect” spherical surface. Next, a point was defined as the center of the newly formed sphere in order to locate the center coordinates of the femoral head during the measurements.

The measuring tool was used as shown in Figure 3 to define three-dimensional distance from the point of origin and the center of the femoral head. The following coordinates were calculated, with the diameter of the femur head being approximately 23mm: X = 91 .882 *mm,* Y = 42.148 *mm,* Z = 160.711 *mm.*

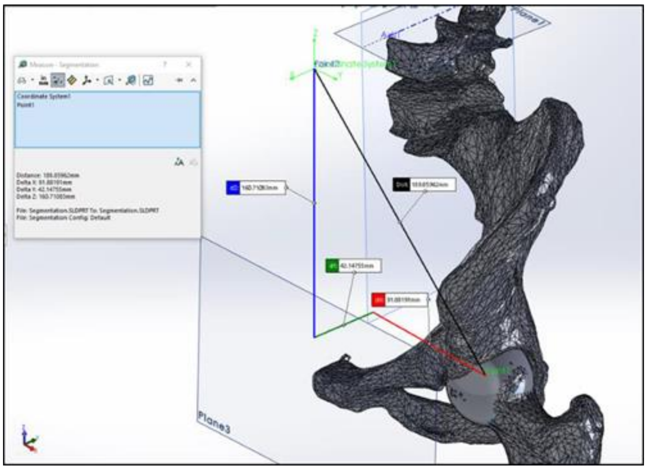

Figure 3. X-Y-Z coordinate system and 3D distance calculation of hip-joint in the solid-modeling software

The same procedure can be applied to the individual hip and femur head components. After the theoretical center of the femoral head is located on the bare pelvis bone, an assembly can be conducted where mating between the theoretical center point of the head and the actual center of the head occurs, thereby joining the two entities back in their original anatomical relative locations, except now allowing freedom of rotation of the femur bone in the socket of the pelvic acetabulum.

In order to return the main axis of the femur bone back to the correct anatomical position found in the CT scans, a cylinder was extruded from a Plane created from 3 points located at the bottom of the section found on the femur bone. An Axis was created from the cylinder. In addition, Right Plane and Front Plane were both used to create another Axis. Angularity between these two axes was determined to be approximately 1.96 deg. Therefore, angular mating between planes and the newly formed axis on the femoral head were performed fixing the femur bone in this correct anatomical location within the acetabular socket.

6. Game-Engine (UNITY 3D Software)

Unity 3D is a software created for the development of digital games but, recently, has been used in several field of study including engineering, medical simulation and architecture. Sigitov et al., [3] have used the platform for rapid prototyping and content generation as has been done in this study. Having successfully modeled the hip-femur assembly in SolidWorks, a SimLab Soft FBX file exporter add-on was used to create the appropriate file type for Unity 3D readiness [9]. A new project was created in Unity in which a pre- fabricated dissection hospital scene obtained from the Unity Asset Store was downloaded and hip-femur joint incorporated. Adjustment to size, lighting, camera, VR node connection and joint physics capabilities (character joint is the term used in Unity) were accounted for in scene production. Real physics applied to the joint were implemented in order to allow the VR user to interact with the anatomical components in the 4-WALL environment. Background C# scripting was performed in communication between Unity software and the VR enabler/Tracker integrated system to allow for head tracking and navigation capabilities by merely walking within the CAVE space as opposed to using a wand for navigation as has been done in the past [10-11-12-13].

7. The 4-Wall VR System Setup

As shown in Figure 4, the 4-WALL consisted of an assembly of 3” x 3” aluminum extrusion connected to one another using L-brackets and round head socket screws. Three aluminum extrusions were used for the top and side supports per screen with additional extrusions used to mount the 4th projector as shown in Figure 5. Each screen was made of acrylic with special coating to allow for stereoscopic capabilities. Four projects were incorporated in the design: InFocus IN5312a with 3D projection and side-by-side settings.

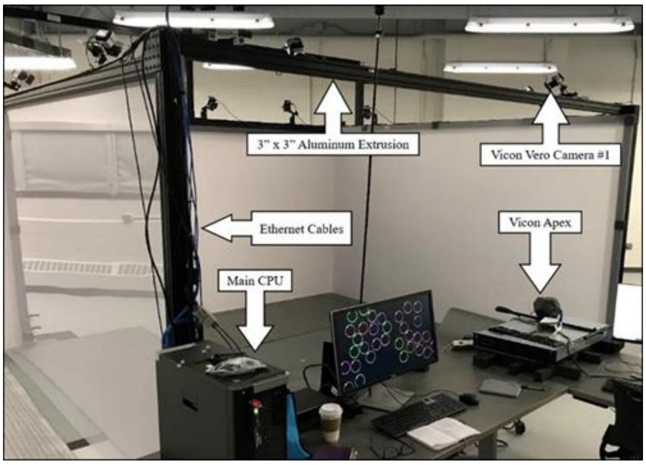

Figure 4. The 4-wall VR setup with optical tracking cameras, interaction device, and main workstation.

Nine optical tracking cameras were mounted to the top extrusion support bars along the length of the screens using six-degrees-freedom adjustable joints and mounting fixtures as shown in Figure 5. Using Ethernet cords and high-quality graphics card, all connections between the cameras were connected to an optical tracking camera lock sync box which was connected to the main CPU. Ethernet server adapter properties were altered to ensure maximum data reception from Optical tracking cameras to Optical tracking Tracker software on main CPU as per guidelines from Optical tracking Quick Guide manual. Calibration of Optical tracking Vero® cameras was undertaken with the assistance of its iPad app and special reflector markers (same markers used in head tracker) to map out incremental clusters of volumes in the 4-wall environment.

Optimization of the location and orientation of all nine cameras along the top sides of the screens was conducted in SolidWorks as shown in Figure 5. In this Figure, each field of view (79.0 deg x 67.6 deg at a total length of 12 m) was modeled and attached to the front of each camera.

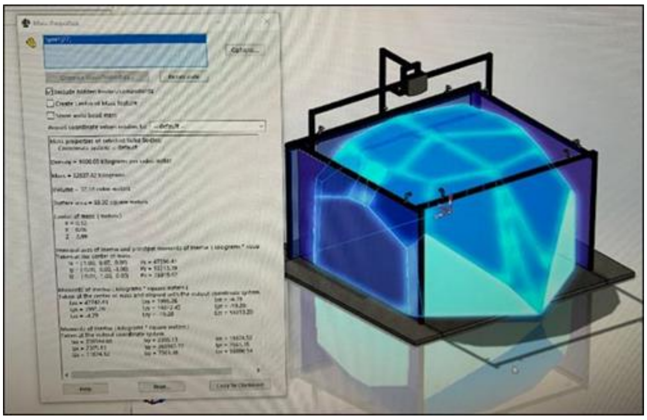

Figure 5. Optical tracking cameras' placement, orientation, optimization, and combined volume calculation.

After each camera was calibrated and coordinate system orientation was determined, "objects" were created within Tracker to identify 3D glasses movement (head tracking) in the VR enabler and ultimately Unity 3D. 3D printing and SolidWorks modeling tools were utilized in creating custom build marker holders mountable on 3D glasses as shown in Figure 6. Once "object was created, a simple text-file based virtual reality peripheral network (VRPN) was used to link the created object in Tracker to the VR enabler software. Using similar syntax, Middle VR allowed us to introduce 3D glasses as an object as was previously done for the Tracker Apex (a device that contains a joystick, buttons and operates as a wand in the VR scene). Once the configuration was complete, stereoscopic cameras setup in the VR-Enabler model were tied to a "tracker" in this instance the 3D glasses. This allows the user to move freely in the 4-Wall VR Environment which real-time tracking to occur in order continuously inform VR-Enabler where the location of the camera (the user's point of view) is in the 4-Wall VR Environment. Having head tracking capabilities transforms the 4-Wall VR Environment experience from forcing the user to stand directly in the middle of the 4-Wall VR Environment to experience the full effect of the stereoscopic cameras to being able to freely move while tracking is happening and the users' head (and eyes) can control the virtual reality experience, giving the system integration continuous feedback for optimal experience.

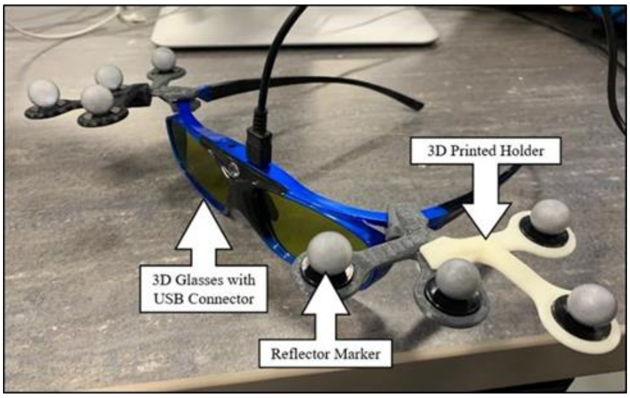

Figure 6. 3D VR glasses with reflectors for head tracking.

5. Results and Discussion

An immersive virtual reality tour in the 4-Wall VR Environment was conducted using Joystick navigation capabilities of the Optical tracking Apex device as shown in the Figure 7 below. Floating capabilities with the 4-WALL VR Environment apparatus were evident as shown in Figure 7.

In Figure 8, 3D glasses were placed directly in front of the camera lens to allow for the camera to capture stereoscopic effects of the projection.

Figure 7. The 4-WALL VR Environment VR simulation of dissection room with patient-specific hip-femur joint.

Anatomical features of the hip-femur joint including greater trochanter, lesser trochanter, intertrochanteric crest, femur head, femur neck, fovea capitis, and the acetabulum portions of the pubic bone, ischial bone, and iliac bone were identified using the VR-Enabler wand pointer. Decomposition of the joint was made possible by developing a VRAction script and collider to the hip and femur components in Unity 3D game engine software, while at the same time, using "Manipulation Return Objects" script was selected for those objects in order to return them in their original position after a set amount of time past disassembly.

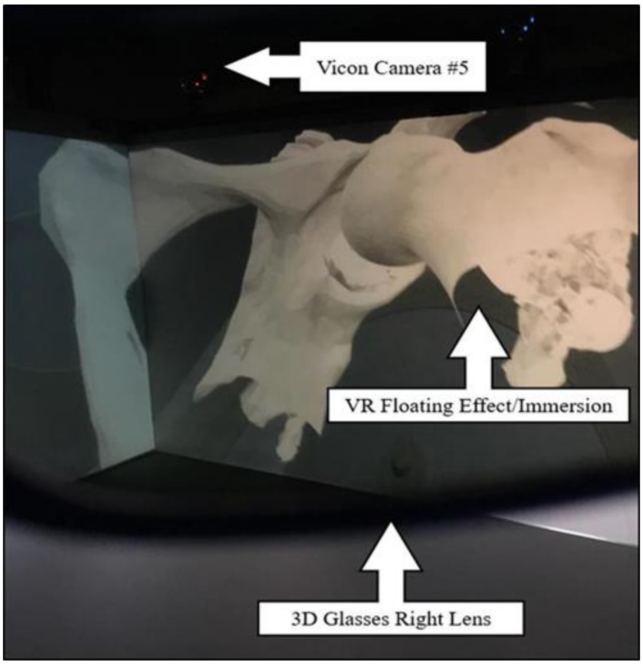

Figure 8. 3D glasses rendering of immersive experience in patient femur bone.

Due to added physics (Character joint) when the femur bone and the acetabulum in Unity 3D, the patient-specific model was dynamic, and the joint was exploded in flexion, extension, abduction, adduction and medial/lateral rotations. As the users immersed themselves in the model, a sense of depth and scaling for anatomical features within the joint was attained. This will aid physicians and researchers like orthopedic surgeons in gaining insight into patient specific volume measurements, distances, and orthopedic surgery specific data critical to tailor each medical intervention to the patient, as opposed to current medical approach which introduces a bit of error into each orthopedic replacement. For example, the Swedish Hip Arthroplasty Register in its Annual Report 2013, Garellick [14] reported that dislocation post total hip replacement (THR) contributed to 13.8% of primary revisions for patients and 22.5% of all second revisions in 2012. In addition, another study found that 22.5% of all THR revisions in the United States were because of instability and dislocation [15]. Being able to visualize hip-femur joints, its dynamics and take vital depth, scaling, and dimensional information in a patient-specific manner can contribute to efforts to lower the stated percentages and increase the efficiencies of said post-operation medical conditions in patients.

Orthopedics is one example of a medical specialty that can be greatly impacted by immersive virtual reality applications and tracking data acquisition.

6. Conclusion

This paper presents a novel patient-specific workflow to produce interactive, immersive and dynamic 3D anatomical models integrated into a 4-WALL VR environment (virtual reality system). This paper elaborates in extensive detail the steps taken to translate CT medical imaging data into accurate 3D model assemblies that are later incorporated into virtual reality software where dynamics, lighting, and interactive capabilities are infused. Lastly, we detail in our workflow the intricacies of designing our 4-WALL VR environment, its components, and specific tools and 3D CAD solutions used to bring to life a hip-femur joint assembly. Finally, we discuss the benefits of this state-of- the-art technology, its future, and how it can be applied to various medical fields in need of visualization and computer modeling capabilities to improve their diagnoses, medical procedures like surgery, and extracting more information from medical imaging data.

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Author contributions

Hesham Tanbour: CT data analysis and transformation, writing-original draft preparation, software, visualization, anatomical insight, tracking system calibration, and validation. **Emad Tanbour:** VR technology environment design and erection, integration, VR hardware design and build, methodology, CAD software, editing and preparing final manuscript, and research project management.

Conflicts of interest

The authors declare no conflicts of interest.

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