Medicine Meets Virtual Reality
K.S. Morgan et al. (Eds.)
IOS Press, 1997

Towards a Novel Augmented-Reality Tool to Visualize Dynamic 3-D Anatomy

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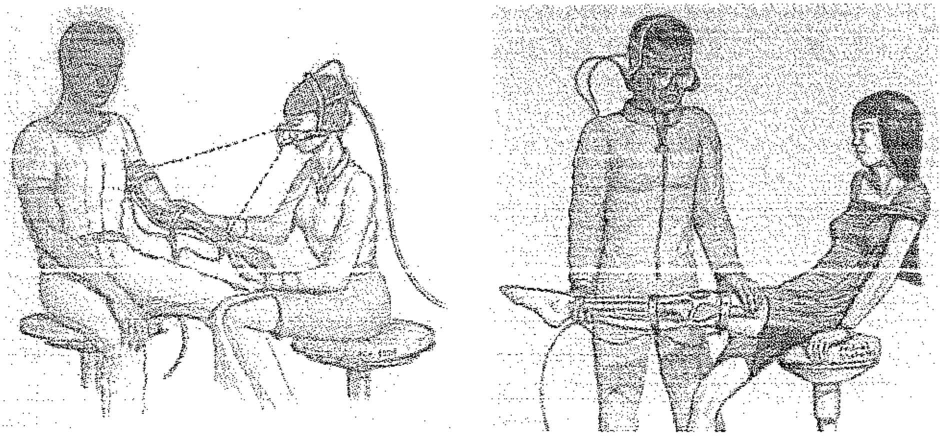
Abstract. Using augmented reality (AR) to teach dynamic 3-D anatomy may impart better understanding of bone dynamics during body movement. We are currently developing an AR tool that will allow superimposition and registration of bone structures on real anatomical counterparts of a human subject. This article describes the application, the problems to be solved, and reports on preliminary developmental studies of a first prototype of the tool. Specifically, studies test approaches to simulating real-time dynamic anatomy, and the feasibility in achieving registration of 3-D anatomical bones on their real counterparts. Such a tool will offer several unique advantages over traditional teaching methods and overcome many of their current limitations.

1. Introduction

Medical and science education benefit from enhanced training tools with richer contents to improve the anatomy learning experience. The long-term objective of this research is to develop and evaluate an augmented reality (AR) tool that will enable a user wearing a see-through head-mounted display (HMD) to visualize, in real-time, synthetic anatomy superimposed on a human subject in motion. Figure 1a and 1b illustrate this unique approach applied to examination of the elbow and knee joints, respectively.



(a) (b)

Figure 1. An artist drawing of a novel teaching-tool for dynamic 3-D-anatomy applied to (a) the elbow joint and (b) the knee joint. (Drawing Courtesy of Andrei State).

Visualizing the 3-D perspective of human anatomy, especially in a living patient, is challenging. This challenge is particularly significant in situations, such as medical evaluation of musculoskeletal disorders. Approximately 40% to 60% of all patients seen in private medical offices have primary complaints referable to the musculoskeletal system [1-3]

Comprehension of complex information is best understood when examined from several perspectives [4-5]. A visualization tool that permits users to *see* internal bone anatomy as a joint is manipulated will help students, clinicians, and researchers better understand normal joint structure and physiology. In addition, the tool could be used to directly observe and study joint changes related to lifestyle choices and pathologies. It also has potential as a patient education tool to explain medical diagnoses, procedures, treatments, prognoses, and the consequences of lifestyle choices such as obesity and high-impact exercise.

An interactive AR tool which demonstrates internal anatomy in real-time motion provides a unique approach to understanding the changing appearance and function of anatomy-in-motion and can augment traditional anatomy teaching methods[6-7]. This project will provide a unique approach to understanding 3-D anatomy that is not available with other teaching methods and that is theoretically more efficient. We shall focus in the early stages of development of this tool on demonstrating motion of normal anatomy. Specific applications, comparing normal anatomy and physiology to pathologies will be developed after the prototype has been evaluated. Once developed, the AR techniques established in this project can be applied to other demonstrations of internal, normally obscured, 3-D structures moving in space.

Anatomy is traditionally taught in a variety of formats including two dimensional printed photographs, slides, labeled drawings, and cadaver dissection labs. Medical education, in particular, includes clinical examination of patients and radiograph correlation with gross anatomy and pathology. Traditional methods often do not allow simultaneous visualization of both internal and external structures. Dissection procedures, for example, demonstrate only one layer of the anatomy at a time (skin, muscles, or bones) and can not be reversed or exactly repeated. The rigidity of cadavers and artificial models prevents realistic palpation and manipulation.

Interactive videodisc, multimedia presentations, and computer dissection simulations have been implemented and evaluated successfully [8-11]. Video and computer-based demonstrations of dissections are infinitely reversible and repeatable, but they do not integrate the palpation of external anatomical landmarks. Electronic tools also do not provide the spontaneous feedback involved with living human models.

Current educational trends support using active learning, individualized learning, and an environment that simulates real-life situations [12-17, 38]. The proposed approach augments traditional methods, and enhances the learning process.

First, the proposed VR experience is active because the user can move around the subject and simultaneously perform anatomical manipulations. Moreover, this approach requires participation of both the user and the subject. Secondly, use of the tool is individualized because manipulations can be repeated as necessary and in any sequence. Finally, the AR tool for dynamic anatomy simulates real-life situations because it provides a unique holistic sensory approach to learning anatomy. It is holistic because it emphasizes consideration of the entire subject instead of focusing on an isolated anatomical structure. It is sensory because it allows the user to visualize internal anatomy and to palpate external landmarks simultaneously. The user will hear and respond to the subject giving feedback about comfort during manipulation. While most traditional methods stimulate the senses individually, VR teaching tools encourage integration of multiple senses, a practice that reflects natural behavior.

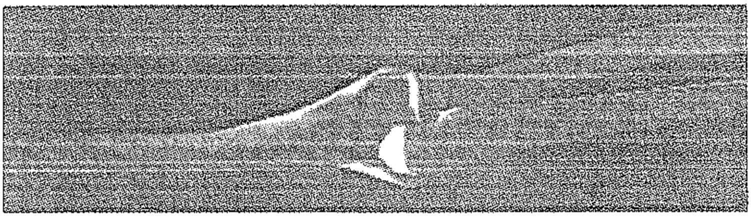


Figure 2. The elbow joint in extension: rendered images of the bones at the joint.

Preliminary laboratory studies tested basic principles of AR applied to the elbow joint. Two essential milestones in the development of the AR tool are reported in this paper: 1. the approach to simulating dynamic anatomy; 2. the feasibility in achieving registration of 3-D anatomical bones on their real counterparts from multiple viewpoints and for multiple users.

2. Simulating Dynamic Anatomy

Computer generated images of the bones were modeled as lists of polygons with a normal at each vertex using Viewpoint's model of an elbow joint. A low resolution model with 690 vertices and 472 polygons was available and a representative set of bones of specific size was digitized to create the Viewpoint model. The rendering was done on an SGI ONYX platform using OpenGL library with simple Gouraud shading. Figure 2 illustrates the rendered model of the elbow joint in extension.

The simplest approach to simulating real-time dynamic anatomy was to place small, lightweight tracking devices on opposing sides of the joint. The tracking data were then used to animate a computer-generated model of a joint. The animation was demonstrated on a conventional computer graphics station. We tested this approach by assessing the realism during simple flexion-extension of the elbow-joint.

This approach was conducted using a magnetic tracker. A good discussion on virtual reality technology can be found in Burdea and Coiffet, (1994) [18]. Two well known versions of magnetic trackers are the Ascension Flock of Birds and the Polhemus 3-space. An extended range Flock of Birds magnetic tracker was used in our experiments. Lastra and Holloway, (1994), and Mine (1993) reported the specifications of this tracker system [19, 39]. The magnetic system used one transmitter on the ceiling above the arm, one receiver on the upper arm, and one receiver on the forearm of the person. The upper arm was kept fixed while the elbow joint was moved. The receivers were mounted on the arm, in relation to palpable anatomical landmarks (e.g. condyles) as shown in Figure 3. The receivers were fastened firmly to prevent sliding along the arm. The mobility of the skin can cause inconsistencies that may require compensation.

The animated graphical bones using real-time tracker data were displayed on a high resolution monitor and were unsatisfactory. The computer-generated images of the bones moved independently, collided, and did not represent true anatomical motion. Possible reasons for the poor results include 1) poor definition of the location of the axis of rotation resulting from errors in specifying the positions of the tracker receivers on the arm, and 2) inaccuracies and/or noise in the tracker devices.

The next step involved a stylized joint (two wooden blocks attached by a hinge) to simplify the components and movement. The dimensions of the stylized joint and the locations of the tracker receivers were modeled precisely in the computer so any remaining error would be attributed to the tracker. Results from this simulation were still highly unsatisfactory. Artifacts included the two blocks intersecting and the blocks becoming unhinged. This confirmed that the main problem was caused by errors in tracker readings which can be caused by both systematic and random errors.

2.1 Systematic errors in magnetic trackers

Metal and electromagnetic devices in the environment distort the field causing systematic errors in position and orientation reports. One general approach to correct systematic errors is carefully measuring tracker inaccuracies and correcting them with a look-up table [20]. An implementation of this approach for the extended range Flock of Birds was performed by other researchers in our laboratory [21].

Livingston and State used an extremely accurate mechanical tracker, the Faro Arm, to provide *true* readings. They computed the difference between these readings and the readings from the magnetic tracker to obtain an error for the magnetic tracker readings. A volume around the transmitter was then mapped for errors in magnetic tracker readings.

The magnetic tracker readings were corrected using a look-up table. Researchers mapped errors in position and orientation at discrete locations in a 1.2 cubic meter volume below the transmitter using the Faro Arm. Resampling these errors on a rectilinear grid, they built a correction table for the magnetic tracker readings. An averaged accuracy in position of 5 mm was achieved after look-up table correction. The achieved accuracy in orientation was below expectations and is being further investigated [21].

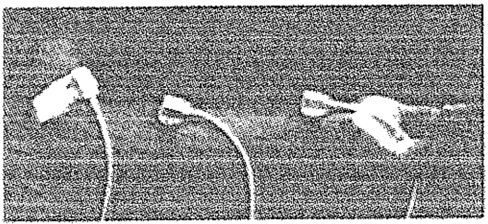


Figure 3. Positioning of tracker receivers on the arm.

2.2 Random errors in magnetic trackers

Random errors reported by the magnetic tracker were also significant because of noise in the system. One approach to correct random errors is averaging multiple tracker readings at any given location in space. The noisier the data, the higher the number of readings to average. This approach could not be fully implemented in a real-time application because of delays incurred when processing raw data.

Another approach is adding a physically-based kinematic model of joint motion to the real-time data. A kinematic model sets additional constraints on the recorded data for ranges of motion, locations of the axes of rotation, and spacing between tracked objects. The kinematic model for the stylized joint was predictable and easily implemented. Even without compensating for systematic errors, results of the implementation of the kinematic model lead to astonishing improvements in simulating realistic motion.

Based on these preliminary results, and given that kinematic models have been successfully applied in other situations [22-27], it is reasonable to believe that applying a kinematic model to real-time tracker data will provide a viable method for simulating computer-generated realistic joint movements. The next step in the development of the AR-based tool for dynamic anatomy was to derive a kinematic model for the joint under study and to integrate it with real-time data.

3. Registration of Real and Computer-Generated 3-D Objects

Proper registration of computer-generated 3-D objects on their real counterparts provides a challenge for display methods [28-30]. It is, however, essential for a convincing presentation. We used the previously described stylized joint to investigate registration of real and computer-generated images.

Registration is affected by two classes of errors: static errors and dynamic errors. Static errors are not time dependent and occur in measurements of various parameters such as: field of view of the HMD, the position of the receivers on the HMD and on the anatomical part, systematic errors in the tracker reports, and overscan of the displays. Static errors have been corrected when proper registration occurs in the absence of motion. We shall essentially report methods and results pertaining to the elimination of static errors because it is a first milestone to achieving convincing dynamic registration. We will first demonstrate multiple, but static, viewpoints.

In the 3-D anatomy application, large errors in static registration may come from multiple sources such as receiver proximity and faulty HMD calibration. Errors caused by interferences between multiple receivers placed in proximity on the anatomical parts around the joint are reported in section 3.1. Results of the calibration of the HMD are given in section 3.2.

Dynamic errors occur when continuous motion is involved. In the case of this application, continuous motion can be the product of head and/or anatomical part movements. Common dynamic errors affecting registration are "noise" and "lag" in the position and orientation data reported by the tracker.

Development of potential solutions to static and dynamic errors were dependent on the type of HMD selected so we will first describe selection of the HMD. There are two primary designs for see-through HMDs, video and optical. These types of HMDs differ in the way they acquire images of a real scene. When using a video see-through HMD, the user sees video images of the real scene. When using an optical see-through HMD, the user has a direct view of the real scene, as if he or she were looking through a thin window. Each design has advantages and disadvantages [31]. The specific application and intent determines the appropriate design.

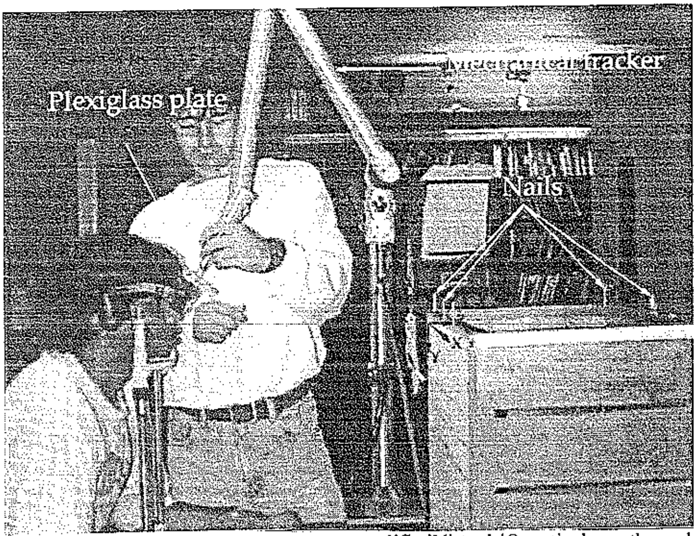


Figure 4. Calibration setup: An HMD user wear a modifiedVirtual-iO optical see-through head-mounted display in a nail sighting procedure.

Video see-through offers better manipulation and enforced registration of real and virtual images both in space and time. An implementation of this technique was successfully demonstrated by Bajura and Neumann, 1994 [32]. They tracked landmarks in a real scene and registered them with equivalent landmarks in a virtual scene to enforce registration. This method, however, may cause sensory conflicts between vision and proprioception. If delays are too long, video images no longer correspond to the real-world scene. In the 3-D anatomy application, integration of the tactile manipulation and the visual image may deteriorate to a point that the experience is not realistic or educationally valuable. A key issue is whether the delays are too long to allow the user to adapt. Held and Durlach, (1987) discuss this problem and give an extensive list of references on the subject [33].

The optical see-through design essentially allows an unhindered view of the real environment and a larger field of view of the real scene than is possible with video see-through design. Because optical see-through systems allow users to see real objects directly while virtual objects are calculated by the computer, it is critical that the system be optimized for low latency. Otherwise, the superimposed virtual objects will lag behind the directly viewed real objects. The optical see-through approach provides a high quality, instantaneous view of the real scene. The investigators decided to first use the optical see-through design in the AR tool because it offers better synchronization of visual information and proprioception for real objects and that is essential in an application involving the clinical manipulation of human joints.

Improved dynamic registration using predictive tracking was demonstrated by Azuma and Bishop (1994) using a monocular optical see-through HMD [29]. We tested real subjects using binocular vision. Complexity is added because any calibration technique needed to be repeated not only for each occurrence of HMD use, but also for each wearer of the HMD. We developed techniques for achieving fast, static registration [34].

A commercially available HMD, the Virtual-iO i-glasses shown Figure 4, was used in preliminary studies. The Virtual-iO glasses are lightweight and mobile, but do not offer the rigid control of a bench prototype HMD [35]. We adapted the Virtual-iO HMD during early experimentation by restricting users to fixed viewpoints when addressing static errors.

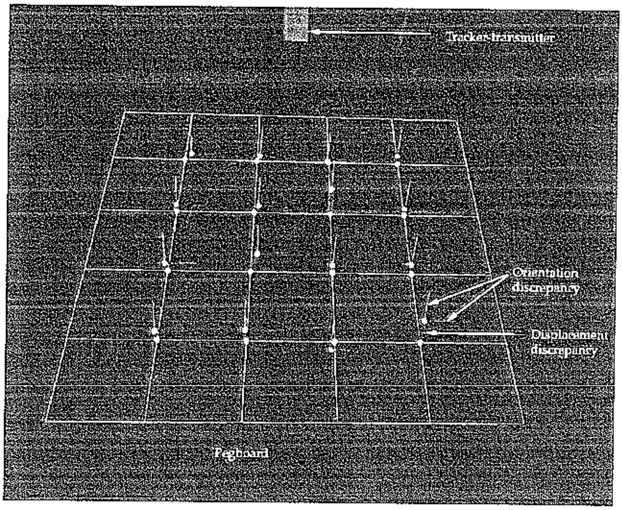


Figure 5. Representation of errors between reports from two receivers for condition number two.

Calibration techniques for both the bench prototype and the Virtual-iO systems were derived that allowed computation of the field of view for the optics, residual optical distortions, and derivation of the different transformations necessary to display the virtual Calibration techniques for both the bench prototype and the Virtual-iO systems were anatomy at a specific depth with the correct viewpoint [34,36].

3.1 Determination of relative errors between tracker reports for two receivers pegged the same way

Because the magnetic tracker enabled multiple receivers to be tracked simultaneously, it was used for tracking the elbow-joint. The study involved at least two receivers (receivers A and B) on a pegboard. The tracker transmitter was located above the pegboard. The purpose of this study was to determine potential interferences between two receivers placed in the proximity of a joint under study. Ideally, all the receivers should report the same value when pegged at the same location. Relative systematic errors can be corrected, assuming the reports from one of the receivers are correct.

The pegboard defining the receivers' plane was placed under the transmitter at the anticipated arm level used in the application. Readings in a representative plane parallel to the X-Y plane of the tracker coordinate system and at various locations on the pegboard were taken. For each receiver, multiple readings at each location were averaged to eliminate the effects of noise in the tracker readings. Three conditions were studied

1. Readings from receiver A were acquired without receiver B. Receiver B was then placed at exactly the same location (in the same orientation) and similar readings were taken without receiver A. The process was repeated at various locations on the pegboard and a discrepancy transform between them was computed for each location.
2. The experiment was repeated with receiver B in the vicinity of receiver A to determine the extent of interference described by changes in the discrepancy transform.
3. The experiment was repeated with the trackers in proximity, but with one receiver turned off to determine whether the power surging through a receiver in the vicinity caused interferences

Discrepancy measures between receivers A and B were obtained at sixteen locations on the pegboard. Fifty readings, taken three seconds apart, were averaged at each location. A visualization tool quantitatively demonstrated how the discrepancies varied over different locations.[1] An illustration is shown in Figure 5. Descriptive statistics for the three conditions are reported in table 1a, 1b, and 1c, respectively. The experiment yielded mean discrepancies over locations on the pegboard of 3 to 5 cm for position, and 3 to 5 degrees for orientation. The significant standard deviations (stdev) reported in Table 1 suggested that a simple transform could not be used to correct for interferences between the two receivers.

Table 1. *Discrepancy measures between receivers A and B (a) for condition 1; (b) for condition* 2; and (c) for condition 3.

A or B	Distance (cm)	Orientation (degrees)
mean	3.4	4.5
min	1.5	0.9
max	4.1	6.1
sdev	0.6	1.1

(a)

Both A and B Active	Distance (cm)	Orientation (degrees)
mean	5.2	4.9
min	2.9	2.8
max	12.0	8.4
sdev	2.7	1.6

(b)

Both A and B, but A or B Active	Distance (cm)	Orientation (degrees)
mean	4.3	3.4
min	1.3	2.2
max	10.6	5.2
sdev	2.1	1.0

(c)

3.2 Calibration of an off-the-shelf optical see-through HMD

The calibration technique for a commercially available HMD, the Virtual-iO system, was based on previous techniques proposed by Azuma and Bishop, (1994) and Holloway, (1995) [29, 30]. The technique allowed computation of the field-of-view for the optics, residual optical distortions, and derivation of the different transformations necessary to display the virtual anatomy at a specific depth with the correct viewpoint [34]. An important factor of the calibration technique is that it must be simple and fast enough to be repeated not only for each HMD user, but also for each session. This is necessary because the position of the HMD on the user's head and the head to eye transforms vary at each use. One assumption was that during one session, the HMD would not move with respect to the user's head. Therefore, one point on the HMD was chosen as the head origin. The calibration technique measured:

- *The transforms between the head-origin and the two eyes* (assuming the HMD did not move on the head once it was tightened).
- *The viewing frustum for each eye* (defining the space in front of the eyes that corresponds to the projected displays. It is required for computing the projection matrix for the view at each eye).

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[1] A transformation from receiver B coordinate system to receiver A coordinate system was defined as the discrepancy. In the figure, it is assumed that the coordinate system attached to A is oriented with x to the right, y to the top, and z away from you.

- *The distortion parameters.* Most HMD systems do not correct for optical distortion to minimize system weight and complexity. Optical distortion does not need correction because it only introduces wrappings of the image without degrading its sharpness [36,37]. An inverse mapping of the optical distortion function to the scene to be displayed can be applied by modeling the distortion of the optics and computing the distortion parameters for the inverse mapping. The Virtual-iO HMD has a narrow field of view. We estimated the distortion to be less that 3% at the edge of the field, so distortion correction was omitted. It could later be compensated as necessary.

Given the high accuracy and precision of the Faro Arm, we considered using it to calibrate the optical see-through HMD. The Faro Arm was too inconvenient to use if attached to the HMD because it was heavy and did not track all orientations for a given position. Moreover, it exerted a force and moved the HMD relative to the eyes of the user. Finally, the Faro Arm was limited to tracking only one object at a time.

Based on these observations, a potential alternative was to use an hybrid combination of trackers, a magnetic tracker (the Flock of Birds) and a mechanical tracker (the Faro Arm). The magnetic tracker was mounted on the HMD. The Faro Arm was used to digitize points in 3-D space. The locations of these points were necessary to compute various transforms for generating the graphics information. Kancherla et al., (1995b) reported details of the calibration procedure and the digitalization of points [34].

The hybrid calibration method required a look-up table for the magnetic tracker, that is built for the environment and the working volume of the application. The look-up table needed to yield fairly accurate results both in position and orientation. As reported, the correction in orientation was not available, therefore we had to create an alternative.

Because the mechanical tracker was the only device calibrated in accuracy and precision, the method had to involve the mechanical tracker without attaching it to the HMD. The mechanical tracker was therefore the sole source of digital position data. One solution to this problem was to mark and digitize three points on the HMD to define two orthogonal axes, and thus an orthogonal coordinate system by computing their cross product. The points were defined as holes on a grid drilled in a Plexiglas plate which was mounted on the HMD (Figure 4). Using the Faro Arm, the three points were digitized each time the position of the user's head changed. This method was not viable for dynamic registration with head movements but was viable to achieve static calibration for various users.

The calibration procedure was implemented and tested in the laboratory using one human subject who repeated the calibration routine three times. Landmark points on the crate (Figure 4) were digitized using the mechanical tracker to define the view plane. The subject then aligned a square drawn on the display with these landmarks to define the size of the frustum or, equivalently, the field of view. To compute the eye to head-origin transform, the subject sighted with each eye two pairs of nails mounted on the crate as shown in Figure 4. The lines joining the pairs of nails intersect at the eye point of the subject. For each location of the subject's head during the sighting procedures, the experimentator digitized the location of the head-mounted display.

The accuracy of the calibration was verified by displaying a 3-D wireframe box superimposed on the crate. The subject observed the scene from multiple static viewpoints. For each viewpoint, the HMD position was digitized. The completion time was five to seven minutes. The procedure yielded accuracy in the order of 5 mm (The graphical box was located within a 5 mm circle centered on the true location of the crate).
The success of the calibration was contingent upon:

- accurate digitization of the head mounted display[2]
- valid assumptions.[3]

The time required to achieve calibration for each use of the HMD comes from the digitization of points in the environment and on the HMD using the mechanical tracker. The process can be expedited by using an optical tracker such as the OPTOTRAK where small light-emitting diodes placed in the environment and on the HMD are tracked using a system of cameras. Such a tracker system will be used in further development of the tool for calibrating the system, tracking anatomical parts, and tracking the user's head. Based on these preliminary studies, we estimate that calibration times for each use of the system can be reduced to a couple of minutes.

4. Conclusion

We have described a novel, augmented reality based tool to demonstrate dynamic 3-D anatomy. We conducted preliminary experimental studies using readily available tracking technology. Preliminary studies addressed several technical challenges surrounding two foci: 1. to test whether graphical bones could be animated realistically, in real-time, and 2. to address registration issues of real and graphical bones. Results of the preliminary studies indicate that realism in the motion of a stylized joint can be greatly improved by adding a kinematic model to the real-time data. Future work consists in applying the same technique to 3-D graphical bones. Results also indicate that the use of magnetic trackers in our laboratory environment limits the performance of the AR tool. Systematic errors were partially reduced using a look-up table. Significant random errors, however, cannot be compensated in real-time. Results of the experiments influenced and, in some instances, changed the research designs and methods for further stages of development of the AR tool. Precisely, the use of optical, instead of magnetic or mechanical tracking, has been adopted for the 3-D dynamic anatomy tool.

5. Acknowledgments

We would like to thank Steve Work from Ascension Technology Corporation for his dedicated help and useful pointers. We thank Mark Singer for his assistance with testing the calibration procedure, and David Harrison for his assistance with video technology. We thank Gregory Burdea for stimulating discussions at earlier stages of this research, Andrei

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[2] The problem we faced was that, though not attached, the mechanical tracker caused the subject's head to move slightly during digitization.

[3] In the nail sighting procedure, we assumed that the coordinate system attached to the subject eye was oriented along the crate coordinate system; our experience with the procedure suggests that this is hard to maintain; An improvement to the calibration procedure would be to constrain further the head position as is done with a bench prototype.

State, Mark Livingston, and Rich Holloway for sharing their expertise at various stages of this work, and Frank Biocca for his helpful and stimulating discussions throughout this research. The research was supported in part by the Office of Naval Research under Grant N00014-94-1-0503 and by a Junior Faculty Award from the University of North Carolina at Chapel Hill.

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