LITERATURE REVIEW OF VIRTUAL ENVIRONMENT RELATED RESEARCH IN VARIOUS SURGICAL DOMAINS

(THIS IS A PART OF A COMPLETE REPORT. ONLY SECTIONS 2 ARE INCLUDED HERE).

2.1. Introduction

Virtual Environments have been used to train medical surgeons in orthopedic surgery. Using such simulators, residents and surgeons can develop or improve their skills in specific orthopedic surgical processes. In this section 2 of this report, a review of related work in the use of virtual environments in various surgical fields are presented. This includes orthopedic surgery, heart surgery, and laparoscopic surgery, among others.

2.2. Orthopedic Surgery

To have an accurate model of human tissue deformation, there was a need to model this realistically according to the layered nature of real human tissues. Qin et al. [9] developed a framework for simulating the soft tissue deformation in an orthopedic surgery. In their work, they first constructed the multi-layered soft tissue model according to the segmented Chinese Visible Human (CVH) datasets, which can provide more details compared to an MRI or CT images. Then the non-linear stress-strain behavior of soft tissues was modeled employing a bilinear 3D mass-spring model and later simulated annealing was used to modify the spring parameters of the model. They used a Physics Processing Unit (PPU) for the first time (as claimed) to perform efficiently the computational analysis of dynamic motions and interactions. They showed that PPU can improve the simulation performance to a great degree. The experimental results discussed highlight the practical use of their model both in providing interactive and realistic models of human tissue deformations.

Delp and Loan [10] developed a graphical tool called SIMM (Software for Interactive Musculoskeletal Modeling), which can be used to develop and analyze musculoskeletal models. Once a model was defined by the user, the functions of each muscle was analyzed by computing its length, forces, moment arms, and joint moments. The user can develop, alter, and evaluate models of many different musculoskeletal structures, which quantify the effects of musculoskeletal geometry, joint kinematics, and muscle-tendon parameters on muscle-tendon lengths, moment arms, muscle forces, and joint moments. A model in SIMM consists of a set of rigid body segments which were connected via joints. The joints were spanned by muscle-tendons actuators which result in generating forces, and hence, joint moments in them. The software was beneficial for the analysis of 3D images alone (such as what we get from CT scanners) doesn't give much information about the function of the muscles and joints because the image itself does not quantify a muscle. SIMM would be of great value for many purposes, such as exploring the effects of musculoskeletal surgeries on the moment-generating capacities of a muscle. The software was the first to use an interactive graphical environment, which gives many musculoskeletal models with no need to program. It was also used in approximately 25 centers worldwide.

Vankipuram et al. [11] outlined a drilling simulation environment which can be utilized to train orthopedic surgeons. They used a 3-DOF haptic device interfaced with this environment. For volume rendering, there were various algorithms in the literature, generally divided into two categories: the Direct Volume Rendering (DVR) and the Surface Fitting (SF) methods. The Marching Cubes algorithm was used in [11] for volume rendering tasks in their outlined approach. To create a realistic drilling simulation, two key components were taken into consideration: one was the appropriate collision detection algorithm and the other was employing the proper voxel removal method. The collision detection algorithm enables the detection of virtual target objects coming into contact with the simulated drilling tool; this was achieved by a hierarchical volume bounding method.

Modeling the drilling procedure in the orthopedic surgery simulators plays a key role in the development of orthopedic surgery simulators. To obtain a realistic feel of the bone drilling process, there was a need to calculate the drilling forces coming into play, which was then communicated to the haptic device that interfaces with the virtual simulation environment. Tsai et al [12] presented a model to calculate these forces when modeling a real-like drilling procedure for building an orthopedic surgery simulator. Their model provides an environment capable of choosing the appropriate drill, plate and screw which best fits the patient-specific bone. In their work, haptic functions which can be added to a volume based surgical simulator were introduced. These functions calculate the loads on cutting tips and chisel edge based on the machining theorem method to acquire forces and torques along the thrust, tangential, and radial directions. A 6DoF PHANTOM haptic device was utilized to let the user control the drill angle, position, and speed. They also validated the effectiveness of their model by simulating a plate-and-screw surgery using the developed haptic functions.

VR simulators can be beneficial in increasing the quality of surgical training while decreasing the long training time needed for the education. Blyth et al [13] carried out a survey regarding the attitude of the surgeon community toward the need for VR simulators. Two groups of surgeons were examined during this survey; the first group includes the surgeons qualified before 1990 and the second group consists of the ones qualified after 1990. In their work, two major key points were studied: (i) the participants were asked about the perceived requirements of a surgical simulator and (ii) the type of task for which the surgical simulator would be useful. In addition, they discussed the degree of acceptance of this kind of simulators by the surgeon's society. The surgical simulators were shown to be beneficial in particular for novice students. The surgeons believed that a realistic simulation of the operation was the most essential need of the VR simulators. In addition, both groups of surgeons concluded that the VR simulators would be helpful, especially for applications in orthopedics, particularly in practicing some techniques such as guide wire placement and minimally invasive surgery, which can provide useful feedback to surgeons in a non-threatening way. In general, they were supportive of the simulators, but they did not think they would have a key impact on the near future of surgical training.

Tsai et al [14] developed a VR orthopedic simulator, which can simulate different orthopedic procedures, including arthroplasty, corrective and open osteotomy, fusion, and open reduction. The simulator was developed on C++ using the OpenGL libraries, and employed computed tomography (CT) or magnetic resonance imaging (MRI) to build the volume data of the orthopedic target and simulate the surgical procedure by providing stereoscopic images of the orthopedic scene. The surgeon wears stereoscopic glasses and uses a surgical instrument attached to a six dimensional-degree tracker to perform the surgical operation. The interface module of the software provided different menus, which allowed the surgeon to select different surgical tools such as bone saws, virtual plates, staples, dissectors, etc., And used different functions including fusion, sectioning surfaces, and determining the collision in order to perform different surgical procedures on solid orthopedic objects such as bone, prosthesis, and bone grafts. The simulator was designed only for performing surgical procedures on rigid orthopedic objects and was not able to model soft tissues and does not provide any force feedback to the surgeon.

During most orthopedic surgery training activities, the medical residents were introduced to correcting the fractures on artificial bones. There were two main problems: (i) synthetic bones were expensive and (ii) for certain types of the bones, the synthetic form might not be available. Further, there were benefits to training using virtual models when they were based on real fracture images (obtained from CT and MRI images) [15]. While VR based systems require advanced processors and equipment, some researchers explored the creation of VSEs, which can be run on typical personal computers (PCs). For example, Sourina et al [15] developed a virtual orthopedic surgery simulator, called Virtual Bone Setter, capable of running on typical PCs, which can be used to train the surgery residents in correcting bone fractures. The software they developed can be run on ordinary PCs without any need for external VR hardware. They also built and used a geometric database of different fractures, as well as different orthopedic objects, such as screws, plates, nails, wires, and locking bolts, which can be selected by the surgeon.

In [16], a VR-based training system for arthroscopic surgery (diagnosis of joint irregularities) was elaborated. The authors investigated the mechanical design, kinematics, dexterity measure and control loop of haptic devices. They also discussed the organ mesh generation, tissue deformation simulation and collision detection techniques. The manipulator mechanism with four degrees of freedom was developed and kinematic analysis of the manipulator was performed using direct and inverse kinematics analysis. The usable workspace of the manipulator was identified using Jacobian matrix and dexterity measures. A control system for the haptic device was developed for tracking the arthroscopic and the surgical instrument. They also further developed a knee model from the visible human project (VHP) color images and 3D meshes for finite element analysis to simulate a series of actions in the surgery. They also used a complex Finite Element Model (FEM) to deal with non-linear tissue deformation and topology changes. An advanced collision detection algorithm was used to detect virtual collisions between arthroscopic instruments and organs.

Kong et al., [17] developed a prototype of a telesurgical system for bone-setting in order to maintain a safe and accurate operation procedure and reduce surgeon's effort using remotely accessible robots. The robotic system can perform slave/master operation, and in semi-automatic and autonomic operation modes. The system also utilized image guidance technology to receive visual feedback for the positioning and trajectory control. Haptic devices were used in the master devices to get user force feedback on tools. In the slave manipulator, a parallel robot with 6 DOF was adopted for its compactness, high stiffness and load capacity in order to maintain safety and loading abilities. VR and AR techniques adopted in this simulation for the guidance of operational processes and the 3D models of the system were created using JAVA 3D techniques. Some of the benefits of the teleoperating system were described and the benefits of these systems were reducing the irradiation damage to the surgeon, improving the reposition and locking nail quality, and relieving suffering of patients. The present system communication was based on TCP/IP networks and time delay was ignored. The force, including position loop control system was implemented to make the position and orientation of the tools precise. The doctors can predefine the surgical procedures using the control and graphical interfaces developed in the human machine interface. Finally, the teleoperation test with a broken bone with the information about images and forces to complete the bone-setting were discussed.

Vanicatte et al., [18] implemented interoperability features in a robot-assisted orthopedic surgery system with smart interaction between medical devices during operations. The authors addressed the current lack of reliable communication between the robot and medical devices which can pose a danger to the patient. A central decision making unit (CDMU) was added to the existing robot assisted surgery systems to monitor and make proper decisions for the patients. Some of the elements that were supervised by the CDMU included the anesthesia machine, imaging devices and the robot assistant. The CDMU also had a telemetry unit interface for transferring and receiving the data from various devices using wireless technology. In this proposed design, a simulation of patients with normal, slightly abnormal, and critical risk states were considered with specific values of physiological data, blood pressures, oxygen saturation, and BIS monitoring. The CDMU collects the physiological state of the patient and the decision support software determines the patient condition and shows the details in the CDMU display. The reaction time from the system was compared with the reaction delay during without interoperability features in robot-assisted surgery environment. It showed the absence of interoperability lead to dangerous inattention mistakes and may cause a significant impact on the patient condition. The CDMU technique enhanced the safety of the surgery and assisted the surgeon, but this had some issues such as lack of standardization of the medical devices and their proprietary wireless technology.

Zhijiang et al., [19] proposed a teleprogramming scheme combined with semi-autonomous control for telesurgery contexts to solve the Internet induced time delay, operation fatigues. Teleprogramming was utilized in the telesurgery systems to control the time delay by using a concise robot control language and semi-autonomous control, which helps the user to operate simultaneously. The present work was applied on the long bone fracture therapies for precise repositioning and locking of intramedullary nails. Parallel and serial robots HIT-RAOS were used to fix the broken bones in addition to a C-Arm X-Ray machine used to collect the images. In order to avoid X-Ray exposure, which could have harmed the surgeon and patient, a virtual surgical simulation system was developed for interaction using JAVA 3D techniques. The teleprogramming scheme utilized the robot languages and a background program to reduce the time delay and it helped the operator performs accurately even when the condition of the Internet was deteriorating. Client and the server part of the Semi-autonomous controls were described. An experiment was conducted for locking of intramedullary nails utilizing the teleprogramming scheme combined with semi-autonomous control. The client and server were 4kms apart and the experiment was repeated 10 times in the following modes: video assisted teleoperation and virtual surgical environment. The results showed that the performance of the virtual surgical environment improved by decreasing the time delay in telesurgery.

Monan [20] developed a finite element model (FEM) of the leg and tissue from the actual 3D geometry and investigated the biomechanical characteristics of the model during the orthopedic surgery. The geometry of the FEM was reconstructed from the CT images and the boundary surfaces were processed using Solidworks. Initially key points were created in the FEM and those key points were used to generate the closed solid models. The FEM were defined as linear elastic and hyper elastic. The bone structures and tendons were called as linear elastic and the soft tissues and muscles were called as hyper elastic models. The Mooney-Relvin model and its functions were used for the finite element models. An experiment was also conducted to observe the force required to separate the two broken bones and distance among them. These forces were obtained by using a force sensor and the ruler made from steel balls. In the experiment, CT images were imposed to see the condition of the patient and from the unloaded condition, every 10 seconds, a parallel robot was moved 1mm forward to conduct the force calibrations. The experimental results were compared with the computational results, which demonstrated the finite element data was reliable. The simulated model was shown to have the ability to predict the force required in the reposition procedure.

Zhang et al., [21] proposed a novel virtual simulation system for robot assisted orthopedic surgery system (HIT-RAOS) to help the surgeon to develop operative planning, surgery rehearsal, telesurgery and training. The hardware of HIT-RAOS contained parallel and serial robots with c-arm X-ray machine for the treatment of long bone fracture reposition operation and locking the intramedullary nails. The surgical environment was divided into three different models and those models were human, auxiliary devices and robot models. The virtual reality (VR) environment of the surgery process was developed using Java3D and VRML techniques. The robot model was created in the pro/engineering geometry models and this embedded with the kinematic details to demonstrate the real time motions in the VRE. Finite element method was used for the leg model and it gave accurate results with real elastic behavior of soft tissues. The geometrical models of the muscles and bones were reconstructed from the CT images of the leg. In the experiment, these models were integrated into the virtual environment and a telesurgery experiment was conducted. The surgery environment contained a real time six degrees of freedom robot on the client side and the virtual system on the server side. These servers and clients were connected via LAN and every 15ms the data was transported to the virtual simulation system and then the virtual parallel robot move according to the real time movement from the client end. The system also contained force and vision feedback to make the perfect movements of the robot. In conclusion, the system proved that the virtual environment was useful and valuable for surgery practice.

Rambani et al., [22] conducted a study of computer assisted orthopedic training system (CAOS) for fracture fixation and validation of its effectiveness among the junior orthopedic trainees. In this study, the CAOS system developed by their simulation and visualization research group was used. It included a fluoroscopy-based navigation system that combines intraoperative fluoroscopy based imaging using c-arm techniques with surgical navigation concepts. This system was especially helpful for the trainees that had less experience in 3D navigation with 2D images. An experimental study was conducted with the groups that had experience in 3D navigation and was compared with the groups that had no exposure to 3D navigation. The results were assessed based on the amount of time taken, accuracy of guide wire placement, and the number of exposures required to complete the process. The scores were analyzed using statistical applications. In the study, the comparison showed a significant decrease in all parameters of the first group that was greater than the second group. Finally, the computer navigated training system improved the accuracy and time taken to complete the surgical procedures.

Rosenblum and Macedonia [23] gave an overview of surgical procedures followed in the common orthopedic surgery training. The most common orthopedic surgery-training students used the synthetic plastic bones to fix the fractured bones using surgical tools and implants. Afterwards, they used the cadaver for practice before moving to a real surgical environment. The potential drawback of synthetic plastic bones was that they easily break before the student can demonstrate surgical procedures and the better synthetic models were quite expensive. In order to learn the techniques, use the respective tools, place the implants, and get muscle memories, the

PC enabled VR techniques were used. This technique included the realistic 3D geometry of the patient from CT or MRI images, collision detection and sounds, real time 3D rendering, and input techniques. A geometric database was developed to store the different type of surgical tools and broken bone models using polygonal mesh with functional descriptions. To detect the collision a pseudo-physical collision detection method was implemented in the model. The environment guided the surgeon to complete the entire surgical procedures and also enabled the realistic sounds during the use of the instruments. In the experiment, the surgeons were requested to practice fixing the inter-trochanteric fracture by inserting the guide wires, pins, and remove the wire. It guides to identify the appropriate DHS screw, plate, and cortex screw sizes. In conclusion, the implemented tool used more sophisticated virtual tools and increases the realism, which gave a better immersion.

Burdea et al., [24] investigated the telerehabilitation system using VR and haptic interfaces in the networked system. The rehabilitation therapy was arranged for remote, rural located patients with recent orthopedic impairments. To monitor the improvement of the patient, they used haptic and network interactions. The system had two personal computers connected to the Internet from home to clinics. The home computer had a mouse/keyboard input, interactive sound generator, InsideTrack 3D magnetic tracker, and a multipurpose control system. The tracker measured position and orientation of the fingertip, and a camera provided the patient a support to interact people by teleconference. The clinic server monitored the patients exercise data and stored it in a database for later analysis. Rehabilitation software had a 3D graphics environment, patient database and graphical user interface. The 3D graphics environment generated the graphical images for the VR environment; graphical user interface helped the patient to select the required exercise mode from the menu options. There were two types of physical and functional rehabilitation that were analyzed in the VR environment. Physical rehabilitation identified the finger force exertion and range of motion; functional rehabilitation examined the maximum force exertion level by varying the difficulty of handling the devices. Obtained results were stored in the database by high and low level formats. The high level stored the specific finger forces and the low level stored the finger forces during exercise. Experimental results of the rehabilitation showed a significant change in the grasping forces and also improved the hand-eye coordination function.

Heng et al., [25] developed a VR training system for knee arthroscopic surgery with a tailor-made force feedback device. The existing haptic devices had a limitation in the positional forces and it did not provide the torque feedback. The developed feedback device had a two-hand haptic interface and it enabled the user to navigate and rotate the probe. The device had four degrees of freedom motion mechanism for each handle. The pitch, yaw, and insertion were the three DOF for the arthroscope and the fourth DOF was rotational, which enhances the surgeon's interaction. Three optical encoders were used to track the position and orientation of the probes. The knee-joints models were designed based on the nondeformable and deformable organs. The bones were modeled using surface meshes and the muscle and ligaments were modeled using tetrahedral meshes. These models were obtained from the human project image datasets and typical constraints in modeling meshes were elaborated. The authors also developed the soft tissue deformation model using complex finite element non-linear methods by topological changes in the operational and non-operational regions; cutting algorithm of the soft tissue by subdividing the tetrahedral meshes by tracking the intersection points among the cutting tool and each intersection; the collision detection technique was included during the navigation and cutting. During the experimental studies, the haptic devices achieved a satisfactory feedback and hand-eye coordination. In the end, the developed system provided a mesh generation, real-time soft tissue deformation, and cutting and collision detection to users.

Padilla-Castaneda et al., [26] discussed the integration of a robotic system and VR applications for the orthopedic rehabilitation of the arm representing the strengthening training and motion recovery. The system allowed exhaustive exercising by motor control, giving visuomotor, haptic feedback and trajectory positioning guidance. The most important part of the system was to assign specific tasks to perform within the virtual environments and helped to evaluate the mobility condition of the patient to personalize the difficulty level of the therapy and provided kineseologic measurements of the patient evaluation. The system used The Robotic rehabilitation device called BRANDO, which simulated the upper extremity of the patient in real time and the physical interaction with the virtual object provided the visual feedback of the patient's arm movements. The system had two VR training applications for the recovery of the elbow and forearm motion and the system Uses Graphical User Interface for managing the system virtually according to the specific patient condition. It included the personalizing the training sessions, tracking the performance of the patients with the managing database of the patient, which consisted the graphical and statistical report. The system took advantage of robotic therapy with task oriented VR at different simulating environments. It also included the patient registration, the personalization of the therapy and the modification of the difficulty level, controlling and monitoring the training sessions, and generating the patient's reports as necessary. The article stated it had conducted pilot experiments with 3 different patients where the patients risked performing more challenging movements and all the patients showed confidence in using the system and many clinical staff were satisfied with these systems.

Eriksson et al., [27] developed surgical training tools using haptic and VR techniques for the milling operation in temporal bone surgery. They utilized the marching cubes algorithm for the visualization of the developed skull bones based on the CT and MRI scanned images. The authors also tried voxel-based haptic rendering techniques for the force feedback. A collision detection method was applied between the probe and VR-object in order to obtain realistic force feedbacks using voxels density values. Material removal modeling of the milling process was developed using the energy-based approach for an accurate detailing in the surgery. H3D API based haptic devices were designed and developed for these systems. The authors also implemented the graphics and haptic interaction in the surgical environment for the better surgical procedures. In this method an updating frequency of 1000Hz was able to give a realistic experience of the bone milling. In the conclusion, the authors presented the future direction in tele-robotic surgery systems using a VR system for milling operation.

Pappas et al., [28] studied the individual surgeon's progress in a VR simulation for Shoulder Arthroscopy. The study was conducted with 43 surgeons and the results were evaluated based on the time of completion, number of probe collisions with the tissues, average probe velocity, and distance travelled from the simulated probe to optimal computer determined distances. The results were compared with the historical data of experienced users up to three years. The results showed improvement over the historical data and also the performance had improved upon the moderate user groups. At the conclusion, the authors demonstrated techniques that could be used for teaching surgery skills more particular to maintain hand-eye coordination. The authors also explained the future directions for actual surgical procedures using advanced simulators.

Lundstrom et al., [29] developed a multi-touch table system for orthopedic surgical planning. The article focused on the 3D visualization table design for better understanding of the surgical planning and also demonstrated the two novel interaction components in the touch tables. The article also utilized the user interaction study to explain the uses of the device. The developed device contains the following features: a large multi-touch display for visualization of clinical scenarios, interface with rendering for interactive, 6DOF interaction with 3D rendering, free orientation along with the main axes, movable alternator pucks for feature sets with touch gestures, and feasible zooming projections. Finally, the developed device enhanced the orthopedic surgeon clinical task with better understating of the complex human anatomy.

d'Aulignac et al., [30] proposed a mass-spring model of the dynamics of a human thigh based on real data to detect thrombosis illness in the vein. The current state of the vein was deduced based on the pressure applied to the echographic probe on the thigh, which subsequently was used to identify the illness. Two different probes were used to study the behavior of the thigh with respect to force being applied. The measurements were taken over the region of the thigh at multiple locations where the robotic arm advances based on data from end effector. The recorded force was repeated until the upper force limit. In order to simulate the real scenario, a two-layer model of the thigh using both linear and non-linear spring was proposed. Using least-squares minimization method, the parameters of the springs were estimated. Finally, a fully functional simulator coupled with a haptic interface was used to train practitioners for echographic exams.

Measure and Chaillou, [31] simulated dynamic behavior in organs without compromising the real time simulation and generality. The author stated the main problems in current models – lack of the realistic organs and tools, interaction with its environment, and structure modifications in the process. They discussed the need for synchronicity in the dynamic models and the types of interactions between the tool and the organ. With this in consideration, the author proposed a mechanical body model - a spring model with a rigid component in order to attain a compromise between memory, realism in real time. Further, they used Euler's method and integrated the equations so to obtain orientation of the parts. They analyzed the model to list down the pros and cons. The conditions for limitations, synchronicity and deformation, were discussed with a possible way to solve the problem partially. The author accepted that the model was under construction, but asserted that though synchronicity had not been reached, the simulation was interactive. The authors stated that instead of simulating with complex models, the proposed simple model, which works in real time realistically, would make it possible.

Mabrey et al., [32] questioned the reliability and practicality of VR in orthopedics and whether VR should be utilized in all orthopedic practices. To answer their questions they researched different trials in VR training versus no VR Training. They discussed many separate cases where surgery residents were split up into two groups: one with VR Training in the surgery and one without. The results in all the cases showed improvements to the students that had trained with VR such as faster completion time, better accuracy, and better overall comprehension of the procedure.

Karaliotas., [33] identified and discussed the many challenges in creating accurate and practical VR simulations for Surgery. These challenges included accurately depicting the complex anatomy of surgical subjects as well as making the use of the surgical tools realistic. The authors also discussed the development of their own VR System that improved some of these aspects. To accurately depict complex anatomical structures they used MR and CT scans to generate a realistic 3D view of the structure. To improve realistic tool movement, they used an NDI Polaris Optical Tracker which helped with real time tool orientation during the simulation.

Willaert et al., [34] explored Patient Specific VR Simulators and discussed the practicality of its uses. They review through 12 different PSVR systems. Out of 12, 11 of them were still in prototype stage while only one was actually commercialized. Their conclusion was that PSVR has a lot of potential and was a very significant technological advancement in the field of medicine.

Karaliotas., [35] discussed the short comings of current medical simulations such as lack of a 3D interface or having to work with animals or test patients. The author also discussed the validity in using VR Simulators to train new and upcoming surgeons. The author went through the history and development of VR and asked questions pertaining to the practicality of surgical simulation such as “Were the skills learned in a virtual environment transferable to an operating room?” The author’s conclusion was that Virtual Simulation training was valid in that it decreases the chances for potential risks by allowing realistic training that was flexible to the certain surgical situation.

2.3. Laproscopic Surgery

Laproscopic Surgery was another surgical field in which VR based simulators were introduced.

Azzie et al [36] developed and validated a pediatric laparoscopy simulator (PLS) subsequent to its adult laparoscopies counterpart. This simulator was designed to teach and assess the pediatric surgical skills by enhancing the adult version so that it represents the unique characteristics for the pediatric surgeries. As detailed in [36], while the simulator inherited many common features of the adult version, it had addressed the previous limitations, including the need for notably reduced working space, the smaller field of view, the more delicate children tissues, and the more precise and sensitive movement required for the surgery. The intra-corporeal suturing was reported as the task which has the greatest difference in performance between the adult and PLS simulators. Subsequently, the simulator was tested with a group of candidates to assess their level of expertise in pediatric surgery. They showed that the PLS simulator was able to differentiate between novice, intermediate, and expert surgeons. Moreover, the results show that the PLS simulator’s tasks were more difficult to perform than the adult simulators, which agreed with the initial hypothesis of the authors.

In the world of robot-assisted surgical training, there were still many obstacles, including the high cost associated with the surgical instruments. One of the major technological innovations in the field of robot assisted surgery was the DA Vinci surgical robot (DVSS). For such surgical contexts, there was a need to train surgeons in using the surgical robots; VR based simulation can enable such virtual training activities. Robotic Surgery Simulator (RoSS) was a novel VR based simulator for the DVSS. RoSS was developed in collaboration between the University at Buffalo and Roswell Park Cancer Institute. Before a surgical simulator could be used, there must be a way to evaluate its validity and as the first step, the face validity of the simulator must be tested. Sexias-Mikelus et al. [37] discussed the face validity of RoSS by performing a study between thirty surgeons and novices. The result showed that RoSS was real close to the DVSS console in terms of virtual simulation and instrumentation. The results of this study had been categorized in different aspects such as: closeness of RoSS to DVSS, feel of the pinch device, movements of the arms, clutch and camera movement, and visual display.

Makiyama et al [38] developed a virtual surgery simulator with the use in laparoscopic renal surgery. The simulator was patient specific; using the CT images of each individual person to build the volume model of the organ under consideration, the simulator enables the surgeon to perform the pre-operative rehearsal process. The physical simulator utilized two forceps, one foot pedal and one scope for the assistants. The pedal made the surgeon perform an electrical cut by pressing it. Different surgical tools were also available and could be changed using forceps and foot pedal by the surgeon. There was also a haptic device which gave the surgeon a much needed tactile feedback of the interactions between the simulated body organ and the surgical tool. The simulation process started by first using the CT data to build a volume model of the live organ using an extended region-growing method [38]. The soft-tissue deformations were modeled using Finite Element Methods (FEM). The simulator discussed in [38] had been used by surgeons in ten cases in clinic centers and reported as a useful tool for performing pre-operative rehearsal. In addition to beginners' training and performing the pre-operative rehearsal, the simulator could also be used by expert surgeons to propose creative techniques and non-routine approaches in laparoscopic surgery, which could enhance the planning process and facilitate a safer operation.

Grantcharov et al [39] examined the impact of VR surgical simulation for improvement of psychomotor skills relevant to the performance of laparoscopic cholecystectomy. Their research objective was to validate the role of VR simulation in surgical training by assessing the possibility of improvement and revision of surgical skills obtained through training in a VR simulation module and its replication in the physical operations. This study was carried out in three departments of abdominal surgery in teaching hospitals using the Minimally Invasive Surgical Trainer – Virtual Reality (MIST-VR). In this study, twenty surgeons with limited experience in laparoscopic surgery participated and they were assigned to do six complex tasks which were designed to simulate the same techniques used during laparoscopy to cholecystectomy. Comparison of performance of the two groups (group 1 trained using VR and the second group which served as the control group) was analyzed using statistical analysis; the authors concluded that surgeons who received the VR training performed laparoscopic cholecystectomy significantly faster than those in the control group; moreover, the VR trained group showed greater improvement in their error and economy of movement.

Aggarwal et al., [40] performed a survey about the attitude and willingness of the senior and junior surgeons toward the VR laparoscopies simulators. They interacted with 245 consultants and their corresponding specialist registrar (SpR) to fill in their questionnaire and express their opinion toward this emerging field of technology. Among these surgeons, 81 percent agreed that VR simulators can help the training community to have a better training in laparoscopic techniques. 90 percent of junior SpRs and 67 percent of senior SpRs were interested in using VR in their training system.

2.4 Heart surgery

Another important surgical area where virtual environments were used was heart surgery. Some of these environments aided in training surgeons for minimally invasive cardiac surgical procedures; others were used for planning cardiac surgical processes.

Peters [41] discussed the development of a VR environment to assist surgeons in minimally invasive cardiac surgery. This system uses VR techniques to integrate anatomical models, intra-operative imaging and models of magnetically tracked surgical tools. Preoperative anatomical models were constructed using an MRI scanner (where various anatomical features were identified). Intra-operative images were acquired using a 2D-trans-esophageal echocardiography (TEE) transducer. An intra-operative VR environment was developed with the pre-operative cardiac models. The virtual environment was complemented with the tracking surgical instruments in the virtual environment. The researchers also described preliminary efforts by using their system for guidance and planning of typical intracardiac procedures. Two of the applications highlighted include a Mitra valve implantation procedure, an Atrial Septal defect (ASD) closure intervention and radio-frequency ablation procedure. The virtual space used in this approach reflected the actual surgical space during heart surgery and was based on images of the heart before and during the surgery itself. Using this environment, the surgeon had access to a global 3D view of the heart, a detailed view of the surgical target, and information on the position of the surgical instruments. The results from this study indicated that the model-to-subject registration technique used to augment the intra-procedure images with the pre-operative models ensures a ~5 mm accuracy for the cardiac structures which were within 10 mm from the valvular region (this was acceptable from a surgical perspective). The accuracy of the VR enhanced ultrasound guidance system was also assessed from a surgeon's point of view. The authors concluded that the use of the VR system helped in the performance of the intra-cardiac surgical process. This approach also supported target visualization, planning and guidance for the surgery.

Par et al., [42] a virtual fixture technique was developed to support robotic cardiac catheter manipulation tasks. The authors classified the haptic virtual fixtures into guidance virtual fixtures and forbidden-region virtual fixtures. The concept of virtual fixtures was used in various fields, including rehabilitation exercise assist system and minimally invasive surgery [43]. Images from X-Ray fluoroscopy were used along with vision-assisted control methods based on the forbidden-region virtual fixture (FRVF) technique were used to prevent collision of the catheter tip and the vessel wall. A master-slave robotic platform was developed for this approach. The master handles provided haptic rendering to the user. An algorithm was developed to support the virtual force generation task, which fed the signal back to the user when the catheter tip penetrated the forbidden region. The overall benefit of this approach was that it could provide additional information to clinicians to safely manipulate the catheters in cardiac procedures.

In cases involving congenital heart diseases, operation planning was vital to the success of the overall surgery as it provides a better pre-operative understanding which could minimize surgical explorations. Sorensen et al., [44] a simulation based approach was outlined to assist in pre-operative planning related to invasive cardiology. The overall emphasis of their research was to translate 2D imaging data into 3D visualization based environments which in turn could promote better understanding of cardiac morphology. The overall approach involved four major steps including data acquisition, segmentation, model generation and VR based visualization. The input data were MRI scans, which provided fairly accurate cardiac dimensions for imaging of cardiac chamber volumes and myocardial masses. Segmentation involved (in general) the classification of pixels into regions. Algorithms were developed to perform segmentation of the 3D cardiac MRI data sets. The VR environment included both hardware and software. These included dual displays in an 'L' configuration, shutter glasses (Crystal Eyes 3D eyewear for stereo viewing), tracking devices (from Polhemus) and an advanced computing processor (Onyx2). For interactions with the VR environment, a scene interaction library was used. A user could perform basic navigation including zooming, rotation, etc by simply moving the hands when holding and activating the stylus trackers.

Berlage at al., [45] outlined the first part in the development of a simulation and planning system for minimally invasive coronary artery bypass surgery. As the authors indicate, though minimally invasive surgical procedures were beneficial to the patients, they were a number of difficulties associated with it. The objective was to create a simulation system that helps the surgeon plan and choose appropriate incisions which can also provide an optimal operation range of the instruments. Their long term interest was to use this system and approach for education and training. The simulation was based on multimodal image data registered to a virtual heart model. The main objective to develop such a system was to help the surgical community plan for such operations and thereby further reduce the complications associated with minimally invasive surgeries. The approach addressed the three primary problems associated with such surgeries: (i) port or incision identification, (ii) training and (iii) spatial orientation for proper and precise motion (during surgical procedures). The advantage of using such a virtual model over a 3D reconstruction was that it incorporated dynamic predictions of the heart motion. The heart model with the ribs and the chest surface had an accompanying set of virtual instruments and a simulated endoscope. These virtual instruments could be moved using an electromagnetic tracker, while the endoscope could be controlled using menu operations or voice activated commands. The endoscope view was simulated by a virtual camera in the scene. This enabled assessment of the spatial accessibility of the operation field in a VR environment. The primary outcomes of this earlier work demonstrated that simulation of minimally invasive cardiac procedures was possible using a virtual heart model (and VR technology).

Thanh et al., [46] discussed the use of a virtual environment with haptic interface to train new surgeons in heart myoblast processes. In the heart myoblast process, myoblast cells were injected into the heart to restore muscular function. The use of a robotic surgical assistant system helped in the process, but the lack of experience on the part of the surgeon caused damage to the surrounding tissue. In [46], a haptic enhanced virtual environment was outlined which can be used to train surgeons to improve hand-eye coordination as well as used to enhance a surgeon's teleoperation robot-assisted surgery skills. The outcomes of experiments on human performance were also discussed (when using and interacting with haptic feedback based virtual environments). This study involved 10 operators repeating the needle insertion and injection ten times; the experiments demonstrated a training success rate of 84.00% and 75% respectively for static and dynamic motion heart scenarios; it was observed that some operators improved their times by 300 % when compared to the training using a static heart scenario.

Ren et al., [47] the use of 3D virtual fixtures to augment the visual guidance system with haptic feedback during minimally invasive heart surgery was detailed. While minimally invasive surgery (MIS) had many benefits over conventional procedures, it had several drawbacks. These include restricted maneuverability, limited field-of-view, and the lack of tactile feedback. The virtual fixtures can be used to provide the surgeon with more helpful guidance by constraining the surgeon's hand motions thereby protecting sensitive structures. VFs can be described as computer-generated forces that were reflected back to the operator as feedback during a surgical procedure. Two categories of VFs were outlined: forbidden-region virtual fixtures (FRVFs), and guidance virtual fixtures (GVFs). GVFs were used to guide the surgeon toward a target and can help an operator or robot to move along desired paths or organ surfaces, FRVFs restricted access to "forbidden" regions and were viewed as hard constraints which prevented an operator/robot from entering forbidden regions. The proposed dynamic virtual fixtures were applicable to many intracardiac procedures, including atrial-septal defect repair, valve repair and replacement, and ablation for atrial fibrillation (among others).

Yu et al., [48] an interactive simulator was described in real-time and tactile catheter navigation. The authors acknowledged that realistic simulation of cardiac intervention was still very challenging because of the complex and dynamic nature of the cardiac intervention process. The myocardium was represented using tetrahedral volumetric mesh which presents the main anatomical information, including details of valve and valve gaps. Different parts of the adjacent tissues were identified by different colors. The cardiac intervention was modeled as a two-body interactive problem; the catheter and the heart were independently modeled. While the heart was modeled using mesh geometry, the catheter was modeled by a number of cylinder rods. The overall simulation environment comprised of a stereographic visual panel, a tactile catheter device and a virtual patient model. The 3 D tracking system used was the Polhemus PATRIOT stylus system. The simulator worked with on a Windows PC workstation with an NVIDIA graphics card; the graphical environment was created using OpenGL Graphic Library.

2.5. Other Surgery

VR based environments and tools were used in a wide range of other surgical domains. A review of environments from various surgical domains was discussed in this section.

Montgomery et al [49] discussed the use of Virtual Environments for Reconstructive Surgery (VERS) from the removal of a soft-tissue tumor; in this paper, the authors review the case of a 17 year-old boy with a severe facial defect arising from the removal of a soft-tissue tumor. They implemented a number of virtual tools and interfaces, including (a) selecting surgical tools to pick up an object in the environment (b) a marker tool to 'mark' on the surface of a target object, and (c) a lighting tool for more precise localization of lighting. They visualized the high-resolution data of the patient and produced color prints from various views; subsequently, the VERS system was used to interact with these data. The virtual system (VERS) can be used to quickly interact with the meshes representing the skull and soft tissue. With the available data, a surgeon was able to virtually cut the bone and examine the fit of a new bone to be placed into the (target) defect area. In the end the system which they created integrates 3D reconstruction, visualization, quantification and manipulation of multi-model patient data for the purpose of surgical planning. The system was found to be instrumental in the preparation and correction of severe craniofacial defect and was well received by the surgical community.

Suzuki et al., [50] the development of a surgery planning system using VR techniques was detailed for the incision of skin and organs. A force feedback device was developed which responds to the pressure of the virtual operator's hand. In this study, they used reconstructed sphere-filled model of the liver and the surface of the liver model was wrapped with the surface image of autopsied liver tissue (using a texture mapping method to obtain a realistic appearance for the simulation). A haptic device was developed with force and motion control manipulators which were attached to the thumb, forefinger and the middle finger of the operator; the forces coming into play was calculated using a 'sphere-filled model' proposed by the authors. The performance of the virtual model was more accurate and the model generated the images virtually without any delay when using a surgical tool. The force feedback device performed surgical maneuvers with the sense of touch more accurately in the real time environment. The developed system was used for surgeries in the abdominal region.

Cecil et al., [5] An information model based framework for the development of microsurgery virtual environment was outlined. Microsurgery involves the sewing together of blood vessels, nerves or tendons, or blood vessels to correct an injury, or congenital defects. In surgical operations, small arteries and veins were reconnected within the operated area; the surgeon uses an extremely thin thread and completes the surgery with the help of microscopes. Cecil et al., [5] The information framework proposed involved the use of information models to capture the complex relationships within a surgical process and a haptic interface based environment to train medical residents in microsurgery. The information model was built using an engineering Enterprise Modeling Language (eEML) where the functional relationships and temporal precedence constraints were explicitly modeled; this model was developed in close interaction with expert micro surgeons. The role of such an information intensive process model in providing a foundation to build VR based simulation environments to train surgeons was also discussed.

Both semi and fully immersive systems require the use of VR sensors such as motion trackers (such as the Flock of Birds® unit from Ascension Technologies) and immersion supporting devices such as interactive ‘wands (such as WorkWand®). Stereo eyewear was typically used to view active stereo in semi or fully immersive environments.

The original CAVE® (Cave Automatic Virtual Environment) was developed in 1992 at the University of Illinois and was an example of a fully immersive system; it had four projection screens which allow users to immerse themselves using sensors and stereovision eye wear. Johansson and Ynnerman [51] discussed different immersive visual interface’s ability to support engineering designers during product design. An analysis was performed to find induced errors in a mechanical product using different display solutions: an immersive workbench (67” screen, Barco projector, CrystalEyes®, head tracking, magic wand® and keyboard), a desktop-VR (21” monitor, CrystalEyes®, keyboard and mouse), and a desktop system (21” monitor, keyboard and mouse). Based on the results, the authors concluded that the immersive displays supported the product designers the best.

2.6 Haptic Devices and Tracking Technology

In this section, discussed some of the haptic and tracking technology from various vendors.

Coutee et al., [52] described the development of an application known as HIDRA (Haptic Integrated Dis/Reassembly Analysis), which provides a haptic feedback through a haptic interface (PHANTOM™). A haptic interface was a peripheral device that measures the forces applied by the user’s avatar (user’s representation in a virtual environment) in 3D space and exerts those forces of the actual user, thereby providing haptic feedback. Providing haptic feedback allowed the user to feel the friction, wiggle and touch. The HIDRA test bed was a two-loop simulation, which provided haptic and graphic rendering. When a user touched or applied force to the virtual object through a PHANTOM™, HIDRA monitored and responded to such forces. The haptic simulation loop of HIDRA continuously calculated the user’s fingertip position and checks for collision of fingertip and the virtual object. If a collision was detected, then equivalent force was exerted on the fingertip through the PHANTOM™.

Springer and Ferrier [53] described the design of a multi-finger force-reflecting haptic interface device for teleoperational grasping. The entire system consisted of a master or haptic interface and a slave or a remote manipulator. The Master tracked the positions of the user and used these positions to manipulate the motion of the slave. The hand mounted mechanism was capable of representing the fingertip position throughout a wide range of grasping motions.

Balijepalli and Kesavdas [54] described the design, implementation and evaluation of a haptic simulator based on a force model that renders precise crisp force feedback using an abrasive hand-grinding tool. Based on a force model for grinding tools, a haptic interface to machining a work piece was developed; 3D Terrain modeling and dynamic texture modification algorithm were developed to simulate the polishing or grinding process. For haptic interaction, a framework for fast and accurate collision detection was implemented by Gregory et al. [55]. The algorithms used polygonal models with real-time hybrid hierarchical representation and exploit frame-to-frame coherence for fast proximity queries.

Magnetic Levitation devices (Maglev) were a haptic technology introduced first at IBM Research and later commercialized by Butterfly Haptics under the NSF Major Research Instrumentation grant with a license from Carnegie Mellon University [56], [57]. Maglev devices utilized a different technology compared to other haptic devices; rather than using mechanical elements such as linkages, motors, cables, and bearings (found in most haptic devices), they interact with the user through a handle which was levitated by magnetic fields. The Maglev device was intended to provide interaction with a high degree of fidelity, position/force bandwidth, and position resolution, and a wider range of possible stiffness. During the past decade, many researchers have worked with haptic technology, which led to Lorentz Levitation devices, including the IBM Magic Wrist, UBC Wrist, the UBC Maglev Joystick, and the CMU Magnetic Levitation Haptic Interface [56, 57].

Maglev haptic devices provide 6 degrees of freedom through a single moving part levitated in a magnetic field. The handle was attached to a “flotor” which floats between stators. The flotor was tracked by optical sensors to determine its position and orientation, and then this information was sent for further processing and then back to the user through the handle [56].

Gurocak et al [58] described the design and implementation of a force feedback hand master haptic device called AirGlove. In a VR environment, touch and force feedback provide realism by considering the physical properties like object rigidity, weight, friction and dynamics of the objects. The AirGlove consisted of an air jet block with 5 ports, a remote box having 6 pressure sensors and a control software. Compressed air was exhausted through the ports of the air jet block to apply thrust force on the user’s hand. AirGlove provided gravitational force feedback to the user as he or she manipulates objects in the virtual environment.

Electromagnetic tracking systems used for immersive systems require a calibrating system as they suffer degradation in accuracy due to stray electromagnetic fields in the vicinity Jayaram et al., [59]. There were two types of tracking systems: one with DC magnetic fields (Flock of Birds) and the other with AC magnetic fields (Polhemus Fastrak). A calibration system called COVE (Calibration of Virtual Environment) was used for measuring static errors of DC magnetic trackers and automatically correcting them and several interpolation techniques. The COVE calibration process consists of five steps: discretization, grid data collection, interpolation, incorporation, and evaluation.

The use of Virtual Surgical Environments (VSE) in daily practice was not yet widespread for various reasons; in Aggarwal et al., [40], some of these reasons were outlined which include lack of familiarity with VR technology, high-priced cost, poor validation of effectiveness as well as the reluctance of surgeons and faculty to invest their time in this emerging area and technology.

2.7 Other Challenges

In this section, a discussion of the challenges involved in the development and evolution of virtual surgical environments will be provided.

One of the major challenges was that the creation of virtual environments was a complex time consuming process. Most of the software tools available on the market today require long periods of training to acquire and hone the software skills necessary to build such environments. In addition, very few of the haptic technology vendors provide training services to teams interested in building simulation tools. Currently, a new generation of software tools which are more user friendly (such as Unity 3D™) holds the potential to change this trend.

The design and development of virtual environments require the collaboration of medical surgeons, software specialists and engineering / science experts. While the process expertise (for a given surgical domain) lies with surgeons, this understanding of a specialized surgical process needs to be studied and modeled prior to the design of a target surgical environment Cecil et al., [3, 4]. The importance of creating information models (which was more common place in the development of engineering simulation environments) prior to the design of virtual environments will enable the implementation of more realistic and detailed simulation environments.

Another key problem is the cost involved in the acquisition of VR equipment (which varies depending on the level of immersion) including trackers / cameras, 3D eyewear, sensors and other peripherals such as controllers, joystick, wands, etc. (Which was needed to interact with the target simulation environment). While the cost of computing processors, 3 D eyewear and trackers came down significantly, the cost of fully or semi immersive technologies is still high; today, semi immersive technologies (including trackers, projectors and software) can range from

$25,000 to $ 200,000.   Fully immersive technology (such as a CAVE system) is more expensive and can cost upwards of $500,000.

There is also a need to conduct more comprehensive assessment of the impact of using VSEs; while several studies indicated their benefit in terms of developing surgical skill for surgeons, more studies are necessary which focus rigorously on the development/technology cost versus benefit/impact in surgical fields and medical training.

The current state of haptic technology also needs to improve if more realistic environments are to be developed. While most of the existing haptic products provide basic force feedback and modeling capabilities, there is a need to develop more advanced technology that can provide more sensitive and realistic force feedback which is crucial for this emerging application area involving training of surgeons. For example, when simulating micro surgical processes, the force feedback should be sensitive enough to be able to simulate a surgical needle piercing the wall of a blood vessel. Development of such next generation haptic technology that are more innovative and low cost is key to wider adoption of virtual surgical environments.

2.8 Conclusion

Initially, the Literature review had been carried out in the orthopedic surgery, heart surgery, laparoscopic surgery and other techniques on the basis of virtual environments. The potential issues and problems on these surgical methods were identified. The following chapter gives the overall design approaches and methods for creating the VR environment for the orthopedic surgery specifically Less Invasive Stabilization System.

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