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Virtual Reality Simulator for Scoliosis Surgery Training: Transatlantic Collaborative Tests

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Abstract *– Scoliosis is a complex deformation of the spine requiring, in severe cases, a highly delicate and invasive surgical instrumentation operation to correct the spinal deformities. Available traditional tools for surgical training have major drawbacks for which virtual reality (VR) technologies and computer simulation can offer solutions. In this paper, we introduce a surgical simulator integrating a complex patient-specific biomechanical model into a VR immersive environment in a collaborative context, the first of its kind for scoliosis surgery training. We present the results for the fully collaborative AVE (audio visual environment) aspects of the simulator. Haptic forces are computed in the biomechanical model, but not yet available as a haptic feedback because of the high forces and torques characteristic of scoliosis surgery, requiring the use of a specifically designed haptic device (in progress). Transatlantic collaborative tests showed that, with our simulator, users on different continents can train collaboratively for scoliosis surgery and visualise the forces and the resulting correction. With the eventual addition of haptic devices, they will also be able to feel the forces remotely.*

Keywords *– collaborative virtual environment, haptic feedback, immersive environment, scoliosis, surgical training*

I. INTRODUCTION

Scoliosis is a complex deformation of the spine and trunk, involving abnormal spinal curvature due to deviations and rotations of the vertebrae. Idiopathic scoliosis arises in otherwise healthy subjects and represents 80 to 85 percent of scoliotic cases [1]. Adolescent idiopathic scoliosis (AIS), in turn, represents approximately 80 percent of idiopathic scoliotic cases. Prevalence of AIS in the general population is 2 to 3 percent, with less than 10 percent of identified cases requiring active treatment [2], or 135 000 Canadians.

Current treatments for AIS are mostly mechanical, i.e. based on load application. A number of factors affect the choice for a specific treatment: patient's age, type and severity of the deformation, etc. Non-operative treatments consisting in bracing are used with the expectation of preventing the progression of the curve until the patient reaches skeletal maturity [3], rather than correcting the deformation. In severe cases, i.e. for adolescents with a primary curve of more than 45 degrees [3], operative treatment is indicated. In a highly delicate and invasive surgical procedure, part of the spine is instrumented and fused to restore trunk balance and normality. Posterior fusion with instrumentation is a standard [4].

Our research focuses on the simulation of posterior fusion surgery based on the CD Horizon instrumentation (Medtronic Sofamor Danek, Memphis, TN). CD Horizon is a modern instrumentation derived from the popular Cotrel-Dubousset instrumentation [5], characterized by the rod rotation manoeuvre. The surgery includes, but is not limited to, these steps: 1) positioning and insertion of vertebral implants (hooks, screws); 2) insertion of a first contoured rod; 3) corrective manoeuvres (rod rotation, vertebral compression and distraction, direct vertebral derotation, etc.); 4) insertion of a second rod; 5) bone grafting for vertebral fusion and installation of devices of transverse traction. Fig. 1 shows pre-op and post-operative radiographs of a scoliotic patient with CD Horizon instrumentation.

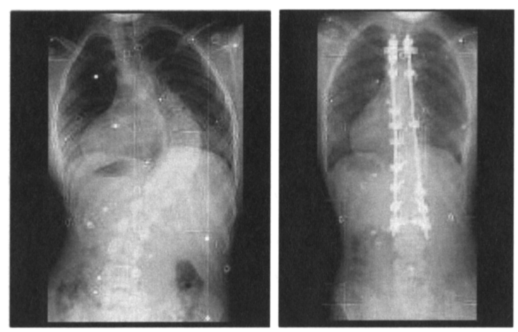

Fig. 1. Pre-op and post-operative frontal radiographs of a scoliotic patient with CD Horizon posterior instrumentation.

For a given scoliotic case, operative strategies vary substantially from one surgeon to another, depending on judgment and experience. There is no consensus among the medical community for optimal implant configurations and surgical plans for a given curve type [6]. Available traditional tools for surgical education and training related to scoliosis surgery (synthetic and cadaveric spines) present major drawbacks, such as: 1) unavailability of young cadaveric spines with scoliosis; 2) questionable behaviour realism; 3) destruction after first use; 4) limited variability in scoliotic cases for training. In light of these facts, it is of the utmost importance to give future spine surgeons a training as complete as possible, and simulation brings additional means to achieve this goal.

This project, a collaboration between mechanical and computer engineers, orthopaedic surgeons, and an industrial partner, deals with the development and testing of a

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collaborative virtual reality (VR) surgical simulator with haptic feedback, as an alternative training tool for scoliosis posterior instrumentation surgery. Such a simulator has clear advantages over traditional training tools: availability, behaviour realism, repeatability, and large variability. It offers the possibility to learn and gain knowledge and abilities, in a virtual environment, over a variety of realistic scoliotic cases, with common or specific difficulties and rarities, without ever risking patients' health. In this paper, we present the results for the fully collaborative AVE (audio visual environment) aspects of the simulator, with haptic forces being computed and displayed, but not yet available as a haptic feedback as such. In the long term, our objective is to develop a collaborative HAVE simulator, including a haptic interface specially designed for scoliotic surgery, which involves high forces and torques, with the aim of creating a practical and realistic surgical training tool. In section II, we review related work regarding virtual reality surgical simulators. In section III, we describe the architecture of the simulator and its three main components: the biomechanical server, the telepresence multi-user server, and the VR simulation client. In section IV, we present typical collaborative usages and the results of transatlantic collaborative tests. We conclude and discuss future work regarding haptic feedback in section V.

II. RELATED WORK

According to McCloy and Stone, the crucial factor for the adoption of VR among the medical community will be the demonstration that VR can lead to reliable and valid systems for training and evaluation [7]. Recent studies aiming at determining the utility of VR simulators for surgical training show that this is the case. For instance, researchers in [8] and [9] showed that training with a VR laparoscopic surgery simulator for specific tasks significantly increases surgeons' performances in the operating room.

A large majority of VR surgical simulators have been developed for minimally invasive surgeries (MIS), such as laparoscopies and endoscopies, perhaps because of the hand-eye coordination challenge. Basdogan and colleagues present a survey of VR-based simulators for MIS training [10]. MIST-VR [11], a training and evaluation system for specific tasks related to laparoscopic procedures, using a conventional computer monitor and two laparoscopic instruments equipped with position sensors, and SIMENDO [12], a hand-eye coordination training and evaluation tool for endoscopic surgeries, using the handle of a real endoscopic instrument and a conventional computer monitor as well, are both examples of such simulators. However, they do not include haptic feedback. Several researchers have been working on MIS simulators equipped with the 3 degrees of freedom (DOF) PHANTOM commercial haptic system (SensAble Technologies), for which capacities in terms of DOF have been augmented in order to simulate surgical tools [13-15]. Visual feedback is done through conventional computer monitors. Immersion Corporation commercialise different MIS simulators that incorporate force feedback through the surgical tools, such as the LapVR for abdominal laparoscopic procedures and the CathLabVR for endovascular procedures. The Virtual Endoscopic Surgery Trainer (Select-IT VEST Systems AG) makes up another example of haptic-enabled commercial MIS simulator. In an opposite direction, Ilic and colleagues have developed their own haptic interface in an interventional radiology simulator, including the manipulation of a 4 DOF (in haptic feedback) catheter [16]. The PHANTOM device has also been incorporated into other types of surgical simulators, such as in temporal bone surgery simulators, in which users see stereoscopic images through two small monitors mounted as glasses [17, 18] or through a conventional computer monitor [19], and in collaborative cataract surgery simulators, offering in one case a haptic, auditory, and visual playback interface from measured expert movements [20] and in another a haptic-enabled telementoring (bilateral telehaptics) system with different immersive displays [21]. Chee-Kong and colleagues adapted commercial haptic systems (CyberGrasp and CyberGlove from Immersion Corporation) and a gaming force-feedback joystick for simulating vertebroplasty surgery [22], using again a conventional computer monitor. Closer to scoliosis surgery, Michelson [23] discusses the way orthopaedic simulation for education will evolve based on the numerous efforts in MIS simulation. Research regarding VR tools applied to orthopaedic surgery has predominantly been focused for intra-operative assistance, for instance for guiding vertebral implant insertion [24, 25].

Most of existing surgical simulation systems, using conventional computer monitors, do not provide a feeling of immersion into the simulation as important as it would be possible to do with VR technology like large volume displays and stereoscopic images (this can be explained in certain cases by the actual technology used in the operating room). Those that make use of such displays are mostly visualization systems (for instance for teaching human anatomy [26]), in which users cannot modify the virtual environment and thus cannot practice surgical manoeuvres. A majority of academic surgical simulators with haptic feedback incorporate commercial haptic devices. Commercial haptic devices are often quite complex and expensive because they are designed for a broad audience, simulating rapid movement and contact with all kinds of virtual objects. Most surgeries do not require a large stiffness from the haptic device, involving organs with a certain compliance, a relatively confined workspace and "delicate" forces, therefore they can be simulated with somewhat generic commercial haptic devices. Posterior instrumentation surgery of scoliotic spines differs in the sense that it requires the application of high forces through moderately slow and of few DOF movements. For instance, during the rod rotation manoeuvre, surgeons apply up to 68 N with an equivalent torque of 14 Nm, as measured in situ during a scoliosis surgery [27, 28], or up to 20 Nm as measured ex situ by an orthopaedic surgeon replicating the movement using a torque-wrench (see fig. 2).

Fig. 2. Ex situ torque measurement setup for the rod rotation manoeuvre.

III. SYSTEM ARCHITECTURE

The simulator, integrating a complex biomechanical model into a VR immersive environment with collaborative functionalities, is based on a client-server topology and is composed of three entities: 1) a biomechanical server, which models the mechanical behaviour of the scoliotic spine and the instrumentation manoeuvres; 2) a telepresence multi-user server, which manages users' telepresence; 3) a virtual reality simulation client, which displays and manages an interactive virtual operating room. Its modular design facilitates the integration of additional functionalities and reuse. In a typical collaborative surgical training session, there is one instance of each server running and as many client instances as there are users participating. Users can be geographically distant. Each client connects individually to both servers using the internet. A global view of the system architecture, all written in C++, is presented in fig. 3.

A. Biomechanical Server

The biomechanical server manages the collaborative instrumentation and application of corrective forces to the spine. It models the biomechanical behaviour of the scoliotic spine and its instrumentation according to the model developed for the pre-operative and surgical simulation software S3 [29], adapted for a collaborative context. It is a kinetic, patient-specific model making use of flexible mechanisms, developed with the Adams SDK (MSC Software). It includes the mechanical properties of the spine (adapted to the patient's flexibility using side-bending tests), the constraints of the spine-instrumentation system, and the external loads applied during the surgery, combined to the reaction forces of the system. The biomechanical server is based on a "centralized-shared" topology, i.e. it stores the unique copy of the state of the spine and its instrumentation to maintain data coherence between the clients. The server accepts requests from clients, simulates surgical steps accordingly, and propagates the simulation results to every connected client so all users see a common virtual scene. Requests coming from clients correspond to surgical steps and manoeuvres such as implant insertion, position modification, and suppression, contoured rod attachment and detachment, rod rotation, etc. Simulation results correspond to updated implant and vertebra position and orientation matrices, and to rod control point positions. The TCP protocol of the TCP/IP model transport layer is used for multicasting simulation results for a guaranteed transmission. This biomechanical server is already fully functional and is used in our collaborative environment.

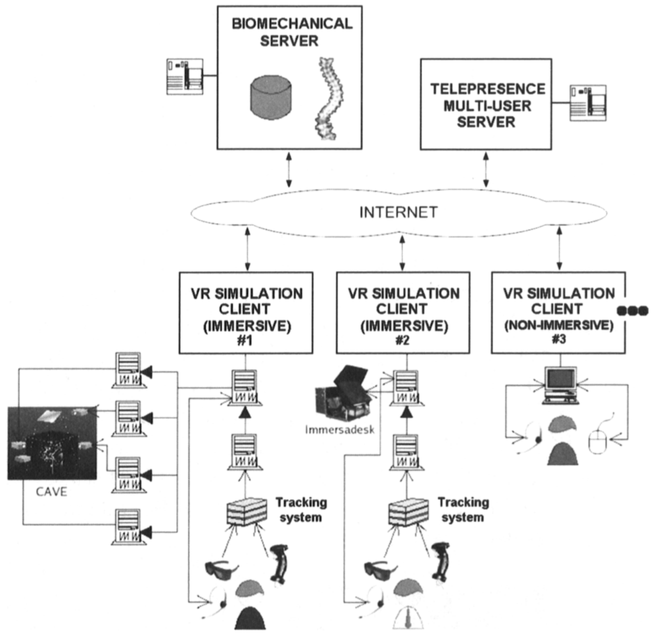

Fig. 3. Global system architecture.

In haptic terms, the biomechanical server works on a impedance approach: users input motion (for instance the rod rotation angle during the rod rotation manoeuvre) and the server computes (outputs) the required force or torque for the motion. In addition to computing the forces generated at the implant-vertebra link, the biomechanical server computes the forces and torques generated at the implant-tool or rod-tool interface, for instance the resulting torque on the rod following the tool rotation (power grip) during the rod rotation manoeuvre. These forces and torques will be used in the impedance command of the haptic interface (work in progress): users will move the haptic device that will react by applying a force/torque accordingly.

B. Telepresence Multi-User Server

For collaborative surgery training, each participant should be aware of the intentions and actions of other participants. The telepresence multi-user server manages the visual information regarding users' feeling of telepresence. Similar to the biomechanical server, the telepresence server is based on a "centralized-shared" topology, i.e. it stores the unique copies of the IDs of all present clients, as well as the last position and orientation of the head, hand (3D wand) and current manipulated virtual object (implant, rod, tool) for each user. It receives this information from each moving participant's corresponding client and relays it back to every client using the UDP protocol of the TCP/IP model transport layer for a fast transmission.

C. Virtual Reality Simulation Client

The VR simulation client is a 3D graphical interactive application designed for a VR immersive environment, such as the CAVE and the ImmersaDesk (Fakespace Systems), although it can run on a standard PC as well in a non-immersive mode. It uses open source third party libraries for facilitating the management of the different VR devices and the PC cluster of the immersive environment (VR Juggler), and the 3D virtual scene (OpenSG). Wearing LCD shutter stereoscopic glasses, users are able to visualise the virtual scene in three dimensions. They manipulate a 3D wand in order to interact with the virtual objects. Both glasses and wand are equipped with a 6 DOF tracking system (Flock of Birds), so the simulation keeps track of users' head and hand movements in space. In non-immersive mode, users visualise the virtual scene in 2D with a standard monitor and interact with the virtual objects using standard keyboards and computer mice. A haptic device, allowing users to perform surgical manoeuvres through a realistic interface from a surgical point of view, will eventually be added to the apparatus (work in progress).

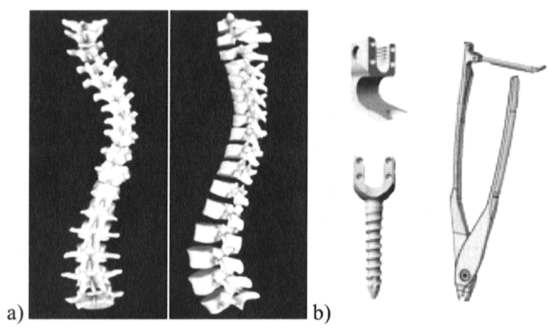

Fig. 4. 3D models. Patient-specific spine in a); examples of implants and tool in b).

The virtual scene, recreating a typical operating room of the Sainte-Justine University Hospital Center in Montreal, consists mainly of a surgical lamp, shelves, patient radiographs, an operating table, a surgical cloth, a plate with all kinds of implants and tools, 3D controls for selecting implants, the patient's body and his/her spine. The patient-specific 3D geometrical spine models (fig. 4a) are reconstructed from multi-planar radiographs [30], and the virtual CD Horizon implant and tool models (fig. 4b), supplied by Medtronic Sofamor Danek, are accurate reproductions of those used by surgeons. Zoomed views focused on an instrumented vertebra, offering different levels of transparency, allow users to verify implants positioning and visualise vertebrae geometry.

Clients send requests to the biomechanical server whenever users execute surgical manoeuvres, and display the new state of the spine as computed by the server. Clients also send information regarding the position and orientation of the users (head and hand) and of the objects they are manipulating (implants, rods, tools) to the telepresence server, and display other participants' manipulated objects and avatars according to the information received from this server. The avatars simply consist of two prisms (one for the head with a facial texture, and the other for the body), and a cylinder for the virtual 3D wand (fig. 5a). Users also communicate using headsets with microphones. Fig. 5b shows a user training in a VR immersive environment.

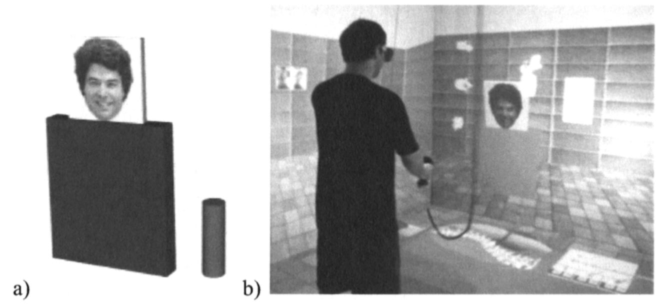

Fig. 5. Example of participants' avatar in a); user training collaboratively in a VR immersive environment (CAVE) in b).

IV. RESULTS AND TRANSATLANTIC TESTS

There are several use cases possible with the VR surgical simulator: solo surgical training (local and remote), collaborative surgical training (local and remote), remote teaching and learning, to name the most typical ones. During training sessions, all participants are actively performing the surgery, preferably in immersive mode with a CAVE or ImmersaDesk system but non-immersive mode with a standard PC is possible as well. During teaching and learning sessions, there are active participants, demonstrating the surgery, and passive participants, observing, asking questions (and eventually feeling passive force feedback). In this section, we present the results of transatlantic tests that were conducted in spring and summer 2008 for these use cases: remote solo training and remote collaborative training. The biomechanical and telepresence multi-user servers are both located at the Ecole polytechnique in Montreal, Canada, and the remote clients for remote solo and collaborative training are located in the Netherlands, about 5500 km from Montreal. On the remote client side (running on a laptop computer in non-immersive mode, which is quite realistic for remote clients anywhere in the world), two internet wireless connections of different bandwidths were tested (7 Mbps/700 kbps and 1,5 Mbps/200 kbps for download/upload) and produced similar results.

A. Remote Solo Training

Local solo training, implying one client running locally on the same local area network as the servers in Montreal, has been tested throughout the development of the simulator. However, remote solo training is of much more interest since it involves additional issues such as network latency. We have shown that it is possible to carry out a complete scoliosis surgery training session with a remote client, involving a "client (Netherlands) ↔ biomech. server (Montreal)" connection. Table 1 presents mean response times for each surgical manoeuvre in solo remote training.

Table 1. Mean response times of surgical manoeuvres for remote solo training.

Surgical Manoeuvre	Response times (s)
	Arithmetic Mean ± Standard Deviation
Implant Insertion	0,13 ± 0,01
Implant Position Modification	0,13 ± 0,01
Implant Suppression	0,11 ± 0,03
Rod Attachment	4,64 ± 0,22
Rod Rotation (1 step)*	0,92 ± 0,22

* 1 step = 8 degrees

These response times, including transmission delays (i.e. starting from the time the client sends a request for a certain surgical manoeuvre until it receives the results from the biomechanical server, after simulation of the manoeuvre on the server side), do not significantly differ from those in local training for the corrective manoeuvres (rod attachment and rotation). Transmission delays add approximately 1,1 tens of a second to each manoeuvre, confirmed by ping tests (indicating the mean roundtrip time for a packet, 113 ms). In contrast, for implant insertion, position modification, and suppression, the transmission delays are perceptible since there is no other additional time spent in computations by the server in this case, but however do not affect the training session much in the actual state of the simulator. They will be taken into account for the real-time haptic device command with a prediction/correction mechanism using pre-computed force/torque profiles and intermediate values calculated by the biomechanical server.

B. Remote Collaborative Training

Two different cases of remote collaborative training have been tested. In the first case, all clients are remotely located (worst case scenario for transmission delays), running on the same PC, in order to measure the time needed for visual updates of the other participant's avatar or manipulated virtual object following a change in position. This case involves "clients (Netherlands) ↔ telep. server (Montreal)" connections. Visual update times (between 1 and 3 tens of a second, depending on network traffic), are acceptable, for gestures and manoeuvres typical of a scoliosis surgery training session are quite slow. Roundtrip times between the telepresence multi-user server and the clients are 0,112 ± 0,018 s on average. Fig. 6 shows a remote client viewing the other remote participant (black avatar) shaping a rod (changes on the rod by the other participant are received from the telepresence server).

The second case of remote collaborative training consists of transatlantic collaborative training sessions. We have shown that it is possible to carry out a complete transatlantic collaborative scoliosis surgery training session according to a predetermined surgical scenario with a first participant (P1) as a local client in immersive mode (CAVE) and a second participant (P2) as a remote client in non-immersive mode, involving "client (Montreal) ↔ biomech. server (Montreal)", "client (Montreal) ↔ telep. server (Montreal)", "client (Netherlands) ↔ biomech. server (Montreal)", "client (Netherlands) ↔ telep. server (Montreal)" connections, and voice sharing between the participants. Table 2 presents mean times for the collaborative completion of each step of this surgical scenario:

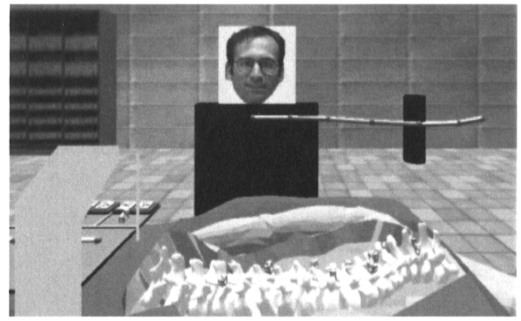

Fig. 6. Rod being shaped by the other remote participant (black avatar).

1) Collaborative implant insertion (8 mono-axial screws in standard position on the concave side of the scoliotic curve in the vertebrae T3, T4, T7, T8, T9, T11, L1, and L2 by P1 verbally guided by P2; 5 mono-axial screws in standard position on the convex side in the vertebrae T3, T4, T8, L1, and L2 by P2 verbally guided by P1.

2) Rod contouring (shaping) by P1.

3) Rod attachment on the concave side by P1.

4) Rod rotation of about 90 degrees in sub-steps by P2.

Table 2. Mean completion times of a predetermined surgical scenario for remote collaborative training.

Step of Surgical Scenario	1)	2)	3)	4)
Mean times (min.)	10	3	1	2

In about 15 minutes, an acceptable time for a surgical training session, two users on different continents can collaboratively, with mixed equipment (VR immersive environment and standard laptop computer), complete a pre-determined scenario for scoliosis surgical training on a specific patient, and visualise the resulting correction to the spine. With the eventual integration of the haptic device (in progress), they will also be able to feel the required forces.

V. CONCLUSION AND FUTURE WORK

We have demonstrated the feasibility of a collaborative VR training tool for scoliosis surgery and conducted transatlantic collaborative tests under realistic real-life conditions. The simulator, a fully collaborative AVE, integrates a complex patient-specific biomechanical model into a VR immersive environment. Haptic forces are computed but not yet fed back to users through commercial haptic devices, because we argue that a scoliosis-specific device should be used to accommodate the distinctive characteristics of scoliosis surgery. The importance of haptic feedback in the simulator as a surgical training tool arises at the manipulation level of surgical tools once they are properly seated. This haptic feedback involves high forces/torques and constitutes a new application context for a medical haptic system. Work in progress includes the design of the haptic device, its command in real-time, and integration into a collaborative HAVE simulator. In the long term, for the simulator to become a realistic and relevant surgical training tool, exhaustive validation regarding the precision and realism of force feedback (compared to complete sets of in situ measured force/torque profiles as applied by surgeons in the operating room, not yet available) and its utility, acceptance among the medical community, and justification in the surgical curriculum, is necessary, if not mandatory.

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