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Framework for Annotation of Haptic Data in Simulated Surgical Procedures

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Abstract. Surgical skills that are increasing in complexity require extensive practice and virtual reality is expected to solve problems in surgical training. In this paper, a framework for annotation of haptic data is proposed. The framework allows recorded simulation to be used for self-learning of surgical manipulation. In addition, an underlying problem of controlling recorded simulation is solved with a composite recording and playback model. Usually, manipulation data from a haptic interface is recorded and re-simulated, which results in difficult control of playback. Alternatively, states of graphic objects can be stored, but this strategy is not very scalable and it loses the original manipulation data. The composite model uses offline re-simulation using manipulator data and provides playback of simulation without losing high quality haptic data.

1. Introduction

The authors aim for computer-mediated knowledge and skill transfer of surgical techniques. This paper describes an annotation framework for surgical simulation and a composite recording and playback model that enables annotation of high quality haptic data. Annotated simulation records (ASRs) act as teaching scenarios that mediate both knowledge and skill.

Patients should not be endangered in training of surgical techniques. Therefore, surgical training is carried out by using plastic models, dummies and animals at the expense of realistic interaction. Surgeons have to stay up to date with new surgical techniques that are continuously increasing in numbers and complexity. Mastery of techniques requires knowledge about the surgical procedure and repetition of manipulation exercises. Textbooks explain standard procedures in detail but learning manipulation skills from a book is, of course, not practical. Training of manipulation skills with teacher's guiding hand is cumbersome since the teacher often interferes with student's interaction in the physical environment. Moreover, well established master-apprentice teaching methodology covers only one-to-one teaching. In brief, teaching surgical manipulation skills to a large number of students is problematic.

The Internet has made distance learning popular since use of network technology solves problems of time and space for teaching and learning activities. Digital learning material is being used in medical education, yet textbooks remain invaluable for their level of detail. Annotation of books is a way to organize one's perspective to the written content. On the other hand, Virtual Reality (VR) provides safe environments for surgical training. Typical

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simulators produce realistic response that can be felt by the teacher and the student. This makes the simulator a communication tool for skill transfer. If a simulator could capture the teacher’s skill and instructions, the teacher would not need to teach students in person, but the students could obtain skills through recorded simulation. Thus, a large number of students could be taught indirectly by using the simulator for skill transfer. Combination of interactive simulation, distance learning methodology and textbooks would introduce a learning environment in which surgical techniques can be learned in virtual lessons.

In this work, record and play approach has been chosen to mediate surgical techniques from a teacher to students. To capture a real surgical procedure would require several new kinds of sensor and image processing technology which are not available yet. Instead, the procedure is recorded in a simulator. ASR will serve as a self-learning scenario, in which live simulation corresponds with the setting that the teacher interacted with when recording the procedure. The system includes haptic feedback and new forms of annotation for learning manipulation.

Methods for recording simulation vary. By recording and feeding back manipulation data from a haptic interface results in re-simulation, which requires the same computation as the original simulation. On the other hand, graphics of the simulation can be stored and restored, but recording large amounts of data during simulation causes interference in feedback to the user. Therefore, a new record and playback method is proposed.

2. Related work

Annotation is a means to organize one’s perspective to content through highlighting, anchoring and linking previous knowledge to new information at hand. As comments and drawings on pages of textbooks have clear value in deep understanding, relevant annotation tasks can be supported in computer systems as well [1].

In the real world suitable methods for teaching haptic skills are missing. When a teacher tries to show manipulation to the student by physical guidance by hand, student’s interaction is interrupted [2]. It is possible to mediate trajectory manipulation skill by guiding trajectory with individual-dependant force profiles, as shown by Srimathveeravalli and Thenkurussi [3] in a case of writing with a pen. Saga *et al.* [4] used opposite forces of recorded haptic data to aid writing exercises. Record and play strategy in virtual environments has major benefits compared with traditional methods (adapted from [5], [6] and [7]):

- Freedom of time, location and number of teachees
- Direct and exact feeling of the model with unlimited repetition
- Flexibility of learning strategies
- Recorded digital data can be evaluated and modified

These studies show the benefit of virtual environments in skill transfer, but their scope does not cover highly complex situations that are encountered in surgical training. To understand dependencies of actions and consequences in difficult procedures, annotation of actions is required. Real surgical skills develop after a number of variations of standard procedures.

Shaffer *et al.* [8] introduced the concept of *Virtual Rounds*, which aims to enhance simulator-based training. *Simulation system* comprehends more than just recreation of a surgical setting. *Reference of the simulation system* covers asynchronous communication through annotations, in addition to synchronous communication. Learning process using simulators requires *review* in form of feedback “on learner’s actions or as a response to learner’s own description”. *Reflection* is a basis for deep understanding and is achieved by self-examination of learner’s actions. In form of annotations, reflection can be either public or private, and the annotations should enable reflective thinking of one’s learning process. *Reach of the simulation engine* means that ”an effective simulation engine not only recreates a setting where learning takes place, but also includes enhanced features that extend beyond what is possible in clinical setting”. Later development of the Interventional Cardiology Training Simulator [9] allowed students to record their procedures and to use the simulator as a flexible learning tool with Undo, Pause and Rewind functions, which can be categorized as *reach of the simulation*. Enabling technology for *reference*, *review* and *reflection* requires exclusive work on annotation of simulated procedures since only few demonstrative examples exist.

An example of annotation of surgical procedures is the Immersive virtual reality Book (ivrBook) [10], which allows students to explore recorded surgical procedures in a CAVE *TM* immersive environment. IvrBooks will be constructed from real surgical procedures captured by future technology, but at the moment the procedure is "performed" on a cadaver. For the student, ivrBook lacks interaction because of the system’s intended usage as a book. Annotation software in the ivrBook imitates free text video annotation, which manages multimedia on a timeline. Learning of manipulation is not covered in ivrBooks.

Annotation of static 3D models is quite a straight-forward as shown already in the AnatomyBrowser project [11]. Hong *et al.* [12] developed a method to highlight deformable pages in their 3D electronic book. To provide a clean layout in interactive 3D illustrations, algorithms that link pictorial and textual elements together were proposed by Ali *et al.* [13].

Annotation is beneficial in the learning process. So far, skill transfer systems focus on well-defined tasks, but in the surgical field few things are well-defined. Annotation of haptic data provides a new method for teaching surgical techniques with variations, thus providing experience in cases with insufficient facts and variable manipulation challenges.

3. Methodology

3.1 Annotation Framework

Figure 1 presents a novel teaching and learning methodology that is based on ASRs. First, a surgical procedure is recorded on a simulator in terms of force and position data that describe teacher’s manipulation at high accuracy. Simulation record (SR) is stored in a database. The SR is enhanced with textbook characteristics when the teacher annotates the SR to demonstrate pedagogical points. The annotation data acts as knowledge transfer medium by combining simulation and textbook characteristics. The teacher can simulate and describe standard cases and variations that textbooks do not discuss. As a result of the annotation process, a self-learning scenario is produced for students who can gain knowledge from the annotations and interact with the same simulated surgical setting in which the teacher recorded the procedure. Also, annotations act as guidance for manipulation. Both knowledge and skill can be mediated through the ASR that acts as *reference of the simulation system* envisioned by Shaffer *et al.* [8]. Also students can annotate their own experiences as a learning diary. This allows self-reflective learning by making notes of own progress and provides *reflection* as in the Virtual Rounds concept [8].

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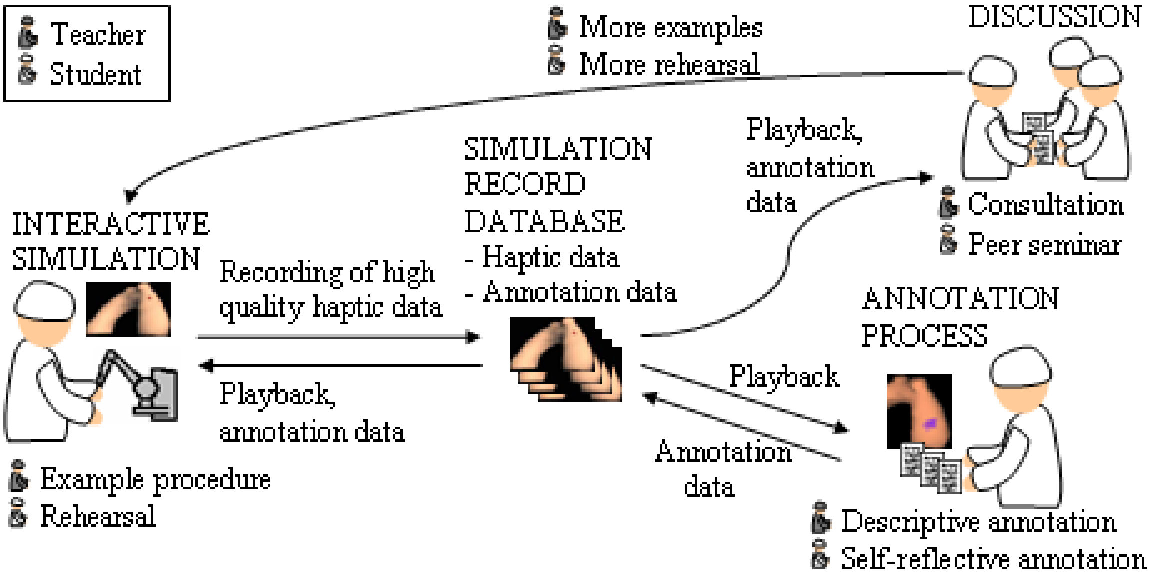

Figure 1. VR-based training using ASRs.

To provide a learning environment where knowledge can accumulate, it is necessary to store the experiences permanently. Annotations and SRs should be stored in a database system which would then act as a source for learning material for a student community, and a channel for discussion between the teachers and the students. This enables *review in the simulation system* [8]. Issues raised from discussion can require new scenarios or variations of standard procedures. Example scenarios can be again created by annotating new recorded procedures. Moreover, evaluation and discussion on students' progress in training can result in a need for more rehearsal until the procedure is mastered on an adequate level. Here, *student* does not only refer to medical students, but rather to a learning role. For example, experienced surgeons can learn new techniques from their peers who have adapted latest techniques earlier and wish to share their experiences.

Annotation of haptic data is a novel concept. In order to instruct how to manipulate, actions must be made comprehensible. Annotation of haptic data in surgical simulation can be defined as comments, notes, or explanation on physical phenomena that are perceivable during manipulation. If forces of recorded simulation are fed back to the user through a haptic interface, the user is passive when receiving force feedback. The user would not learn how to produce the forces herself. Therefore, in addition to provide explanation as a comment or a note, annotation of haptic data can guide manipulation towards the correct way, the teacher's example. Then, the user would feel forces produced by her actions in the same way as the teacher did when recording the example manipulation.

If manipulation of a teacher is to be annotated, means for segmenting and annotating force and position data in relation to time have to be developed. Flexible playback of a simulation is necessary. Skimming of has to be possible so that selected parts of a simulation can be annotated. Recording routines must not interrupt feedback to the user. Otherwise correct manipulation cannot be captured. Flexible playback control should enable selection of any position on the timeline.

The annotation process is explained in Figure 2. Nature of manipulation can be detected from the haptic data automatically. Segmentation is already done by software for essential parts. Each action corresponds to a segment and each segment can be annotated individually. Aggregating small segments into meaningful manipulation requires human judgement depending on the pedagogical case. Auto-segmentation can cover complex techniques, such as pattern recognition, or simple methods, depending on the nature of manipulation being annotated.

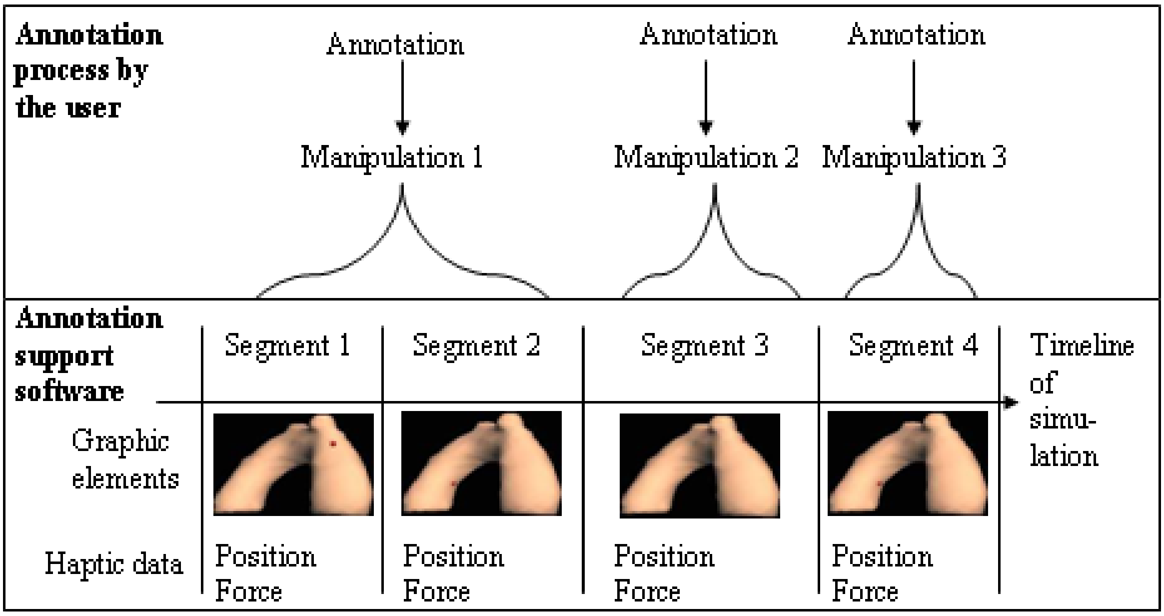

Figure 2. Annotation of haptic data through graphic elements.

3.2 Composite Recording and Playback Model

In recording and replaying surgical simulation there are mainly two strategies: manipulator strategy and graphics strategy. Choice of strategy results in tradeoffs between quality and nature of recorded data and flexibility in control of playback, which sets restrictions to use of recorded simulation.

Manipulator strategy requires complete re-simulation. Recording of a surgical simulation is usually done by storing manipulation data from the user through the haptic interface. The data typically consist of position of the manipulator interface, which results in minimal data size in the SR. This data is then fed into the simulator to reproduce the simulation. In addition to position data, also force data created by the simulation engine can be recorded. Force data is a typical evaluation criterion in concurrent surgical simulators. In physics-based simulators, which typically have very high calculation cost already, the manipulator strategy playback may require extra hardware to avoid disturbance in the simulation. Also, it is hard to skim the re-simulated playback which is linear in nature. Every state is a result of previous states in the simulation so that, for example if the manipulator is suddenly set inside a surface model, collision with the 3D model's surface will not happen. This fact makes it difficult to choose a position in the middle of the timeline of the record, thus preventing efficient skimming.

In graphics strategy only visual parts of surgical simulation are recorded. In surgical simulation surface objects are usually modelled as meshes that consist of vertices. A vertex is a place in 3D space defined as x, y, z coordinates. In a simulation dealing with deformable soft tissues, movement of vertices in a 3D mesh can be recorded by storing their displacement coordinates. This approach requires lots of data being recorded during live simulation – displacement of each vertex is stored at chosen frame-rate. High frame-rate affects the simulation in a negative way because of increased computation and bandwidth limitations. The more vertices, the more data is required to be stored at the expense of recording frame-rate. Playback of graphics, instead, is very light compared to re-simulation, since actual calculation is not done when new positions are count directly from displacement data in the SR. Most importantly, the graphic playback can be controlled in a very flexible way. Since the recorded data is basically a 3D animation, it can be replayed at a chosen speed, skimmed, or played backward if needed, and choosing a point on the timeline is easy. The graphics strategy, however, loses an important part of the simulation – the accurate manipulation data. Optimal recording and playback strategy would record minimal amount of data and replay the simulation as graphics.

To avoid large amount of recorded data and heavy computation in playback, a composite recording and playback model for surgical simulation is proposed. The composite model reduces need for bandwidth in recording and computation in playback phase. Figure 3 shows how the recording proceeds to graphic playback of the simulation. The composite model combines the best features of the manipulator and the graphics strategies.

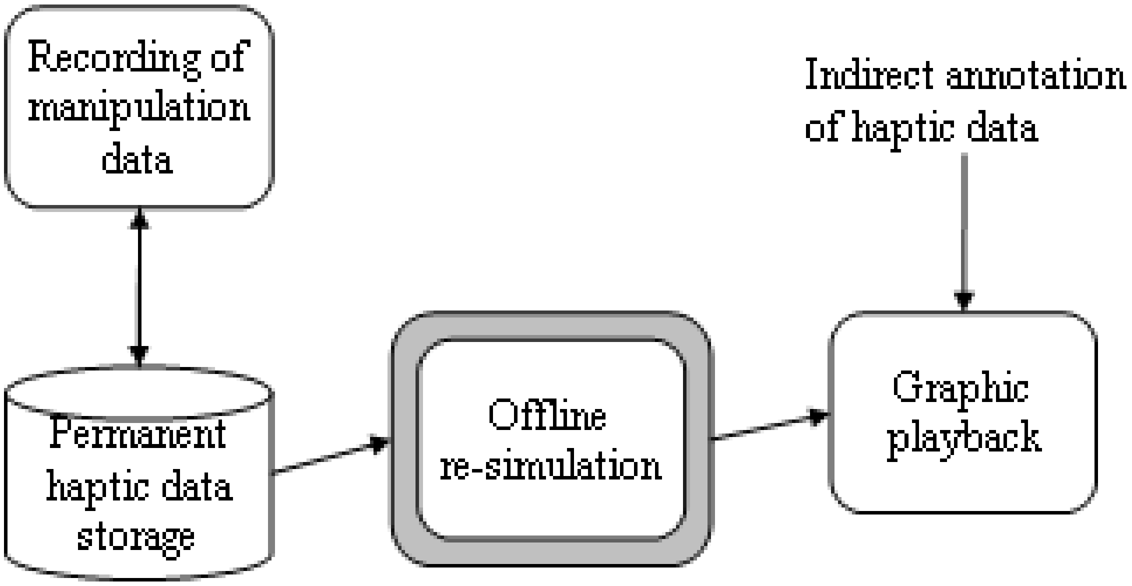

Figure 3. Composite recording and playback model.

Manipulation data is first recorded and then used for offline re-simulation without user's interaction. The purpose of the re-simulation is to produce a graphics log file without real-time requirements so that the trade-off between 3D model's size and frame-rate is eliminated. The simulation can be paused while states of graphic objects are stored since feedback is not provided to the user. Now, the simulation can be replayed by displaying only the graphic part of the simulation, yet all the accurate manipulation data remains. By choosing a set of frames in the graphic playback the haptic data can be segmented and annotated indirectly.

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The re-simulation can be executed when needed, so that for permanent storage of the simulation consists of the recorded haptic data and the target model. The graphics record can be produced just before playback is needed. Furthermore, haptic data could be later used for haptic guidance, as studied in [3], [4], [5] and [7], with or without graphic playback.

4. Example: Annotation of Palpation of the Aorta

Palpation of the aorta is a common, yet potentially fatal, procedure before actual open heart surgery. The surgeon touches the surface of the aorta in order to find a region that can be clipped to stop blood flow before open heart procedures. Diseased parts of the aorta containing blood clots should not be clipped. If the aorta is touched too hard, the blood clot can be set loose into circulation, which results in a fatal complication. Diseased parts have higher stiffness than the healthy parts, which should be detected by palpating.

Normally, the aorta is pinched with two fingers. Sometimes, the surgeon has to use only one finger and the finger is kept on the surface of the aorta and stroked back and fort along the surface. Skill of palpation of the aorta consists of three important aspects:

- Touch with fingers should be firm enough to detect hard and soft tissue on fingertips.
- When touching, the used force should not be very high. Otherwise, there is a risk of setting a blood clot loose into the circulation.
- When a diseased part is found, its borders have to be identified. Then, clipping can be performed safely outside the borders.

Annotation of multimedia is based on timeline that is segmented to semantic entities. Timeline-based approach is applicable in ASRs, too. Timeline of the palpation has to be segmented into segments that indicate meaningful actions in the palpation procedure.

To teach palpation of the aorta without a teacher present is a difficult task. For the above-mentioned pedagogical points, the following physical phenomena should be annotated:

- Force during the manipulation: a) force threshold used by surgeons and maximum threshold allowed, b) direction of the force to demonstrate the two touching techniques.
- Contact points between the finger and the surface of the aorta.
- Borders of the blood clot on the surface of the aorta to indicate the diagnosis.

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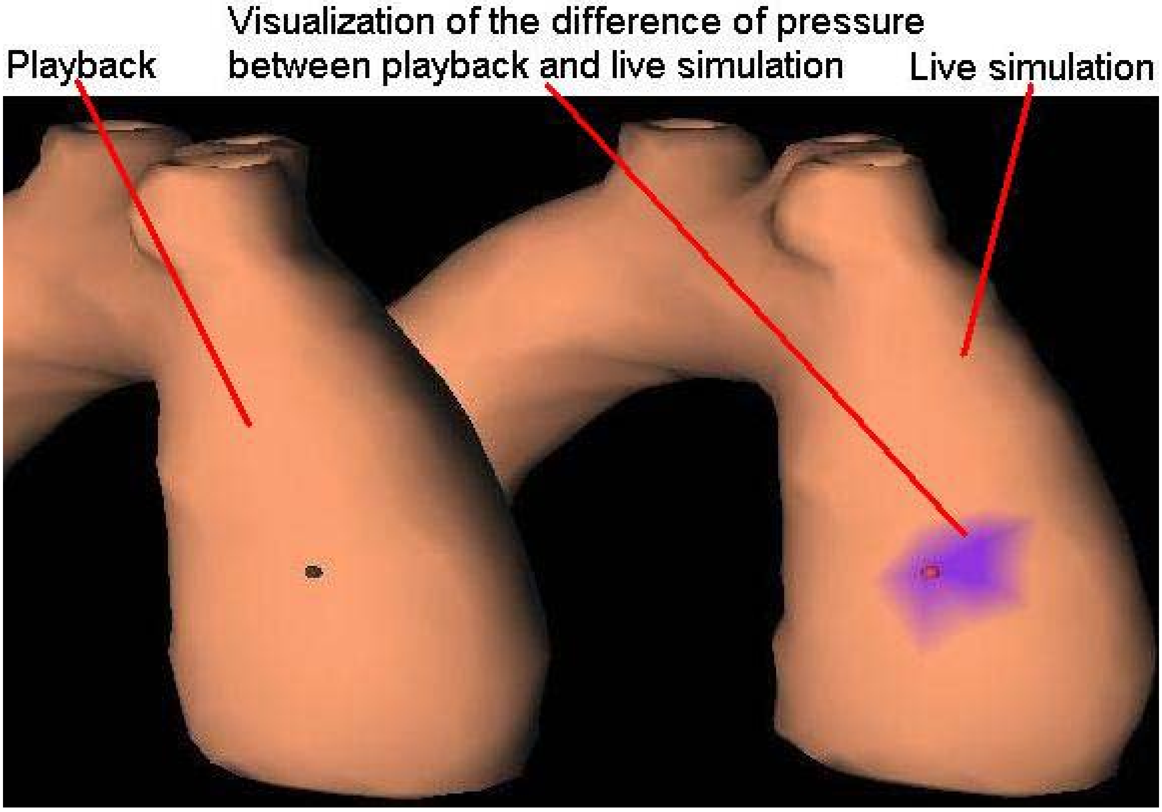

Figure 4. Dynamic pressure visualization (from [14]).

This example demonstrated what kind of physical phenomena can be annotated, but abstract physical phenomena can be hard to understand from numbers. Therefore visualization is required to display annotations in a manner that is easily comprehensible to human. Usually, force in relation to time is visualized as a force curve. As shown in Figure 4, a visualization technique was developed to teach maximum force and force curve in palpation of the aorta [14]. The visualization technique displayed difference between force threshold in user’s manipulation and in an example manipulation as dynamic change in colour depth on the surface of the 3D organ model.

5. Experiment

The experiment was to prove that the composite recording and playback model provides better frame-rate to SRs than the normal graphics strategy, for example 33 fps. The playback can be then used as an accurate and easily controllable representation of the recorded high quality haptic data.

Medical VR simulation Library (MVL) [15] is targeted on training of palpation of organs in different states of diseases. The system provides basic methods and various organ models to build new simulation scenes with a few lines of C++ programming code. It is capable of realistic modeling of interaction with soft tissues by using Finite Element Method (FEM) – based algorithms. Visual feedback is implemented with OpenGL libraries. Hardware consists

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of a desktop computer connected with a PHANToM^{TM} interface. Haptic feedback is created with Ghost SDK. MVL allows the user to feel reaction forces as resistance in the simulation when touching a virtual organ through PHANToM^{TM} . Because of only one haptic interface being available, in the case of palpation of the aorta, the user can palpate withö just one finger. This setup corresponds to one of the two palpation techniques used by surgeons.

In the experiment, MVL was running on a Xeon 3.2 GHz dual processor with 4 Gb RAM. PHANToM^{TM} Desktop was used as the haptic interface. MVL was modified to record manipulation data from PHANToM^{TM} at about 1000 Hz. Position of the manipulator and forces were stored as 4-byte float numbers. Recorded data size is 24 KB/sec.

An aorta model of 1397 displaceable vertices was manipulated for 27.0 seconds and the manipulation was recorded. Manipulation consisted of sequential touching on different sections of the aorta's surface with about one second transition phases between touching. The recorded manipulation made all the displaceable vertices to change position.

Position data was fed from the log file back into the simulator. In this way, several graphic data log files at different frame-rates were created from a single recorded manipulation. Two modes of recording were implemented into the re-simulation phase: real-time mode (RT) and non-real-time (NRT) mode. RT-mode was to simulate user's manipulation in a repeatable manner. It was implemented so that graphics logs with various frame-rates could be compared with logs created in NRT-mode, which represents the proposed composite model. In RT-mode, the position data was synchronized to be fed into the simulation at about 1000 Hz to match the original speed of the simulation. All calculations were executed normally except that PHANToM^{TM} interface was bypassed. Each recorded frame of vertex displacement was marked with a timestamp at accuracy of a microsecond. In NRT-mode the position data was fed without synchronization to the original recording rate. Timestamps were calculated from the chosen frame-rate and amount of position data fed. In another words, the NRT-mode just performed the calculations necessary to produce the graphics log.

The graphics log contained displacement coordinates for each vertex of the aorta model and for the visible manipulator object controlled by the user. Also force vector was included to the graphics log for future annotation of force. Size of the graphic data was 4 bytes x 3 x (1397 + 2) = 16 788 bytes/frame when the aorta was deforming. Chosen frame-rate determines the actual size, for example at 33 fps results in about 554 KB/sec.

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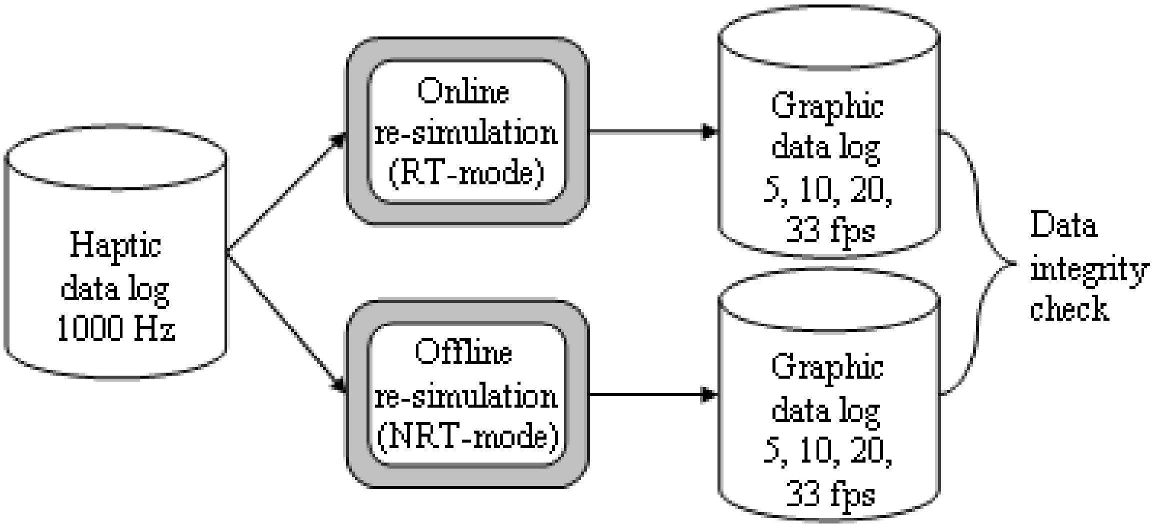

Figure 5. Experiment setup with RT- and NRT-modes.

Freedom of real-time requirements was expected to be the greatest benefit of the offline re-simulation. The re-simulation is halted when a frame is stored. Therefore, NRT-mode should provide high frame-rate with accurate data, which should not be possible in RT-mode.

As shown in Figure 5, eight graphics log files were created from the recorded haptic data at frame-rates varying from 5 to 33 fps. In RT-mode the timestamps in each frame should lengthen during recording because of bandwidth problems. Thus, re-simulation would last longer than 27.0 seconds. Finally, all the data (vertex displacement, manipulator position and force vector) should match in every log file though the timestamps were not synchronized. For example, every 4th frame in a 20 fps log should match with a frame in a 5 fps log.

6. Results

Because of large amount of data being recording, timestamps were lengthened in RT-mode, as can be seen in Table 1. In NRT-mode, though re-simulation lasted longer than the original 27.0 seconds, timestamps were correct. Data matched in all logs except the ones produced at 33 fps, since 1000 ms/33 fps results in 30,3030…ms interval for every frame recorded. Therefore, all the frames were not directly comparable. RT-mode re-simulation made the simulation slower but did not affect to states of the simulation. Yet, slow simulation would affect the feedback to the user.

In RT-mode at 33 fps, timestamps were lengthened by 70.0%, which makes it unusable for playback. In NRT-mode at the same frame-rate of 33 fps, rounding error made the timestamps differ by 0.9%. Re-simulation in NRT-mode at 5 fps was 2.74 seconds faster than the original simulation.

By using the composite model, creation of a graphics log of 33 fps is possible without interference in the simulation when recording. In addition, data was not distorted. Thus, the composite model provides scalable recording of simulations containing deformable objects.

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Table 1. Results of the re-simulation experiment with RT- and NRT-modes.

Re-simulation mode	**Frame-rate (fps)**	**Execution time (sec)**	**Timestamp error (%)**
RT	5	31.83	+17.9
RT	10	34.87	+29.1
RT	20	39.21	+45.2
RT	33	45.91	+70.0
NRT	5	24.26	0
NRT	10	27.11	0
NRT	20	36.78	0
NRT	33	39.56	+0.9

7. Discussion

To enable flexible recording and playback of surgical simulation, a composite model for recording and replaying surgical simulation was proposed. The method can be utilized in most of the concurrent simulations, in which a deformable 3D model is a surface mesh consisting of vertices. In the annotation process graphic playback of the simulation is a representation of the haptic data. In the experiment, manipulator’s position and force data was included in the graphics log, which can facilitate annotation of force at accuracy of 33 Hz. Yet, it should not be forgotten that the most accurate data is the original haptic data recorded at about 1000 Hz. The annotation framework enables description of recorded surgical procedures in terms of any physical phenomena that can be simulated to serve pedagogical purposes in medical training. For example, the graphics log could include collision points between manipulators and target models. Annotations encapsulated to high quality haptic data act as knowledge and skill transfer media.

The ivrBook [10] demonstrated how annotations can be text or links to multimedia. In annotation of haptic data, visualization of the physical phenomena is also important. In [14], visualization was applied to magnitude of force so that visual feedback was given to the user when her manipulation differed from the pre-recorded example manipulation. This approach seems promising for indirect teaching of manipulation skills. Further analysis is required to identify the underlying physical phenomena that can be annotated for other surgical procedures. For example, controlled destructive manipulation, such as cutting and ablation, would probably need different kind of annotation.

Figure 6 shows how haptic data has been annotated and shown in the simulator. On the basis of the force data, the simulation was divided into segments automatically. Each segment is either a continuous contact between the manipulator and the organ or a transition phase without any contact. For palpation of the aorta, this segmentation is simple but efficient, and the person annotating can aggregate individual segments into meaningful manipulation. In other surgical cases, more complex auto-segmentation would require other methods, for example pattern recognition. By using the graphic playback as representation of the haptic data, recorded manipulation was examined and important segments were annotated with free text and a visualization to make use of force easily comprehensible.

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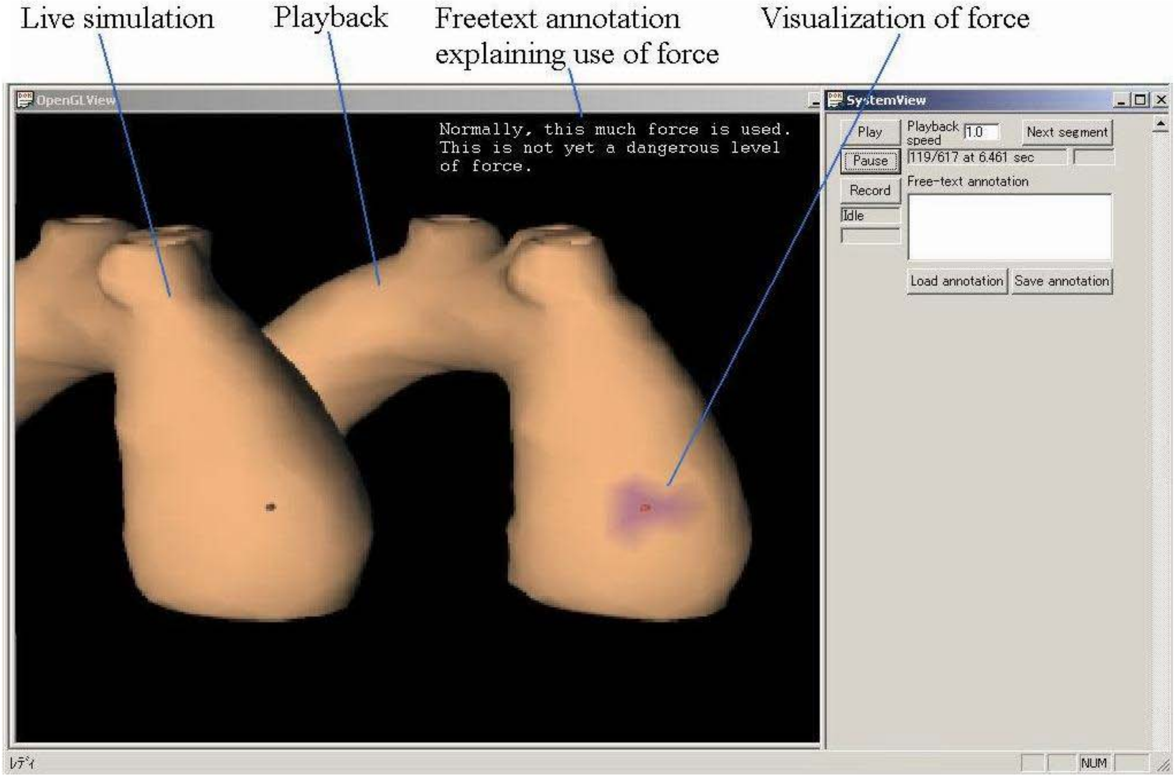

Normally, this much force is used. This is not yet a dangerous level of force.

Playback speed 1.0

119/617 at 6.461 sec

Idle

Figure 6. Annotated playback and live simulation.

8. Conclusion

The annotation framework for simulated surgical procedures was designed to combine interactive simulation with textbook characteristics to enable novel ways for self-learning by using ASRs. The framework allows recorded simulation to be annotated in terms of physical phenomena – haptic data, position and force, at very high level of quality. To enable a flexible annotation process, a composite recording and playback model was proposed and proven effective. For technical part, it is now possible to build teaching scenarios from recorded simulation by annotating manipulation data. This facilitates learning of surgical techniques and gaining manipulation skill without teacher’s presence.

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