DEVELOPMENT OF AN AUGMENTED VIRTUAL REALITY SIMULATOR FOR TRAINING OPHTHALMOLOGISTS IN PHACOEMULSIFICATION CATARACT SURGERY

by

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LIST OF ABBREVIATIONS

3D	-	Three Dimensional
AR	-	Augmented Reality
CAD	-	Computer-aided Design
CANARIE	-	Canada's Advanced Research and Innovation Network
CCC	-	Continuous Curvilinear Capsulorhexis
CPU	-	Central Processing Unit
CT	-	Computed Tomography
DC	-	Direct Current
DOF	-	Degree of Freedom
ECCE	-	Extracapsular Cataract Extraction
FEM	-	Finite Element Model
GPS	-	Global Positioning System
GUI	-	Graphical User Interface
HTF	-	Hospital Tuanku Fauziah
ICCE	-	Intracapsular Cataract Extraction
IOL	-	Intraocular Lens
IOP	-	Intraocular Pressure
MRI	-	Magnetic Resonance Imaging
OBJ	-	Object File
PARC	-	Palo Alto Research Centre
PCO	-	Posterior Capsule Opacification
PMMA	-	Polymethylmethacrylate
RAM	-	Random-access Memory
VR	-	Virtual Reality
XML	-	Extensible Markup Language

Pembangunan sebuah Simulator Realiti Maya Terimbuh untuk Latihan Oftalmologi dalam Pembedahan Katarak Fakomulsifikasi

ABSTRAK

Katarak dikategorikan sebagai penyakit penglihatan umum dalam golongan pesakit yang besar setiap tahun. Pembedahan katarak fakomulsifikasi merupakan teknik pembedahan yang digunakan pada masa kini untuk mengeluarkan katarak dari mata pesakit-pesakit dan memulihan penglihatan mereka dengan memasuki sebuah kanta buatan. Keadah pengajaran master-perantis tradisional digunakan secara lazim dalam latihan pembedahan katarak fakomulsifikasi untuk memindahkan kemahiran latihan daripada seorang pakar oftalmologi kepada seorang pengamal perubatan. Cara latihan ini termasuk latihan pembedahan makmal basah atas mayat haiwan and manusia. Walau bagaimanapun, perbezaan dalam anatomi dan ciri-ciri mekanikal antara haiwan dengan manusia mungkin mengakibatkan kesilapan yang serius semasa pembedahan. Di samping itu, eksperimentasi atas haiwan dan manusia dalam penyelidikan, pengujian dan pengajian perubatan telah dikenali sebagai satu isu yang kontroversial disebabkan oleh isu etika dalam penyelidikan perubatan. Simulator-simulator yang sedia ada agak tidak lengkap dan tidak mampu memberikan latihan pembedahan maya dan penyeliaan untuk prosedur-prosedur utama pembedahan katarak fakomulsifikasi. Sebuah simulator realiti maya terimbuh yang mampu menyediakan satu persekitaran maya yang terkawal kepada pelatih-pelatih perubatan dan ahli-ahli oftalmologi untuk menjalani latihan pembedahan atas subjek manusia maya, telah dicadangkan untuk mengatasi kesuntukan-kesuntukan tersebut. Simulator yang dicadangkan mengandungi sebuah platform pembedahan maya yang terdiri daripada pengantaramuka haptik, pengantaramuka grafik penguna, instrumen pembedahan maya dan model mata tiga dimensi. Keempat-empat prosedur utama pembedahan katarak fakomulsifikasi, iaitu insisi kornea, kapsulorhexis, fakomulsifikasi, dan implantasi kanta intraokular (IOL), telah disimulasikan dengan meggunakan pelbagai jenis modifikasi topologi atas anatomi mata manusia. Simulator yang dicadang juga mampu memberikan penyeliaan kepada pengguna-pengguna melalui system bimbingan grafik pembedahan tanpa kewujudan instruktor dan parameter-parameter prestasi telah dimasukkan ke dalam system latihan pembedahan maya untuk meningkatkan kesedaran dan kemahiran pelatih-pelatih pembedahan. Sepasang peranti haptik Phantom® Omni telah digunakan dalam simulator yang dicadangkan sebagai pengantaramuka manusia-komputer untuk pengguna supaya menggerakkan instrumen pembedahan maya dalam persekitaran tiga dimensi. Sudut pandangan dan model-model tiga dimensi instrumen pembedahan maya dan anatomi mata boleh dipilih dan ditukar dengan menggunakan pengantaramuka grafik penguna yang interaktif. Keempat-empat procedure utama pembedahan katarak fakomulsifikasi telah berjaya disimulasikan dengan maklum balas haptik minima pada kadar 1 kHz dan rendering grafik pada kadar 30 bingkai sesaat. System bimbingan grafik pembedahan yang direka bentuk dalam simulator tersebut mampu bertindak balas dengan tindakan dan prestasi pengguna-pengguna sepanjang prosedur-prosedur. Keputusan menunjukkan pelatih-pelatih dapat meningkatkan prestasi mereka dengan penyeliaan yang diberikan oleh system bimbingan tersebut. Satu kajian eksperimen telah dijalankan oleh kumpulan yang terdiri daripada pelatih-pelatih perubatan dan ahli-ahli oftalmologi. Hasil eksperimen tersebut menonjolkan perbezaan pengalaman pembedahan antara mereka. Kesedaran dan prestasi pelatih-pelatih perubatan bertambah baik secara beransur-ansur sepanjang latihan pembedahan. Simulator yang dicadang telah dibandingkan dengan simulator-simulator lain yang sedia ada dan keputusan tersebut menunjukkan kemunasabahan yang tinggi dalam latihan maya pembedahan katarak fakomulsifikasi.

Development of an Augmented Virtual Reality Simulator for Training Ophthalmologists in Phacoemulsification Cataract Surgery

ABSTRACT

Cataract is categorised as a common vision illness that is diagnosed in a large group of eye patients every year. The majority of such patients affected by this illness suffer from aging, diabetes or overexposure to ultraviolet radiation. Phacoemulsification cataract surgery is the surgical technique that has been currently used to remove the cataract from the patients' eye and restore their vision by implanting an artificial lens. The traditional master-apprentice teaching method has been commonly used in phacoemulsification cataract surgery training to transfer the surgical skills from a professional ophthalmologist to a medical practitioner. This teaching method includes wet-lab surgical training on animals and human cadavers. However, differences in the anatomy and mechanical properties between animals and humans may lead to lethal errors during a real surgical operation. In addition, experimentation on animals and humans in medical research, testing and education has been a controversial issue due to the ethical concerns in medical research. Existing simulators are somewhat incomplete and unable to provide virtual surgical training and supervision for the main procedures of phacoemulsification cataract surgery. An augmented virtual reality simulator, which is capable of providing a controlled virtual environment for medical trainees and ophthalmologists to conduct surgical training on virtual human subjects, is proposed to solve these constraints. The proposed simulator consists of a virtual surgical platform, which is formed by a haptic interface, graphical user interface (GUI), virtual surgical instruments and three dimensional (3D) eye models. The four main procedures of phacoemulsification cataract surgery, namely corneal incision, capsulorhexis, phacoemulsification, and intraocular lens (IOL) implantation, are simulated by using different types of topological modifications on the anatomy of the human eye. The proposed simulator is also capable of providing supervision to users via the graphical surgical guidance system without the presence of a human instructor and performance parameters are applied into the virtual surgical training system to increase the surgical awareness and skill of the medical trainees. A pair of Phantom® Omni haptic devices is used in the proposed simulator as a human-computer interface for users to manoeuvre the virtual surgical instruments in the 3D environment. The view and the 3D models of surgical tools and anatomy of eyeball can be selected and changed by using the interactive GUI. The four main procedures of phacoemulsification cataract surgery were successfully simulated at the minimum haptic feedback rate of 1 kHz and a graphical rendering rate of 30 frames per second. The graphical surgical guidance system, which is designed in the simulator, was able to react and respond interactively to the action and performance of the users throughout the procedures. The results indicate that medical trainees were able to improve their performance with the supervision that was provided by the guidance system. An experimental study on a set of performance parameters was conducted by a group of medical residents and ophthalmologists. The experimental results highlight the difference in actual surgical experience between ophthalmologists and medical trainees. The awareness and performance of the medical trainees progressively improved throughout the surgical training trails. The proposed simulator was compared with other existing simulators and the results indicate high plausibility in the virtual training of phacoemulsification cataract surgery.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Cataract is categorised as a common vision illness that is diagnosed in a large group of eye patients every year. The majority of such patients affected by this illness suffer from aging (Owsley et al., 2002), diabetes (Kyselova et al., 2004), or overexposure to ultraviolet radiation (Seddon et al., 1995). Cataract is the clouding of the lens, which is situated behind the iris and the pupil. The reduction in clarity of the lens prohibits the penetration of light into the retina, which seriously reduces vision. Cataract is classified into two stages, early cataract stage and advanced cataract stage. The symptoms of early cataract stage, such as blurred vision and appearance of halos around lights, usually can be rectified with sunglasses and magnifying lenses. However, when cataract grows larger and increasingly dense with time to advanced cataract stage in the form of a visible white and milky spot on the lens, surgical treatment is required to avoid permanent vision loss. Phacoemulsification cataract surgery is the most common surgical technique that has been currently used to remove the cataract from the patients' eye and restore their vision by implanting an artificial lens.

Phacoemulsification cataract surgery is one of the microsurgical techniques that require operative performance based on decision-making and dexterity. It is one of the microsurgeries that is hard to master because it involves the surgeon's ability to withstand psychological pressure during the surgery procedures, which affects greatly on their surgical performance (Wagner et al., 2002). Junior surgeons usually encounter this problem because they lack actual surgical experience and a strong mind. This may be caused by the limited number of surgical study samples and equipment provided for surgical training during their studies because the number of medical scholars has grown rapidly in the past 10 years (Khalifa et al., 2006). The traditional master-apprentice teaching method has been commonly used in cataract surgery training because it is the best approach to transfer the surgical skills from a professional ophthalmologist to a medical practitioner. This teaching method includes wet-lab surgical training on animals and human cadavers, which has proven to be a fine method for reducing the risk to both medical practitioners and patients by permitting training, practice, and testing in a controlled environment prior to real-world exposure (Khalifa et al., 2006). However, differences in the anatomy and mechanical properties between animals and humans may lead to lethal errors during a real surgical operation.

This serious constraint has lead to the idea of introducing computer-based surgical training, which is capable of providing a controlled virtual environment for surgeons to conduct assessments and experiment on virtual human subjects, which are generated and visualised three-dimensionally on the digital display unit (Bharathan et al., 2013; Pohlenz et al., 2010). This implementation represents a new alternative for the training of new surgeons without risking live patients. The main advantage of the VR surgical simulator is that the rare events that are encountered during actual surgical operations can be specified and customised in the training system to provide the surgeons with some challenges during their practice and thus increase their awareness and ability to handle such events (Haerizadeh & Frappell, 2013; Yang et al., 2013).

VR simulator is classified as imitations of real-world phenomena in a controlled environment. Hazardous or rare events, which may lead to severe injury or loss of property in actual situations, can be mimicked through computer-generated simulations using virtual reality as a medium to study the outcomes and investigate the preventative measures without any risk. The latest technology allows education, training, and testing via a virtual environment to increase the proficiency of individuals before they are assigned a task that requires extreme concentration and responsiveness. An example of such system is virtual reality training system for live-line workers developed by Park, Jang, and Chai (Park et al., 2006). The purpose of this system is to provide cost-effective training to reduce the possibility of electric accidents during Cut-Out-Switch (COS) replacement work. In addition, the successful implementation of a training simulator in the aviation academy has triggered interest among researchers to transfer this technology to the medical field. With the invention of a force-feedback haptic device, virtual reality surgery simulator is becoming a hot future prospect, that is capable of providing an alternative way to conduct surgical training in addition to experimentation on human dummies and animal cadavers (Liu et al., 2003).

The implementation of a virtual reality surgery simulator can be incorporated in cataract surgery because it can generate the physical details of the patient's eye using the data provided by CT and MRI scans (Satava, 1993). The capability of the current computed tomography technology to generate three-dimensional patient models for graphical representation is very informative and helps surgeons make surgical decisions and plans (Platz & Knapheide, 2000). This finding led to the goal of implementing the model into a computer-generated simulator for surgical education and training. The surgical simulators that have been developed and are available in the market for various surgical areas, such as endoscopic surgery (Van Sickle et al., 2011), endovascular surgery (Van Herzeele & Aggarwal, 2008), and laparoscopic surgery (McDougall et al., 2006), have received positive feedback from clinical validation articles. Therefore, surgical rehearsal and training can be conducted using the simulator, and this is particularly beneficial for inexperienced junior ophthalmologists because an ophthalmologist with a good mastery of cataract surgery is required for a surgical operation of cataract since any mistake may cause surgical trauma, which leads to permanent blindness or prolongs the patient's recovery.

Finally, the latest computer graphics technology allows the performance of a simulation to the level of reconstructing real-life situations to improve and attain a medical professional's specific competencies (Carron et al., 2011), but the implementation of a virtual reality simulator into the surgical training has always remained a debatable topic between researchers and surgeons. Although computer simulations do provide a realistic surgical environment, where surgical complications and traumas during an actual operation can be mimicked in virtual training environments to increase the awareness of surgeons and medical practitioners, the main issue lies in the capability of virtual reality surgical training compared with the traditional master-apprentice model and the observational model.

1.2 Motivation

Experimentation on animals in medical research, testing and education has been a controversial issue because there are few problems on animal research, one of the problems is the ethical concerns of using animals in medical research. Animals in laboratories are frequently treated as object that can be manipulated at will, with little value for their lives beyond the cost of purchase. American Anti-Vivisection Society (AAVS), who is the oldest non-profit animal advocacy and educational organization that opposes and works to end other form of cruelty to animals, believes that animals have the right not to be exploited for science. In addition, there is an also scientific limitation of using animals in surgical experimentation. Animal studies do not reliably predict human outcomes due to the differences between human and animals in term of physiology, anatomy and metabolism.

Apart from animal experimentation, surgical training on live patient also consists of ethical concern. Although surgical training on patient is the most effective way to learn the surgical skill and get the actual surgical experience, but the incompetency of medical trainees may bring significant risk to the patient's well-being. This can lead to a very serious matter on the violation of human rights if the mistake made by the trainee causes blindness. In addition, the eye banks in many countries, which are responsible for harvesting and distributing all corneas in the country, are facing the shortage donors. Some eye patients with blindness or visual impairment are required to follow the long waiting list of corneal transplantation that may takes a few months' time or up to a few years' time. Therefore, it is more important that the donated corneas are reserved for the patients for corneal transplantation rather than used by the medical trainees to conduct their surgical training and experimentation on phacoemulsification cataract surgery.

The issues addressed above can be considered as a great motivation for the research and development of an improved computer-based simulator with the incorporation of augmented virtual reality (AVR) technology to provide a virtual surgical environment as an alternative platform for medical trainees to train their phacoemulsification cataract surgical skills in a controlled and protected situation. The training system in the proposed simulator will be a useful tool to increase the proficiency of the ophthalmologists and will contribute to the introduction of virtual surgical training into the medical field.

1.3 Problem Statements

Virtual surgical training is relatively new for ophthalmologists and medical trainees. The virtual surgical environment generated from the computer has to be similar with the actual surgical environment, because users usually find difficulty to adapt themselves into an unfamiliar surgical training platform. This is one of the main constraints that exists in the virtual surgical platform of the existing simulators. The basic requirement for the development of phacoemulsification cataract surgery simulator is to include an interactive graphical user interface with functional features to provide a user-friendly platform and a pair of haptic devices for user to customize the virtual surgical environment and manoeuvre the virtual surgical tools.

Secondly, various existing VR surgical simulators for phacoemulsification cataract surgery are able to simulate part of the main procedures of the surgery, namely corneal incision, capsulorhexis, phacoemulsification, and IOL implantation. However, none of them have completely incorporated all of the four main procedures into their simulator yet. This is the main concern in convincing the ophthalmologists and medical trainees to conduct their surgical training by using the virtual surgical simulator, which a VR simulator with complete procedures could be more prominent.

Thirdly, in view of the fact that VR phacoemulsification cataract surgery simulator is able to allow ophthalmologists and medical trainees to train their surgical skills away from operation room or wet-lab, the problem lies in the capability of the existing simulators to provide supervision without the presence of a human instructor. Augmented virtual reality graphical surgical guidance system is believed to be able to solve this matter by providing an interactive graphical supervision in the simulator. This system can improve the effectiveness of the virtual surgical training by guiding the users with various types of written instructions and graphical indicators according to the stage of cataract surgery procedures.

Lastly, there is also a concern on the capability of the existing VR phacoemulsification cataract surgery simulators to increase the awareness of the ophthalmologists and medical trainees from the provided virtual surgical training. A set of parameters that is introduced and incorporated in the proposed surgical simulator, is expected to be able to measure the types of mistake made by the users. This can be a significant approach in improving their carefulness through the repetitive training by using the proposed simulator, which appears to be important in reducing the risk of surgical complications on the eye patient during actual operation.

1.4 Thesis Objectives

This thesis concerns with the development of a computer-based simulator that incorporates AVR technology for phacoemulsification cataract surgery training. More precisely, it focuses on the creation of a virtual surgical environment with human-computer interactions that allows users to conduct surgical training via a computer and a pair of force-feedback haptic devices. This thesis presents the results of our efforts toward this aim, which was divided into the following four objectives.

Objective 1: To develop a virtual reality surgical platform with three dimensional graphical representation and haptic sensation.

The main intention of this objective is to set up and construct a virtual reality surgical platform that is capable of providing three-dimensional surgical environment and sensible haptic force feedback. The architecture of the proposed simulator is generally consists of four main parts: haptic interface, graphical user interface (GUI), virtual surgical instruments, and 3D modelling. The haptic rendering system, which is responsible for tracing the movements of the user and the feedback generated by various types of sensation on different parts of the human eyeball, will be incorporated into the virtual surgical platform along with a pair of haptic devices that serve as the interface between user and computer. On the other hand, a GUI with different types of control will be included in the simulator to allow users make selection on the anatomy of human eye, surgical instruments, and field of view. The surgical instruments, which are used during phacoemulsification cataract surgery, will be virtually constructed and rendered in the proposed simulator. In accordance to this, a graphics rendering system is going to be developed to generate a three-dimensional mesh model of the human eye in a virtual surgical environment. The proposed surgical platform will be compared with other developed simulators to identify the differences in the functional features.

Objective 2: To simulate the main procedures of phacoemulsification cataract surgery with visual realism at the standard minimum rate of 24 frames per second and haptic realism at the rate of 1 kHz.

Phacoemulsification cataract surgery consists of four main procedures throughout the operation: corneal incision, capsulorhexis, phacoemulsification, and IOL implantation. These four procedures require different types of surgical techniques, such as incision, grasping, tearing, emulsifying, rotation, and implantation, to modify the structure of the eye during surgery. The topological modifications on the three-dimensional mesh of the virtual eye model will be developed into the simulation system using suitable methodological approaches to simulate the surgical techniques. Dynamic surface deformation will be implemented into the proposed simulator to imitate the visual feedback of the ocular tissue during the actual surgical operation. In order to simulate the surgical procedures with fluid motions, the standard minimum refresh rate of 24 frames per second is required for the visual output along with the rate of 1 kHz for haptic feedback. The proposed phacoemulsification cataract surgery simulator will be compared with other developed simulators to show the difference of the graphical performance in simulating each procedure.

Objective 3: To design an interactive graphical surgical guidance system using augmented virtual reality for the training of phacoemulsification cataract surgery.

The proposed simulator is planned to be a virtual surgical platform that provides an alternative method through which medical trainees can interactively train their surgical skills. Augmented virtual reality will be used to design a graphical surgical guidance system that will provide different types of indicators to supervise the trainees with respect to the stages of the surgical operation. These indicators will respond to the action and performance of the users in each surgical procedure. In addition, the objective of each surgical procedure will be illustrated on the virtual surgical environment, and the system will notify the users if they make any careless decision during their surgical training to increase their awareness. The effectiveness of the surgical guidance system will be clarified by comparing the results of the virtual surgical training conducted with and without the supervision from the system.

Objective 4: To apply a set of performance parameters for training in improving the surgical awareness of ophthalmologists and medical trainees.

A surgical training system will be incorporated into the proposed simulator with a set of performance parameters. These parameters are going to be identified and obtained by observing live operations and video-recorded surgical operations, and