A Haptic Training Environment for the Heart Myoblast Cell Injection Procedure

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***Abstract*—The heart muscle of a cardiac arrest victim continues to accumulate damage throughout its lifetime. This reduces the heart's ability to pump sufficient oxygen and nutrient blood to meet the body's needs. Medical researchers have shown that direct injection of pre-harvested skeletal myoblast cells into the heart can restore some muscle function [1]. This operative procedure usually necessitates the surgeon to open a patient's chest. The open chest procedure is usually a lengthy process and often extends the recovery time of the patient. Alternatively, a high accuracy surgical aid robotic system can be used to assist the thoracoscopic surgery [2][3]. While the robotic surgical method aids faster patient recovery, a less experienced surgeon can potentially cause damage to surrounding tissue.**

This paper presents a study into the development of a virtual haptically-enabled heart myoblast injection simulation environment, which can be used to train new surgeons to get hands on experience with the process. The paper also discusses the development of a generic constraint motion technique for needle insertion. Experiments on human performance measures and efficacy, while interacting with haptic feedback training models, are also presented. The experiment involved 10 operators, with each person repeating the needle insertion and injection 10 times. A notable improvement in the task execution time with the number of repetitions was observed. Operators improved their time by up to 300% compared to their first training attempt for a static heart scenario. Under a dynamic heart motion, operator's performance was slightly lower, with the successful rate of completing the experiment reduced from 84% to 75%.

Keywords—*Haptics, robotics, surgery, cardiac arrest, myoblast injection* (key words)

I. INTRODUCTION

A heart attack event occurs when a blood vessel becomes blocked in the heart. This disrupts the blood flow to the heart muscle, which reduces its functionality and weakens the heart's capability to perform its essential life functions. This in effect causes failure to adjacent organs, as inadequate nutrients and oxygen are delivered to cover the body's requirements.

Stem cells and other protein cells sourced from the patient's own body have been shown to have the capability to rejuvenate and recover heart muscles [1]. The application process requires either open chest surgery, to directly injected skeletal myoblast cells into the heart, or employs a robotic aid for minimal invasive surgery. Both operative procedures have their benefits and drawbacks. The open chest surgery extends a patients recovery time, while the robotic-based surgical method relies on the surgeon's experience controlling the robot. In both operations controlling and handling of surgical tools is a challenging task. In the majority of times, the operations are successful, but the accuracy of the transplantation or the deep cut itself is not guaranteed. This is usually caused by in process equipment handling, which requires a fully focused mind and precise hand-eye coordination to complete such task. No matter how focused or experienced the surgeon is, even minimal noise coming from hand movement can induce error, offsetting the distance of a real cut or an injection area compared to the actual planned target. Another issue, when operating using an aid robot, is controlling of the amount of pressure applied to the organ. The lack of resistance with the environment reduces the awareness and gentleness of the surgeon performing the task on the organ tissues. This would lower the quality and effectiveness of the procedure, and might cause damage to adjacent organs.

This research investigated the development of a haptic training environment for the myoblast cells heart injection procedure. The primary goal of the environment is to provide effective, simple and applicable training that it can be used by early career surgeons to train hand-eye coordination when completing an operative injection procedure. A second aim is to enhance surgeon's teleoperated robot-assisted surgery skills, by through gaining familiarity in using onscreen stream video with haptic feed back for surgery. This is an early preparation for future surgery when the open chest operation is no longer required, as surgeons operate directly from clear ultrasound images or on real-time 3D geometric constructions from the patient body organs.

Section II reviews the history and application of robotics and haptics used in medical aided surgery are reviewed. Techniques used in the training model for constrained motions, path guidance and a planning method for accurate needle insertion are then described in Section III. Section IV discusses the experimental results and evaluates the effectiveness of the training model. Finally, Section V provides our finding on the developed training model.

II. ROBOTICS AND HAPTIC IN MEDICAL APPLICATION

A. *Robotics in Medicine*

Although robots have been widely adopted in industry, replacing the human worker in high precision tasks and harsh operating environment, robotics only began its journey into the medicine discipline in 1985. At this time the first robot used was a Puma 560, which was introduced by Kwoh et al. [3] to perform high precision neurosurgical biopsies. Minimal invasive, small incision or keyhole surgery, which is favorable over conventional open cut operations due to the risk of infection is lower and recovery time is shorter, was first applied in laparoscopic surgery in 1987 [4]. Since then robotic systems have been successfully applied for transurethral resection of the prostate [5], aiding hip replacement surgeries [6][7], knee replacement [8] and other medical applications.

The operational precision of robots makes them an appealing alternative in difficult surgical procedures. For example, the IRB200 ABB robot has the basic resolution unit of approximately 0.125mm. This high precision metric is not easily achieved by humans, even by the most experience surgeon, when performing a simple injection task. Accuracy in procedures such as orthopedic or eye surgery is required, to ensure that the operated organ returns to its neutral state and to prevent damage to adjacent tissues. Damage to neighbouring tissue can cause paralysis, psychosis or even death, especially in the area of neurosurgery [9]. The benefits of high precision robotics have not only been employed in neurosurgery [10], but also in micro manipulation of cell injection, which includes pronuclei and intracytoplasmic sperm injection.

Traditional cell injection manipulation requires long training and the success rate is low for even an experienced scientist. However, with the aid of a computer controlled 3 DOF micro-robotic system, the successful rate is 80%, as demonstrated in Kobayashi et al. [11]. Wang et al. [12] also utilised a 3 DOF semi-automated micro-robotic system that combined with computer vision for sequential cell injection. They have demonstrated that the micro-bot system can achieve a throughput rate of 25 endothelial cells per minute, with a survival rate of 95.7% and a success rate of approximately 82.4% for sample size of 1012. However, this system required the operator to manually selects and mouse clicking to execute the injection process. The fully-automated injection system using vision-based algorithm to recognise immobilised zebra fish embryo structure was also investigated by Wang et al. [13]. The process involves initially estimating the cytoplasm circumference contour, then approximating the cytoplasm center. After this the needle is transformed to point toward the direction of this center and a batch injection process begins. This technique have been reported to have a throughput of 15 zebrafish embryos per minute, with a survival rate of 98% and a success rate of 99% for a sample population of 350 embryos.

B. *Haptic Feedback in Robotic Surgery*

In surgery, having absolute control over precision is difficult; however, this problem in most operative procedures can be addressed with an aiding surgical robot. Although there are many benefits of robotic surgery technology, a downside is the absence of a sense of touch. Lacking a sense of touch in a surgery limits the ability of the surgeon to control how much pressure is applied to the body tissues. This can lead to adverse affects, such as damaging the surface and functions of organ underneath or the adjoining organ. Many researchers have begun to investigate haptic feedback in medical surgical applications [14][15][16][17], to address these existing technology shortcomings.

Accuracy of haptic feedback systems in surgical application requires greater attention by the research community in the areas of technology development and evaluation of efficiency and effectiveness. As surgical procedures involve live human subjects, there is not room for error.

In searching for a realistic force feedback scheme, Mayer et al. [14] developed a haptically-enabled feedback robotic system with 8 DOF, and used it for telepresence endoscopic heart surgery. The studies used a pair of Phantom™ premium devices for force feedback and controlling the open and close of micrograppers. The evaluation of 25 cardiac surgeons using their designed system for tying knots have shown that haptic feedback significantly influences the amount of applied forces, but it has no affect on detection error and performance time. It was also found that surgeon fatigue level decreases while the perception level increases. This enhanced the safety level of the patient. The same study using haptic feedback on tying surgical knots, with fine sutures, was made by Yuh et al. [17] on 10 surgeons, who each tied 10 knots with and without force feedback using the da Vinci robotic system. The researchers have also shown that the knot processing time is not affected by haptic feedback, while the suture breakage rates are lower. It also found that haptic feedback primarily benefits novice robot- assisted surgeons.

C. Haptic Virtual Training

Application of haptics for surgical procedure is also needed in simulation and training modes. The idea is to get the operator or trainee surgeon to become familiar with the operation procedure, prior to commencement of a real process. Following this idea, Andreas et al. [18] developed a multi-point collision detection algorithm, for haptic feedback, in bone drilling surgical procedure. Their works used a refresh rate of 6 KHz in force calculation, for increase in the realism of a fracture simulation model. Their test results on trial surgeons have suggested that the haptic feedback simulator drilling system is nearly comparable to a real procedure. The interaction with volumetric implicit surface for shape modification in dental drilling and filling simulation model has also been developed by Kim and Park [19]. Their research uses a constructive solid geometry (CSG) point-set Boolean method for modification of shape. Instead of using multiple contact points model that causes the haptic device to loose its stability, when the position of the points involved in force computation are changed, Kim and Park used a single point model, but with the collision detection and force computation performed on an offset surface. They have suggested that this method is more stable than the multi-points collision detection methods.

Needle injection in medical applications requires high precision hands and eyes coordination. This ensures that the injected material is applied to the correct area and does not harm healthy tissue. Early researchers who investigated in this area are Mullins et al. [20]. Their research investigates a spherical voxel-based technique to model real time tissue deformation and haptic feedback for needle injection. This method used the actual recorded forces and torque data of composite materials, and applying them in the needle insertion algorithm. This method is promising in providing a realistic force feedback injection 'feeling' at different penetrated depths, on different organs and in different orientations. The only drawback is the number of data points that need to be captured for each organ at different orientations which is unlimited.

Lian et al. [21] developed a rheological computation model to simulate injection of polymethylmethacrylate into cancellous bone. It was suggested that the rheological methodology provides a viable option compared to the Finite Element method, as it provided accurate injection pressure computation, which enabled haptic force feedback in real-time for virtual training model.

Our research on myoblast cells heart injection falls within haptic virtual training discipline. The main idea is to train the surgeon with hand-eye coordination in the high precision needle insertion, cell injection process. We are using a methodology for needle guiding and injection. The next section describes the model developed for training the needle insertion procedures and the contact motion constraint methods.

III. HEART MYOBLAST CELL INJECTION SYSTEM

A. Haptic Heart Injection Model

Heart myoblast cell injection is a medical treatment used to rejuvenate and recover damage heart muscles. We have developed a training model to simulate this process. It can be used to train hand-eye coordination of trainee surgeons, in handling the haptic tool for high precision injection tasks. The model utilised the Sensable Phantom® Omni haptic device for force feedback. A snapshot of the virtual simulation environment is shown in Fig. 1.

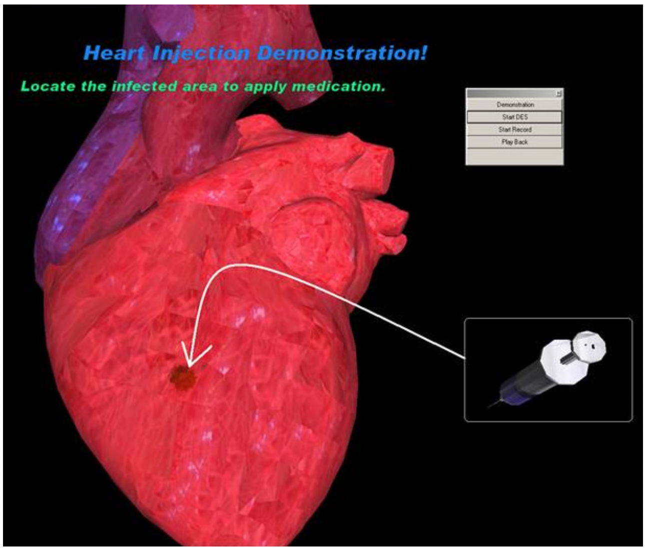


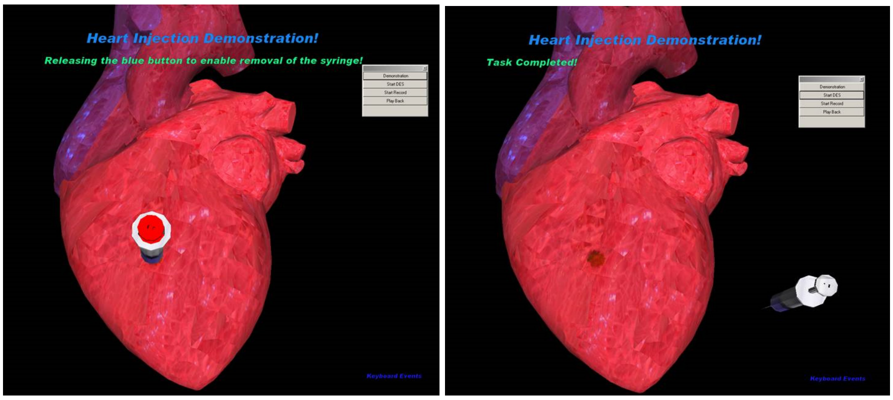
Figure 1. Myoblast cell injection training environment.

The training model includes the following types of interaction: 1) Demonstration, 2) Discrete event simulation, 3) Record User and, 4) Playback. The demonstration mode shows how the injection task is completed. The Discrete event simulation mode involves adding discrete events to the training session. The Record User and Playback modes record user tool transformations and allowed them to be played back for evaluation and comparison to the demonstration.

The procedure used in the training model involves the following procedures:

- Located the infected area with the syringe object.
- Inserting the needle to the infected area.
- Apply cell injection.
- Remove the syringe to complete the task.

These procedures are illustrated in Fig. 1, Fig. 2a and Fig. 2b respectively.



Heart Injection Demonstration!

Releasing the blue button to enable removal of the syringe!

Heart Injection Demonstration!

Task Completed!

2a) 2b)

Figure 2. a) Insert syringe on the infected and inject myoblass cells, b) Remove syringe to complete the task.

B. Injection Path Guiding and Constrained Motion Methods

The heart myoblast injection process required high level of precision in order to avoid damage to surrounding tissue by non-smooth hand motions. This means that the orientation of the syringe tool needs to be constrained such that its orientation remains the same from the moment of first contact with the heart surface tissues to the final penetrated depth, and up until the needle is extracted. There are two methods developed to solve this simple problem.

The techniques are:

- guided path method; and
- motion-based method.

The guided path method involves using a predefined injection trajectory (which is linear in this case) to guide and constraint the syringe orientation and depth position. Lets assume that a discrete straight line with a length L passes through the points P(0, 0, 0) and Q(-L, 0, 0) in a (x, y z) OpenGL coordinate system. Then the normal projection of this line from the syringe needle into the surface of the heart is equal to the transformation of the syringe needle at the beginning of the contact. This is illustrated in Fig. 3. With this projection of a straight line, normal in the direction of the needle, into the contact surface, we can constraint the motion of the syringe to move linearly, and provide haptic feedback by setting the static and dynamic friction in the direction of this line. This method allows us to perform injection at any required angle.

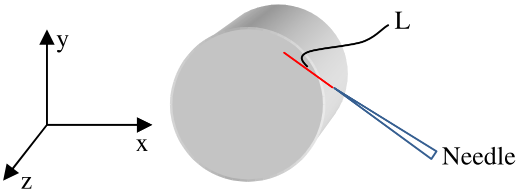


Figure 3. Guided path method.

The motion-based method firstly involves determining the transformation matrix, M, that is the result of its rotation and translation matrix R and T of the needle, at the point of contact with the surface, respectively. In order to move in the direction of the syringe needle orientation, in OpenGL, the new translation vector, T', of the original T based on the first row values of the rotation matrix, is computed. The computation is given in (1).

$$T_{3,i} + ds \bullet R_{0,i} = T'_{3,i}, \quad \forall\, i \in \{0, 1, 2\} \qquad (1)$$

Where $ds \leq 0$ is the change in spring compressed distance computed from Hooke's equation, $F = kds$. Assumed that ds is negative in the direction of injection motion. If we constrained $\mathrm{Max}(|ds|) = L$ then the needle cannot go beyond this point.

C. Needle Insertion on a Dynamic Heart Motion

Hand-eye coordination is a challenging task with needle insertion, especially when the target area on the heart surface is dynamically in motion. The dynamics is caused by the continuous contraction and relaxation of cardiac muscle tissues. This research assumes that the target surface area of the heart tissue translates between 0 to 13 mm, in the x, y and z directions, during the muscle's contraction. The force acting on the needle during the insertion and injection, F_c, is scaled to 0.3N. The direction of this force is assumed to be pointing from the previous translation point P_{n-1} towards the new translation point P_n. The force vector component for each translating index n can be computed by equation (2).

$$F_n = F_c\lambda_n \qquad (2)$$

Where $\lambda_n = (1/d)(d_{xn}i + d_{yn}j + d_{zn}k)$, is the unit vector. The values d_{xn}, d_{yn} and d_{zn} are the change in x, y and z positions from points P_{n-1} to P_n, respectively. The dimension d is the magnitude of a straight line compute from the point P_{n-1} to P_n.

IV. EXPERIMENTS AND RESULTS

In order to assess the performance of 10 operators in using the training environment, two set experiments were carried out for both static and dynamic heart scenarios. In the experiment, each operator performs the injection task 10 times on the target infected area. If the operator injected to the wrong area on the heart, it will be counted as an unsuccessful attempt. If the operator breaks the guided force constraints that restricted the syringe orientation at the injection process, it will also count as a failed attempt and be count in the overall scores. The overall results and total success training percent have been tabulated in Table 1, and plotted in Fig. 4 and Fig. 5, respectively.

The results in Table I suggest that when the heart is in motion it is harder to successfully complete the training. Although the mean and median successful training completion time is significantly lower compares to the static heart environment, by approximately 6 seconds. These results were expected since the operators become familiar with the training environment. These results are promising and clearly indicated that operator task execution time improves overtime with regular training using the haptic model.

The plot in Fig. 4 shows both successful and unsuccessful attempts. The unsuccessful trial attempts were omitted from the analysis. From this graph, it can be seen that the majority of the operators make some improvement with respect to the increases in the repetition index. This is clearly shown in the success trial trend line, which indicates a negative rate of change of task completion time over the repetition index. The graph also shows that operator 4 made no improvement within this 10 trial samples, their success rate is only 50.00%. Operator 8 also has this problem, although their success rate is 70.00%, their successful attempt times fluctuate without showing a clear improvement. It is also observed that some operators improved the task execution time more than 300%, reducing the time from 33 seconds in the first attempt down to 10 seconds.

TABLE I. OPERATOR SUCCESS TRAINING RESULTS FOR STATIC AND DYNAMIC HEART SIMULATION

Performance Metrics	**Static Heart**	**Dynamic Heart**
Success (%)	84.00	75.00
Mean Success Time (secs)	18.61	11.91
Median Success Time (secs)	17.31	11.50
Standard Deviation (secs)	7.99	4.58

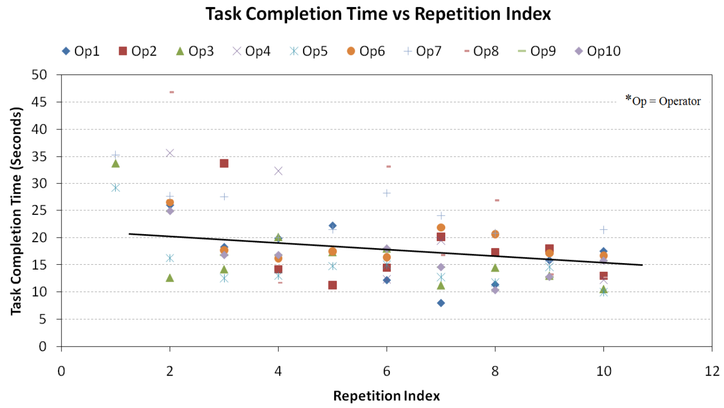


Figure 4. Operator task executed time over 10 samples for static heart model.

Targeting a dynamic moving infected area on the heart surface is a significantly challenging task, as demonstrated in Fig. 5. The results have shown a slight positive trend, which means that operator performance actually reduces slightly. This may have been caused by the intense eye focus, as operator trying to move the needle to the target area. If this level of focus extended for a long period of time, the operator's performance will be affected.

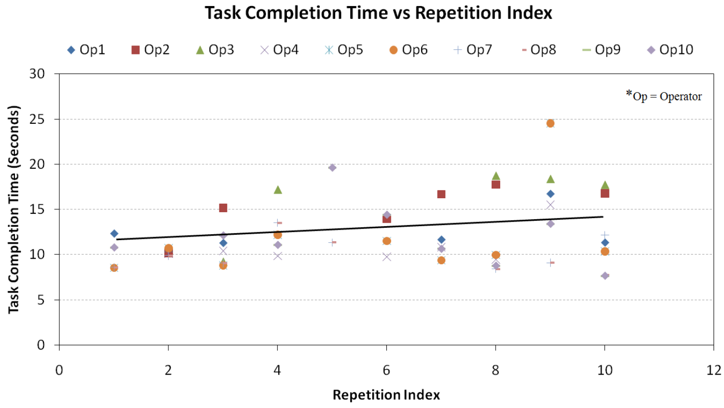


Figure 5. Task executed time over 10 samples for dynamic heart model.

V. CONCLUSION

This paper discusses a virtual haptic enabled heart myoblast cell injection simulation training environment. The aim is to train a surgeon's hand-eye coordination, in handling a haptic tool for a high precision injection task. Two simple needle insertion motion constrained techniques based on guided path and motion-based are presented. Experiments involving 10 operators, who each perform the needle insertion training task 10 times, recorded a training success rate of 84.00% and 75% respectively for static and dynamic motion heart scenarios. There was an observed improvement in the task execution time as the number of repetition increased, and some operators have shown to improve their task execution time of up to 300%, compared to their first training attempt in the static heart scenario. The dynamic heart motion, needle insertion and injection scenario have shown that there were no improvement in the task completion time. As the target area is in motion, it is significantly harder to hit the targeted area during this initial experimental trial. These results are promising regarding the application of haptic simulators in training robot assisted medical procedures.

This platform can be extended to include vision-enabled technology for injection, plan layout and interface with a surgical robot to perform haptically-enabled, rapid cell injection.

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