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Development of a Suture/Ligature Training System designed to provide quantitative information of the learning progress of trainees

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Abstract—**Surgeons, during a medical intervention, perform different kinds of manual tasks with dexterity and precision. In order to assure the success of the intervention, medical students are trained several years using training models so that they can perform such tasks with accuracy to avoid any possible risk to patients. However, current training models are merely designed to imitate the surgical procedure without providing any further information about the how well the task was done. For that reason; in this paper, the development of a Suture/Ligature Training System is proposed to imitate surgical procedures as well as provide quantitative information of the learning progress of trainees. As a first approach, a training system was designed to simulate the suture and ligature tasks. The proposed training system includes a skin dummy with an array of embedded photo interrupters to detect the movement of the skin dummy; without requiring any modification on the surgical instrument. In this paper, different task parameters were proposed to understand trainees' learning progress and different experiments were carried out to identify the evaluation parameters that may provide useful information about how well the task was performed. As a result from the experiments, the evaluation parameters for the suture and ligature were determined. Finally, an evaluation function was proposed and further experiments were proposed to verify its effectiveness. From the results of the experiments, we could effectively distinguish quantitatively the differences of skill levels between surgeons and unskilled persons as well as identifying the learning progress of trainees by plotting the learning curve.**

I. Introduction

In recent years, medical doctors are continuously doing research in collaboration with engineers to introduce novel instruments and methods to enhance the effectiveness of surgery procedures. However, there is still lack of a comprehensive research about how to evaluate the real effectiveness of such instruments and methods; in particular, from the education point of view.

For that purpose, since April 2004, authors have proposed starting a long term project in order to develop a patient robot which could serve as an evaluation tool to verify the effectiveness of surgical instruments and medical procedures.

In order to develop such kind of robot, two designing principles should be satisfied: simulate realistically the task conditions during a medical procedure and provide useful information to understand the trainee' progress (Figure 1). Regarding the first principle, the simulated organs of the robot should be designed as similar as possible as human ones (from the point of view of anatomy and physiology). In relation to the second principle, the patient robot should embed an array of sensors to enable the acquisition of quantitative data that could provide an idea about how trainees are actually improving their skills during the learning process [1].

In this paper, in order to achieve our long term goal, we have developed a prototype of a training system which provides quantitative information of the learning progress of trainees while performing surgical tasks. In particular, the suture and ligature tasks were considered. There are in fact, more than ten different types of core surgical skills which are called fundamental motions [2]. Such fundamental motions include suture, ligature, incision, grasp, hold, etc. In particular, suture and ligature tasks are basic surgical procedures needed in nearly all interventions. Therefore; as a first approach of our research, we focused on developing a prototype of a training system which embeds sensors in order to acquire quantitative information of trainees' performances as well as proposing an evaluation function to understand how well trainees are performing the task.

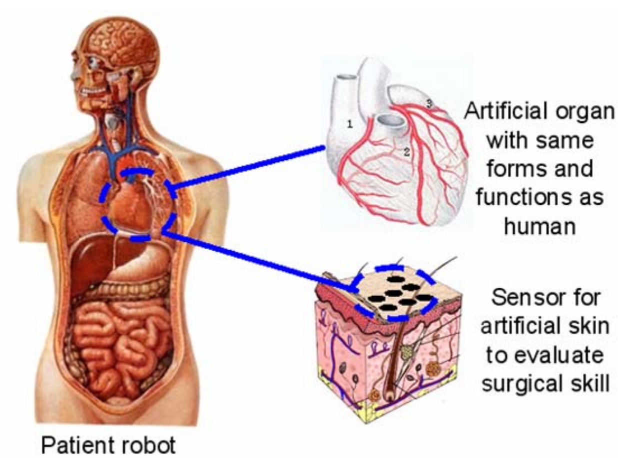

Fig. 1. The proposed patient robot should simulate realistically the human organs as well as embed sensors in order to provide detailed information about trainees' improvements.

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II. Surgical Skills Evaluation

Since the start of this project, we have been working in close contact with experienced surgeons to develop the proposed training system. We believe this cooperation is highly important because the quality of such basic surgical techniques has been rarely discussed in the surgical literature due to the lack of means for quantitative measurements. As a result, up to now, there is no scientific methodology for verifying the real effectiveness of such techniques [3].

Some researchers have proposed to evaluate surgical skills based on parameters such as task completion time and error ratio [4, 5], which are also commonly used in endoscopic surgery training systems. However, such surgical tasks requires little time to be completed so it is preferable to take into account other task parameters which may be useful for evaluating better the quality of the surgical task. Few studies on surgical skills, in fact, have added the analysis of the force as an evaluation parameter. In particular, O' Toole et al [6] proposed the analysis of the force while performing the suturing task while using a training system.

In this paper; the prototype of a suture/ligature surgical training system, that nearly simulates the conditions while performing surgical task, is detailed. Furthermore, in order to acquire quantitative information of the task, a set of task parameters were considered based on our discussions with surgeons. In particular, regarding the suture task the following task parameters were considered: task completion time, needle's insertion angle/speed (Figure 2a) and shear force (Figure 2b). Regarding the ligature task the following task parameters were considered: completion time, optimum applied force (Figure 3a) and force distribution on both hands during tying the knot (Figure 3b). A set of experiments were carried out to verify if the proposed task parameters could effectively provide quantitative information to detect the differences among different levels of skill (surgeons against unskilled persons). From the experiments, we could identify the evaluation parameters which then were used on a proposed evaluation function. Finally, a set of experiments were proposed to verify the effectiveness of the proposed evaluation system.

III. Surgical Training System

Most of the conventional training systems, that simulate the task conditions while doing a suture, involve the realization of a straight incision on a latex sheet (Figure 4). Most of such systems are produced by various medical companies specialized on selling training equipments. However, such training systems are merely designed to reproduce the tasks conditions of the surgical procedure without providing any further information about how well trainees are actually improving their skills.

Thus, in order to acquire quantitative information while trainees are practicing the task, sensors could be embedded either on the surgical tool or within the skin dummy. Most of the existing surgical training systems, which have been proposed to acquire the applied force by trainees during the task [7-9], are designed using a surgical tool with an attached force/torque sensor.

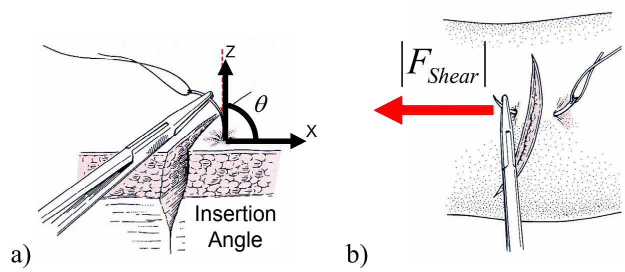


Fig. 2. a) Needle insertion angle is defined between the needle and the z-axis; b) direction of the shear force produced during suture placement.

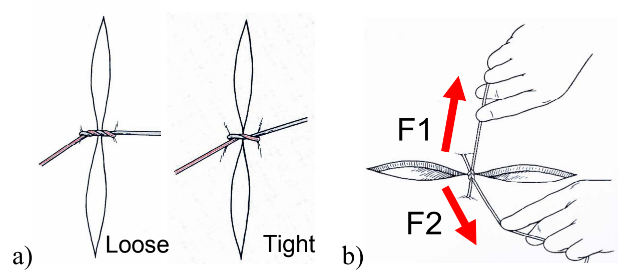


Fig. 3. a) Representation of the optimum force during the ligature task; b) force distribution of both hands (F_1=F_2).

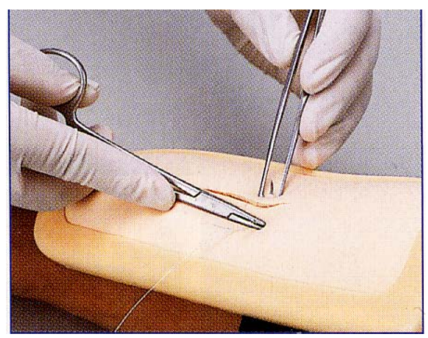


Fig. 4. Screenshot from a conventional surgical training simulator.

However, those kinds of systems may affect the performance of trainees due to collisions between the tool and the dummy as well as limit the freedom of motion of the surgical tool. Furthermore; trainees may have difficulties to perform the same task with real surgical tools because they are trained with a modified tool. For that reason, we proposed the design of a surgical training system with embedded sensors on the skin dummy without modifying the surgical tool.

A. System Description

In order to provide an environment which nearly simulates the tasks conditions required to perform surgery procedures, a prototype of the suture/ligature training system has been developed (Figure 5). This system consists of a skin dummy, a webcam, sensors and a personal computer. A dummy skin normally used to practice suturing was developed by Kyoto Kagaku Co. Ltd. (company based in Japan, focused on developing medical training equipments). The skin dummy was made by using pringel (made of polyurethane rubber) which has almost the same touch sensation as human skin. The pringel has a thickness of 2mm; where the urethane foam with a thickness of 10mm was attached to it (Figure 6).

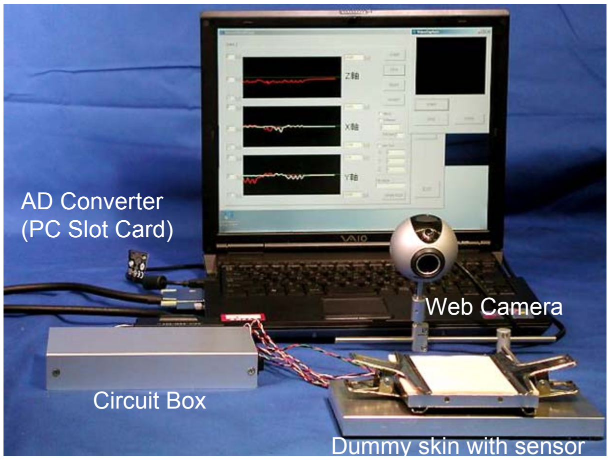


Fig. 5. Screenshot of the developed surgical skill training simulator at Waseda University.

Regarding the sensor mechanism, we embedded an array of photo interrupters (SG-105) developed by Kodenshi Co. under the skin dummy as shown in Fig. 6. The SG-105 photo interrupter combines a GaAs IRED with a high-sensitivity phototransistor in a super-mini package with dimension of 2.7 mm x 3.2 mm. The light which is emitted from GaAs IRED; is then reflected by the surface of skin dummy placed above the photo interrupter. The reflected light is then detected by a phototransistor. When the distance between photo interrupter and dummy skin becomes closer, the amount of the reflected light becomes larger. Thus, the electric current that flows inside the phototransistor will increase in proportion to amount of the reflected light. By using this mechanism, we can sense the movement of skin dummy due to the applied force while performing suture and ligature tasks [10]. In order to sense the three-dimensional movement of skin dummy, we embedded one photo interrupter under the skin dummy and four photo interrupters located on both sides of skin dummy.

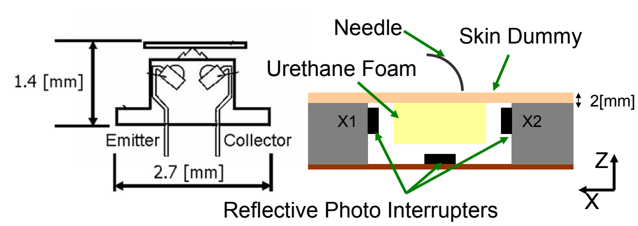


Fig. 6. Detail of the proposed sensor mechanism to measure the movement of the skin dummy.

B. *Analysis of Sensor Performance*

In order to assure the accuracy of the measurement of the movement of the skin dummy while performing surgical skills, we have developed an experimental device to test the proposed sensor mechanism (Figure 7). Such experimental device was designed to reproduce the basic movements, proposed by Seki [3], realized while performing the suture task. As a result, it is possible to accurately control the angle/speed of the needle at which the incision is realized on the skin dummy.

Therefore, the experimental device was programmed to perform the same movement while suturing for ten times meanwhile the movement of the skin dummy was registered using the developed sensor system. As it is shown in Fig. 8, we found a high repetitiveness of the sensor measurement. Furthermore; we also determined the sensitivity of the sensor system while applying a force directly along the vertical axis of the dummy skin. For this purpose, we have used a mechanism controlled by a DC motor and the output voltage obtained from the sensor system was recorded. As a result, the sensor system can handle a maximum load of 20g.

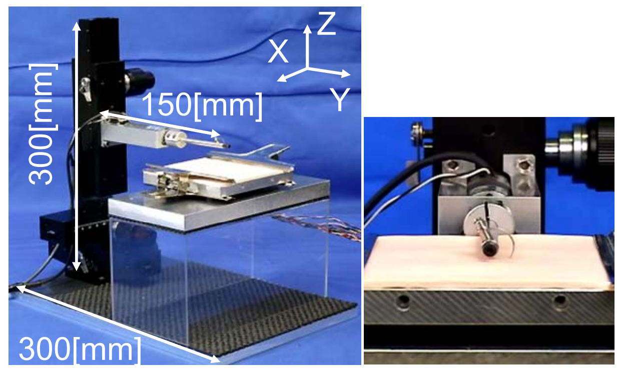


Fig. 7. Suture device used for testing the proposed sensor system.

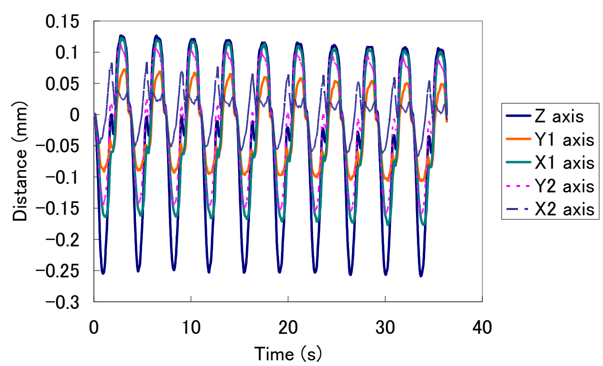


Fig. 8. Results of the experiment carried out to verify the sensor performance (variation in results between repetitions: σ_Z=0.01, σ_{Y1}=0.006, σ_{X1}=0.008, σ_{Y2}=0.008 and σ_{X2}=0.006).

IV. Evaluation Parameters Identification

Based on our discussions with surgeons, a set of task parameters were considered. Regarding the suture task the following task parameters were considered: task completion time, needle's insertion angle/speed, and shear force. Regarding the ligature task the following task parameters were considered: completion time, optimum applied force and force distribution on both hands during tying the knot. However, in order to propose an evaluation function, it is preferable to perform experiments to verify if the proposed task parameters are useful or not to quantitatively evaluate the surgical skill.

Therefore, we perform preliminary experiments using the proposed training system to detect which of the proposed task parameters are useful to detect quantitatively the differences among persons with different level of expertise (surgeons and unskilled persons). For that purpose, we have collected data from three surgeons (having more that five years of experience) and three unskilled persons (having no experience at all about the considered tasks). None of all the subjects considered for the experiments had previously used the sensor system. Regarding the unskilled persons, they were taught how to perform the surgical procedures before the experiment by watching a video showing a surgeon performing the task.

A. Suture Task

Regarding the needle's insertion angle/speed parameter, at first, we perform an experiment using the experimental device (Figure 7) to identify the relation between the angle/speed while inserting the needle and the movement of the skin along the Z axis. Therefore, we programmed the experimental device to perform suture placement while changing the angle and speed parameters of needle's insertion. The results are shown in Fig. 9a and Fig. 9b. The distance on the y-axis represents the movement of skin dummy during suture placement along the Z axis. Negative values represent when the skin dummy is pushed and positive values represent when the skin dummy is pulled. We found that the skin dummy movement downwards along Z axis becomes larger when the angle and/or the speed are increased.

According to surgical literatures, suture placement with a large insertion angle (around 90^{o}) will assure better sealing properties of the gap between wound edges. In fact, we found that the surgeon group (Figure 10a) has larger downward movement of skin dummy during suture placement than the unskilled person group (Figure 10b). By comparing the results obtained on these experiments, we conclude that a suture placement with large needle's insertion speed and angle will cause a larger downward movement of the skin dummy. Therefore, we have considered as evaluation parameter the movement of the Z axis to evaluate the angle/speed while inserting the needle.

Another task parameter considered for the suture placement is the shear force; which is the force applied to the skin tissue. A suture with large shear force will cause damage on skin tissue. Therefore, we calculated the movement of skin dummy along X axis (X1 - X2) to compute the shear force (Figure 11). In fact; we found, from our discussion with surgeons, that a suture placement having a large movement of skin dummy along X axis will indicate a large shear force. From the experimental data collected from surgeons and unskilled persons (Figure 12), smaller movements of skin dummy were detected on surgeons respect to unskilled persons. Furthermore, there is a significant difference of the suture completion time between surgeons and unskilled persons (8.8 s and 17.0 s respectively). From the results obtained in these experiments, the completion time and shear force parameters were considered useful for evaluating trainees' performances.

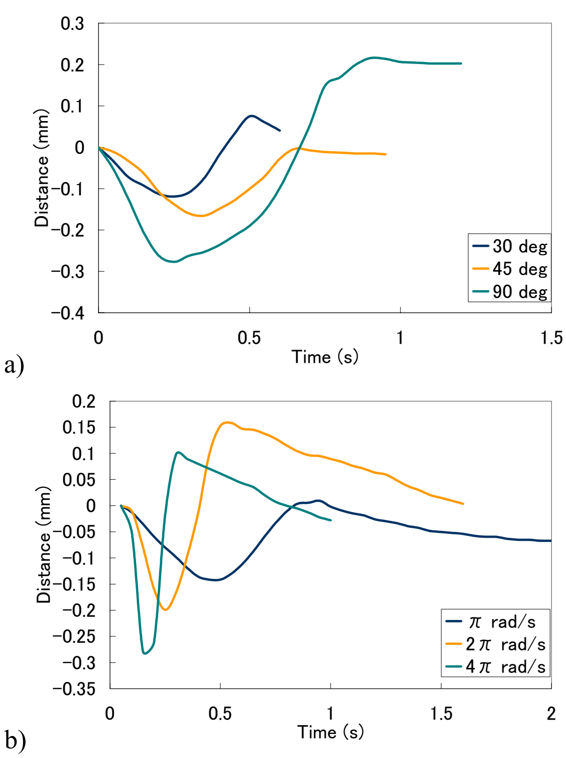


Fig. 9. Movement of the skin dummy: a) Different angles of insertion (insertion speed of π rad/s); b) Different speeds of insertion (insertion angle of 90 deg).

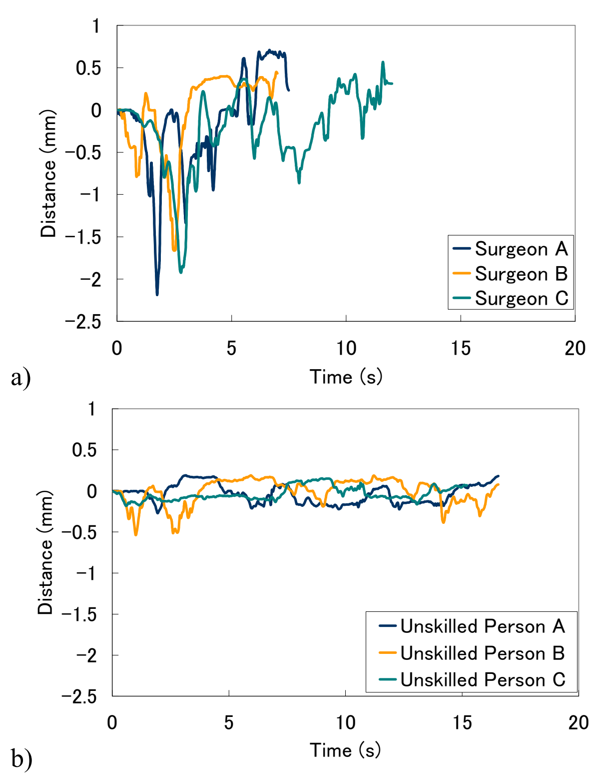


Fig. 10. Movement of the skin dummy: a) surgeon's case; b) unskilled person's case.

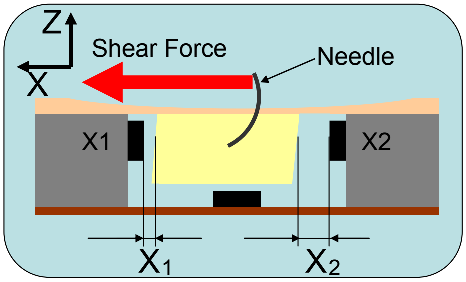


Fig. 11. The shear force is produced while doing the suture placement.

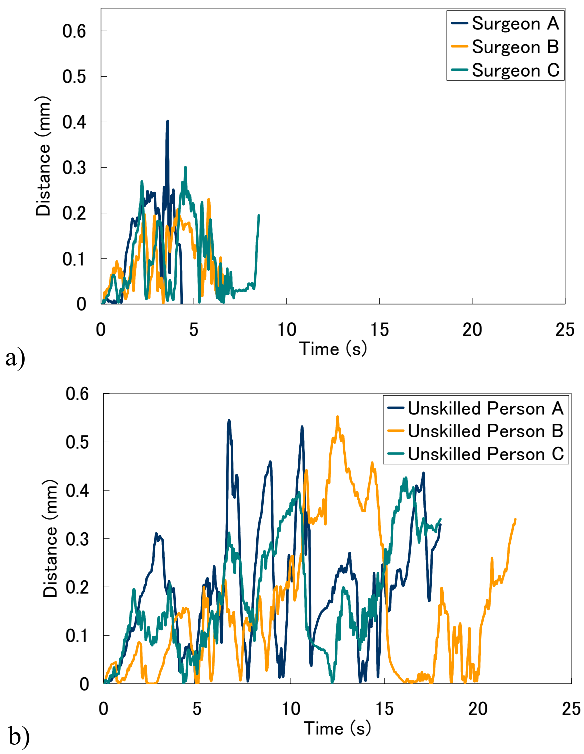


Fig. 12. Detected movement along X axis ($X_1 - X_2$): a) surgeon's case; b) unskilled person's case.

B. Ligature Task

Regarding the task parameters of the ligature task, the considered parameters are as follows: task completion time, optimum force during ligature and force distribution on both hands while tying the knot.

Regarding the optimum force, in the surgical literature, there is no formal methodology to decide the optimum force that should be applied during the ligature task. Therefore, we have considered the average force applied by surgeon group as the optimum force.

Regarding the force distribution; at first, we perform an experiment to determine the relation between performing the task with one or both hands and the movement of the skin. Therefore, we used a load cell in order to measure the force while tying the knot. Experimental results are shown in Fig. 13. We found that ligature with one hand will cause a larger movement of the skin dummy along X axis (X1 –X2).

From the surgical literature is known that a big damage to skin tissue occurs when only one hand is used for the ligature in contrast to the case when both hands are used. In order to verify the usefulness of the force distribution parameter, we collected data from surgeons and unskilled persons to measure the movement along X axis (X1 – X2). From the data obtained in Fig. 14, it is observed that surgeon group has

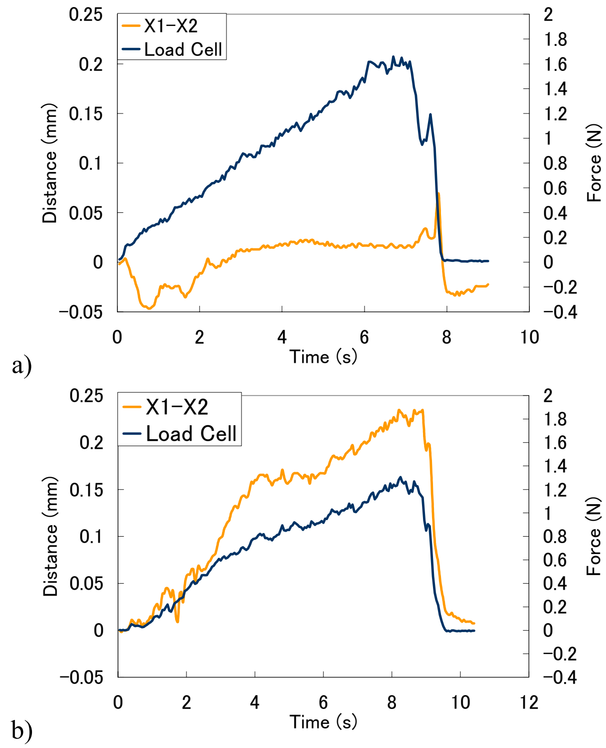


Fig. 13. Movement along X axis ($X_1 - X_2$) and force while performing the ligature task: a) one hand case; b) both hands case.

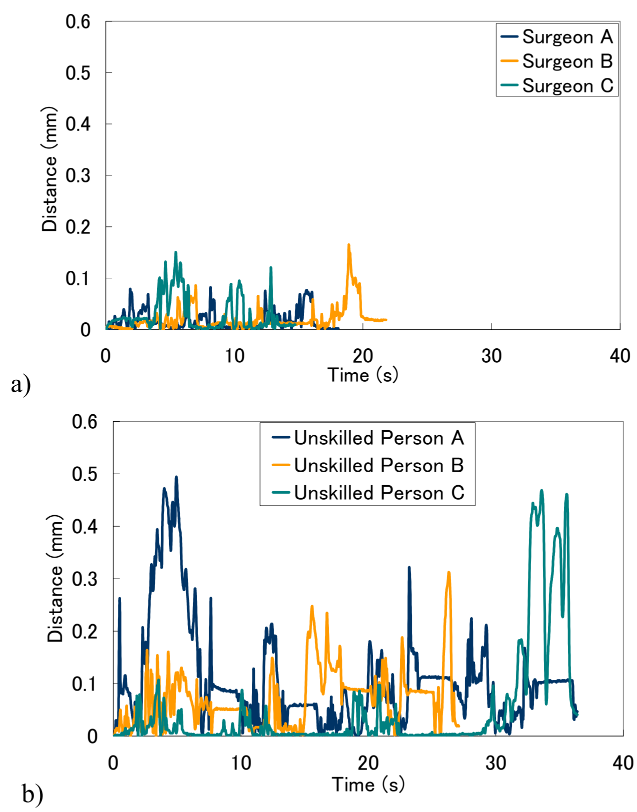


Fig. 14. Detail of the proposed sensor mechanism to measure the movement of the skin dummy.

smaller movements of skin dummy compared to unskilled ones. This is because surgeons applied equal forces on both hands during ligature causing less damage to the skin tissue. Therefore, the distribution force was confirmed to be useful in evaluating trainees' performances.

V. Evaluation Function: Suture and Ligature

A. Normalization of the Evaluation Parameters

In order to simplify the analysis of the proposed evaluation parameters so that an evaluation function can be proposed, all the parameters from both tasks (suture and ligature tasks) were normalized from 0 to 100. We considered that when the evaluation parameter value is more than 100, the evaluation score will be set to 100 and if the evaluation parameter value is below than 0, the evaluation score will be set to 0.

In order to calculate the normalized value of each of the considered parameters for the ligature and suture task; at first, we have observed to the raw data obtained from the experiments with surgeons and unskilled persons. We have observed that in the case of the completion time, needle insertion angle/speed, and shear force parameters during the suture task; it was easily observed that performances from the surgeon group had generally highest values; meanwhile the performances from unskilled persons were generally the lowest values. From this observation, we have considered as normalization parameters the maximum average value of the surgeon group and the minimum average value of the unskilled person group.

Regarding the ligature parameters, the same observation was found regarding the completion time and shear force parameters. However; in the case of the applied force parameter, we couldn't find easily a big difference between the surgeons and unskilled persons groups. Therefore, in order to determine the normalization parameters for this evaluation parameter, the average value of the surgeon group was considered as the maximum score value (100) and the minimum score value (0) from those obtained from the measured applied force in case of surgeons and unskilled persons.

B. Procedure

After determining the evaluation parameters, we proposed an evaluation function which can output a quantitative score depending on how well the task was performed (task quality). As a first approach, we proposed a heuristic way to determine such a function. Therefore, we have proposed different evaluation functions and experimentally tested their effectiveness. Finally, the evaluation function selected was the one which demonstrated to be useful for quantitatively showing the differences among persons with different levels of expertise. As a result, the suture evaluation function is defined as (1) and the ligature one as (2). In this paper, the coefficient weights of the proposed evaluation functions were also experimentally decided.

$$E_{Suture} = \omega_1 / T_{Suture} + \omega_2 Z_{\min} + \omega_3 \Big/ \int_0^T |\Delta x(t)| dt \qquad (1)$$

T_{Suture}: Suture Completion Time
$\Delta x(t)$: X1 - X2
Z_{min}: Minimum value of Z Axis
$\omega_{1,2,3}$: Coefficient Weights (ω_1=24, ω_2=40 and ω_3=35)

$$E_{Ligature} = \frac{\omega_1 N_{Lig}}{T_{Lig}} + \frac{\omega_2}{\int_0^T |\Delta x(t)| dt} + Max_{Lig}$$

$$Max_{Lig} = \frac{\omega_{3Z}}{|Max_Z - Idle_Z|_{Max}} + \frac{\omega_{3Y}}{|Max_Y - Idle_Y|_{Max}} + \frac{\omega_{3X}}{|Max_X - Idle_X|_{Max}} \qquad (2)$$

T_{Lig} : Ligature Completion Time
N_{Lig} : Ligature Times
$\Delta x(t)$: X1 - X2
$\omega_{1,2,3}$: Coefficient Weights (ω_1=55, ω_2=20 and ω_{3Z}=5, ω_{3Y}=5 and ω_{3X}=15)
$Max_{Z,Y,X}$: Maximum displacement of each axes during ligature
$Idle_{Z,Y,X}$: Voltage value measured in idle mode

VI. Experiments and Results

In order to verify the effectiveness of the proposed evaluation function, an experiment was carried out. The objectives of the experiment were two: verifying if the proposed evaluation function is able of quantitatively detecting differences on skill levels (i.e. surgeons versus unskilled persons); and verifying if the proposed evaluation function is able of detecting the improvements of trainees while performing the task by plotting the learning curve.

Regarding the first objective of the experiment, we collected data from ten surgeons and eleven unskilled persons while performing the suture and ligature tasks using the developed training system. The resulting data for the evaluation scores of all the considered subjects are shown in Fig. 15 (x-axis shows the evaluation score of suture and the y-axis shows the evaluation score of ligature). From this graph, we can see that by using the proposed evaluation function, we can distinguish quantitatively the differences of skills levels among subjects. In fact, by performing a statistical analysis (t-test), we found a significant difference ($p<0.05$) between the surgeons and unskilled persons while analyzing the resultant evaluation score.

Regarding the second objective of the experiment, we have collected the performance of six unskilled persons while being trained to perform the suture and ligature skills for 12 times. During the training process, subjects received verbal advices from a surgeon to improve their performances. In Fig. 16, the obtained learning curve is showed. As we can see, the evaluation function seems to be useful for understanding the learning progress of trainees; however, we require performing further experiments considering more trainees to demonstrate its real effectiveness.

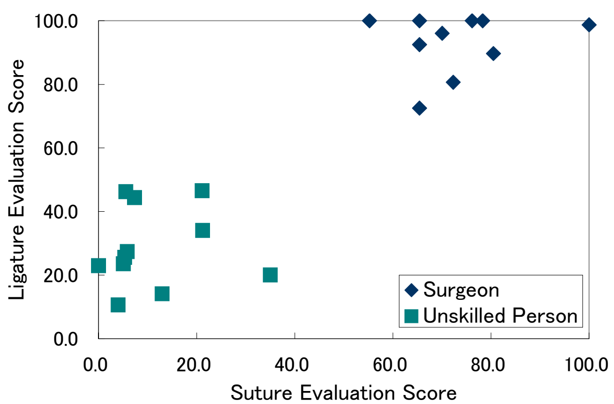
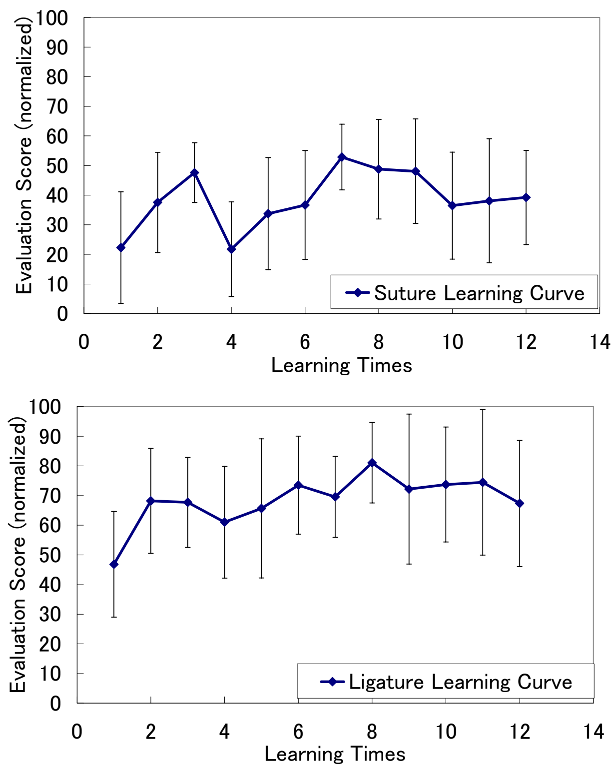


Fig. 15. The graph shows the results obtained while comparing the performance between surgeons and unskilled persons using the proposed evaluation function.



a)

b)

Fig. 16. Learning curves obtained from the experiment carried out: a) suture's case; b) ligature's case.

VII. Conclusions and Future Work

In this paper, we have presented a novel surgical training skill system which provides quantitative information of the learning progress of trainees. In order to evaluate the trainees' performances, different evaluation parameters were proposed depending on the task to be considered (i.e. suture and ligature). After validating the effectiveness of each of the proposed parameters, an evaluation function was experimentally proposed. A set of experiments were carried out to verify the effectiveness of evaluation function. As a result, the proposed evaluation function could quantitatively distinguish the differences of skill levels among surgeons and unskilled persons. Furthermore, using the proposed evaluation function, we could distinguish quantitatively the improvements of trainees by plotting the learning curve.

As a future work, we require further improvements of the sensor system so that other task parameters could be considered. In addition, in order to verify the real effectiveness of the proposed evaluation function; further experiments will be proposed by considering even more subjects for the experiment so that a more accurate analysis can be realized.

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References

[1] K. Nishikawa, Y. Park, M. Aizuddin, K. Yoshinaga, K. Ogura, M. Umezu and A. Takanishi: "Development of Carbon Microcoils (CMC) Sensor System with High Sensitivity for Effective Acquisition of Tactile Information", Proceedings of the 2005 IEEE International Conference on Intelligent Robots and Systems, 2005.8W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.

[2] S. Seki: "Basic Principles of the Operative Techniques and Their Practical Knacks (in Japanese)", KANEHARA & Co., Ltd., Tokyo, 2002.

[3] S. Seki: "Techniques for better suturing", British Journal of Surgery Vol. 75, pp. 1181-1184, 1988.12.

[4] Rosen J., Hannaford B., MacFarlane M.P., Sinanan M.A.: "Force controlled and teleoperated endoscopic grasper for minimally invasive surgery- experimental performance evaluation", In Proc. of the IEEE Trans. Biomed. Engineering, pp.1212-1221, 1999.

[5] Emam T.A., Hanna G.B., Kimber C., Dunkley P., Cuschieri A.: "Effect of intracorporeal-extracorporeal instrument length ratio on endoscopic task performance and surgeon movements", Arch. Surg., pp. 62-65, 2000.

[6] O' Toole R.V., Playter R.R., et al.: "Measuring and developing suturing technique with a virtual reality surgical simulator", J. Am. Coll. Surg. Vol. 189, pp. 114-127, 1999.

[7] Rosen J., Hannaford B., Richards C.G., Sinanan M.N.: "Markov modeling of minimally invasive surgery based on tool/ tissue interaction and force/torque signatures for evaluationg surgical skills", in Proc. of the IEEE Trans. Biomed. Engineering, pp.579-591, 2001.

[8] Y. Yamauchi, J. Yamashita, O. Morikawa, et al.: "Surgical Skill Evaluation by Force Data for Endoscopic Sinus Surgery Training System", In Proc. of the 5th International Conference on Medical Image Computing and Computer-Assisted Intervention, pp. 44-51, 2002.

[9] S. Seki: "Suturing Techniques of Individual Surgeons- Differences in Accuracy and Mechanics", Japanese Journal of Surgery Vol. 19, pp. 424-431, 1989.

[10] M. Aizuddin, N. Oshima, R. Midorikawa, A. Takanishi: "Development of Sensor System for Effective Evaluation of Surgical Skills", In Proc. of the 2006 IEEE/ RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 678-683, 2006.