Hands-free Interface for Surgical Procedures Based on Foot Movement Patterns

Toshikazu Kawai, Masanori Fukunishi, Atsushi Nishikawa, Yuji Nishizawa, and Tatsuo Nakamura

***Abstract*— A hands-free interface has been developed to allow a single surgeon to control a locally operated forceps manipulating robot. It is based on the use of a pressure sensor sheet placed on the floor to measure temporal changes in the center of gravity of the operator's foot, in addition to the applied force. Pattern recognition was carried out during trials with endoscope specialists and students for six different types of foot movements. The specialist patterns were then used to develop an interface for controlling a robot with five degrees of freedom. Using this control interface, it was found that the robot could successfully handle a model organ during simulated surgery.**

I. Introduction

Minimally invasive endoscopic surgery can lead to cosmetically appealing results, less tissue damage and early rehabilitation, because it is an accurate surgical procedure that offers an expanded field of view and leaves only small scars. To perform accurate surgery, it is important for the organ in question to be grasped and pulled in two directions, and cut when it is under sufficient tension. A surgeon and an assistant held the forceps in this way historically. However, surgeons must manipulate tools with insufficient degrees of freedom (DOFs) and the effects of hand tremors need to be minimized. In addition, cooperation is required between the doctor performing the surgery and assistants using an endoscope or forceps. Many master-slave controlled manipulators [1] have been developed to solve these issues. For example, the well-known da Vinci surgical robot [2] is operated remotely by a surgeon in a non-sterilized area. The time delay and latency with the control system are short enough to be ignored for surgeon in the operating room. Such systems allow high positional accuracy because of the use of tools with multiple DOFs, motion scaling and low-pass filtering to counteract tremors. Because of the possibility of emergencies occurring, local operation must be considered safer than remote operation. A large number of locally operated surgical robots and devices have been developed. The latest systems include the manually controlled 3-DOF mechanical forceps Radius [3], the intelligent armrest EXPERT with passive brake control stabilization allowing tremor elimination [4], and the endoscope-holding voice-controlled robot ViKY XL [5]. However, there is no locally operated forceps robot that can grasp organs and provide traction continuously. To this end, we have proposed a manipulator that can act as a third arm for a surgeon in the sterile environment of the operating room. We developed a locally operated detachable end-effector manipulator (LODEM) based on a selective compliance assembly robot arm (SCARA), and a mobile LODEM that can be disassembled into compact parts [6-7]. This manipulator has 5 DOFs, an acting force of more than 5 N, and an accuracy of better than 0.5 mm, and has been applied to *in vivo* laparoscopic cholecystectomy.

The operation for the organ to be grasped and pulled using the forceps robot is provided when the field of view is expanded. Since the robot spends far more time just holding an organ than actually being controlled by the surgeon, the control interface should be as unobtrusive as possible, so that the surgeon can concentrate on the surgical procedure. Ideally, it should be hands-free and capable of controlling a LODEM with 5 DOFs. Although ViKY XL [5] and AESOP [8] are voice controlled, Naviot is controlled via forceps-mounted buttons [9], and FreeHand is controlled via a head-mounted sensor [10], the interface provides only 2 or 3 DOFs. Monitoring leg motion beneath the operation table is one possible method for controlling a LODEM. The use of optical displacement sensors is a popular method for measuring the trajectory of moving objects. However, it would be necessary to attach sensor markers to the legs of the surgeon, who would need to stand in front of a 3D detector in order to avoid blind spots. Furthermore, performing leg movements while standing may be difficult because it would be necessary to maintain constant foot contact with the floor in order not to lose balance.

To overcome these difficulties, a method is proposed for recognizing foot movement patterns based on changes in the center of gravity of the foot, and the applied force. This can allow a hands-free control interface that can provide 5 DOFs. The manipulator can be operated by the surgeon's foot, and the system can be removed from the floor near the surgical table when not required. It will allow surgical procedures to be performed safely by a single surgeon in a sterile area near the patient. Foot movements are detected based on measurements using a pressure sensor sheet and pattern recognition. A pattern recognition model is developed, and a state transition diagram is constructed for controlling the LODEM. Finally, the performance of the interface is evaluated while performing simulated surgery.

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T. Kawai and M. Fukunishi are with the Major in Biomedical Engineering, Osaka Institute of Technology, Osaka, 535-8585 JAPAN (phone: +81-6-6954-4740; e-mail: kawai@bme.oit.ac.jp)

A. Nishikawa is with the Department of Textile Science and Technology, Shinshu University, Ueda, 386-8567 JAPAN (e-mail: nishikawa@shinshu-u.ac.jp)

Y. Nishizawa was with the Department of Gastroenterological Surgery, Kagawa University, Kita-gun, 761-0793 JAPAN. He is now with the Department of Colonic Surgery, National Cancer Center Hospital East, Kashiwa, 277-8577 JAPAN (e-mail: yunishiz@east.ncc.go.jp)

T. Nakamura is with the Frontier Medical Sciences, Kyoto University, Kyoto, 606-8507 JAPAN (e-mail: nakamura@frontier.kyoto-u.ac.jp)

II. Tracking Foot Center of Gravity

A. Selection of Foot Movements

Six foot movements that are possible while standing and maintaining contact with the floor were selected, based on a consideration of the human musculoskeletal system. These are (a) adduction and abduction of the hip point, (b) extension and flexion of the hip point, (c) medial and lateral rotation of the heel, (d) medial and lateral rotation of the toe, (e) inversion and eversion, and (f) dorsiflexion and plantar flexion. These movements are shown in Fig. 1.

B. Method and Results for Tracking Foot Center of Gravity

For the six types of movements described above, the position (x, y) of the foot center of gravity, together with the downward force f were measured using a pressure sensor sheet (cell spacing: 12.5 mm, number of cells: 720, sheet size: 375×300 mm, resolution: 4 mm, sampling time: 0.01 s, detecting system: electromagnetic induction type, LL sensor, Xiroku Inc.). The operator wearing socks stood in front of the table and placed the right foot on the sensor sheet which was on the floor in a simulated surgery environment. Pre-trial training involved performing each of the foot movements several times. The participants were five endoscope specialists and ten engineering students who gave written informed consent. A total of six trials were performed for the specialists and ten for the students. The experimental setup is shown in Fig. 2. The experiments were approved by the ethics committee at Osaka Institute of Technology.

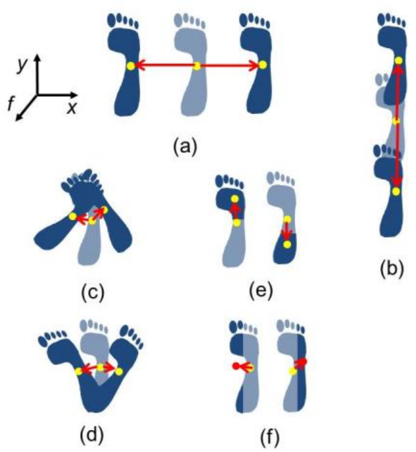

Figure 1. Six possible foot movements when standing with feet in contact with the floor based on the human musculoskeletal system. The center of gravity is indicated by the circles.

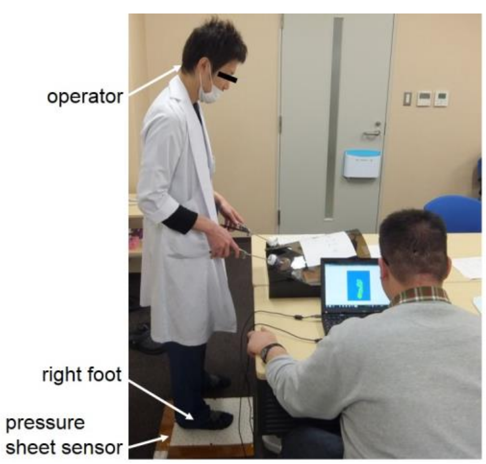

Figure 2. Experimental setup for measuring the temporal changes in the center of gravity of the foot, together with the applied force using a pressure sensor sheet.

Three different patterns can be seen in the results: flat, step, and pulse. Since the step and pulse patterns can be either upward or downward, this gives a total of five patterns.

C. Method for Recognizing Foot Movements

Foot movements were recognized based on the five patterns described above using two time-dependent functions. The recognition model is shown in Fig. 3. The input signal $M(t)$ is a function of the measured values of x, y and f, and is expressed as

$$M(t) = (x(t), y(t), z(t)). \tag{1}$$

The input signal pattern is extracted using the functions $g(M)$ for x, y and f, which are then combined to give the function $h(g)$. The extraction function $g(M)$ is determined by a two-step process involving both the first and second derivatives with respect to time of the input signal $M(t)$, as shown in Fig. 4. The time derivative dM/dt during a sampling period Δt is given by

$$dM/dt = \{M(t+\Delta t) - M(t)\} / \Delta t. \tag{2}$$

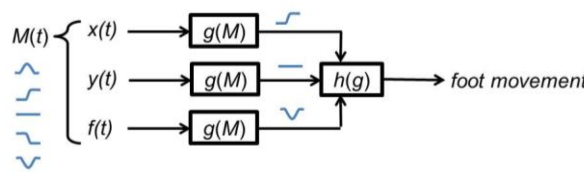

Figure 3. Recognition functions for foot movements. The function $g(M)$ extracts the pattern from the input signal $M(t)$ for x, y and f, and the function $h(g)$ recognizes the foot movement based on the combination of the three patterns.

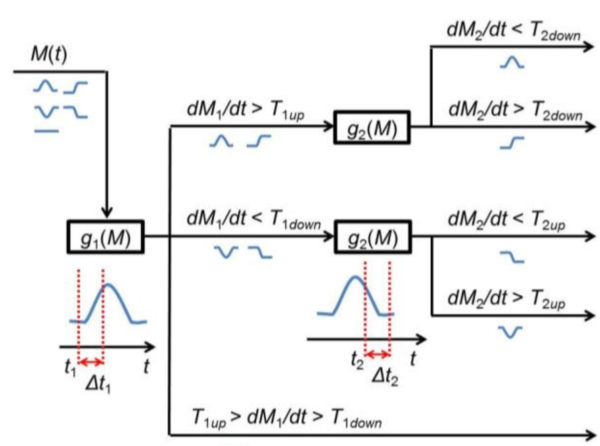

Figure 4. The extraction function $g(M)$ is constructed in two steps by continuously comparing the first and second time derivatives to threshold levels during the sampling interval.

In the first step, the function $g_1(M)$ is determined based on the initial variation in $M(t)$. The time derivative dM_1/dt is continuously compared to the threshold levels T_{1up} and T_{1down} during the sampling interval Δt_1. In the second step, the function $g_2(M)$ is determined based on the final variation in $M(t)$ by calculating the second derivative with respect to time, and continuously comparing to the threshold levels T_{2up} and T_{2down} during the sampling interval Δt_2. These threshold levels are set by trial and error based on the experimental results in section II *B*. When the input direction is tilted from the vertical direction on the sensor sheet, it is corrected using a rotation matrix based on the calculated tilt angle.

D. Results and Pattern Analysis

Figure 5 shows the pattern in *f*, *x* and *y* for the six foot movements measured during the trials involving the all specialists, and Fig. 6 shows the corresponding data for the nine in ten students.

The foot movement is identified based on the three patterns for *f*, *x* and *y*. Similar patterns were found for the specialists and the students, except for the *y* position in motion (c) and (d), and the force *f* in motion (e) and (f). The difference arises from the fact that the specialists kept their weight on both feet, whereas the students shifted it to their left foot. The *y* position to keep balance for surgeons was changed after the movements. The force *f* was increased when the area contact with the floor was decreased.

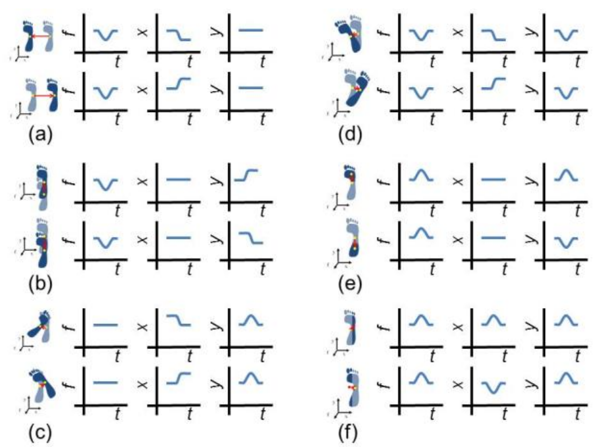

Figure 5. Recorded patterns for center of gravity and applied force for endoscope specialists. Five types of patterns can be identified: flat, ±step, ±pulse.

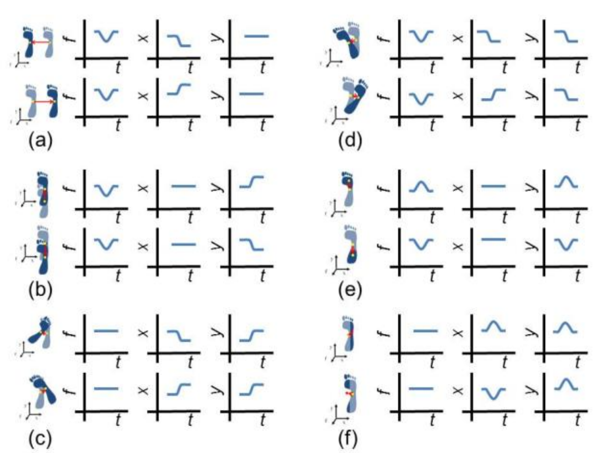

Figure 6. Recorded patterns for center of gravity and applied force for students. Compared to the specialist patterns, differences occur for the *y* position in movements (c) and (d), and for *f* in movement (f).

III. HANDS-FREE CONTROL INTERFACE

A. Control system for LODEM

The control interface for the LODEM was constructed based on the analysis of the foot movements of the specialists. The state transition diagram relating the five foot movement patterns to a specific LODEM axis is shown in Fig. 7. For safety reasons, a SELECT mode to confirm the selection and a MOVE mode to actually perform the action are included. The driven axis of the LODEM is selected based on the correlated foot movement in the IDLE mode. Permission to perform the movement is granted by removal of the foot in the SELECT mode. The movement continues while the foot is held down, and stops when it is raised. The system is started by drawing the character 'S' with the foot, and is locked by the character 'L' or when the time limit is exceeded. The character 'S' is recognized as a combination of a negative step, a positive step and another negative step for $x(t)$. The character 'L' is recognized as a combination of a positive step for $x(t)$ and a negative step for $y(t)$.

Simulated surgery was performed on a surgically realistic gall bladder model (50128, Limbs & Things) to evaluate the performance of the control interface. The model was placed in a laparoscopic training box (Endowork-pro II , KARL STOLZ) and was viewed through an endoscope (10 mm diameter, SHINKO KOHKI). The endoscope was positioned at the foot of the surgical table and the monitor at the head. The manipulator [7] attached to the forceps was positioned at the right hand side of the table. The operator stood on the left hand side of the table and controlled the manipulator using the foot controlled interface. The operator was an endoscope specialist, and used a scissors in the right hand and the forceps in the left hand. The foot movement patterns for changing to different modes were displayed on the PC monitor in text format, together with the recognition results and the corresponding foot pressure distribution. The time of recognition after the foot movement was finished was set 0.1 s.

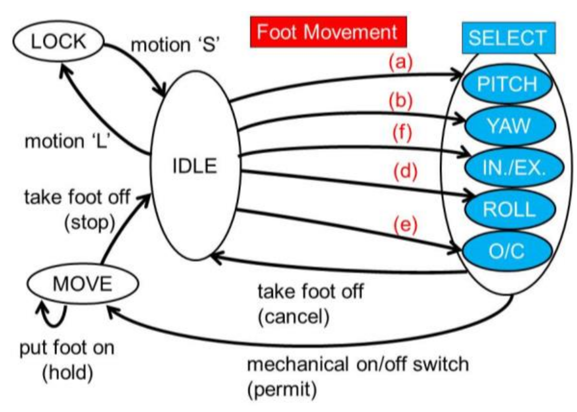

Figure 7. State transition diagram relating five foot movements to a particular LODEM axis.

It is not necessary to calibrate the process in order to work the model immediately. The training time and the time between confirmations of the recognized pattern to movement of the selected axis were measured. The participant was an endoscope specialist and a trial was performed.

B. Results of Simulated Surgery

Figure 8 shows the simulated surgical procedure. The selection modes associated with different foot movements are displayed for the operator in Fig. 8(a). The gall bladder model could be grasped and pulled in all directions by the forceps attached to the manipulator controlled using the proposed interface. The surgeon could also pull the model organ in opposite directions using the forceps in the left hand, and dissect it using the scissors in the right hand, as shown in Figs. 8(b) and 8(c). The training time was about five minutes because the recognition rate was different for each foot movement. The time between pattern confirmation and movement of the selected axis was about three seconds. It took a few seconds for the movement to stop following raising of the foot.

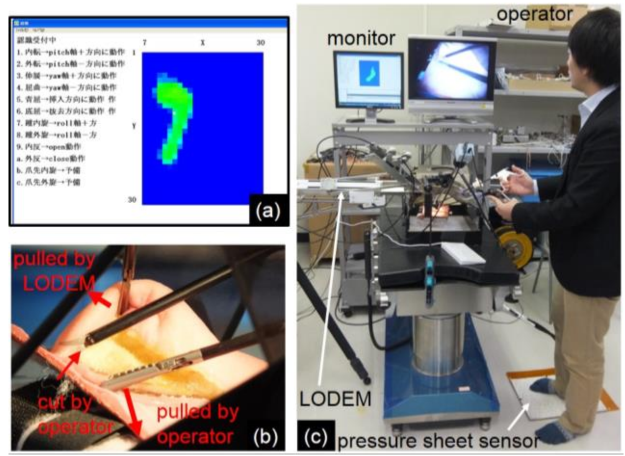

Figure 8. Simulated surgery performed on a surgically realistic gall bladder model by a specialist using the control interface and LODEM: **(a)** selected foot movement displayed on the monitor, **(b)** the handling of the model in the training box, **(c)** simulated surgery.

IV. Discussion

To use the interface quickly and easily, the operator should not have to spend an extensive amount of time in training. For this reason, in the time derivative method for identifying foot movements, a trial and error approach was used to determine the threshold levels. However, the recognition rate was lower for some foot movements because they did not give rise to a strongly changing pattern. To improve the recognition rate and set the thresholds automatically, machine learning is one possible approach [11]. Because the recognition rate is not on 100%, the selection and permission modes are required for safety reasons. The permission time was long because the recognition information was displayed in text format for the operator. The lag time is acceptable within 0.33 s [12]. This time could be reduced by using a graphic display.

The pressure sensor sheet used in this study was constructed from cells that are vertically split by coils and a metal sheet. After the foot is removed from the sheet, it takes a few seconds for the sheet to return to its undeformed position. This is the reason not to stop the motor drive at once. To avoid this effect, a different detecting system could be used, such as one based on capacitance.

V. Conclusion

A control system for a surgical robot was proposed based on an analysis of foot movements detected using a pressure sensor sheet. This was achieved by measuring the temporal change in the center of gravity of the operator's foot, together with the applied force. The interface was found to be effective for controlling a LODEM with 5 DOFs.

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