간담췌 외과용 방향능동제어 다관절 복강경 수술기구의 개발

Development of a Direction-Controllable Multi-joint Laparoscopic Surgical Instrument for Hepatopancreatobillary Surgeries

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1. Introduction

Minimally invasive surgery (MIS) is being a momentum in general surgery because of fast recovery time, cosmetic issues, and reduced surgical risk factors. Since Phillipe Mouret of France performed cholecystectomy successfully in 1987 and further NIH in USA approved it as a standard surgical technique, laparoscopic surgery has widely been recognized as an significant and popular method in many subspecialties in medicine. However, there are still some difficulties in vision and manipulation to avoid potential complications. Due to binocular disparity existing in a laparoscope with even current 3D imaging technique, surgeons have complained about eye fatigue, dizziness, and nausea after laparoscopic surgeries. Moreover, a limited vision field from rigid-type laparoscopes gives surgeons discomfort, and led medical device companies to develop flexible-type laparoscopes. Even for the laparoscopic surgical instruments such as graspers and dissectors, tiltable or direction-controllable devices providing more degrees of freedom make surgeon perform complex operative procedures through a few ports in a patient's body. With the advent of Natural Orifice Transluminal Endoscopic Surgery (NOTES), the demand for innovative tools as well as appropriate preoperative planning for the selection of access points has been increased. During laparoscopic surgery, most surgeons experience pain caused by awkward posture and high repetition because many laparoscopic instruments have rigid shafts and their handles are not comfortable to manipulate. These problems usually make it difficult to perform precise motions. Although several flexible-type laparoscopic instruments exists, their direction control mechanism mostly works by pulling guide wires and the change of their mechanical properties due to their repeated use will bring inaccurate control of direction. Robotic systems such as the ZEUS (Computer Motion, Goleta, Calif) and the da Vinci (Intuitive Surgical, Mountain View, Calif) provide sophisticated movements controlled remotely but they require additional space in the operation room and increased set-up time. Furthermore, multiple ports should be made on a patient undergoing surgery. This study presents a new multi-joint laparoscopic surgical instrument for hepatopancreatobillary surgeries. It consists of distal end, joints, and Shape Memory Alloy (SMA) springs with bias springs for direction control. The thermomechanical characteristics of SMA spring and its displacement were evaluated during thermal cycling, and also, accumulated temperature of SMA was analyzed when its displacement was fixed at a constant length. A grasper, scalpel, or retractor can be placed at the distal end, and its control mechanism is out of the range of this study.

2. Design of a Direction-controllable Laparoscopic Grasper and Experimental Setup

Shape Memory Alloy (SMA) has been widely used as active structures or acutators in many fields since it was first applied to aircraft in 1960. Especially in medical applications, SMA is used for medical stents, catheter, and screws. SMA has higher tensile strength and strain with longer fatigue life than piezoelectric, polymer, electrostatic, and magnetostrictive materials that present shape memory effect. In addition, SMA springs shows approximately 80% strain in the longitudinal direction, and so it is profitable to use a SMA spring actuator for the medical instrument whose motion demands large strain. Fig. 1 shows the diagram of the multi-joint laparoscopic instrument operated by SMA spring actuators and the experimental setup. In the experiment, a simplified experimental setup was made to evaluate the theromomechanical characteristics of a SMA spring with and without thermal cycling. A 6 mm SMA spring whose inner and outer diameters are 0.4 mm and 3.7 mm, respectively, was connected to the clamps, and a 10 mm bias spring with 4.2 mm diameter was linked to the one end of the SMA spring for the restoration of the original length.

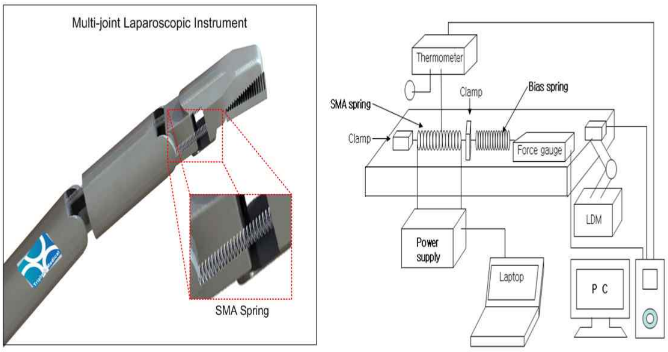
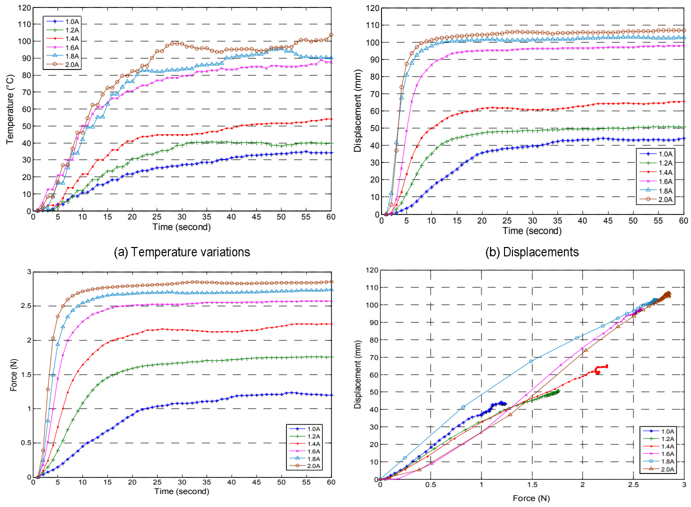


Fig. 1 A diagram of the Direction-controllable multi-joint laparoscopic surgical instrument and the experimental setup

3. Thermoelectrical characteristics of the SMA spring

First, a square wave current ranging from 1.0 A to 2.0 A with 0.2 A increase each was continuously applied to both ends of the SMA spring for 60 seconds so that the thermomechanical properties of the SMA spring were analyzed, and temperature and force variations of SMA were measured by a thermometer and a digital gauge, respectively. The displacement data of the SMA spring was collected using a laser displacement sensor. The strain rate of the SMA spring was overall proportional to the magnitude of induced current and the force variation showed a similar pattern to the temperature change (Fig. 2). In addition, the currents less than 1.6 A was not enough to achieve the length change (about 90 mm) within the expected time duration for the direction control. The temperature of the SMA spring accumulated for the duration showed slower response than other variables. During the thermal cycling test, 1.6 A current induced for 10 seconds and then the SMA spring was cooled down for another 20 seconds. 80 cycles in total were practiced and the hysteresis loop between displacement and force is shown in Fig. 3. The significant decrease of the displacement and force due to the thermal cycling was not observed after the second cycle but the size of hysteresis loop got smaller cycle by cycle. Thus, energy dissipation



(a) Temperature variations (b) Displacements

(c) Force variations (d) Force-displacement curve

Fig. 2 Variations of temperature, displacement, and force of SMA spring at constant currents

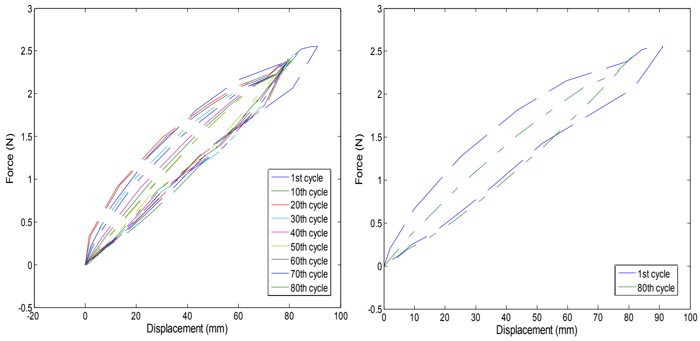


Fig. 3 Displacement-force curve of the SMA spring after thermal cycling (80 cycles)

rate was decreased gradually. The temperature accumulation in the SMA spring was 70°C in average (CV% = 3.8). It means that the heating and cooling time for the thermal cycling were appropriate so that another shape memory training could be avoided which might change the thermomechanical properties of SMA permanently. Wang et al. reported that the displacement of the SMA spring (Ti-49.8 Ni) was continuously decreased during 500 times of thermal cycling and also, the rapid change of the displacement was observed after the first cycle.

4. Direction Control by the SMA Actuator

The main factor that influences the direction control of the multi-joint laparoscopic instrument is of minimizing the displacement of the SMA spring at a specific length, and it can be achieved by reducing temperature variation of SMA. Since Macki et al. presented the hysteresis model in 1993, various methods based on phenomenological approaches or constitutive laws have been used to predict the hysteresis loop. The purpose of those studies was accurate control of SMA actuators mostly SMA wire-type actuators but the stability of the predicted models will not be guaranteed. Peng et al. suggested a simple and practical method for the motion control of SMA actuators. Two key variables which directly affect the displacement of SMA are an induced current and a cooling method. However, without consideration of a cooling device, the magnitude of current and the current inducing time rate are important factors. To maintain the initial displacement (about 75 mm) given by 1.6 A current induced for 10 seconds, the temperature rate and displacement rate of the SMA spring were calculated, and then programmed thermal cycling for 15 minutes was performed. The

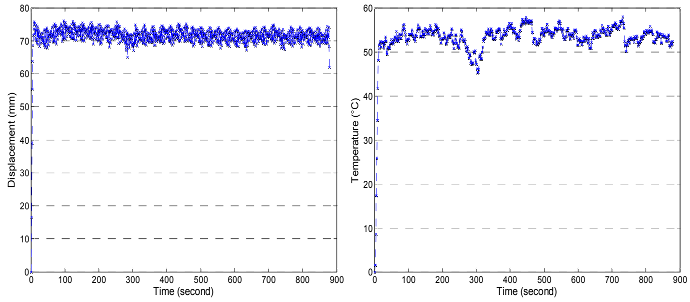


Fig. 4 Displacement and temperature change during the direction control of the SMA spring actuator

results are shown in Fig. 4. The mean displacement error was -4.18 mm (CV% 42.6) and the mean temperature error was 5.42°C (CV% 36.2).

5. Conclusion

The thermomechanical properties of the SMA spring actuator with thermal cycling has been evaluated and then applied to the direction control of the distal end of the multi-joint laparoscopic instrument. A further study is required to confirm the fatigue behavior of the SMA spring due to thermal cycling.

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