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Development of a Measurement System for Laparoendoscopic Single-Site Surgery: Reliability and Repeatability of Digital Image Correlation for Measurement of Surface Deformations in SILS Port

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ABSTRACT

Objective: Analysis of mechanical measurements in laparoendoscopic single-site surgery (LESS) is important for instrument design and surgical simulators. The aim of this study was to develop a measuring system for different instruments and manipulations in LESS using a single-incision laparoscopic surgery (SILS) port.

Methods: The loads on the SILS port were applied and recorded by the universal material testing machine by the following method. The handle of the forceps inserted in the SILS port was connected with the machine by a fishing wire and pulled at a constant rate. The surface deformations (displacements and strains) of the SILS port were recorded with digital image correlation (DIC) simultaneously. The correlation between deformation measurements and loads were analyzed. This experiment was repeated 8 times.

Results: Strong correlations existed between deformation measurements calculated by DIC and objective criteria "loads" applied and recorded by the universal material testing machine ($r > 0.98$). The correlation coefficients were statistically significant ($P < .001$). A high repeatability of the results appeared in all repetitions of the experiment.

Conclusions: A DIC measurement system has been developed for LESS, and comprehensive mechanical parameters of a SILS port can be obtained precisely by using this system. It is reliable and repeatable for evaluation of instruments and manipulations in LESS.

Key Words: Laparoendoscopic single-site surgery, Measurement system, Digital image correlation.

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INTRODUCTION

Since being introduced in 2007, laparoendoscopic single-site surgery (LESS) has rapidly gained popularity with surgeons as well as within the medical instrument manufacturing industry. Almost all traditional laparoscopic surgeries can be performed using the LESS approach, including surgeries for morbid obesity and liver, spleen, and gastrointestinal diseases.[1] However, the procedure is more difficult than traditional laparoscopic surgeries because of associated technical challenges including the crowding of the laparoscope and instruments around the umbilicus, the loss of triangulation between the 2 instruments in the operative field, and the required ambidexterity of the surgeons to adopt relatively difficult maneuvers.[2] To overcome these problems in LESS, new instruments and manipulations have been developed.[3,4] Although these improvements may seem beneficial, one important question remains: Do these improvements really benefit LESS?

Digital image correlation (DIC) is a relatively new strain measurement technique that uses a digital camera for continuous capturing of the surface of the samples during mechanical testing. The surface of the samples is covered with a random speckle pattern. A computer program compares the location of the ink dots in the speckle pattern that are captured in consecutive time points and calculates the displacement and strain fields all over the surface. Accuracies of up to 0.01 pixel are reported for DIC deformation measurement.[5] Except for a few studies,[6] DIC has not been widely used for full-field deformation measurement in the testing of soft tissues such as the SILS port. The surface deformations that can be measured of the SILS port are important for understanding its mechanism with different instruments and manipulations.

The aim of the current study was to evaluate the repeatability and reliability of the DIC measurement system by comparing surface deformations recorded using this proposed system with objective criteria "loads" applied and recorded by the universal material testing machine simultaneously. The results of the deformations measurement are used to further evaluate instruments and manipulations that have been developed for LESS and to find a better

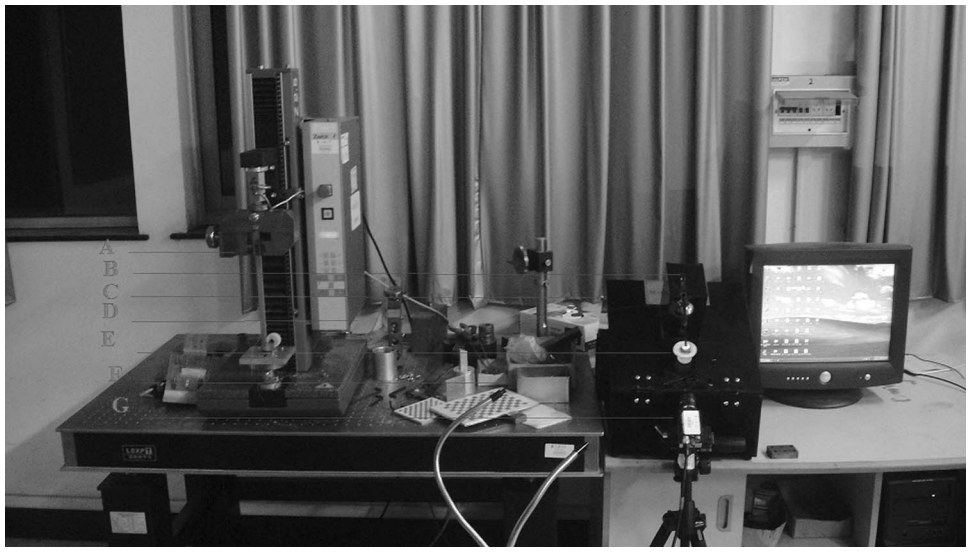

Figure 1. Mechanical test by the universal testing machine and DIC measurement test. A, Universal material testing machine; B, forcep; C, box trainer; D, fishing wire; E, SILS port; F, fiberoptic lights; G, camera.

improvement that can promote the development of LESS.

MATERIALS AND METHODS

Components of the Experiment

A straight forceps (Yida Medical Device Co. Ltd, Hangzhou, Zhejiang province, China) and a universal testing machine (BZ2.5/TSIS, Zwick GmbH, Ulm, Germany) were included in this study. The measurement system based on DIC was composed of a box trainer (Model 200, Ruihong Laboratory Equipment Co Ltd, Shanghai, China), a SILS Port (Covidien, Mansfield, Massachusetts), and a charge-coupled device camera type CV-A1 (Jai, Copenhagen, Denmark) (**Figure 1**).

Objective Criteria "Loads" Applied and Recorded by the Universal Material Testing Machine

The straight forceps was inserted in the SILS port. The universal testing machine was connected to the handle joint of the forceps by a fishing wire and was pulled 50 mm at a constant rate of 0.33 mm/s. Once the machine was started, it began to apply loads on the forceps, which physically disabled the surfaces of the SILS port. Throughout the tests, the universal testing machine and its associated software recorded the load-time curves.

Figure 2. SILS port with a white background and a red random speckle pattern.

Deformations Measurement Recorded with DIC

The anterior surfaces of the SILS port were tagged with spray paint for the DIC with a white background color and a red random speckle pattern (**Figure 2**).

When the universal material testing machine is pulling the forceps, the load applied on the SILS port will deform the port surface. The deformations were recorded by a charge-coupled device camera with a frame rate of 1 Hz. The camera created a stereo view of the surface from which the displacements and surface strains were calcu-

lated during the DIC program (Matfolt Co, Ltd, Shanghai, China) (**Figure 1**).

All of the experiments were repeated 8 times.

Statistical Analysis

A Pearson correlation analysis was conducted to investigate the relationship between deformation measurements calculated by DIC and objective criteria "loads" applied and recorded by the universal material testing machine.

All statistical analyses were conducted by using SPSS statistical software (version 15.0; SPSS, Inc., Armonk, New York). Statistical significance was set at $P < .05$.

RESULTS

Table 1 shows the results of the 8 experiments. The Pearson correlation coefficients between deformation measurements (displacements and strains) and loads were very high ($r > 0.98$, $P < .001$). Extremely similar repeatability results appeared in all repetitions of the procedure, as shown in **Table 1**. Because of the high similarity of the results, we chose one of the repetitions to visualize it in scatter diagrams (**Figures 3 to 5**).

DISCUSSION

As with most new surgical techniques, the early development of LESS was fraught with problems: a loss of triangulation, clashing of instruments and the instruments with the telescope and camera head, and a lack of maneuverability. New instruments and manipulations were developed by the pioneers to enable surgeons to overcome these difficulties. However, whether these improvements benefit LESS lacked an objective evaluation. There have been several studies that attempted to assess the benefit,[7,8] because the measurements were subjective indexes including the operation success rates, errors, etc, and they lacked definite and objective assessment criteria. We set up a contacting mechanical system to compare the articulating instruments and the cross-handed manipulation with conventional instruments. The study indicated that more force and time were needed by using cross-handed manipulation in LESS.[9] However, contacting mechanical components, such as the sensor or gauge used in the aforementioned studies, were vulnerable to external environmental interference during measurement. Therefore as a whole they cannot reflect more comprehensive mechanical changes.

Table 1.
The Pearson Correlation Analysis Between Deformation Measurements and Loads in all Repetitions of the Experiment

Repetition	r for Load and Strain	r for Load and Horizontal Displacement	r for Load and Vertical Displacement	*P* value
1	0.985	−0.983	0.985	< .001
2	0.989	−0.986	0.991	< .001
3	0.993	−0.990	0.994	< .001
4	0.991	−.0987	0.993	< .001
5	0.992	−0.990	0.994	< .001
6	0.990	−0.990	0.990	< .001
7	0.996	−0.993	0.996	< .001
8	0.998	−0.997	0.998	< .001

r, correlation coefficient.

DIC, an advanced noncontacting measurement system, has seen explosive growth in the past 2 decades. In recent years, the method has been modified and extended to encompass a large number of novel measurement systems. The term *digital image correlation* refers to the class of noncontacting methods that acquire images of an object, store images in digital form, and perform image analysis to extract full-field shape and deformation measurements. Within the broad field of image analysis, DIC is generally considered a subset of digital image registration techniques. The technique can be used to measure and observe the local mechanical behavior in natural and seminatural textures of different material such as metals, ceramics, and polymers.[10,11]

In this study, based on the DIC, we aimed to develop a reliable noncontacting mechanical measurement system to evaluate instruments and manipulations in LESS using the SILS port. According to the repeated experimental results of our study, 2 important conclusions can be drawn. First, the noncontacting mechanical measurement system based on DIC is proven to be reliable, because the measurement results show almost a perfect linear correlation with the objective criteria "loads." Second, an extreme similarity of the results appeared in all repetitions of the experiment, demonstrating the high repeatability of the measurement system.

The proposed system design has several advantages. It is suitable for use in experimental and clinical practice

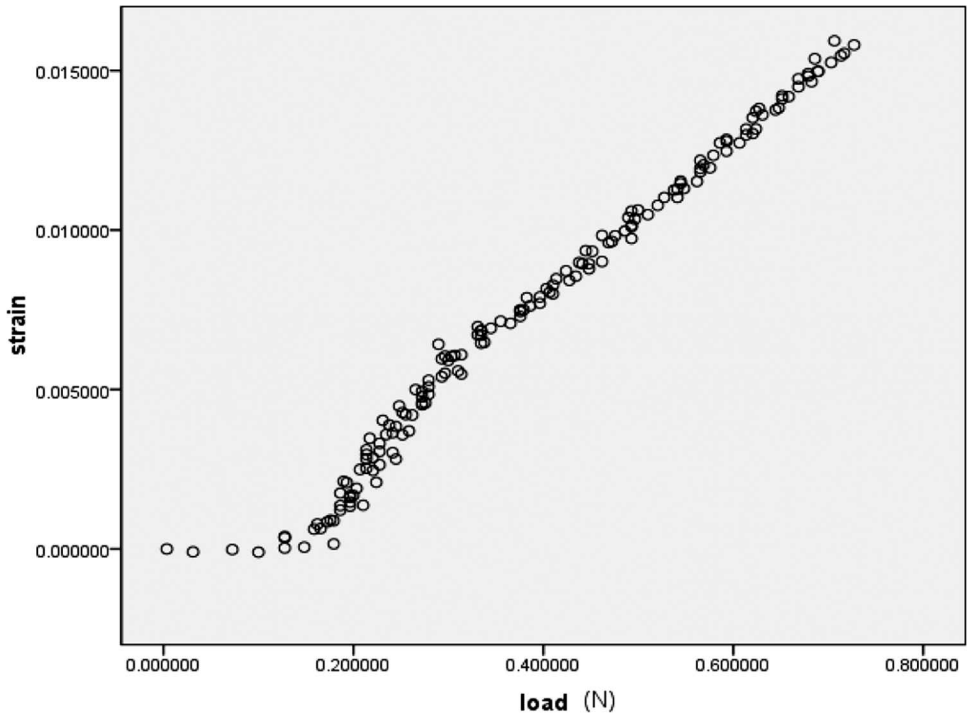

Figure 3. The linear correlation between load and strain.

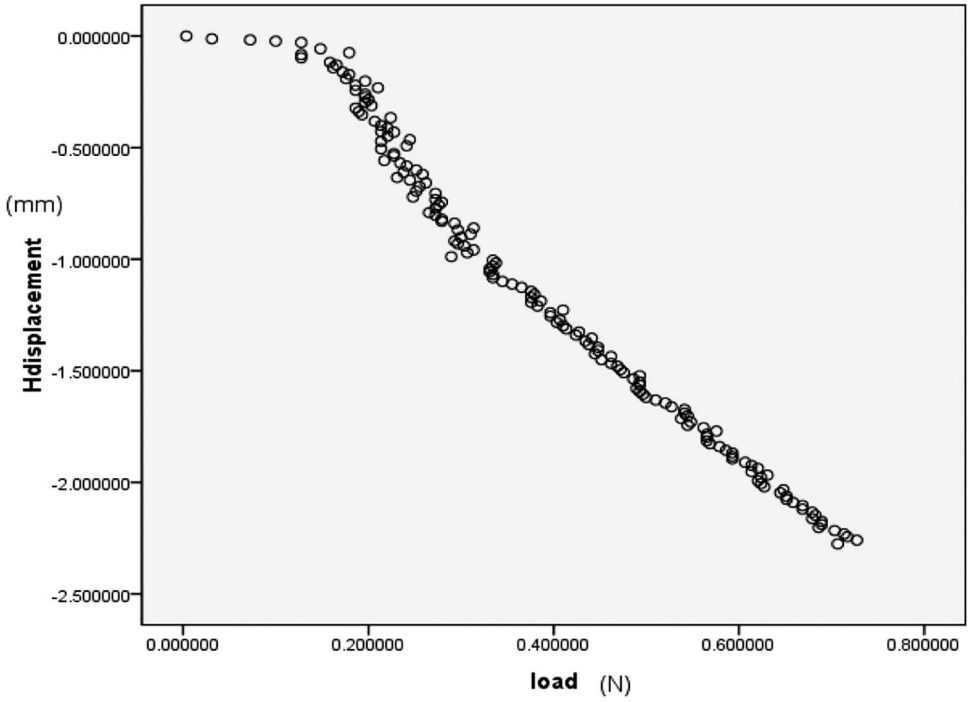

Figure 4. The linear correlation between load and horizontal displacement.

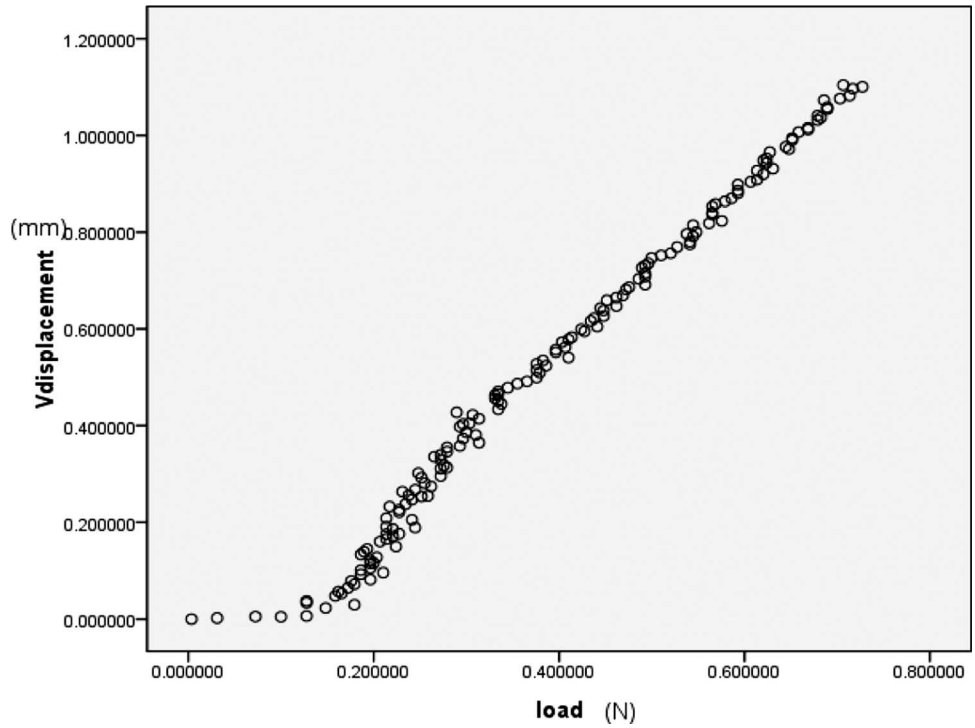

Figure 5. The linear correlation between load and vertical displacement.

because all its components are movable and isolated from the patient. No training or handling adjustments are required because all deformations are captured and analyzed by the camera and its attached software. It reflects more comprehensive and subtle mechanical changes than other measuring systems. Because of the system's high reliability and repeatability, there are several applications for the newly developed noncontacting mechanical measurement system. The objective and comprehensive measurements will provide a good feedback tool for evaluation of new instruments and manipulations in LESS. In addition, the system's use in experimental and clinic practice would help to refine movement and tissue handling in the teaching and training of LESS. Moreover, it can also be used to define force patterns incurred during certain surgical postures and the effect of muscle fatigue.

A limitation of the current study is that only the SILS port from Covidien was tested even though a wide variety of assessment devices for LESS have being produced by several companies. It would increase the practical value of this study to compare other assessment devices. However, because the DIC measuring system reflected the deformations of the assessment devices no matter which assessment device was used, the results should be similar to the present study. It is another limitation that we did not study whether these findings were transferable to performance on human tissue. Clinical validation studies will be pursued to determine the system's discriminatory ability as a diagnostic tool in clinical practice.

CONCLUSION

With the reliable and repeatable DIC mechanical measurement system, LESS will become more common because of the rapid advances in technology and the use of better instruments.

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