ORIGINAL ARTICLE

Computer Vision Distance Measurement from Endoscopic Sequences. Prospective Evaluation in Laparoscopic Ventral Hernia Repair.

Running head:

CV Distance Measurement from Endoscopy

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Abstract
Background Research in computer vision and mobile robotics has developed a family of popular algorithms known as Visual Simultaneous Localization And Mapping (Visual SLAM). These algorithms can provide 3D models of body cavities using the images obtained from standard monocular endoscopes. The 3D models can be used to estimate hernia defect measurements during Laparoscopic Ventral Hernia Repair (LVHR).
Methods We conducted a descriptive and comparative prospective study to analyze results from 15 patients who underwent LVHR. Three methods of measurement were used in each patient: two classical methods (needle and tape) and a new visual SLAM measurement (VSM) method. The major and minor axes of the ellipse-shaped hernia defect were measured.
Results Both axes could be measured using the VSM method in all patients except one (93%). The tape method measured 63% of the axes, but was difficult to perform because of patient comorbidities and because of limited range of motion of the laparoscopic tools. The needle method obtained 73% of measurements, because of patient comorbidities. The tape method was the most accurate (accuracy up to 0.5 cm because of tape resolution). The needle method was relatively inaccurate, with a mean error of >3 cm. The VSM method was as accurate as the tape method. The mean time taken to perform measurements was 40 s for the VSM method (range, 29–60 s), 169 s for the needle method (range, 66–300 s), and 186 s for the tape method (range, 110–322 s).
Conclusions The needle method is relatively inaccurate and invasive. The tape method is accurate, but is not easy to perform and is relatively time consuming. The VSM method is non-invasive and fast, and is as accurate as the tape method.

Keywords LVHR · Computer Vision · Visual SLAM · Hernia Defect Measurement

Ventral hernias may occur naturally or as a result of previous surgery (incisional hernias). The reported overall prevalence of ventral hernias ranges from 2% to 13% [1-3] for the incisional case being a common pathology confronted by surgeons.

Repair of a ventral hernia ideally involves placement of a prosthetic mesh in the preperitoneal subaponeurotic plane, in a tension-free manner with the edges well beyond the borders of the hernia defect. Uniformly distributed intra-abdominal pressure contributes to fixation of the mesh (Pascal's principle), reducing the risk of recurrence. Both open surgery with retromuscular mesh placement and laparoscopic surgery with intraperitoneal mesh placement can benefit from uniformly distributed intra-abdominal pressure (Fig. 1).

Historically, the most widely used surgical treatment for ventral hernias was the open retromuscular (Rives-Stoppa) repair procedure, which had the best outcomes for most incisional hernias and some primary ventral hernias. This procedure involves extensive parietal dissection and placement of a non-resorbable polypropylene or polyester mesh behind the posterior rectus fascia. Developments in biocompatible materials and endoscopic surgery [4] have enabled laparoscopic placement of bilaminar intraperitoneal prosthetic mesh, with minimal dissection. The mesh overlies the hernia defect and extends 3–5 cm beyond the borders of the defect [5, 6], and is fixed to the abdominal wall with tackers using the double-crown technique [7], or transfascial sutures, or a combination of these methods; an evaluative review of the fixation methods can be found in [6]. Primary closure of the hernia has good outcomes, but is technically complex [3, 8]. Recently, biological adhesives such as fibrin have been used to fix the prosthetic mesh in place [9]. However, there are still uncertainties in the laparoscopic technique regarding the optimal mesh type, mesh fixation method, and measurement of hernia defect size; and the incidence of seromas.

The laparoscopic ventral hernia repair (LVHR) technique offers the advantages of the laparoscopic approach, i.e., a short hospital stay, less postoperative pain, and fast postoperative recovery. The procedure carries an acceptable risk of complications, a low risk of recurrence, and an excellent cosmetic result. LVHR is considered to be a good alternative to open surgery, at least in experienced hands [8, 10].

The LVHR procedure is strongly based on the size of the hernia defect, but few studies have reported on methods of measuring the defect. We present a new computerized method of measuring the size of the hernia defect using endoscopic images: the Visual Simultaneous Localization And Mapping (Visual SLAM) measurement (VSM) method. We compared this method with two classical methods of measuring the size of the defect: 1) external measurement based on needle insertion, and 2) internal measurement using a tape measure.

The VSM method uses only a standard laparoscope and a standard computer. The method can be smoothly integrated into the LVHR procedure, to provide measurements that are as accurate as the classical methods but take less time and do not require insertion of needles or a tape measure into the abdominal cavity.

SLAM algorithms were originally developed for the field of mobile robotics. When a mobile robot enters a room for the first time, these algorithms enable the robot to exploit images gathered from its camera, while exploring the room, to recover a 3D model of the room and determine its exploratory trajectory. Medical endoscopic exploration mimics the robotic scenario: a hand-held camera (the endoscope) moves along an unknown trajectory while exploring a body cavity. Previous publications have reported on extensive research using SLAM algorithms to process monocular and stereo endoscopic images; nice reviews can be found in [11, 12].

The current study builds on our previous research. We previously used SLAM algorithms to process monocular medical endoscopic sequences in real time [13]. We also reported a proof-of-concept application of SLAM to measure the size of the hernia defect during LVHR [14]. Finally, we assessed the precision and the accuracy of the method from an engineering point of view in [15]. In the current study, we conducted a clinical validation of this technique during LVHR surgery. We were able to recover 3D models of the abdominal cavities by processing images obtained from standard monocular endoscope, without needing stereo endoscope. Unlike visual SLAM using stereo images, visual SLAM using monocular images provides an up-to-scale 3D model of the cavity. To compute the actual measurements of the defect, we defined the real scale of the 3D model using a laparoscopic tool with a known tip size.

Materials and Methods

Subjects

This descriptive and comparative prospective study analyzed data from 15 patients who underwent LVHR between April 2011 and July 2012. LVHR was performed with a bilaminar intraperitoneal tissue-separating mesh. The mesh was fixed in place using transfascial non-absorbable sutures at the four cardinal points (four vertices of the hernia), and the edges of the mesh were fixed using absorbable tackers according to the double-crown technique [7]. For each LVHR procedure, measurements were performed using three methods: the two classical methods (needle and tape) and the newly proposed VSM method. All intraoperative images were obtained using a standard monocular endoscope (Image 1, Karl Storz, Germany) and processed using a standard computer (Intel Core i7CPU, 2.93 GHz, 4 GB RAM).

The study protocol, including the documents for obtaining informed consent from patients, were approved by Comité Ético de Investigación Clínica de Aragón (CEICA) and were in accordance with the Spanish law 14/2007 regarding biomedical research.

Surgical procedure

Antibiotic and antithrombogenic prophylaxis were administered to all patients**.** Abdominal access was established. The edges of the parietal defect were drawn on the skin, guided by tactile localization. A pneumoperitoneum was created by inserting a Veress needle into the left upper quadrant. A pressure of 12 mmHg was used to safely separate the viscera from the abdominal wall. Three trocars were placed along a line as far as possible from the hernia defect: two 5-mm diameter working trocars, and a central 10-mm diameter trocar for the camera and for inserting the prosthetic mesh (Fig. 2). A camera with a direction of view angle of 30º or 45º was used to examine the anterior abdominal wall, particularly the areas around the trocars. The abdominal cavity was explored to locate the viscera, identify adhesions, and locate and evaluate all hernia defects. 13 patients had a defect in the central abdominal wall or the right flank, and in these patients the ports were placed in the left flank. 2 patients had a defect in the left flank, and in these patients the ports were placed in the right flank.

After creating the pneumoperitoneum, the fat and visceral adhesions were dissected from the hernia sac. Adhesiolysis was performed at the borders of the hernia defect to locate the edges of the intact abdominal wall. For adhesions close to the intestines, monopolar coagulation was avoided to prevent inadvertent perforation. Then, peritoneal fat was dissected around the defect to prepare the abdominal wall for the fixation of a prosthetic mesh.

To assess the size of the defect without enlarging the hernia, the pneumoperitoneum pressure was reduced to 8 mmHg. The two diameters of the defect were measured to determine the required size of the prosthetic mesh using the three measurement methods. First, four needles were placed through the abdominal wall under endoscopic guidance to determine the sizes of the two main axes of the defect, which was considered to be elliptical in shape; after correct insertion of the needles, an external tape measure was used to measure the distances between them (Figs. 3a, 3b) (video “02_ClassicalMethods.mpg”). Second, a sterilized tape measure was introduced into the abdominal cavity to measure the two axes of the defect (Fig. 3c) (video "02_ClassicalMethods.mpg"). Third, the defect was measured using the VSM method (video "03_VSM.mpg"); the surgeon fixed a forceps inside the abdominal cavity and moved the tip of the laparoscope in a cross-shape, keeping the tip of the forceps and the defect in the field of view (Fig. 4b); after the surgery was finished, the endoscopic sequence was processed to estimate the size of the defect (Fig. 4c); in the first image of the sequence, several points were marked: two predefined points on the forceps, whose relative distance was known, to define the scale, and five or more points at the borders of the defect to estimate the hernia contour and size (Fig. 4a).

The mesh was rolled along its major axis and grasped with forceps to insert it through the 10 mm trocar. Inside the abdominal cavity, the mesh was unrolled and oriented to cover the borders of the hernia defect. The mesh was fixed at the four cardinal points with non-absorbable monofilament sutures, and then fixed along the edges with tackers according to the double-crown technique, with 1 cm between tackers.

An abdominal compression bandage was applied postoperatively to prevent seroma. Oral ingestion was started after 8 hours and ambulation was started after 12 hours. Patients returned for a follow-up visit after 30 days.

The main steps of the whole LVHR procedure are summarized in the attached video "01_LVHR.mpg".

Results

We repaired ventral hernias in 15 patients (Fig. 5), including 9 females (60%) and 6 males (40%). The mean patient age was 42 years (range, 27–69 years). Ten patients (67%) had recurrent hernias and five (33%) had primary hernias. The mean operation time was 80 min (range, 40–120 min). Patient comorbidities included obesity (n = 9), hypertension (n = 7), smoking and alcoholism (n = 3), diabetes mellitus (n = 2), chronic obstructive pulmonary disease (n = 2), ischemic heart disease (n = 2), chronic renal failure (n = 1), and human immunodeficiency virus infection (n = 1). Six of the patients did not have any comorbidities. The size of the defect ranged from 1 × 2 cm to 4 × 7 cm. There were no cases of seroma, hematoma, relapse, infection, or other complications related to the prosthetic material.

Figs. 6a and 6b show the measurements obtained by the three methods: needles, tape, and VSM. The VSM method failed in one patient because of particularly poor image quality (Fig. 5o), but both axes could be measured using the VSM method in all the other patients (93%). Regarding needle and tape methods, 7 patients had extensive intra-abdominal adhesions whose laparoscopic adhesiolysis was very time-consuming. As these patients were classified as ASA III patients and suffered from intraoperative hemodynamic instability during anesthesia, only one of the two measurement methods was used in order to minimize the operation time; the tape method was applied in 4 patients (Figs. 5c, 5d, 5i, 5j) and the needle method was applied in 3 patients (Figs. 5l, 5m, 5n). The tape method was finally applied in 12 patients obtaining 19 out of 24 measurements (79%; 1 measurement per hernia defect axis), or 19 out of 30 measurements (63%) if all 15 patients are considered. The main reason for inability to perform all measurements was the difficulty of the procedure because of limited range of motion of the laparoscopic tools. Finally, the needle method was only used in 11 out of 15 patients (73%).

The accuracy of measurement methods was compared. The tape method was the most accurate (accuracy up to 0.5 cm because of tape resolution). The needle method was rather inaccurate, always resulting in an excessively large value (average excess of 3 cm). There were no significant differences between the VSM and tape methods, indicating that these methods are equally accurate.

Fig. 6c shows the time taken to perform measurements. VSM was the fastest method with a mean time of 40 s (range, 29–60 s). The needle method had a mean time of 169 s (range, 66–300 s). The tape method had a mean time of 186 s (range, 110–322 s); note that this mean time would be greater if all 24 measurements had been obtained.

Discussion

Compared with the traditional surgical methods of treating ventral hernias, LVHR in general and our VSM method in particular have irrefutable benefits, including accurate confirmation of the diagnosis and objective measurement of the hernia defect. These techniques can be used to identify and measure both the main defect and secondary defects, to ensure that the implanted mesh will cover all defects.

Use of VSM to perform measurements during LVHR minimizes the risk of infection, because VSM prevents exposure of the abdominal cavity to additional external instruments. Unlike the needle method, the VSM method does not cause injury to areas with scar tissue, and therefore does not expose the patient to the risk of contamination from areas of inflammation or microabscesses resulting from previous laparotomy.

Our study focused on perfecting a method of measuring the size of the hernia defect. To date, no significant assessment of measurement method has been reported in the literature. The needle method provides approximate measurements, but the measurements tend to be too large because the needles are not inserted perfectly perpendicularly. This method is also invasive and carries a risk of hemorrhage if a blood vessel is injured. The tape method is accurate but is difficult to perform and can be time consuming making the measurement unfeasible. The VSM method is non-invasive, fast, and accurate.

Traditional endoscopic surgery displays and disposes of the image sequence. However, visual SLAM, with the addition of an exploratory maneuver, can use the image sequence to estimate measurements. This study represents the first human *in vivo* experimental validation of the feasibility of using SLAM with endoscopic images obtained during surgery. The 15 patients studied showed variability in terms of textures, illumination, port placement, and exploratory trajectories. In spite of this variability, all the image sequences could be processed using our visual SLAM method, indicating that this method is useful in a variety of situations.

We are interested in extending this method to other surgical procedures such as flexible endoscopy and thoracoscopy. This method may also be useful for intra-abdominal measurements of organs such as the spleen or adrenal glands, to determine the required size of the extraction ports.

Our measurement method can be smoothly incorporated into the workflow during LVHR because it uses standard endoscope images and the surgeon only needs to perform the cross-shaped motion. Unlike the other methods assessed, no additional tape measure or needles are necessary, which simplifies the workflow. Our system was able to obtain accurate measurements. The system can be extended to support augmented reality insertions, to guide the surgeon during alignment of the prosthesis with respect to the border of the hernia defect and increase the ease of the procedure. Augmented reality insertions may also be used to display preoperative information to provide assistance during the procedure.

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Disclosures

Ernesto Bernal, Santiago Casado, Óscar G. Grasa, J.M.M. Montiel and Ismael Gil have no conflicts of interest or financial ties to disclose.

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<u>FIGURE CAPTIONS</u>:

Fig. 1 Intra-abdominal pressure helps to secure the prosthetic mesh in the intraperitoneal sublay position to the abdominal wall

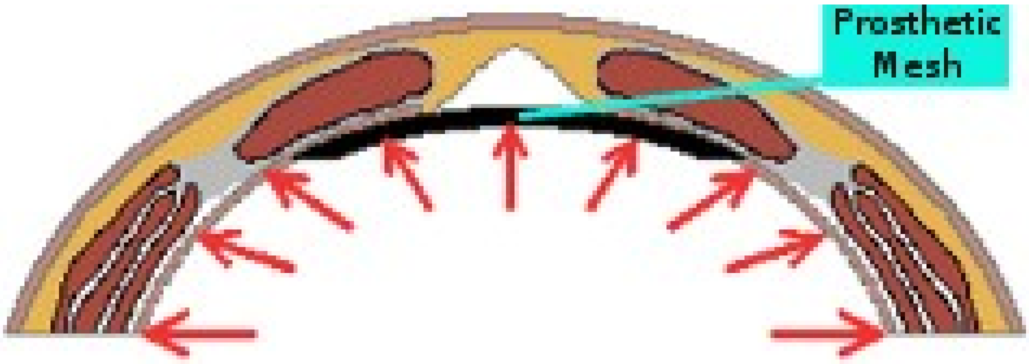
Fig. 2 Trocar locations in the left flank

Fig. 3 (a, b) Needle insertion method. (a) Internal view of the needles at the borders of the defect. (b) External measurement between the needle insertion points. (c) Tape measure method, with direct internal measurement of the defect

Fig. 4 (a) Two points on the forceps were used to define the scale (crosses), and five or more points were marked at the borders of the hernia defect, in an elliptical shape (dots). (b) Cross-shaped movement of the tip of the endoscope. (c) Visual SLAM measurement

Fig. 5 Images of all 15 cases

Fig. 6 (a, b) Measurements of hernia defect size using the three different methods. Use of the tape obtained 63% of the total measurements, use of the needle obtained 73%, and use of VSM obtained 93%. Measurement using the tape is considered to be the most accurate. Measurement using VSM was found to be as accurate as measurement using the tape, but measurement using the needle was significantly less accurate. (c) Time taken to perform measurements using the different methods. The VSM method was the fastest



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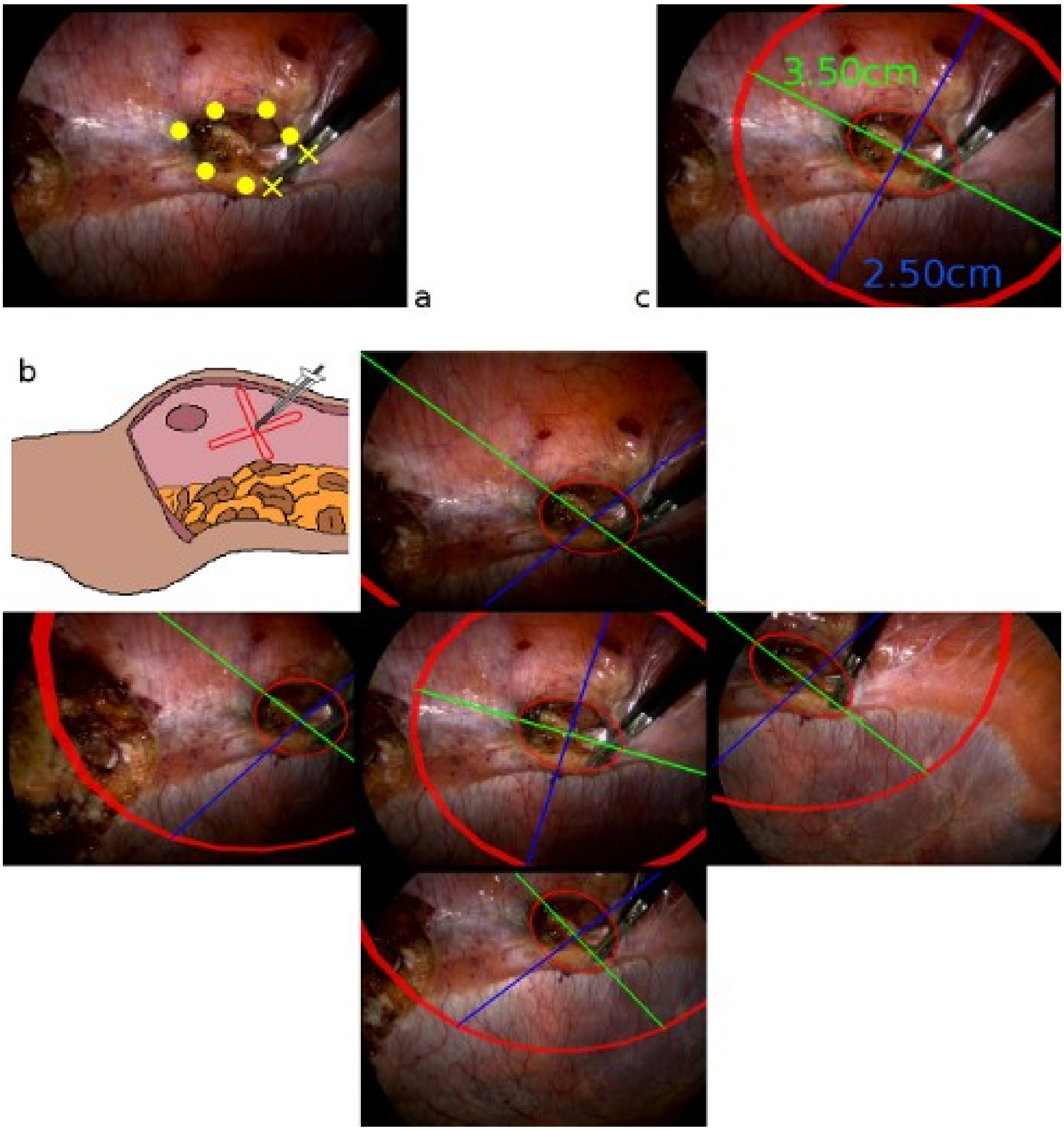

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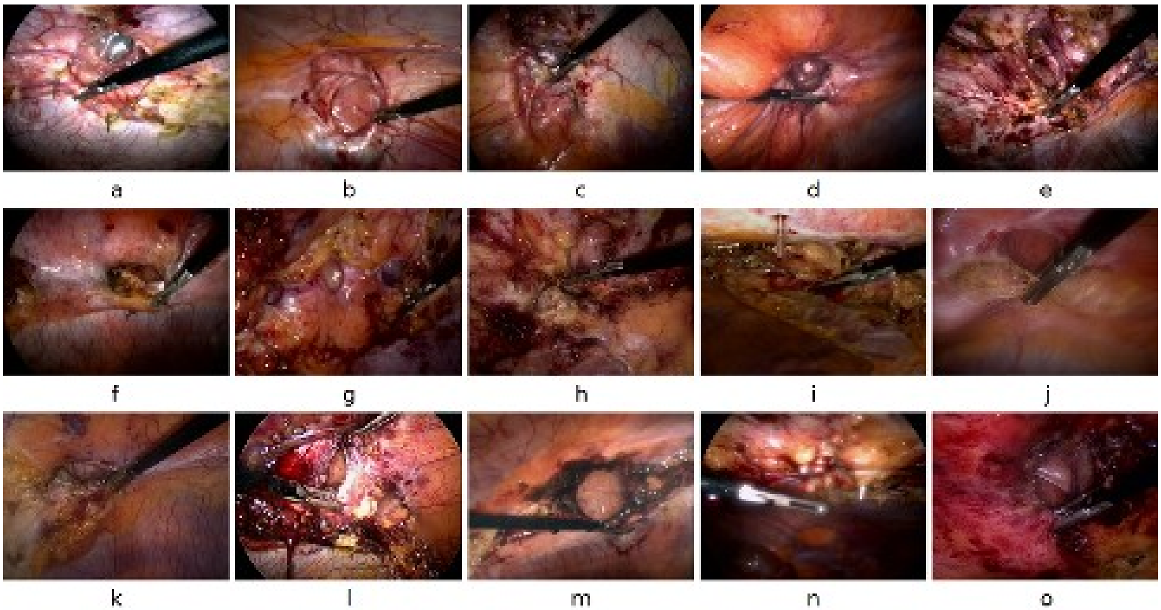

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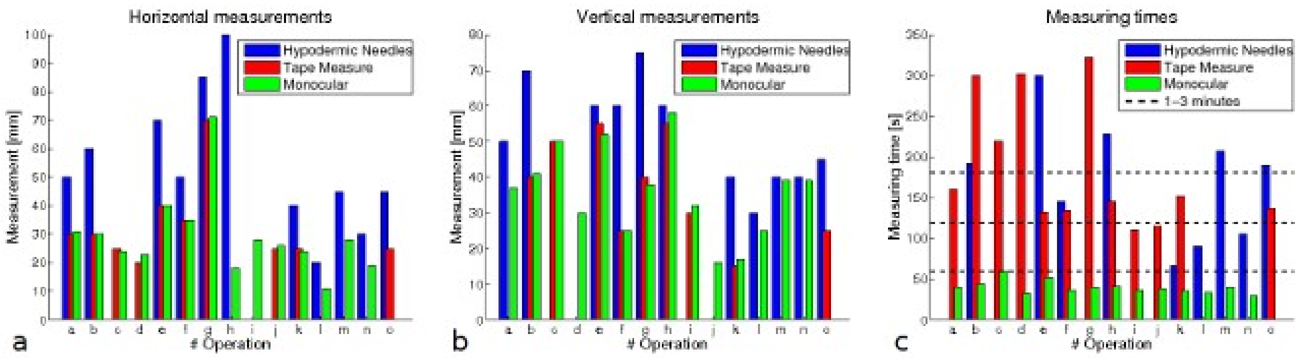

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