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INTRODUCTION

Tube thoracostomy (TT), where a tube is placed between the lungs and the chest wall to drain air and/or fluids introduced by injury or disease, is a crucial procedure with both routine and emergent applications. It has high complication rates (up to 37.9%) [1], particularly for residents [2] and emergency physicians [3]. Inadvertent tissue punctures during insertion can cause severe complications, including rare immediate fatality [4]. We propose semi-automating TT tool insertion, as merging the accurate haptic sensing capabilities of a medical robot with the dexterity and perspicacity of a physician could help protect against non-target tissue puncture. To avoid insertional complications, operators must a) position and b) orient tools correctly, and must c) halt insertion immediately upon breaching the parietal pleural membrane. We focus here on preliminaries required for c) and leave a) and b) to future work. We report a prototype sensorized needle-insertion device named NID0 that records manual tool-tissue interactions with *ex vivo* porcine ribs, a realistic tissue phantom for TT [5], from contact to puncture of the parietal pleura. The acquired dataset showcases tissue characteristics and informs future puncture detection algorithms.

MATERIALS AND METHODS

NID0 combines a linear stage (DDS300-E/M with BBD201 controller from Thorlabs, USA) with a six-axis force/torque sensor (Mini40 with amplifier from ATI, USA), a three-axis accelerometer (EVAL-ADXL354BZ from Analog Devices, USA), two cameras (C922s from Logitech, Switzerland), and a custom tissue mount. Data are collected via a multifunction I/O device (USB-6215 from National Instruments, USA) communicating with QUARC real-time control software (Quanser, Canada) in Simulink 9.1 (Mathworks, USA) on a desktop PC (Zoostorm with i5-6400 processor). The two audio/video streams are recorded simultaneously at 60 frames per second via OBS Studio (H. Bailey and OBS Project contributors) on a laptop (Dell Latitude with i7-6600U processor). Both computers use Windows 10. Figure 1 (a) depicts NID0's system-level design, while Fig. 1 (b) shows the physical apparatus in use.

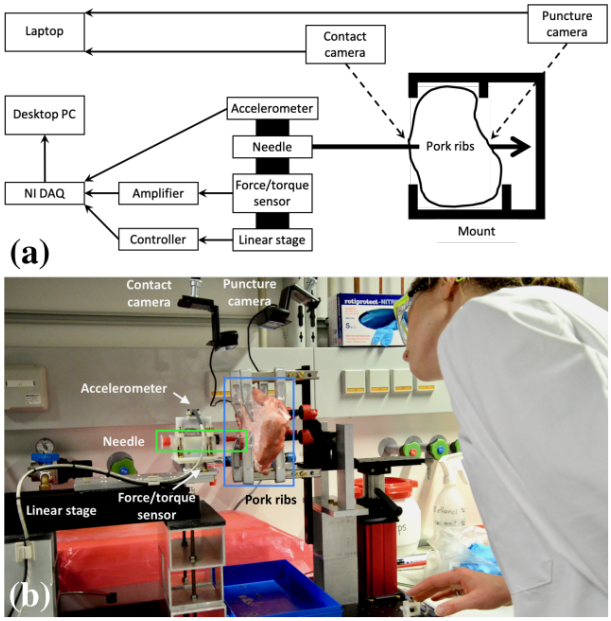

Fig. 1 (a) Block diagram of the system. (b) NID0 being used to collect *ex vivo* insertion data.

Operators manually advance the stage carriage such that a bevel-tip 9 cm, 18G needle (Cook Medical, USA) contacts and punctures intercostal spaces within fresh, room-temperature, commercially available pork ribs. Rib sections are secured at four corners in the custom mount, which positions the ribs perpendicularly to the needle-insertion axis and allows for natural intercostal tissue displacement in response to needle forces. Manual taps on the NID0 frame synchronize the audio/video streams with their data counterparts during each trial. An author manually labels contact and puncture events in trial videos, and post-processing scripts in Matlab r2020a (Mathworks, USA) map event labels to data streams.

TABLE I Mean and standard deviation of insertion force, velocity, penetration depth, and duration for all trials.

Collection	n	Mean Force [N]	Maximum Force [N]	Mean Velocity [mm/s]	Maximum Velocity [mm/s]	Penetration Depth [mm]	Duration [s]
Session 1	28	1.8 ± 0.5	3.3 ± 1.3	18.9 ± 6.0	81.1 ± 23.8	33.7 ± 10.2	2.3 ± 0.7
Session 2	17	2.0 ± 0.8	4.1 ± 1.7	29.3 ± 9.1	92.0 ± 39.3	38.5 ± 3.2	1.8 ± 0.5
Session 3	18	0.5 ± 0.1	1.0 ± 0.2	22.5 ± 6.4	54.6 ± 13.3	19.0 ± 2.3	1.5 ± 0.5
All sessions	63	1.5 ± 0.8	2.9 ± 1.7	22.7 ± 8.2	76.5 ± 30.1	30.8 ± 10.5	1.9 ± 0.7

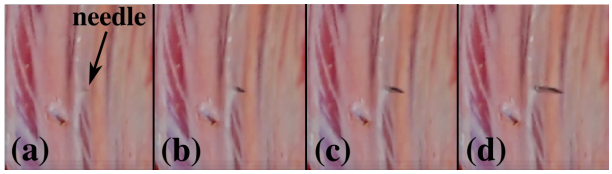

Fig. 2 The needle ruptures the pleural membrane in stages: (a) membrane displacement, (b) tip perforation, (c) bevel emanation, and (d) full needle penetration.

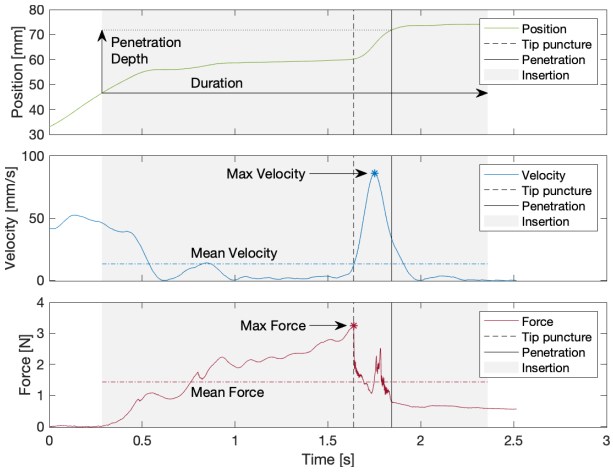

Fig. 3 Position, velocity, and force during a typical Session 1 trial, with forward (gray) needle motion and metrics labeled.

Basic statistical measures are extracted and analyzed in Minitab 21 (Minitab Inc., USA).

RESULTS

Non-medical operators performed 63 manual insertions across three sessions, where each session had its own tissue sample. Visible membrane rupture occurs in stages (Fig. 2); we define puncture as needle tip perforation because it provides the most reliable force signature. Generally it presents as the first rapid decrease in force (dashed line in Fig. 3) and can accompany both increasing and decreasing needle velocity due to the manual nature of insertions. Tissue inhomogeneity can yield a region characterized by one or more rapid force decreases between tip puncture and full needle penetration, i.e., between dashed and solid vertical lines. Table I lists mean and max force, mean and max velocity, penetration depth, and duration within sessions and overall. Table II contains the results of a three-way analysis of variance, which identifies sessions as a statistically significant factor affecting maximum insertion force.

TABLE II Analysis of variance (ANOVA) for maximum insertion force, $\alpha = 0.05$.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Session	2	20.8	10.4	7.47	0.001
Mean Velocity	1	0.1	0.1	0.05	0.820
Max Velocity	1	2.9	2.9	2.06	0.157

DISCUSSION

We present a sensorized data-collection device and apply it to a critical step in tube thoracostomy using an *ex vivo* model. We report the haptic response of the parietal pleura, which is poorly documented in the literature. Metrics varied significantly across sessions due to the different tissue samples employed, matching anecdotal physician reports of high inter-patient variability. The identified force maximums will inform future tissue phantom and robot designs, and patterns visible in the data will be used to develop real-time methods for pleural membrane puncture identification. Tissue variation due to the time interval between harvesting and experimentation is a limitation of this work. Furthermore, it is important to consider live pleura with respiratory rhythm and pulsatile blood flow, versus an *ex vivo* model such as this. Next steps include automating needle insertion to enable consistent tissue characterization and analyzing how a wider range of factors affect puncture force.

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