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DESIGN OF AN ULTRASOUND PROBE HOLDER TO MINIMIZE MOTION ARTIFACT DURING SONOGRAPHY

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ABSTRACT

Standard diagnostic ultrasound imaging procedures heavily rely on a sonographer for image acquisition. Given the ultrasound probe is manually manipulated by the sonographer, there is a potential for noise artifacts like blurry acquired images caused by involuntary hand movements. Certain surgical procedures can also cause patients to exhibit involuntary "jumping" movements while on the operating table leading to further deterioration in ultrasound image quality. In this study, we attempt to mitigate these problems by fabricating a 3D-printed ultrasound probe holder. Due to the lightweight nature of the device, it can attach to surgical retractors without influencing the functionality of the retractor. Therefore, the 3D printed probe holder not only reduces relative motion between the probe and the patient, but also reduce the need for a sonographer during complex surgeries.

Keywords: Neurosurgery, neurological imaging, functional imaging, intraoperative imaging, ultrasound, probe-holder, 3D printing

NOMENCLATURE

FEA	Finite Element Analysis
CAD	Computer-Aided Design
3D	Three Dimensional

1. INTRODUCTION

Ultrasound is a non-ionizing and portable imaging modality that is widely used for intraoperative imaging [1]. Ultrasound imaging typically involves a sonographer holding an ultrasound probe in place while images are acquired. This could result in blurry images due to hand-motion artifacts, especially as a result of fatigue during long durations of image acquisition [2-5]. Additionally, some surgical procedures can cause involuntary patient reflexes during ultrasound image acquisition. For example, during surgical procedures that induce spinal cord injuries in porcine models, a weight is dropped on the spinal cord. For this procedure, an ultrasound probe is held by hand over the spinal cord to constantly image spinal cord blood flow and perfusion. Once the weight hits the spinal cord, the animal involuntarily jumps, and the spine can push against the ultrasound probe, resulting in reduced image quality [6]. There have been some reports of using robotic arms with end-effectors to hold the ultrasound probe in place and reduce issues due to image quality caused by motion artifacts [7]. However, these robotic systems are expensive, and do not prevent the relative

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motion between the patient and the probe especially during involuntary patient reflexes [8].

FIGURE 1: SURGERY FOR SPINAL CORD INJURY STUDIES: (A) THE SURGICAL FIELD, (B) A SONOGRAPHER IMAGING THE SPINAL CORD

Here, we describe the development of a new ultrasound probe holder that reduces all potential sources of motion artifact during image acquisition while also minimizing cost and having a small footprint. The probe holder was designed to be mounted to a surgical retractor within the sterile field, and as a result, needed to be fabricated using biocompatible materials. The probe holder design was validated using finite element analysis, therefore ensuring structural integrity during use.

2. MATERIALS AND METHODS

In order to reduce motion between the probe and the region being imaged, the holder was designed to attach to the subject being imaged. The hypothetical attachment site would be a surgical retractor, which is typically used to keep the surgical field open. The device consists of a probe clamp to hold the probe, a flexible gooseneck that allows the probe to be moved around to different regions of interest, and a base clamp that can be used to mount the probe holder to the patient.

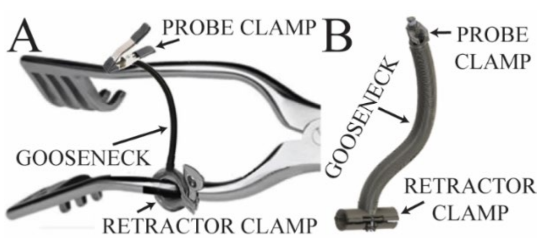

FIGURE 2: DESIGN OF THE PROBE HOLDER: (A) ANIMATED ON A SURGICAL RETRACTOR (B) CAD MODEL OF THE PROBE HOLDER

2.1 Finite element analysis of a simplified probe holder design

A simplified version of the probe holder shown in Figure 2 was first statically loaded, and then simulated using finite element analysis (FEA). FEA is a computational tool commonly used for structural analysis that models how an object would respond to certain forces. These include the stress experienced by an object in response to the applied forces given certain boundary conditions. The object is initially covered in points, commonly called nodes, which are connected by a mesh. Given the interconnected nature of the mesh, mathematical equations can be used to relate the stress experienced at one node to the stress experienced at another node. The algorithm then integrates all of these individual behaviors to produce the overall behavior of the simulated object. The FEA analysis was performed to ensure the probe holder can bear the weight of the probe without causing stress on the holder which may cause it to break. For the finite element analysis (FEA), the probe holder designed in Figure 2 was simplified to the CAD model seen in Figure 3. This simplification allowed for no complications in running the FEA while not undermining the fundamental design of the probe holder. The model parameters are given in Table 1. The gooseneck in the model was assumed to be rigid in its deformed state with the retractor clamp rigidly fixed on its inner edges. Two separate forces of 0.5 N and 2N were applied on the inner edges of the probe clamp along the negative z-axis. These two forces approximately cover the weight range of the Canon Aplio i800 system probes, one of which was used in this study.

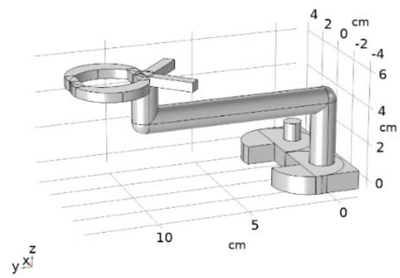

FIGURE 3: CAD MODEL OF THE SIMPLIFIED PROBE HOLDER USED FOR FINITE ELEMENT ANALYSIS

TABLE 1: PARAMETERS FOR THE FEA MODEL

Component	Parameters	Value
Retractor Clamp	Minimum Inner Width	4cm
	Material Young's Modulus Poisson's Ratio	Acrylic Plastic $3.2x10^9$ Pa 0.35
Gooseneck	Diameter	0.7cm
	Reach	10cm
	Material Young's Modulus Poisson's Ratio	Steel AISI 4340 $20x10^9$ Pa 0.28
Probe Clamp	Minimum Inner Diameter	2cm
	Material Young's Modulus Poisson's Ratio	Acrylic Plastic $3.2x10^9$ Pa 0.35
Model Mesh	Maximum Element Size Minimum Element Size	1.22 cm 0.153cm

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2.2 Design using commercial off-the-shelf (COTS) components

The design was assembled using COTS components described in Table 2. The i33LX9 probe of the Canon Aplio i800 system was affixed to the holder. The assembled probe holder is shown in Figure 4B and 4C holding the Canon Aplio ultrasound probe.

TABLE 2: PARAMETERS OF THE COTS COMPONENTS

Component	Parameters	Value
Retractor Clamp 	Minimum Opening Diameter	9 mm
	Maximum Opening Diameter	50 mm
	Weight	159g
	Material	Aluminum and Metal
Gooseneck 	Length	13 inches
	Weight	472g
Probe Clamp 	Jaw Opening	2.76 inches
	In-throat Depth	2.17 inches
	Weight	120g
	Material	Metal

2.3 Validating the efficacy of the proposed probe holder

To validate the need for such a probe holder, a series of systematic tests were conducted. The goal of these tests was to image the forearm and analyze the motion artifact if any.
The following three tests were performed:

(i) Imaging the forearm with a handheld ultrasound probe (Figure 4A).

(ii) Imaging the forearm with an ultrasound probe held by the holder attached to a test bench (Figure 4B).

(iii) Imaging the forearm with an ultrasound probe held by the proposed probe holder assembled using COTS components (Figure 4C).

In these tests, the forearm was placed on the table. The i33LX8 probe was used to acquire the ultrasound images. The image acquisition frequency, imaging depth, and gain were kept constant. The forearm was first kept stationary, and then moved in a manner similar to the "jump" of pigs during spinal cord injury procedures. To monitor the motion of the area on the forearm being imaged, an accelerometer (MMA8452) was mounted near the imaged region. The arm was moved to imitate the "jump" of pigs when needed and movement was confirmed using the accelerometer. The images acquired in all of these tests were assessed for image quality. The images were then compared to the time-stamped motion of the imaged region as recorded by the accelerometer (using the Arduino IDE).

FIGURE 4: IMAGING THE FOREARM WITH THE ULTRASOUND PROBE (A) HELD BY HAND, (B) HELD IN PLACE BY A HOLDER ATTACHED TO THE TABLE, (C) HELD BY THE PROPOSED PROBE HOLDER

3. RESULTS AND DISCUSSION

The FEA results indicate that the gooseneck bore most of the applied load (colored red in Figures 5 and 6). Given our assumptions of a rigid connecting structure, this is reasonable

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since the other parts are either lower in mass or are securely attached to the gooseneck. In both cases, i.e minimum and maximum load, the stress experienced by all the parts were lower than their material's corresponding yield strength [9,10].

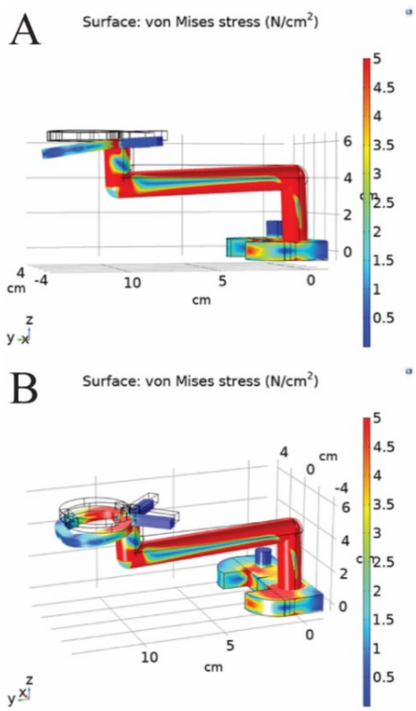

FIGURE 5: FEA FOR THE 0.5N DOWNWARDS FORCE

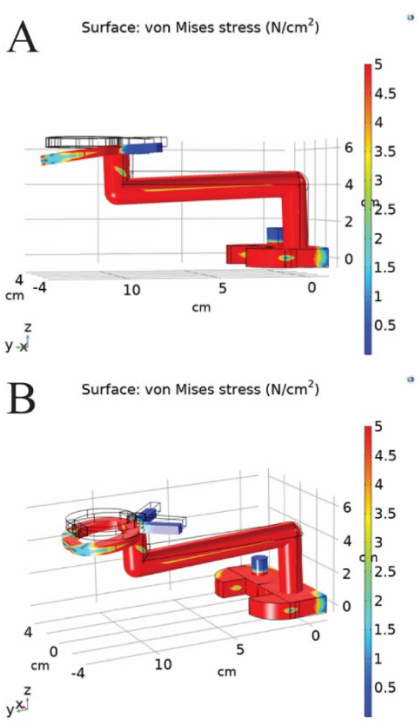

FIGURE 6: FEA FOR THE 2.0 N DOWNWARDS FORCE

After FEA was performed on the proposed probe holder, the assembled prototype was subjected to three tests to validate the efficacy of the probe holder in terms of minimizing motion artifacts during imaging. For each of the three tests, two images were taken, one before the arm was moved in a sudden upward motion, and one after. When the ultrasound probe was held by hand, a blurred image was seen when the hand was moved in a sudden upward motion (Figure 7B). Similar image quality was obtained when the probe is held by the holder fixed to the table (Figure 8B). However, when the proposed probe holder was attached to the arm itself, the image quality was clear (Figure 9B). By attaching the proposed holder to the arm, the relative motion between the probe and area being imaged was eliminated. Therefore, in this proof-of-concept experiment, the proposed probe holder was successful in obtaining a clear image despite the motion of the forearm.

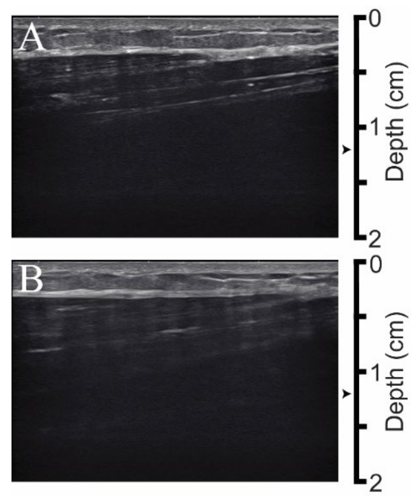

FIGURE 7: PROBE HELD MANUALLY AND(A) IMAGED BEFORE ARM MOTION, (B) IMAGED AFTER ARM MOTION

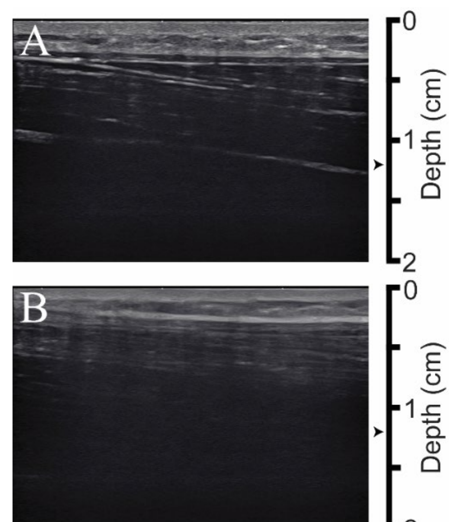

FIGURE 8: PROBE HOLDER CLAMPED TO TABLE (A) IMAGED BEFORE ARM MOTION, (B) IMAGED AFTER ARM MOTION

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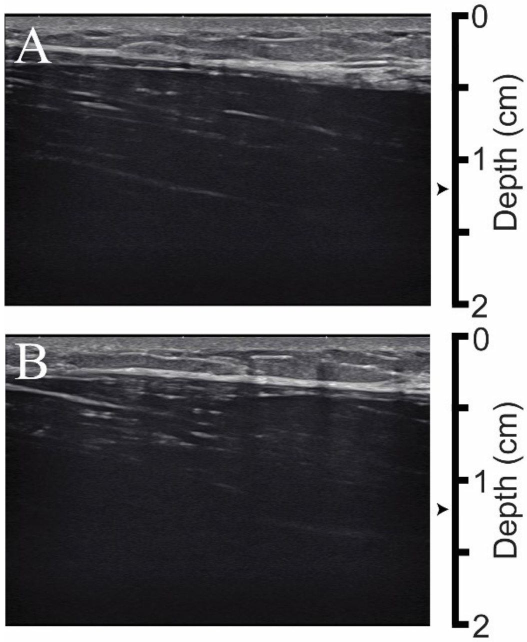

FIGURE 9: PROBE HOLDER HELD BY INDIVIDUAL RUNNING THE TEST (A) IMAGED BEFORE ARM MOTION, (B) IMAGED AFTER ARM MOTION

The COTS model weighed 1251 grams. When attached to a sturdy surface, it held the three ultrasound probes securely, with negligible movement. Despite its weight, the COTS model is a good candidate for standard ultrasound procedures, wherein relative motion is insignificant, and the holder can be attached to a table or fixture beside the operating table. The COTS model, however, could not maintain its position when attached to a retractor in a mock-surgery setup (Fig 10). The extended gooseneck-probe setup exerts a torque on the retractor, thus rendering the system unstable about its center of mass.

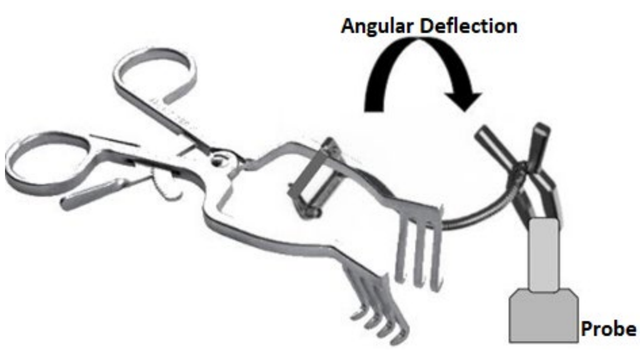

FIGURE 10: DEFORMATION DUE TO TORQUE (NOT TO SCALE)

To reduce the torque, and in turn, the weight of the model, we performed an analysis with four possible 3D printable materials: PA 2200, LOCTITE 3D 5015, LOCTITE 3D 5010, and MED 610. These materials were chosen based on their structural properties and biocompatibility. The densities of these materials are listed in Table 3. A 3D model of the COTS probe holder was developed for 3D printing using Fusion 360. Finally, volumes of individual parts were obtained using the 'Properties' option in the design workspace. Table 4 shows the weight of the model using the above materials and compares it with steel (factor = [mass_steel]/[mass_material]).

TABLE 3: DENSITIES OF THE MATERIALS FOR 3D PRINTING

Material	Density (g/cc)
Steel	8.05
PA 2200	0.93
LOCTITE® 3D 5015	0.99
LOCTITE® 3D 5010	0.99
MED610	1.18

TABLE 4: WEIGHTS OF THE DIFFERENT MODELS

Part	Vol (cc)	Mass steel (g)	Mass PA 2200 (g)	Mass LOCTITE® 3D 5015 (g)	Mass LOCTITE® 3D 5010 (g)	Mass MED610 (g)
Clamp	105.73	851.09	98.32	104.67	104.67	124.76
Neck	51.32	413.13	47.73	50.81	50.81	60.56
Base	21.79	175.39	20.26	21.57	21.57	25.71
Total	178.83	**1439.60**	**166.31**	**177.04**	**177.04**	**211.02**
Factor			8.66	8.13	8.13	6.82

The 3D printed model is at least 6.8 times lighter than its steel equivalent. At 211 grams, this holder will exert minimal torque on the retractor while holding the probe in place. The significant weight reduction and compact design make 3D- printing an attractive option for this probe holder.

We aim to finalize our CAD design and print it using the most suitable of the previously mentioned plastics. This will be determined by the force exerted on the retractor and the ability of the gooseneck to not deform while holding the probe. Next, we will conduct benchtop trials with the holder and surgical retractors. We will also assess user-friendliness and preferences with the help of neurosurgery residents. Upon successful completion, we will then use the holder during porcine surgeries.

4. CONCLUSION

In this study, we presented an ultrasound probe holder design that can be mounted on the patient, and therefore be used to improve image quality by reducing the blur associated with the motion of the ultrasound probe. Different avenues to fabricate this probe holder were pursued. Due to its superiority in terms of weight, a proof-of-concept 3D printed, light-weight ultrasound probe holder is designed and proposed.

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