Tracked ultrasound calibration studies with a phantom made of LEGO® bricks

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ABSTRACT

PURPOSE: In this study, spatial calibration of tracked ultrasound was compared by using a calibration phantom made of LEGO® bricks and two 3-D printed N-wire phantoms. **METHODS:** The accuracy and variance of calibrations were compared under a variety of operating conditions. Twenty trials were performed using an electromagnetic tracking device with a linear probe and three trials were performed using varied probes, varied tracking devices and the three aforementioned phantoms. The accuracy and variance of spatial calibrations found through the standard deviation and error of the 3-D image reprojection were used to compare the calibrations produced from the phantoms. **RESULTS:** This study found no significant difference between the measured variables of the calibrations. The average standard deviation of multiple 3-D image reprojections with the highest performing printed phantom and those from the phantom made of LEGO® bricks differed by 0.05 mm and the error of the reprojections differed by 0.13 mm. **CONCLUSION:** Given that the phantom made of LEGO® bricks is significantly less expensive, more readily available, and more easily modified than precision-machined N-wire phantoms, it prompts to be a viable calibration tool especially for quick laboratory research and proof of concept implementations of tracked ultrasound navigation.

Keywords: Tracked ultrasound, calibration, phantom. N-wire phantom

1. INTRODUCTION

Real-time tracked ultrasound imaging is a non-invasive and safe approach to facilitate needle-based interventions such as biopsy, drug delivery and surgical ablation. These procedures require a degree of accuracy maintained by an accurate and consistent spatial and temporal calibration that relates the image pixels of the ultrasound to the coordinate system of the tracked probe.

An object of known geometry (calibration phantom) is frequently used for spatial calibration of tracked ultrasound probes (Mercier *et al.* 2005). One family of phantoms, the so called N-wire phantoms (Chen *et al.* 2009, Carbajal *et al.* 2013), have a rigid structure that typically supports a wire configuration of known position within the coordinate system of the phantom. The ultrasound beam intersects with each N motif of the phantom in three locations. Because the relative position of the N motifs are known and because the position of the ultrasound probe is tracked, the spatial orientation of the ultrasound image can be found. Through this method of calibration, the spatial calibration is obtained for every degree of freedom of the ultrasound probe.

The N-wire configuration is achieved by placing three wires in an "N" pattern parallel to each other across the center of the phantom, such as shown in Figure 1 and 2.

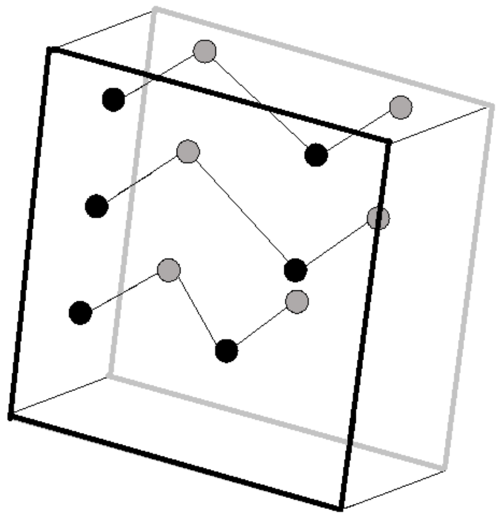

Figure 1. N-wire configuration.

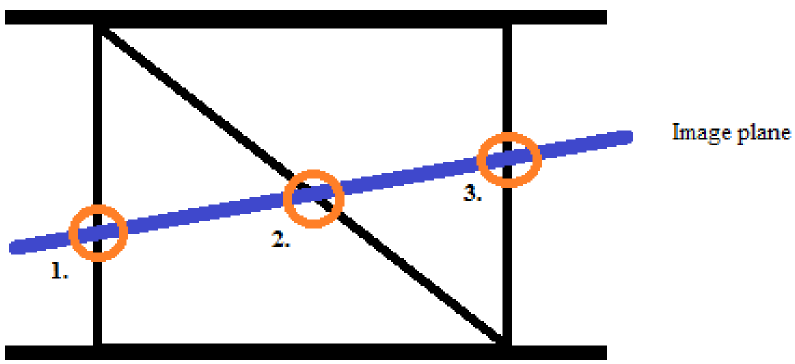

Figure 2. Ultrasound image plane intersection with wires at the three labeled locations.

N-wire phantoms require accurate manufacturing, where 3-D printing may be used to achieve a minimized tolerance necessary in the implementation and segmentation of the wires seen in Figure 2. The calibration phantoms fCal-2.0 and fCal-3.1, shown in Figure 3 and Figure 4, are examples of 3-D printed N-wire phantoms. The protocols and software used with the fCal-2.0/3.1 phantoms by Carbajal were used in this study and are available on the open source Public software Library for Ultrasound research software toolkit (http://www.plustoolkit.org). Grids on opposing sides of the phantom, which the wires pass through, allow for a variety of wiring configurations with easily described locations. The fCal-2.0, with internal dimensions of 4.0 x 10.0 cm and a depth of 3.5 cm, and the fCal-3.1, with internal dimensions of 4.0 x 12.5 cm and a depth of 15.0 cm, can accommodate probes within limitations from their widths (10.0 and 12.5 cm respectively).

An easily modifiable, readily available worldwide, and low-cost alternative N-wire phantom is the fCal-L-1.0 (Walsh *et al.* in review), for which all parts required for fabrication, previously used in medical imaging (Guler *et al.* 2012), are available by order through the LEGO® website. A companion paper by Walsh *et al.* also accepted for publication at this conference, describes the design process, embodiment and building of the fCal-L-1.0. The internal dimensions of the fCal-L-1.0 are 4.0 x 6.5 cm with a depth of 4.6 cm. The objective of this study was to determine if the fCal-L-1.0 is an adequate calibration tool when measured against the fCal-2.0/3.1 phantoms. This study was designed to compare the accuracy and variance of the fCal-L-1.0 and printed phantoms under various experimental conditions.

2. METHODS

For the calibration testing under standard conditions, a SonixTouch (UltraSonix, Richmond, British Columbia, Canada) ultrasound machine with a SonixGPS (UltraSonix) electromagnetic tracking system was used with a L14-5/38 UltraSonix linear probe at a frequency of 10 MHz. The calibration took place in a room temperature water bath with an imaging depth of 45 mm, the typical depth of needle insertions. The phantom, stylus, and ultrasound probe were tracked using a fixed 8 mm electromagnetic position sensor. For equipment testing, where the phantoms were tested using various probes and tracking devices, a C5-2/60 UltraSonix convex probe with a frequency of 5MHz, a BPL9-5/55 UltraSonix side-firing linear wand probe with a frequency of 10MHz, and a Polaris Spectra optical tracker (Northern Digital Inc, Waterloo, Ontario, Canada) were used. The three phantoms used are shown in Figures 3, 4, and 5. All have an N-wire configuration of 30 mm across and 10 mm between each layer of wiring. These dimensions were used due to the results achieved in past studies (Carbajal *et al.* 2013).

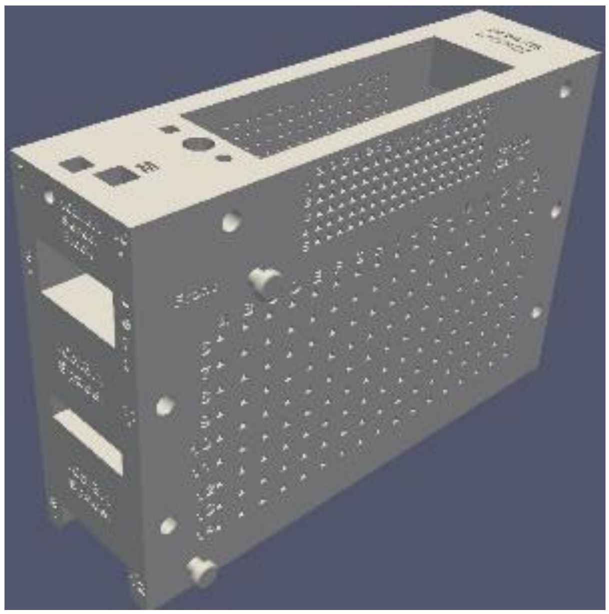

Figure 3. fCal-3.1 calibration phantom (Carbajal *et al.* 2013).

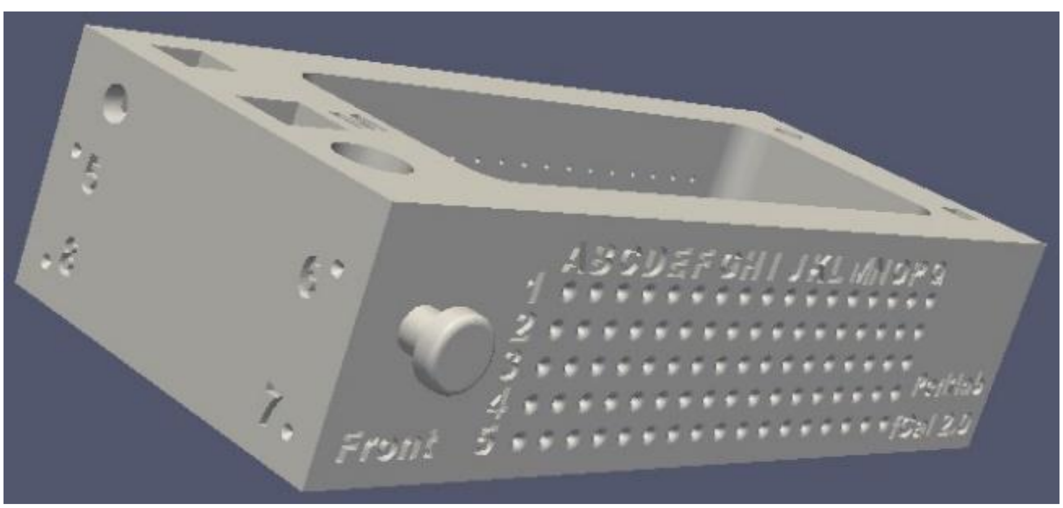

Figure 4. fCal-2.0 calibration phantom (Carbajal *et al.* 2013).

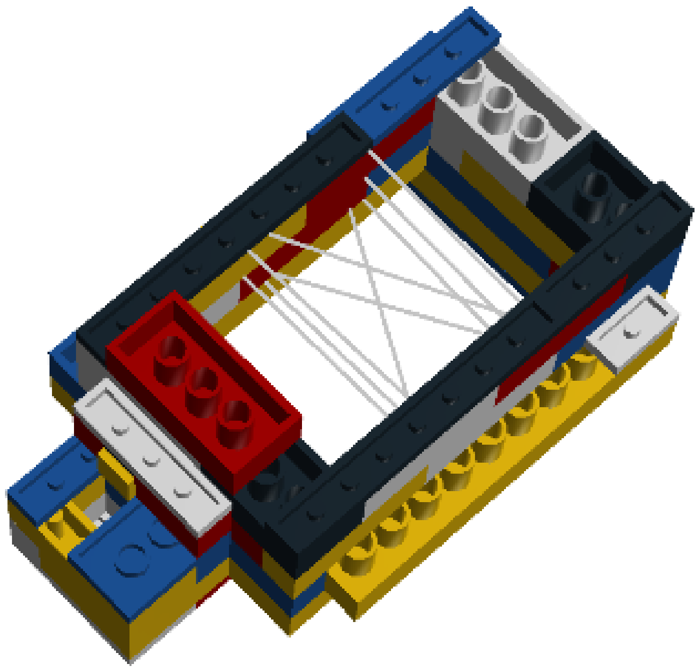

Figure 5. Calibration phantom made of LEGO® bricks (Walsh *et al.* 2013).

A stylus calibration was first performed to determine the location of the tip of the stylus. This was achieved by selecting the best result of multiple pivot calibrations. The stylus was then used to locate registration points on the phantom. Then, a spatial calibration was performed by running the ultrasound probe across the wires from one side of the phantom to the other, collecting cross sectional images of the wires in multiple probe orientations at 50 frames per second from the tracker and 30 frames per second from the ultrasound video.

To test the spatial calibration with the three phantoms under standard conditions, twenty trials were performed by a single operator on all phantoms. For evaluation of calibrations with various equipment, three trials were completed for each tracker while using the linear probe and three were completed for each probe while using the electromagnetic tracker. The 3-D image reprojection error is used to evaluate the accuracy of calibrations and standard deviation of image reprojections was used to evaluate the variance of calibrations. The error of reprojection was determined through the average distance of multiple transformed points from the image plane to the reference plane from the actual position of the point in the reference coordinate system. The standard deviation is determined by the spread of the locations of the transformed points. To make the error estimation less biased, the collected frames were split into two groups: one group was used for computing the calibration and the other was used for computing the error.

3. RESULTS AND DISCUSSION

The average error and average standard deviation over twenty trials are shown for each N-wire phantom in Table 1.

Table 1. 3-D reprojection error average and standard deviation values

Phantom	Average error (mm)	Average standard deviation (mm)
fCal-3.1	0.91	0.53
fCal-2.0	0.74	0.43
fCal-L-1.0	0.87	0.48

The fCal-2.0 phantom was found to produce the calibrations with the highest accuracy and lowest variance. The fCal-3.1 phantom was found to have the lowest accuracy and highest variance. Calibrations were achieved using both the optical tracker and the electromagnetic tracker, with the optical tracker delivering more accurate calibrations with lower variances.

The linear and wand probes were able to produce calibrations with all three phantoms. The difference between the accuracy and variance of the fCal-2.0/3.1 and fCal-L-1.0 calibrations was largest when calibrating with the wand probe. In all cases the fCal-2.0 and fCal-L-1.0s achieved calibrations with higher accuracy and lower variance than those with the fCal-3.1 phantom. Exceptions to this were the variance of the fCal-L-1.0 calibration when using the wand probe and how the convex probe was only able to calibrate with the fCal-3.1 phantom. The results of the experiments are shown in Figures 6 and 7.

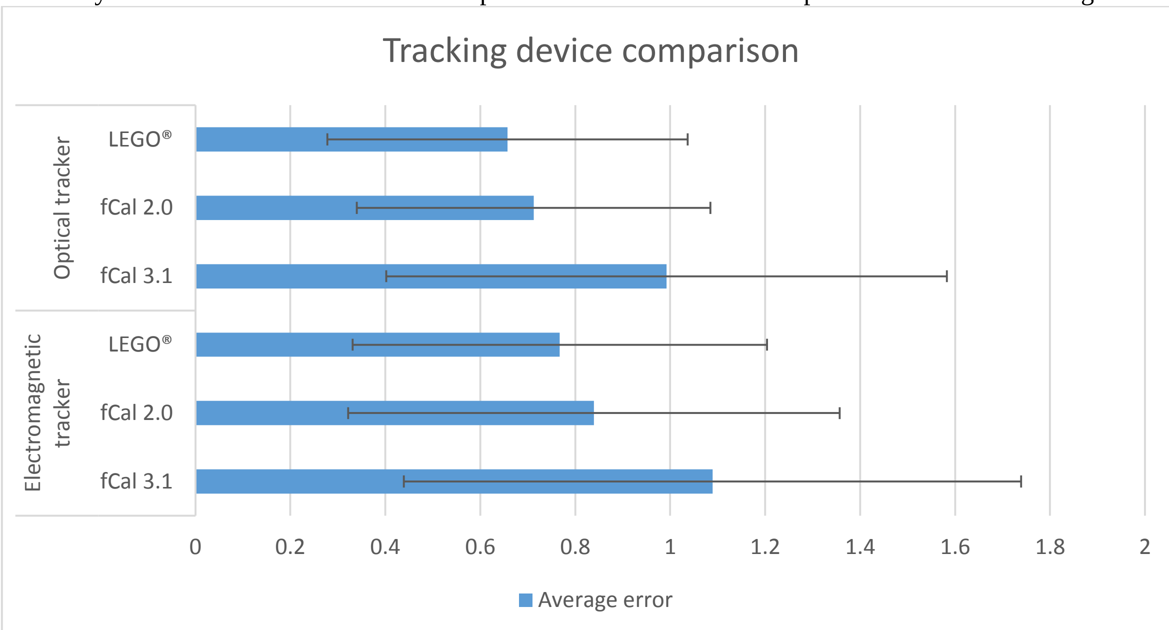

Figure 6. Average error of varied tracking devices with average standard deviation shown.

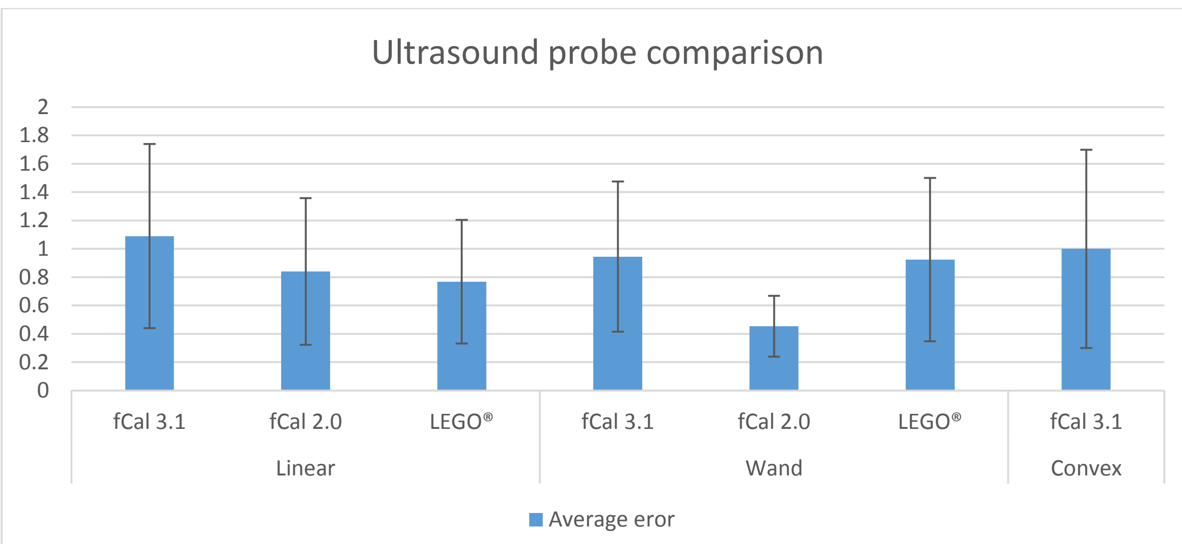

Figure 7. Average error of varied ultrasound probes with average standard deviation shown.

Under standard conditions the fCal-2.0 and fCal-L-1.0 delivered similar results. The fCal-3.1 produced calibrations with a consistently higher error and greater variance than the other two phantoms. This can be attributed to how the structure requires assembly as a means to minimize cost and printing time given the large region necessary for calibrations at an imaging depth greater than 8 cm and therefore introduces error between configuration and actual geometry. An F-test was performed on the standard deviation of the results collected from the calibrations with fCal-L-1.0 and those collected from the calibrations using the fCal-3.1 and fCal-2.0 phantoms. A summary of these results are shown in table 2. It was found that all calculated values were less than the F value at p = 0.10. This indicates that no significant variance between the results obtained by the phantom. No result was achieved for the experiments with the convex probe as calibrations were only obtained with the fCal-3.1. The accuracy of the calibrations were analyzed using a two-tailed t-test. The difference between the accuracy of calibrations performed with the fCal phantoms was found to be insignificant, as the calculated values were less than the T value at p = 0.10. This indicates that there was no variance between the accuracy of the calibrations achieved with all three phantoms under standard conditions and all other conditions tested excluding calibrations performed with the convex probe. The accuracy achieved with the convex probe was found to be statistically different between the calibrations with the fCal-L-1.0 versus those with the fCal-3.1. This result corresponds with observed results as the fCal-L-1.0 could not achieve calibrations when using the convex probe. From the statistical analysis on the collected data, it can be concluded that no significant difference was found between the fCal-L-1.0 and 3-D printed phantoms under the tested apparatus, excluding when used with the convex probe.

Table 2. A summary of the statistical analyises performed on the results obtained from the fCal-L-1.0 through experimentation and the 3-D printed phantoms.

Equipment used	Phantom under comparison with FCal-L-1.0	F-test	F at P = 0.10	T-test	T at P = 0.10
Standard conditions	FCal-3.1	1.22	1.88	0.25	1.69
	FCal-2.0	1.25	19	0.89	2.13
Linear probe	FCal-3.1	2.22	19	0.71	2.13
	FCal-2.0	1.41	19	0.18	2.13
Wand probe	FCal-3.1	1.18	19	0.05	2.13
	FCal-2.0	7.22	19	1.33	2.13
Convex probe	FCal-3.1	0	19	2.47	2.13
	FCal-2.0	--	19	---	2.13
Electromagnetic tracker	FCal-3.1	2.22	19	0.71	2.13
	FCal-2.0	1.41	19	0.18	2.13
Optical tracker	FCal-3.1	2.42	19	0.83	2.13
	FCal-2.0	1.03	19	0.18	2.13

Under various experimental conditions it was found that the wand probe achieved the most accurate calibrations. When using the wand probe, however, the fCal-L-1.0 calibrations had the greatest variance of the three phantoms and had more significantly different results from the fCal-2.0 phantom than when under other testing conditions. This discrepancy can be attributed to the structure, specifically the brick circled in Figure 8, of the fCal-L-1.0, which prevented the probe from being positioned parallel to the plane of the wires as is also shown in Figures 8.

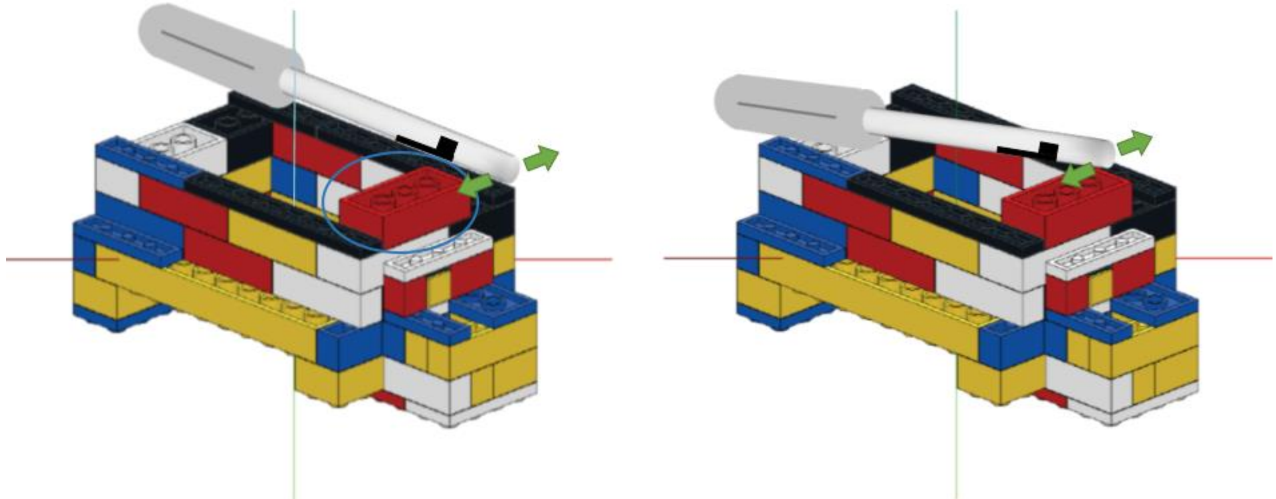

Figure 8. LEFT: Probe positioning in the parallel plane. RIGHT: Positioning of the probe with a tilted angle to accommodate the structure of the fCal-L-1.0.

Calibrations were achieved with both tracking devices and therefore the three phantoms can be used in protocols requiring either tracker. The linear probe produced the best average calibrations across the three phantoms. The limited accommodation of the convex probe with the fCal-L-1.0 and fCal-2.0 phantoms is a constraint of their designs. The fCal-L-1.0, however, can be easily modified to accommodate the different probes.

A calibration error of less than a millimeter was achieved by all three phantoms over numerous trials. The discrepancy between the accuracy and variance of the phantoms is insignificant and can be probably mostly caused by the error of the electromagnetic tracker. It was found that all calibrations are most accurate with the lowest variance when using the linear probe with the optical tracker. This can be attributed to how the optical tracker has greater accuracy than the electromagnetic tracker. The improvement of the accuracy of the calibrations from phantom to phantom may be due to the gain in experience of the operator. This however was discounted when studying varied conditions of calibration as the order of the phantoms tested was changed. Another potential source of error is that different materials were used for the strings of the phantoms. An experiment was done to determine if this would have an effect on the calibration results. It was found that as long as the wires are identifiable and that the ultrasound software is able to segment the image, the calibration results are practically identical.

Future experimentation may look to determine a modification to the design of the fCal-L-1.0 with aims of accommodating larger probes and alternative wiring. These designs would then be compared to existing calibration tools to determine if accuracy and variance are compromised with these changes. A compromise of size and accuracy could be an explanation for the fCal-3.1 consistently delivering more inaccurate results than the fCal-2.0 and fCal-L-1.0.

The significance of these results is that the fCal-L-1.0 was able to produce calibrations statistically equivalent to calibrations produced by printed N-wire phantoms. There is a potential for error during assembly and for the phantom to come apart as its structure is not fixed, however, the low cost, availability, and modification potential of the LEGO® parts, the fCal-L-1.0 may allow for a more accessible calibration option of tracked freehand ultrasound in laboratory experiments and perhaps even in clinical systems.

4. ACKNOWLEDGEMENTS

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