Title: Characterizing the biomechanical differences between novice and expert point-of-care ultrasound practitioners using a low- cost gyroscope and accelerometer integrated sensor: A pilot study

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ABSTRACT

Introduction: Point-of-care ultrasound (POCUS) has become an important diagnostic tool in acute care medicine; however, little is known about the biomechanical differences between novices and experts as they acquire abdominal and cardiac views.

Methods: A low-cost ($50 CAD) gyroscope and accelerometer integrated sensor was assembled and affixed to an ultrasound probe. 17 participants: 9 novices and 8 experts, were recruited to perform 3 abdominal (right and left upper quadrant, suprapubic) and 4 cardiac (parasternal long and short axis, subxiphoid, and apical 4 chamber) scans on a standardized patient. Participant demographics, time per scan, average acceleration, average angular velocity, decay in acceleration and angular velocity over time, and frequency of probe movements were analyzed. Video capture with blinded video review was scored.

Results: On video review, experts had higher image optimization and acquisition scores for both abdominal and cardiac scans. Experts had shorter scan times for abdominal (7s vs 26s, $p=0.003$) and cardiac (11s vs 26s, $p<0.001$) scans. There was no difference in average acceleration (g) between novices and experts performing abdominal (1.02 vs. 1.01, $p=0.50$) and cardiac (1.01 vs. 1.01, $p=0.45$) scans. Experts had lower angular velocity (º/s) for abdominal scans (10.00 vs. 18.73, $p<0.001$) and cardiac scans (15.61 vs. 20.33, $p=0.02$) There was a greater decay in acceleration over time for experts performing cardiac scans compared to novices (-0.194 vs. -0.050, $p=0.03$) but not for abdominal scans or when measuring angular velocity. The frequency of movements (Hz) was higher for novices compared to experts for abdominal (16.68 vs 13.79, $p<0.001$) and cardiac (17.60 vs 13.63, $p=0.002$) scans.

Discussion: Our data supports the concept of ‘window shopping’ as a method by which experts obtain abdominal and cardiac views, where sliding is used to find an acoustic window, then smaller rocking and tilting probe movements are used to refine the image. Window shopping may be a useful conceptual framework to help learners sequence the correct probe movements.

INTRODUCTION

Point of care ultrasound (POCUS) is performed to answer specific and often time sensitive clinical questions.[1-5] In contrast to consultative ultrasound, POCUS practitioners integrate ultrasound into their bedside assessment to aid in diagnosis and management.[6] With its increasing adoption, POCUS has become an essential tool for many acute care clinicians.[3, 5-9]

Despite widespread use of POCUS, little is known about how individual ultrasound probe movements are used to generate images. Previous research using hand motion analysis of clinicians performing Focused Assessment with Sonography in Trauma (FAST) examinations and ultrasound guided venous access have begun to characterize this.[10-14] These studies use multiple sensors or cameras integrated into a commercial system, which may have cost, portability, and line of site implications that limit their widespread use. In addition, analysis of individual probe movements (sliding, rotation, tilting or rocking of the probe [Figure 1]), decay of movement over time, frequency of movements, and other potentially important markers of sonographic expertise have not yet been characterized. By understanding differences between how novices and experts sequence POCUS movements, we can provide targeted feedback and coaching to learners. Additionally, with sufficient validity evidence, a low-cost sensor could be used as an adjunct for assessing sonographic expertise.

The objective of this study was to characterize the biomechanical fingerprints of POCUS novices and experts performing FAST and basic cardiac scans using a custom low-cost ($50 CAD) sensor.

METHODS

Research Ethics Board (REB) approval was obtained through the Ottawa Health Science Network Research Ethics Board (REB # 20200298-01H). The protocol was published on the Open Science Framework (OSF) prior to data collection (https://osf.io/qd9uw/).

Sensor Design

A low-cost, custom-made accelerometer and gyroscope integrated sensor was designed and affixed to an ultrasound probe. The sensor is based on an inertial measurement unit (MPU-6050 from InvenSense) comprising a tri-axis digital accelerometer set to a full-scale range of 2*g* (where *g* is the gravitational constant) and a tri-axis digital gyroscope set to a full-scale range of 250 degrees/sec (^{o}/s). Raw acceleration and angular velocity data were sampled along each axis every 20 milliseconds (ms) using an Arduino UNO microcontroller via the I2C protocol. The MPU-6050 is mounted on a SEN0140 breakout board by DFrobot. The total cost of the individual sensor components and the microcontroller was less than $50 CAD. The sensor is connected to the ultrasound probe by way of custom 3D printed mount and rubber securing bands (see Figure 2). The sensor was mounted to the phased array probe (1 – 5 MHz) on a Sonosite™ M-Turbo ultrasound machine. More information on the design and calibration of the sensor is available on OSF (https://osf.io/qd9uw/).

Recruitment and Participants

A convenience sample of POCUS novices and experts were recruited through emails sent to resident and staff physicians from the University of Ottawa Department of Emergency Medicine, Department of Medicine, Department of Anaesthesia and Division of Critical Care. As this was a pilot project, no sample size calculation was performed.

Novice POCUS practitioners were defined as residents, fellows or staff physicians who had completed less than 50 supervised cardiac and FAST scans. Expert POCUS practitioners were defined as residents, fellows or staff physicians who had completed 50 or more supervised cardiac and FAST scans *and* who were enrolled in or had completed a 1-year ultrasound fellowship *or* who were advanced level POCUS instructors at the University of Ottawa.

Data Collection

Demographic information was collected from the study participants including age, gender, post graduate level of training, specialty, number of supervised cardiac and abdominal scans, frequency of POCUS use in clinical practice, and self-reported confidence for FAST and cardiac scans. The data collection form is available in Appendix 3.

All data collection was performed in November 2020 at the University of Ottawa Skills and Simulation Center. A single male standardized patient (SP) who was positioned supine was used for each participant. Gel was generously applied to the SP before each scan to eliminate the need for additional probe movements. All scans were video recorded using a single GoPro™ camera with simultaneous ultrasound screen capture without audio. Identity of the participants were concealed using gowns and gloves. Clinicians performed 7 scans on the SP: right upper quadrant (RUQ), left upper quadrant (LUQ), suprapubic (SUP), parasternal long axis (PSL), parasternal short axis (PSS), subxiphoid 4 chamber (SX), and apical 4 chamber (A4C). The starting position and 'target view' for each scan were standardized and included in the instructions to participants before each scan (Appendix 1 & 2). Probe movements were recorded until the target view was achieved (as determined by an expert observer) or until 60 seconds had elapsed.

Blinded Video Review

The blinded, anonymized, videos were later analyzed by two independent POCUS experts. Two of the four domains (image acquisition and image optimization) of the Ultrasound Competency Assessment Tool (UCAT)[15], a previously published ultrasound competence assessment tool, were used to grade the proficiency of the scan (Appendix 4). Modification of the UCAT tool was necessary as domains 'preparation' and 'clinical integration' were not assessed. Any discrepant scores between the two reviewers were averaged. Interrater reliability was calculated using a Cohen's kappa.

Data Analysis

Analysis of the raw sensor data was performed in Python v3 along the following metrics: time per scan (determined on video review by a blinded observer), average acceleration, average angular velocity, decay in acceleration and angular velocity over time, and frequency of probe movements. At each point in time, angular velocity (or acceleration) data points along the three axes were summed in quadrature to obtain the total angular velocity (or acceleration). These values were then averaged over the entire scan duration to obtain a single average angular velocity or acceleration value for each participant-scan. Decay in angular velocity and acceleration over time was defined as a decrease in the amplitude of movement from the start to finish of the scan, which was evaluated using a rank correlation between the total angular velocity or acceleration and time. Frequency of movement was quantified by determining the frequency threshold below which lay 90% of the frequencies of probe movement. This was done using a Fourier transform of the acceleration and angular velocity data, and integrating the spectral content, starting at zero, until reaching 90% of the total spectral content.

Comparisons between novices and experts were performed using Mann-Whitney U test for continuous variables and Fisher's exact test for categorical variables. Statistical significance was set at a p-value of ≤ 0.05. All statistical analyses were performed using SAS version 9.4. Medians with interquartile range (IQR) and frequencies with percentages are provided where appropriate. Plots were generated using the Matplotlib library in Python v.3.

RESULTS

Demographics

The demographics of novices and experts are provided in Table 1. Experts had performed more supervised FAST (50 [50 – 150] vs 5 [1 – 10], $p<0.001$) and cardiac (75 [50 – 550] vs 5 [3 – 10], $p<0.001$) scans and reported greater confidence performing those scans ($p<0.001$ and $p=0.002$, respectively) than novices.

Blinded Video Review

The blinded video review results for combined abdominal and cardiac scans are shown in Table 2 and individual scans are provided in Appendix 5. Experts had higher image acquisitions scores for abdominal (2.5 vs. 2.0, $p=0.005$) and cardiac (2.5 vs. 2.0, $p=0.004$) views. Their image optimization scores were also higher for abdominal (2.5 vs. 2.0, $p< 0.001$) and cardiac (2.5 vs. 1.5, $p<0.001$) scans. Inter-rater reliability was poor for the blinded reviewers (kappa=0.13).

Sensor Data

The time, acceleration, angular velocity, decay in movements, and frequency data for the combined abdominal (RUQ, LUQ, and SP) and combined cardiac (PSLA, PSSA, A4C, and SX) scans are displayed in Tables 3 and 4 and in Figure 3. The data for individual scans is available in Appendices 6 to 8. Experts had shorter scanning times (seconds) for both abdominal (7s vs. 26s, $p=0.003$) and cardiac (11s vs 26s, $p<0.001$) scans. The average acceleration (g) did not significantly differ between novices and experts for abdominal (1.02 vs. 1.01, $p=0.50$) and cardiac (1.01 vs. 1.01, $p=0.45$) scans. Experts had lower angular velocity (^{o}/s) for abdominal scans (10.00 vs. 18.83, $p<0.001$) and cardiac scans (15.61 vs. 20.33, $p=0.02$). There was a greater decay in acceleration over time for experts performing cardiac scans compared to novices (-0.194 vs. -0.050, $p=0.03$) but not for abdominal scans (0.022 vs. -0.012, $p=0.48$). There was no significant difference in the decay in angular velocity between novices and experts (Table 4). Finally, the frequency of movements (Hz) was higher for novices compared to experts for both abdominal (16.86 vs. 13.79, $p<0.001$) and cardiac (17.60 vs. 13.63, $p=0.002$) scans.

DISCUSSION

Compared to novices, experts had greater experience and confidence with POCUS, and on video review demonstrated greater proficiency with image acquisition and optimization. Experts acquired images faster, with lower angular velocity movements, and with lower frequency movements. For cardiac scans, there was a greater decay (or diminution) of movement over the course of the scan for experts compared to novices. In sonographic terms, this suggests experts move the probe more smoothly and efficiently, with less tilting and rocking of the probe. It may also support that experts use the technique of ‘window shopping’ to efficiently obtain abdominal and cardiac views.

Anecdotally, many novice POCUS learners have difficulty sequencing probe movements to obtain views. Some educators have introduced the concept of ‘window shopping’ to communicate the correct sequence of movements to learners. First, an acoustic window is found (shopped for) by sliding the probe in the region of interest. For example, during a right upper quadrant FAST scan, an acoustic window of the liver might be found by sliding in the mid-axillary line between the lower ribs. Once a window is obtained, the sonographer then optimizes the image through rotation, tilting, and rocking of the probe to identify the region of interest (i.e. hepatorenal interface). With time and experience, these movements become intuitive for POCUS experts; however, novices may attempt to optimize a view before an acoustic window is found. This may translate into large amplitude (higher angular velocity) rocking and tilting movements, higher frequency, and less efficient movements, as seen in our study. This hypothesis is also supported by the fact that for experts performing cardiac scans, there is a clear diminution in the amplitude of acceleration over time. This suggests that once experts have found an acoustic window, they use small and deliberate movements to optimize their view.

Previous POCUS biomechanics research using hand motion analysis have shown similar findings to our study. Zago *et al.* found that compared to novices, experts performed scans quicker, with fewer movements, and shorter path lengths.[11] Ziesmann *et al.* also found experts performed scans quicker, with fewer movements than novices.[13] One advantage to our study is the ability to distinguish between acceleration and angular velocity. In our study, novices and experts demonstrated similar overall accelerations, whereas experts had lower angular velocities. This may be because while both novices and experts slide the probe with similar acceleration, experts correctly identify the acoustic window and then use smaller and more deliberate rocking and tilting (angular velocity generating) movements to optimize their view.

In recent years there has been important work developing and collecting validity evidence for POCUS assessment tools.[15-19] These tools are designed to assess the technical skills of image acquisition and optimization, however, require a human assessor to be present.[15] This may be feasible at some institutions, however, could limit generalizability to the global POCUS community. The interrater reliability for these tools are also variable.[15] The concept of integrating sensors, specifically hand-motion analysis, into a comprehensive and evidence-based POCUS assessment tools has previously been suggested.[11] One benefit to a gyrometer and accelerometer integrated sensor similar to ours would be the relative low-cost ($50 CAD) and ability for parts to be ordered online and shipped to anywhere in the world to be assembled. This could allow for remote feedback and coaching, which could help globalize ultrasound education. Furthermore, the ability for a sensor like ours to measure acceleration and angular velocity in the X, Y, and Z axis may help identify additional markers of sonographic expertise that could be used as part of assessment or coaching tools.

Although our team had several hypotheses for the expected biomechanical differences between novices and experts, there likely are other important features that distinguish the two groups. To further explore this, artificial intelligence (AI) or deep learning techniques that incorporate sensor data could be used to identify additional markers of sonographic expertise. AI has successfully been employed in identifying pathology on ultrasound images,[20-22] and preliminary studies looking at deep learning strategies for POCUS biomechanics have also been performed.[23-25] With additional research, a real-time feedback system to optimize probe movements would be feasible. Moreover, a deep learning classifier to grade sonographic expertise could also be used as an adjunct to traditional assessment tools.

Limitations

This study has some important limitations. Firstly, our convenience sample is small, although similar to other studies assessing POCUS biomechanics.[11, 12] Additionally, as none of the POCUS assessment tools have validity evidence to assess technical skills with blinded video review, we modified the UCAT tool only using the acquisition and optimization domains. Although this was successful in discriminating novices and experts, it utilizes the tool beyond its intended purpose. This may account for our the poor interrater reliability compared to the original UCAT assessment tool.[15] Furthermore, there are some important considerations when translating our sensor's acceleration and angular velocity data into individual probe movements. Although angular velocity best correlates to the rocking or tilting of the probe, some angular velocity could be generated when the probe is slid on a non-planar surface (e.g. from anterior chest to below the nipple during A4C). In addition, the research setting may have led clinicians to perform POCUS differently than they would have without observation. Finally, only one standardized patient was used, and the results may not translate to other patients with different body habitus, positioning, or pathology.

Conclusion

Collectively, our research supports the concept of ‘window shopping’ as a method by which experts obtain abdominal and cardiac views. Additional research to validate the use of our sensor as part of a POCUS assessment tool would be valuable. Similarly, further analysis of the dataset using deep learning techniques might detect biomechanical differences that we have not yet identified, which would be a first step in developing an automated sensor that provides real-time feedback to learners as they scan.

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All authors contributed to the study design, data interpretation, manuscript writing, and editing. RS and TH designed and fabricated the sensor and programmed the software used to analyze the sensor data. MH also helped analyze the sensor data. MJN performed the statistical analysis.

References

1. Whitson MR, Mayo PH. Ultrasonography in the emergency department. *Crit Care*. 08 2016;20(1):227. doi:10.1186/s13054-016-1399-x
2. Kim DJ, Francispragasam M, Docherty G, et al. Test Characteristics of Point-of-care Ultrasound for the Diagnosis of Retinal Detachment in the Emergency Department. *Acad Emerg Med*. 01 2019;26(1):16-22. doi:10.1111/acem.13454
3. Lewis D, Rang L, Kim D. Recommendations for the use of point-of-care ultrasound (POCUS) by emergency physicians in Canada. CJEM2019.
4. Wong C, Teitge B, Ross M, Young P, Robertson HL, Lang E. The Accuracy and Prognostic Value of Point-of-care Ultrasound for Nephrolithiasis in the Emergency Department: A Systematic Review and Meta-analysis. *Acad Emerg Med*. Jun 2018;25(6):684-698. doi:10.1111/acem.13388
5. Prager R, Sedgwick C, Lund A, et al. Prospective Evaluation of Point-of-Care Ultrasound at a Remote, Multi-Day Music Festival. *Prehosp Disaster Med*. Oct 2018;33(5):484-489. doi:10.1017/S1049023X18000821
6. Prager R, Wu K, Bachar R, et al. Blinding practices during acute point-of-care ultrasound research: the BLIND-US meta-research study. *BMJ Evid Based Med*. Nov 2020;doi:10.1136/bmjebm-2020-111577
7. Arntfield RT, Millington SJ. Point of care cardiac ultrasound applications in the emergency department and intensive care unit--a review. *Curr Cardiol Rev*. May 2012;8(2):98-108.
8. Prager R, Bowdridge J, Kareemi H, Wright C, McGrath TA, McInnes MDF. Adherence to the Standards for Reporting of Diagnostic Accuracy (STARD) 2015 Guidelines in Acute Point-of-Care Ultrasound Research. *JAMA Netw Open*. May 2020;3(5):e203871. doi:10.1001/jamanetworkopen.2020.3871
9. Prager R, Gagnon L, Bowdridge J, et al. Barriers to reporting guideline adherence in point-of-care ultrasound research: a cross-sectional survey of authors and journal editors. *BMJ Evid Based Med*. Jan 2021;doi:10.1136/bmjebm-2020-111604
10. Clinkard D, Holden M, Ungi T, et al. The development and validation of hand motion analysis to evaluate competency in central line catheterization. *Acad Emerg Med*. Feb 2015;22(2):212-8. doi:10.1111/acem.12590
11. Zago M, Sforza C, Mariani D, et al. Educational impact of hand motion analysis in the evaluation of FAST examination skills. *Eur J Trauma Emerg Surg*. Dec 2020;46(6):1421-1428. doi:10.1007/s00068-019-01112-6
12. Good RJ, Rothman KK, Ackil DJ, Kim JS, Orsborn J, Kendall JL. Hand motion analysis for assessment of nursing competence in ultrasound-guided peripheral intravenous catheter placement. *J Vasc Access*. May 2019;20(3):301-306. doi:10.1177/1129729818804997
13. Ziesmann MT, Park J, Unger B, et al. Validation of hand motion analysis as an objective assessment tool for the Focused Assessment with Sonography for Trauma examination. *J Trauma Acute Care Surg*. Oct 2015;79(4):631-7. doi:10.1097/TA.0000000000000813
14. Gunabushanam G, Nautsch F, Mills I, Scoutt LM. Accessible Personal Ultrasound Training Simulator. *J Ultrasound Med*. Jun 2019;38(6):1425-1432. doi:10.1002/jum.14820
15. Bell C, Hall AK, Wagner N, Rang L, Newbigging J, McKaigney C. The Ultrasound Competency Assessment Tool (UCAT): Development and Evaluation of a Novel Competency-based Assessment Tool for Point-of-care Ultrasound. https://doi.org/10.1002/aet2.10520. *AEM Education and Training*. 2020/08/13 2020;n/a(n/a)doi:https://doi.org/10.1002/aet2.10520
16. Millington SJ, Arntfield RT, Guo RJ, et al. The Assessment of Competency in Thoracic Sonography (ACTS) scale: validation of a tool for point-of-care ultrasound. *Crit Ultrasound J*. Nov 2017;9(1):25. doi:10.1186/s13089-017-0081-0

17. Millington SJ, Hewak M, Arntfield RT, et al. Outcomes from extensive training in critical care echocardiography: Identifying the optimal number of practice studies required to achieve competency. *J Crit Care*. 08 2017;40:99-102. doi:10.1016/j.jcrc.2017.03.020
18. Skaarup SH, Laursen CB, Bjerrum AS, Hilberg O. Objective and Structured Assessment of Lung Ultrasound Competence. A Multispecialty Delphi Consensus and Construct Validity Study. *Ann Am Thorac Soc*. Apr 2017;14(4):555-560. doi:10.1513/AnnalsATS.201611-894OC
19. Bahner DP, Adkins EJ, Nagel R, Way D, Werman HA, Royall NA. Brightness mode quality ultrasound imaging examination technique (B-QUIET): quantifying quality in ultrasound imaging. *J Ultrasound Med*. Dec 2011;30(12):1649-55. doi:10.7863/jum.2011.30.12.1649
20. Baloescu C, Toporek G, Kim S, et al. Automated Lung Ultrasound B-Line Assessment Using a Deep Learning Algorithm. *IEEE Trans Ultrason Ferroelectr Freq Control*. 11 2020;67(11):2312-2320. doi:10.1109/TUFFC.2020.3002249
21. Arntfield R, VanBerlo B, Alaifan T, et al. Development of a convolutional neural network to differentiate among the etiology of similar appearing pathological B lines on lung ultrasound: a deep learning study. *BMJ Open*. 2021;11(3):e045120. doi:10.1136/bmjopen-2020-045120
22. Ghorbani A, Ouyang D, Abid A, et al. Deep learning interpretation of echocardiograms. *npj Digital Medicine*. 2020/01/24 2020;3(1):10. doi:10.1038/s41746-019-0216-8
23. Wang Y, Droste R, Jiao J, et al. Differentiating Operator Skill during Routine Fetal Ultrasound Scanning using Probe Motion Tracking. *Med Ultrasound Preterm Perinat Paediatr Image Anal (2020)*. Oct 2020;12437:180-188. doi:10.1007/978-3-030-60334-2_18
24. Holden MS, Xia S, Lia H, et al. Machine learning methods for automated technical skills assessment with instructional feedback in ultrasound-guided interventions. *Int J Comput Assist Radiol Surg*. Nov 2019;14(11):1993-2003. doi:10.1007/s11548-019-01977-3
25. Tyrrell RE, Holden MS. Ultrasound video analysis for skill level assessment in FAST ultrasound. *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization*. 2020:1-5. doi:10.1080/21681163.2020.1835549

Table 1. Participant characteristics

Demographic	Novices (n = 9)	Experts (n = 8)	p-values
Age, median (IQR)	28 (27 – 28)	37 (36 – 43.5)	<0.001^{+}
Male, n (%)	6 (66.7)	8 (100)	0.21$^{\wedge}$
Post Graduate Year of Training (PGY), median (IQR)	3 (3 – 3)	5.5 (4 – 13.5)	0.003^{+}
Completed an Ultrasound Fellowship, n (%)	0 (0.0)	5 (62.5)	0.009$^{\wedge}$
Specialty of Practice, n(%)			0.006$^{\wedge}$
Internal Medicine (IM)	6 (66.7)	0 (0.0)	
Emergency Medicine (EM)	2 (22.2)	7 (87.5)	
Number of Supervised FAST Scans, median (IQR)	5 (1 – 10)	50 (50 – 150)	<0.001^{+}
Number of Supervised Cardiac scans, median (IQR)	5 (3 – 10)	75 (50 – 550)	<0.001^{+}
Self reported confidence in performing FAST Scans (Likert*), median (IQR)	3 (2 – 4)	5 (5 – 5)	<0.001^{+}
Self reported confidence in performing Cardiac Scans (Likert*), median (IQR)	3 (2 – 4)	5 (4.5 – 5)	0.002^{+}

IQR=Interquartile Range; FAST=Focused Assessment with Sonography in Trauma
*Likert: 1=no confidence, 2=little confidence, 3=neither confident nor not confident, 4=somewhat confident, 5=very confident
$^{+}$Mann-Whitney U test
$^{\wedge}$Fisher's exact test

Table 2. Video review scores (median) based on modified UCAT

	Acquisition			**Optimization**		
Scan	**Novice**	**Expert**	**p-value+**	**Novice**	**Expert**	**p-value+**
Abdominal Scans	2	2.5	0.005	2	2.5	<0.001
Cardiac Scans	2	2.5	0.004	1.5	2.5	<0.001
Cohen's Kappa (95% CI)	0.13 (0.04 – 0.22)			0.13 (0.03 – 0.25)		
CI=Confidence Interval; + Mann-Whitney U test						

Table 3. Median time, acceleration, and angular velocity for novices compared to experts

	Time (s)			Acceleration (g)			Angular Velocity (°/s)		
Scan	**Novice**	**Expert**	**p-value**[+]	**Novice**	**Expert**	**p-value**[+]	**Novice**	**Expert**	**p-value**[+]
Abdominal Scans	26	7	0.003	1.02	1.01	0.50	18.83	10.00	<0.001
Cardiac Scans	26	11	<0.001	1.01	1.01	0.45	20.33	15.61	0.02

[+] Mann-Whitney U test

Table 4. Median decay in acceleration and angular velocity and frequency threshold below which 90% of movements occurred

	Decay in Acceleration			Decay in Angular Velocity			Frequency Threshold (Hz)		
Scan	**Novice**	**Expert**	**p-value^{+}**	**Novice**	**Expert**	**p-value^{+}**	**Novice**	**Expert**	**p-value^{+}**
Abdominal Scans	-0.012	0.022	0.48	0.0617	0.0467	0.44	16.86	13.79	< 0.001
Cardiac Scans	-0.050	-0.194	0.03	-0.144	-0.199	0.47	17.60	13.63	0.002

$^{+}$ Mann-Whitney U test

Figure 1. Illustration of sliding, tilting, rotating and rocking probe movements.

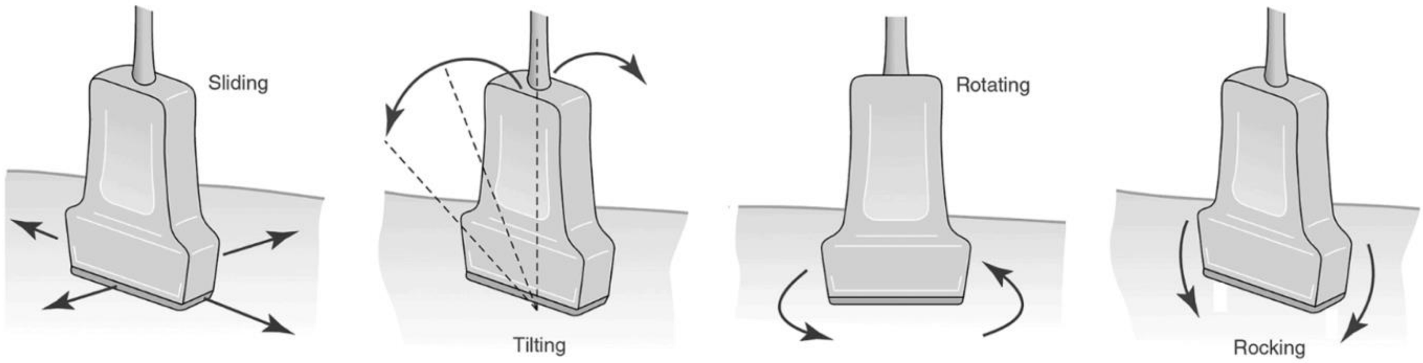

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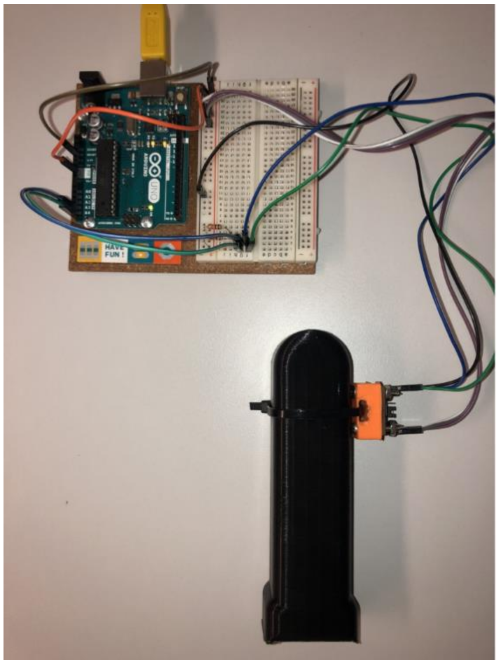
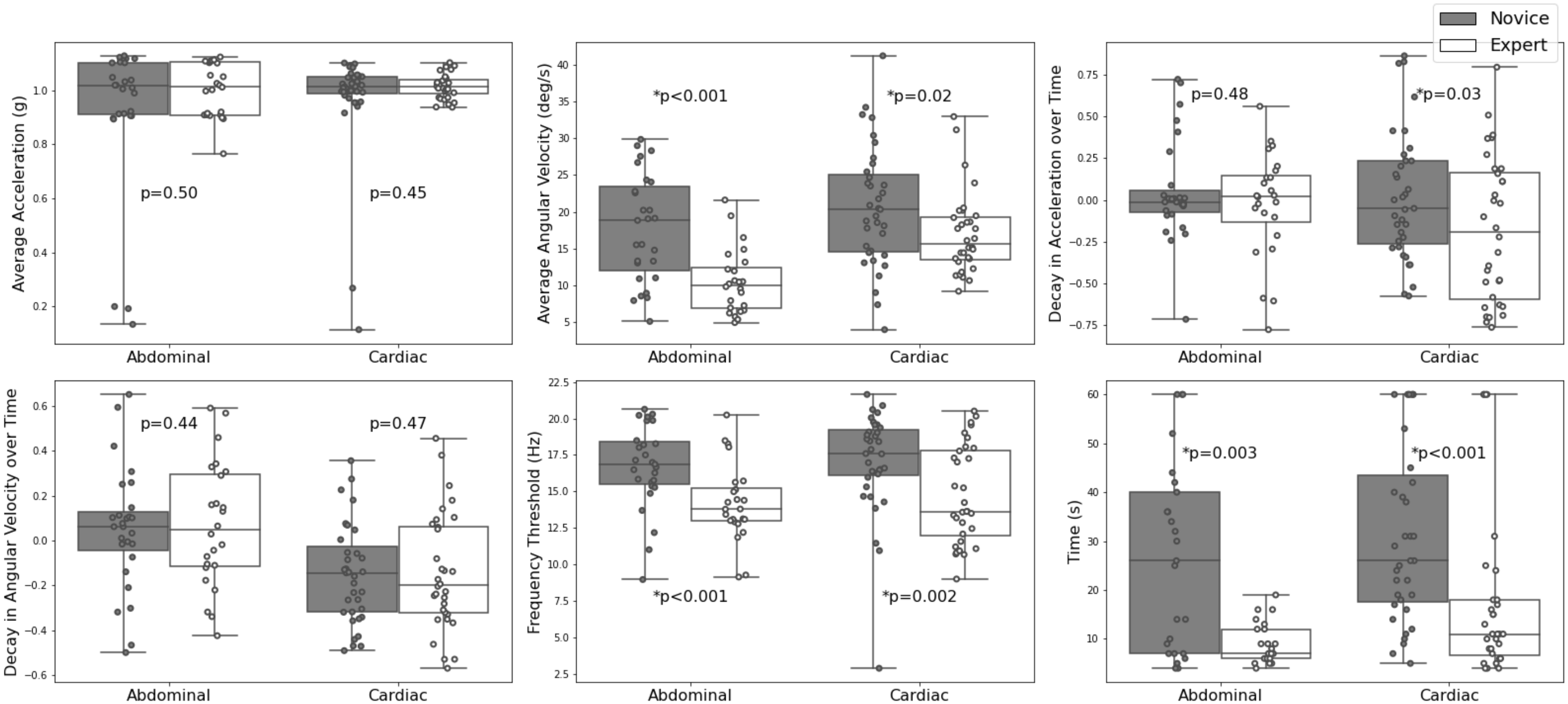
Figure 2. Sensor module



Legend: Sensor affixed to a simulated ultrasound probe.

Figure 3. Comparison of novice and experts for time, acceleration, angular velocity, decay in acceleration, decay in angular velocity, frequency for abdominal and cardiac scans



APPENDICES

Appendix 1. Starting position for each scan

Scan	Starting Position Description
RUQ	Probe parallel to bed on the right side of SP mid axillary line at level of xyphoid process
LUQ	Probe parallel to bed on the left side of SP mid axillary line at level of xyphoid process
SUP	Probe vertically positioned in coronal plane on model 5cm above the pubic symphysis
PSL	Probe aligned vertically, indicator towards SPs head, positioned on the left 3^{rd} rib 2cm lateral to the sternum
PSS	Probe aligned vertically, probe indicator towards SP's head, positioned on the left 3^{rd} rib 2cm lateral to the sternum
SX	Probe aligned vertically over the xyphoid process probe indicator towards the patient's left
A4C	Probe aligned vertically over the rib located 2cm below the left nipple, probe indicator towards the SP's head

RUQ= Right Upper Quadrant; LUQ=Left Upper Quadrant; SUP=Suprapubic; PSL=Parasternal Long Axis; PSS=Parasternal Short Axis; SX=Subxiphoid 4 Chamber; A4C=Apical 4 Chamber;

Appendix 2. Necessary view for each scan to be deemed to be complete

Scan	Stopping Position Criteria
RUQ	View of the liver and kidney that demonstrates the hepatorenal interface
LUQ	View of the spleen and the diaphragm that demonstrates the spleno-diaphragmatic interface
SUP	View of the bladder in short axis that is at the level of the prostate in males, or uterus in female
PSL	Long axis view of the left ventricle that does not significantly foreshorten the ventricle, and that clearly shows both leaflets of the mitral valve.
PSS	Short axis view of the left ventricle centered in the screen at the level of the papillary muscles
SX	View of the heart showing all 4 chambers, specifically ensuring that both the right and left ventricle are visible.
A4C	View of the heart showing all 4 chambers, with the septum vertical in the screen and centered, ensuring that the atria are not significantly foreshortened.

RUQ= Right Upper Quadrant; LUQ=Left Upper Quadrant; SUP=Suprapubic; PSL=Parasternal Long Axis; PSS=Parasternal Short Axis; SX=Subxiphoid 4 Chamber; A4C=Apical 4 Chamber;

Appendix 3. Data Collection Form

<table>
<tr><td>Unique Participant Identifier</td><td rowspan="5"></td></tr>
<tr><td>Age</td></tr>
<tr><td>Gender</td></tr>
<tr><td>Year of Training
(PGY year if resident or years into clinical practice if staff)</td></tr>
<tr><td>Specialty of Practice</td></tr>
<tr><td colspan="2"><u>Highest Level of Ultrasound Training (circle one):</u>
Ultrasound Fellowship   Core Residency   Other course(s) (please specify)</td></tr>
<tr><td>Estimated number of supervised cardiac exams performed</td><td rowspan="2"></td></tr>
<tr><td>Estimated number of supervised FAST exams performed</td></tr>
<tr><td colspan="2"><u>During my clinical practice, I perform point-of-care ultrasound (circle one):</u>
every day   most days   most weeks   rarely   never</td></tr>
<tr><td colspan="2"><u>For the following questions, please rate your confidence on a scale from 1 to 5:</u>
1 = no confidence
2 = little confidence
3 = neither confident nor not confident
4 = somewhat confident
5 = very confident</td></tr>
<tr><td>My confidence in acquiring FAST scan is</td><td rowspan="2"></td></tr>
<tr><td>My confidence in acquiring basic cardiac views are</td></tr>
</table>

Appendix 4. Modified Ultrasound Competency Assessment Tool[15]

Domain	Performance Rating		
	Competent performance of SOME criteria	Competent performance of MOST criteria	Competent performance of ALL criteria
Image Acquisition - Hand & probe positioning - Identify appropriate landmarks - Thorough visualization of target - Efficiency of probe motion - Troubleshoots technical limitations	1	2	3
Image Optimization - Centers area of interest - Overall image quality for interpretation - Troubleshoots patient obstacles - Optimizes machine settings (gain, focal zone, depth, frequency)	1	2	3

Appendix 5. Video review median scores for each individual scan

	Acquisition			Optimization		
Scan	**Novice**	**Expert**	**p-value+**	**Novice**	**Expert**	**p-value+**
RUQ	2	2.5	0.06	1.5	2.5	0.006
LUQ	2	2.5	0.17	2	2.5	0.09
SUP	2	2.5	0.17	2.25	2.5	0.09
PSL	2	3	0.02	2.25	2.75	0.02
PSS	2.5	2.75	0.25	1.5	2.75	0.13
SX	1.5	2.5	0.02	1.5	2.25	0.02
A4C	1.5	1.75	0.69	1.5	2	0.34
Combined Abdominal	2	2.5	0.005	2	2.5	<0.001
Combined Cardiac	2	2.5	0.004	1.5	2.5	<0.001
Cohen's Kappa (95% CI)	0.13 (0.04 – 0.22)			0.13 (0.03 – 0.25)		

RUQ= Right Upper Quadrant; LUQ=Left Upper Quadrant; SUP=Suprapubic; PSL=Parasternal Long Axis; PSS=Parasternal Short Axis; SX=Subxiphoid 4 Chamber; A4C=Apical 4 Chamber; CI=Confidence Interval;

+ Mann-Whitney U test

Appendix 6. Median time, acceleration, and angular velocity for each individual scan

	Time (s)			Acceleration (g)			Angular Velocity (°/s)		
Scan	**Novice**	**Expert**	**p-value+**	**Novice**	**Expert**	**p-value+**	**Novice**	**Expert**	**p-value+**
RUQ	35	10.5	<0.001	1.10	1.00	0.44	19.05	10.57	0.081
LUQ	14	6.5	0.01	0.92	1.01	0.40	20.21	7.08	0.004
SUP	6.5	7	0.82	1.02	1.01	0.48	13.03	9.41	0.068
PSL	14	7	0.03	1.01	1.01	0.37	18.10	13.00	0.097
PSS	29	11	0.07	1.00	1.01	0.30	14.44	18.43	0.37
SX	31	12	0.01	1.08	1.02	0.37	20.89	15.00	0.003
A4C	42	20	0.38	1.02	1.01	0.25	25.09	19.02	0.24
Abdominal Scans	26	7	0.003	1.02	1.01	0.50	18.83	10.00	<0.001
Cardiac Scans	26	11	<0.001	1.01	1.01	0.45	20.33	15.61	0.016

+ Mann-Whitney U test; RUQ= Right Upper Quadrant; LUQ=Left Upper Quadrant; SUP=Suprapubic; PSL=Parasternal Long Axis; PSS=Parasternal Short Axis; SX=Subxiphoid 4 Chamber; A4C=Apical 4 Chamber;

Appendix 7. Median Decay in Movement for each individual scan

	Decay in Acceleration			Decay in Angular Velocity		
Scan	**Novice**	**Expert**	**p-value+**	**Novice**	**Expert**	**p-value+**
RUQ	0.0055	0.0027	0.44	0.101	0.115	0.37
LUQ	-0.0252	0.0781	0.015	0.0105	-0.0696	0.40
SUP	0.289	-0.303	0.068	0.0982	0.0796	0.48
PSL	0.00054	-0.354	0.0119	-0.130	-0.150	0.33
PSS	-0.0503	-0.0049	0.23	-0.144	-0.222	0.33
SX	0.202	-0.321	0.13	-0.190	-0.216	0.44
A4C	-0.213	0.0045	0.36	-0.196	-0.216	0.48
Abdominal Scans (combined)	-0.012	0.022	0.48	0.0617	0.0467	0.44
Cardiac Scans (combined)	-0.050	-0.194	0.03	-0.144	-0.199	0.47

+ Mann-Whitney U test; RUQ= Right Upper Quadrant; LUQ=Left Upper Quadrant; SUP=Suprapubic; PSL=Parasternal Long Axis; PSS=Parasternal Short Axis; SX=Subxiphoid 4 Chamber; A4C=Apical 4 Chamber;

Appendix 8. Median Frequency of Movements for each individual scan

	Frequency Acceleration		
Scan	**Novice**	**Expert**	**p-value**+
RUQ	18.01	15.30	0.019
LUQ	16.99	13.61	0.009
SUP	15.76	12.95	0.15
PSL	16.60	11.14	0.046
PSS	16.46	16.27	0.27
SX	17.58	13.60	0.009
A4C	19.12	17.87	0.09
Abdominal Scans (combined)	16.86	13.79	< 0.001
Cardiac Scans (combined)	17.60	13.63	0.002

+ Mann-Whitney U test; RUQ= Right Upper Quadrant; LUQ=Left Upper Quadrant; SUP=Suprapubic; PSL=Parasternal Long Axis; PSS=Parasternal Short Axis; SX=Subxiphoid 4 Chamber; A4C=Apical 4 Chamber;