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ORIGINAL CONTRIBUTION

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 novice and expert practitioners.

Methods: A low-cost ($50 CAD) gyroscope and accelerometer integrated sensor was assembled and affixed to an ultrasound probe. Seventeen participants, nine novices and eight experts, were recruited to perform three abdominal and four cardiac 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 (7 s vs. 26 s, $p = 0.003$) and cardiac (11 s vs. 26 s, $p < 0.001$) 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 (°/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: This study supports the feasibility of a low-cost gyroscope and accelerometer integrated sensor to quantify the biomechanics of POCUS. It may also support the concept of "window shopping" as a method by which experts obtain abdominal

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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.

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 sight implications that limit their widespread use. In addition, analysis of individual probe movements (sliding, rotation, tilting or rocking of the probe), decay of movement over time, frequency of movements, and other potentially important markers of sonographic expertise have not yet been characterized. Together, these movements make up the biomechanical fingerprint of a POCUS scan, which could be compared between novices and experts to help instruct the correct sequencing of probe movements for an individual scan. One example is the concept of "window shopping," which can be used to emphasize the importance of sliding to find an acoustic window before other movements are used to optimize the view. Additionally, with sufficient validity evidence, a low-cost sensor could be used as an adjunct for assessing sonographic expertise.

The objective of this pilot 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/s (°/s). Raw acceleration and angular velocity data were sampled along each axis every 20 ms using an Arduino UNO microcontroller via the I2C protocol. The MPU-6050 was 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 was connected to the ultrasound probe by way of custom 3D printed mount and rubber securing bands (see Figure 1). The sensor was mounted to the phased array probe (1–5 MHz) on a Sonosite™ M-Turbo ultrasound machine. More information on the design, calibration, and initial validation of the sensor is available on OSF (https://osf.io/qd9uw/). Additional information on the degree of measurement error of the sensor can also be found at the same OSF link.

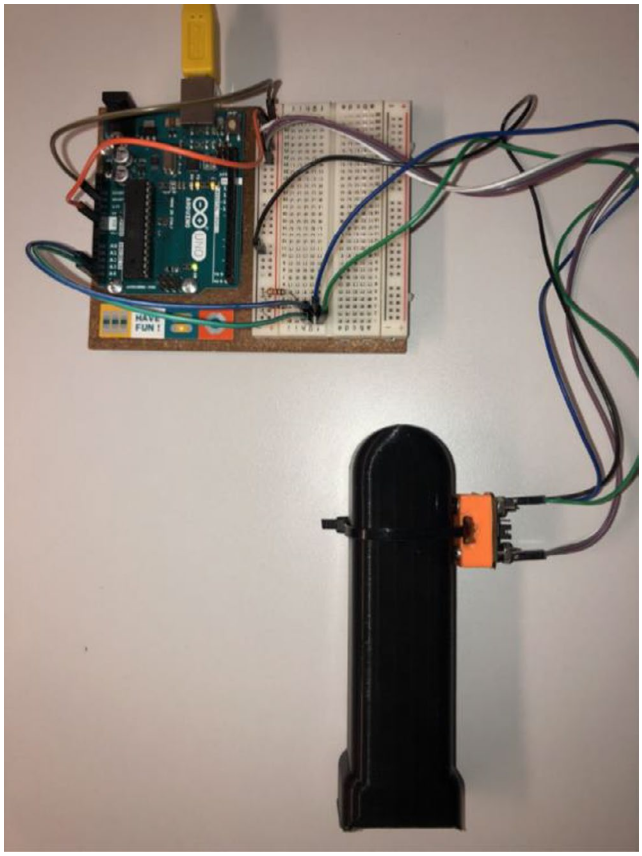

FIGURE 1 Sensor module. Legend: sensor (orange) affixed to a simulated ultrasound probe

Recruitment and participants

A convenience sample of POCUS novices and experts were recruited through e-mails 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. Written informed consent was obtained from all participants.

Novice POCUS practitioners were defined as residents, fellows, or staff physicians who had completed <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, postgraduate 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 Table S3.

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 seven 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 (Tables S1 and S2). Probe movements were recorded until the target view was achieved (as determined by an expert observer) or until 60 s had elapsed. The expert observer was not blinded to the participant identity.

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 (Table S4). 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. This threshold was chosen as it was able to best discriminate novices and experts. To help correlate sensor outputs to probe movements, it is useful to note acceleration is primarily generated during the horizontal translation of the probe over a surface (e.g., sliding), whereas angular velocity is primarily generated through rocking or tilting the probe.

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 Table S5. 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

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[a]
Male, *n* (%)	6 (66.7)	8 (100)	0.21[b]
Postgraduate year of training (PGY), median (IQR)	3 (3–3)	5.5 (4–13.5)	0.003[a]
Completed an ultrasound fellowship, *n* (%)	0 (0.0)	5 (62.5)	0.009[b]
Specialty of practice, *n* (%)			0.006[b]
IM	6 (66.7)	0 (0.0)	
EM	2 (22.2)	7 (87.5)	
Number of supervised FAST scans, median (IQR)	5 (1–10)	50 (50–150)	<0.001[a]
Number of supervised cardiac scans, median (IQR)	5 (3–10)	75 (50–550)	<0.001[a]
Self-reported confidence in performing FAST Scans (Likert[c]), median (IQR)	3 (2–4)	5 (5–5)	<0.001[a]
Self-reported confidence in performing Cardiac Scans (Likert[c]), median (IQR)	3 (2–4)	5 (4.5–5)	0.002[a]

EM, emergency medicine; FAST, Focused Assessment with Sonography in Trauma; IM, internal medicine; IQR, interquartile range.

[a]Mann-Whitney U test.

[b]Fisher's exact test.

[c]Likert: 1 = no confidence, 2 = little confidence, 3 = neither confident nor not confident, 4 = somewhat confident, 5 = very confident.

TABLE 2 Video review scores (median) based on modified UCAT

	Acquisition			Optimization		
Scan	Novice	Expert	*p*-value[a]	Novice	Expert	*p*-value[a]
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; UCAT, Ultrasound Competency Assessment Tool.

[a]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[a]	Novice	Expert	*p*-value[a]	Novice	Expert	*p*-value[a]
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

[a]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[a]	Novice	Expert	*p*-value[a]	Novice	Expert	*p*-value[a]
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

[a]Mann-Whitney U test.

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 2. The data for individual scans are available in Tables S6–S8. Experts had shorter scanning times (s) for both abdominal (7 s vs. 26 s, $p = 0.003$) and cardiac (11 s vs. 26 s, $p < 0.001$) 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 (°/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 experience, these movements become intuitive for POCUS experts[13]; 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 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

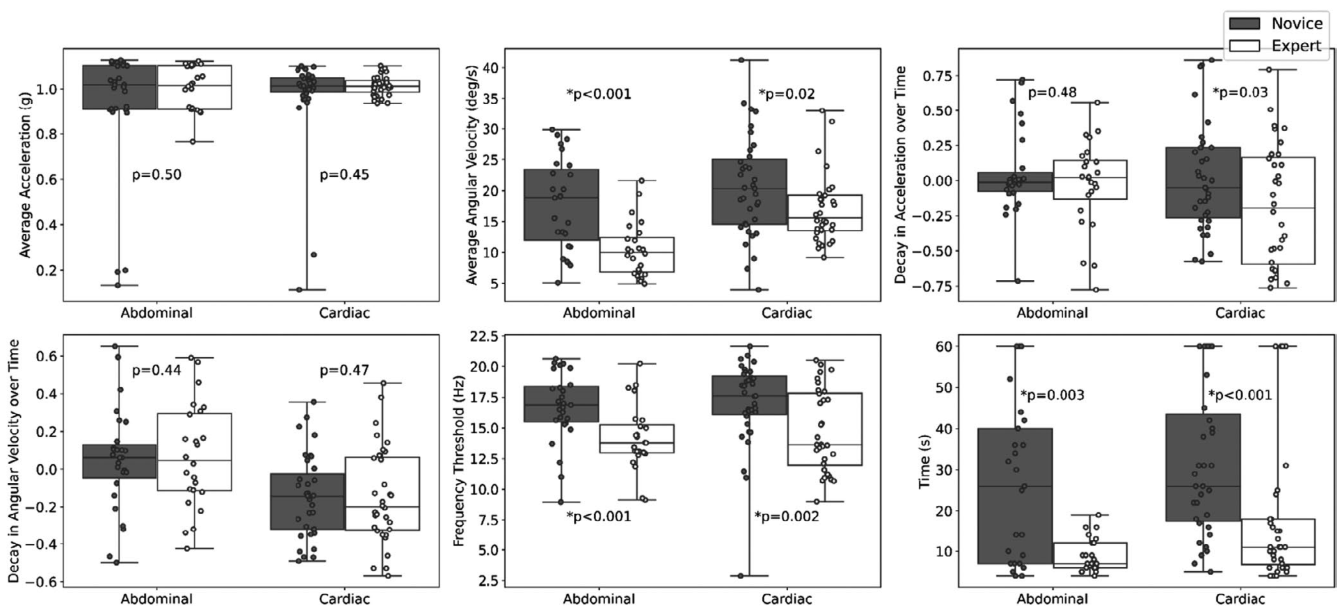

FIGURE 2 Boxplots comparing novice and expert times, acceleration, angular velocity, decay in acceleration, decay in angular velocity, and frequency for abdominal and cardiac scans

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 identified the acoustic window and then used smaller and more deliberate rocking and tilting (angular velocity generating) movements to optimize their view. The differences in acceleration, angular velocity, and diminution of movements between cardiac and abdominal scans also suggests there is not a universal sequence of movements that works for all POCUS scans, but rather that each scan or region of interest might have a biomechanical fingerprint that can be characterized and compared between novices and experts. These fingerprints may vary for each individual patient based on body habitus, positioning, and other pathology.

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 but require a human assessor to be present.[15] This may be feasible at some institutions; however, it 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 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. As well, the expert observer determining the scan stop point was not blinded to participant status, potentially introducing bias. Additionally, the expert participants were on average older than novice participants, which could have led to differences in probe movements. As well, most participants were male, which could have implications for generalizability. Finally, only one standardized patient was used, and the results may not translate to other patients with different body habitus, positioning, or pathology.

CONCLUSION

This pilot study demonstrates biomechanical differences in probe movements between novice and expert POCUS practitioners that can be detected by a low-cost accelerometer and gyroscope integrated sensor. Further research is needed to fully explore the concept of window shopping to determine its value to POCUS educators and learners.

CONFLICT OF INTEREST

None of the authors have financial or other conflict of interests.

AUTHOR CONTRIBUTIONS

All authors contributed to the study design, data interpretation, manuscript writing, and editing. Ross Prager and Timothy Hodges designed and fabricated the sensor and programmed the software used to analyze the sensor data. Matthew Holden also helped analyze the sensor data. Marie-Joe Nemnom and Timothy Hodges performed the statistical analysis.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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