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A pilot study to precisely quantify forces applied by sonographers while scanning: A step toward reducing ergonomic injury

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Abstract.
BACKGROUND: There is a significantly high rate of work-related musculsokeletal injuries in sonography professionals. To date, assessment of risk factors for work- related injuries in sonographers has been based primarily on surveys, subjective reports, and observational methods. There is a need to develop quantitative techniques to better understand risk factors and develop preventive interventions.
OBJECTIVE: We pilot tested a high-resolution force-measuring probe capable of precisely measuring forces applied through the transducer by sonographers and used this novel direct measurement technique to evaluate forces during abdominal imaging.
METHODS: Twelve sonographers with varied experience, ranging from 1–33 years, performed routine abdominal scans on 10 healthy volunteers who had varied body mass indices (BMI). Imaging was conducted using the force-measuring probe, which provided real-time measurement of forces, and angles. Data were compared by sonographer years of experience and subject BMI.
RESULTS: In total, 47 abdominal examinations were performed as part of this study, and all images met standards for clinical diagnostic quality. The mean contact force applied across all exams was 8.2 ± 4.3 Newtons (N) (range: 1.2–36.5 N). For subjects in the high BMI group (BMI>25, $n = 4$) the mean force was 10.5 N (range: 8.9–13.2 N) compared to 7.9 N (range: 5.9–10.9 N) for subjects with normal BMI (BMI = 18.5–25, $n = 6$). Similarly, the mean maximum force applied for subjects with high BMI (25.3 N) was significantly higher than force applied for subjects with normal BMI (17.4 N). No significant difference was noted in the amount of force applied by sonographers with more than 5 years of experience ($n = 6$) at 8.2 N (Range: 5.1–10.0 N) compared to less experienced sonographers ($n = 6$), whose forces averaged 8.1 N (Range: 5.8–10.0 N).
CONCLUSIONS: It is feasible to directly measure forces applied by sonographers using a high-resolution force measurement system. Forces applied during abdominal imaging vary widely, are significantly higher when scanning subjects with high BMI, and are not related to sonographer years of experience. This force measurement system has the potential to provide an additional quantitative data point to explore the impact of applied forces on sonographer related musculoskeletal injury, particularly in conjunction with various body positions, exam types and force durations.

Keywords: Ergonomics, ultrasound, sonographers, injury, force measurement, work-related injury

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1. Introduction

Sonography is often the first line of diagnostic and surveillance imaging for several medical conditions. For quality image acquisition, it is essential that the ultrasound waves propagate into the area of interest, requiring the sonographer or sonologist to optimize the ultrasound wave propagation pathway (i.e., acoustic window). Finding a good acoustic window requires the sonographer to hold the transducer against the patient's body using various positions and angles. Unfortunately, applying pressure through the transducer during image acquisition can result in significant musculoskeletal stress and may lead to an increased risk for musculoskeletal injury [1].

Work-related musculoskeletal disorders are common in the field of sonography with more than 90% of sonographers scanning in pain [2, 3]. Similarly, in Australia and the United Kingdom up to 80% of sonologists have reported having musculoskeletal symptoms [4]. Moreover, according to a report from the US Occupational Safety and Health Administration (OSHA), musculoskeletal disorders accounted for 640,000 annual lost workdays, and as many as 20% of sonographers have an occupational injury severe enough to end their careers [5, 6]. The majority of musculoskeletal symptoms are reported in the shoulders, wrists and hands [3]. These upper extremity disorders and symptoms are primarily due to poor sonographer positioning (e.g., sustained shoulder abduction, wrist deviation) and pressure applied through the transducer, combined with sonographer and patient demographic factors (e.g., years of experience, patient abdominal girth) and the amount of time needed to complete the imaging evaluation [1, 7, 8].

In addition to extensive self-report and survey studies documenting the high incidence and prevalence of upper extremity disorders in sonography professionals, studies evaluating risk factors are becoming more prevalent. Multiple observation based studies have reported poor body positioning of sonographic professionals performing their work, some linking these poor postures to musculoskeletal symptoms [9–11]. Muscle activation patterns during scanning have been measured using motion tracking and surface electromyography, providing quantitative evidence of poor postures and sustained muscle activation of shoulder and hand muscles [12–14]. Although advances in quantitative measures of posture and muscle activation are being actively explored, few studies have attempted to directly quantify the forces being applied to and through the transducer during sonographic imaging.

The paucity of real-time, accurate quantitative metrics to evaluate musculoskeletal risk in sonography professionals hampers the development of technical, educational, and regulatory solutions to this vexing problem. Although there are a multitude of risk factors requiring objective investigation, we developed and pilot tested a device to measure one of these factors: forces applied through the transducer during sonography examinations. The objectives of this study were (1) to evaluate the effect of the external force-measuring device on image acquisition quality, (2) to evaluate applied force variability during routine abdominal sonography, and (3) to relate this variability to sonographer experience and body mass index (BMI) of healthy volunteers being imaged.

2. Material and methods

2.1. Study design

In this prospective study, volunteer sonographers performed abdominal examinations on healthy volunteers of varying body mass index using a force-measuring ultrasound probe. The Institutional Review Boards at the Massachusetts Institute of Technology (MIT) and Massachusetts General Hospital (MGH) approved this study. The study was HIPAA compliant and informed consent was obtained from all subjects who participated in the study.

Twelve sonographers working at our institution expressed interest and were recruited to complete the sonographic scans of the healthy volunteers in the research study. Sonographers presently experiencing musculoskeletal disorders were excluded from participating in the study. To analyze differences related to work experience, the sonographers were split into two groups: "more experienced" (>5 years) and "less experienced" (≤5 years). Ten healthy volunteers agreed to participate in the study. To evaluate correlations between sonographer force and patient size, body mass index (BMI) was calculated for each healthy volunteer using the formula; BMI = weight (in kg)/height^2 (in m). Volunteers were categorized into groups using the following ranges: < 18.5 (underweight), 18.5–25 (healthy weight), 25–30 (overweight), > 30 (obese) [15].

The sonographers performed abdominal sonograms on the ten healthy volunteer subjects on different days over a period of nine months.

Sonographers were instructed to treat the healthy volunteers as they would normal patients, and to follow the standard protocol for acquiring abdominal sonograms at our institution. The 12 sonographers did not perform examinations on the same set of healthy volunteers; instead availability in scheduling led to pairing of individual sonographers with volunteer subjects, resulting variability in the number of healthy volunteers that each individual sonographer scanned. Despite variability, each sonographer completed sonographic evaluations of at least two different healthy volunteers, and each healthy volunteer was scanned by at least two different sonographers.

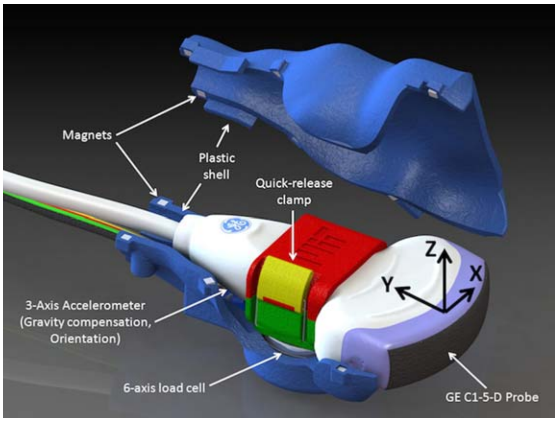

Fig. 1. Rendering of the hand-held force-measuring ultrasound probe, which attaches to a GE C1-5D abdominal probe, and measures the relative forces applied between the ultrasound probe and patient in the X, Y, and Z axes. Force is predominantly applied along the Y-axis.

2.2. Force-Measuring Probe (FM-probe)

A hand-held force measuring device developed at MIT [16, 17] was used to measure the contact forces, and orientation angles of an off-the-shelf GE C1-5D abdominal ultrasound probe (Fig. 1). The device was attached to the transducer via a quick- release, 3D-printed, locking plastic clamp and an outer plastic shell secured via magnets. An ATI Mini-40 six-axis force sensor in the clamp (ATI Industrial Automation, Apex, NC) measured the relative forces applied between the sonographer's hand and the ultrasound probe. Embedded within the plastic shell, an ADXL-335 tri-axial accelerometer measured the orientation of the probe with respect to gravity, and enabled compensation for probe weight. The device increased the thickness of the transducer by approximately 1 cm and the total mass of the device was 200 g, similar to the weight of the ultrasound transducer alone.

The FM-probe's cabling was coupled to the cable of the ultrasound transducer using Velcro strap to reduce excess strain on the sonographer performing the scan. The FM-probe cable was connected to the electronic component housing, which transmitted data to a Dell Inspiron 17R laptop (Fig. 2). During each sonographic exam, a thin layer of gel was applied to the probe face, and then a sterile cover was placed around the system (transducer and FM-probe) to prevent excess gel from entering the electronic components. Forces, and transducer orientation were sampled at a rate of 60 Hz using a custom LabVIEW program running on the laptop. A graphical user interface display provided readings in real time so that the researchers could verify data collection; however, the sonographers were blinded to the laptop display during the conduct of the sonographic evaluation.

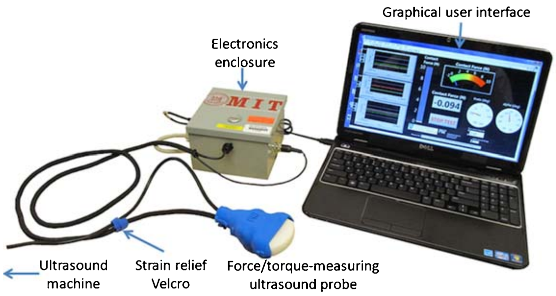

Fig. 2. The complete force measurement system. The ultrasound probe cable is Velcro-strapped to the device cable to provide strain relief. A steel enclosure houses the electronic components while a laptop displays and records the probe contact forces, and angles in real-time.

2.3. Statistical analysis

Maximum force was identified and mean force across the duration of the scan was calculated for each abdominal scan. Descriptive statistics were calculated across the full sample and within groups based upon the healthy volunteer BMI (i.e., normal and high) and sonographer years of experience (i.e., less-experienced and a more experienced), as defined previously. Measures of central tendency in continuous data were described as median (or mean) and range, and categorical data were described as frequencies and percentages. Correlations were explored between force, volunteer BMI, and sonographer level of experience. An unpaired Student's *t*-test was performed to compare the forces applied by members within each group.

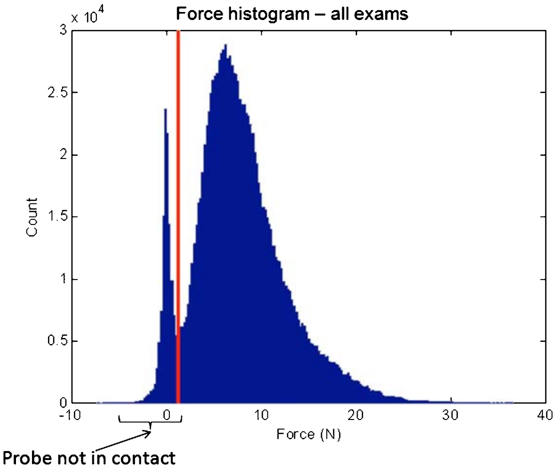

Fig. 3. Histogram of the applied force for all 47 exams. X-axis indicates force range; Y- axis is the number of times that force range was recorded. Force data below 1.2 N, which indicate times at which the probe was not in contact, are neglected.

Both weighted and non-weighted mean forces were calculated. "Weighted" forces are the sonographer forces weighted by the number of exams in which healthy volunteers or sonographers participated. All calculations were conducted with Matlab R2013b. Two-sided p values less than 0.05 were considered statistically significant.

3. Results

The twelve sonographers (M:F = 2 : 10) had a mean experience of 10.3 years (range: 1–33 years), with six sonographers in each of the two experience groups. Sonographers performed an average of 4 abdominal ultrasound examinations (range: 2–6). The 10 healthy volunteers (M:F = 8 : 2) had an average BMI of 26.9 (range: 20.8–36.0). None of the healthy volunteers were underweight (BMI<18.5). Four volunteers fell into the High BMI group and 6 volunteers were categorized as having Normal BMI.

In total, 47 abdominal scans were completed. Images obtained from all scans were noted to be of adequate diagnostic quality, indicating the use of the FM-probe did not impact the ability of the sonographers to conduct their examinations. A histogram of the forces applied in all 47 exams is shown in Fig. 3. Although the distribution is biased towards lower forces, two prominent peaks are noted at 0 N and 5.8 N. The peak at 0 N is produced by periods during which the probe was not in contact with the healthy volunteers' skin, and therefore no force was exerted. There are a small number of measurements below 0 N due to a combination of signal noise and possible traction on the ultrasound transducer cable during scanning. To eliminate data from the times when the probe was not in contact with the volunteer all forces below 1.2 N (thick red line) were disregarded.

Average forces and mean maximum forces across the full sample, and stratified by sonographer experience and volunteer BMI group are presented in Table 1. The range of forces applied by sonographers across all exams was 1.2 N to 36.5 N with a mean of 8.2 N (SD, 4.3 N), and median of 7.4 N. The maximum force applied by any sonographer was 36.5 N, which was 6.7 standard deviations above the mean force. A scatter plot of sonographer years of experience versus mean contact force is shown in Fig. 4. No significant differences were noted in the average forces and mean maximum forces applied by sonographers with different levels of experience. Average forces and mean maximum forces applied by the less experienced were 8.2 N and 18.7 N, as compared to 8.1 N and 19.1 N by the more experienced sonographers, respectively.

In contrast to finding no differences based on sonographer years of experience, differences were noted in forces applied based on volunteer BMI. Mean force differences between the two BMI groups approached significance (High BMI, 10.5 N; Normal BMI, 7.9 N; $p = 0.056$), and the mean maximum force of 25.3 N applied by sonographers when scanning volunteers in the High BMI group was significantly higher than the mean maximum force applied in the Normal BMI group (17.4 N, $p = 0.019$). A scatter plot of the mean force for each of the 47 exams versus volunteer

Table 1
Mean axial forces across the full examination and mean maximum axial forces applied during abdominal examinations by sonographer experience and healthy volunteer BMI groups

Group	Mean Axial Force, N			Mean Maximum Axial Force, N		
	Average	Range	p-value	Average	Range	p-value
Less Experience ($n = 6$)	8.2	5.1–10.0	0.881	19.1	11.6–26.0	0.792
More Experience ($n = 6$)	8.1	5.8–10.0		20.1	11.1–22.8	
Normal BMI ($n = 6$)	7.9	5.9–10.9	0.056	17.4	14.1–20.8	0.019
High BMI ($n = 4$)	10.5	8.9–13.2		23.7	19.3–29.9	

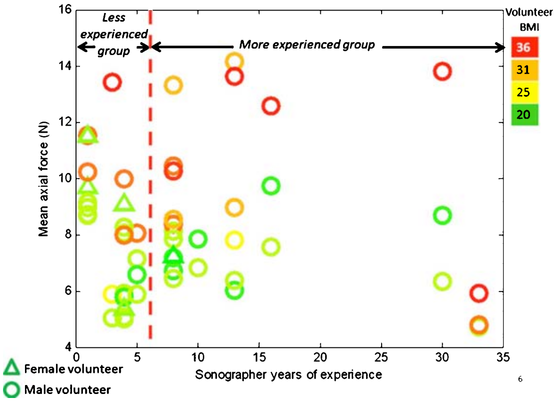

Fig. 4. Mean contact force versus years of sonographer experience, with each icon colored with respect to healthy volunteer BMI.

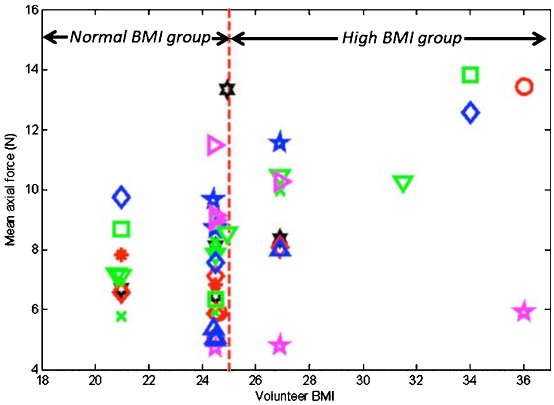

Fig. 5. Mean axial force applied by individual sonographers plotted by the BMI of each healthy volunteer subject within the normal and high BMI groups. Each unique icon represents a unique sonographer.

BMI is shown in Fig. 5. While most sonographers apply different forces for different patients, analysis of the scatter plot indicates that some sonographers (e.g., pink triangle and blue star) apply consistently higher forces, while others (pink star) apply consistently lower forces despite the BMI of volunteer being scanned. When the contact forces are averaged for each healthy volunteer, the force versus BMI characteristics are shown in Fig. 6. In this plot, higher forces are correlated with increasing BMI, as evidenced by the trendline ($y = 0.32x + 0.5$, $R^2 = 0.61$).

When force applied by sonographers was weighted by the number of exams in which volunteers and sonographers participated, the findings held. Force applied by experienced sonographers averaged 8.3 N (18.4 N max), similar to the less experienced sonographers who averaged 8.0 N (19 N max). Statistically

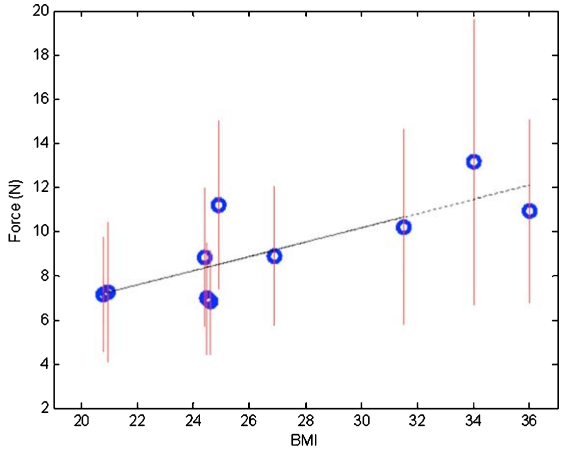

Fig. 6. Mean contact force by BMI of each healthy volunteer subject. Blue circles indicate average force applied for each subject ($n = 10$), red lines span ± 1 standard deviation, and the black line indicates best linear fit ($y = 0.32x + 0.5$, $R^2 = 0.61$).

significant differences ($p = 0.05$) were noted by BMI group, with mean contact force of 9.8 Newtons (N) (22.4 N max) for subjects in the high BMI group and 7.5 N (17.3 N max) for subjects in the normal BMI group.

4. Discussions

We measured the axial forces applied during abdominal sonography by a number of sonographers on healthy volunteers using a force-measuring device. This force-measuring ultrasound probe (FM-probe) attaches to an off-the-shelf abdominal transducer and has been shown to measure forces accurately to 0.35 Newtons [16]. The device was used to record axial forces in 47 abdominal sonography examinations involving 12 professional sonographers with varying level of experience and 10 healthy volunteers with a range of BMI's. This study has two important findings related to musculoskeletal symptoms and development of work-related musculoskeletal disorders in sonography professionals: (1) sonographers use of force is highly variable and independent of years of experience and (2) higher forces are used when scanning patients with higher BMI.

With our direct, real-time FM-probe, we found sonographers performing similar abdominal examinations use a wide range of forces from 1.2 N to 36.5 N with a mean axial force of 8.2 N (SD, 4.3 N). In their study, Burnett and Campbell- Kyureghyan [18] reported maximum axial forces for abdominal imaging ranging between 8.7 N and 65.5 N. Habes and Baron [10] noted similar findings with average axial forces ranging between 11.6 N and 21.4 N, average peak forces at 37.8 N and a maximum peak force of nearly 65 N. In these two previous studies, force was measured using force gauges (e.g., Ergo Fet 300) during scanning simulations. Using the real-time FM-probe to directly measure axial force during scanning resulted in a narrower range of forces across the actual scanning, as well as lower peak forces at about 60% of the maximums obtained in through simulation in previous studies. Using a FM-probe to obtain real-time measurement of forces during sonographic imaging provides a more valid and potentially more accurate measurement of force than simulations.

Musculoskeletal injuries and disorders in sonography professionals have been attributed to numerous factors related to equipment (e.g., equipment design), [19] sonographer/patient demographics (e.g., work force aging), [3] and administrative factors (e.g., increasing patient volumes) [5]. Our study evaluated the relationship of force to two potential mediating factors, sonographer experience and patient BMI. Although we expected sonographer experience to be related to force, as has been documented in previous studies, [20] no significant differences were noted in our direct measure of axial force based on sonographer experience in our study. In contrast, our study, does support previous reports indicating that sonographic forces increases as patient BMI increases [20]. Mean and maximum axial forces were found to be significantly higher when scanning healthy volunteers with high BMI compared to those with normal BMI. Given the high prevalence of obesity in adults and children in our society, respectively at 34.9% and 16.9%, [21] the contribution of forces to the development of work-related musculoskeletal disorders in sonography professionals is highly likely and needs to be studied in future studies.

The ability to directly measure axial force with the FM-probe provides an opportunity to begin exploring the relative impact and interrelationship of force along with other quantitatively measured risk factors during imaging. Newtonian mechanics implies that the forces measured in our study are the same as those applied to the sonographer's arm during the scanning process. However, use of electromyography to evaluate the actual muscle activation patterns that coincide with these forces, [12, 14, 18] along with motion tracking to document joint positions [13] can provide a robust assessment of the biomechanical factors involved in sonographic imaging. Moreover, in addition to axial forces through the transducer, direct measurement of grip forces required to hold the transducer – which can be in excess of 100 N – should be explored [22].

In additional to describing the relationship of these factors to one another, future prospective studies will need to ascertain how variation in forces and body positions correlate with musculoskeletal symptoms and injuries in sonography professionals. Identifying salient risk factors or specific position/force thresholds is an important step for developing effective educational training [23]. These quantitative methods (e.g., electromyography, force measurement) may be of additional use in developing biofeedback techniques as a preventive intervention for musculoskeletal disorders in sonography professionals.

Our study has several limitations: (1) Even though all sonographers imaged healthy volunteers with variable BMI's, not all sonographers imaged the same group of healthy volunteers. Given the heterogeneity of body morphology in individuals, an ideal study would have a fixed number of healthy volunteers in whom the same set of sonographers can perform an equal number of examinations. (2) The sonographers were blinded to the graphical display of contact forces, but prior knowledge of the study objectives may have biased their mechanism of performing the abdominal sonography examination. (3) The FM-probe marginally increased the dimensions of the probe, which could have affected the way sonographers applied forces during the abdominal examinations. (4) We studied variation in forces for an abdominal examination that consists of several sub-components such as scanning the liver, gall bladder, spleen, pancreas, kidney and abdominal vessels. Different sonographers may have slightly variable techniques to measure different organs and hence maximum and mean contact forces measured in this study may require additional evaluation specific to individual organs.

5. Conclusions

This study provides preliminary supporting evidence for the use of a force-measuring probe to directly measure real-time forces applied by sonographers during scanning. Specifically, our data indicates that forces applied during abdominal imaging varied by sonographer, and although independent of sonographer experience, forces were positively correlated with patient BMI. The ability to quantify forces in real-time provides a first step towards the valid and accurate measurement of forces applied by sonographers and could be an additional data point to study workplace injuries amongst sonography professionals.

Conflict of interest

None to report.

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