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ABSTRACT
For more than two decades, surveys of imaging technologists, including cardiac sonographers, diagnostic medical sonographers and vascular technologists, have consistently reported high prevalence of work-related musculoskeletal discomfort (WRMSD). Yet, intervention research involving sonographers is limited. In this study, we used a participatory approach to identifying needs and opportunities for developing interventions to reduce sonographers' exposures to WRMSD risk factors. In this paper, we present some of those needs. We include descriptions of two interventions, targeted for cardiac sonographers, that were developed, through an iterative process, into functional prototypes that were evaluated in pilot tests by practicing sonographers. One of these interventions is now in daily use. We would like other engineers and ergonomists to recognise this area of opportunity to apply their knowledge of biomechanics and design in order to begin to address the high prevalence of WRMSDs in sonographers, by working with sonographers to develop useful and usable interventions.

Practitioner Summary: This paper discusses needs, opportunities and methods for working with sonographers in order to develop interventions to reduce their exposure to risk factors for work-related musculoskeletal discomfort. Results from field tests of two novel interventions targeting cardiac sonographers are also presented.

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1. Introduction

Cardiac sonographers (CS) are health care professionals who perform medical ultrasound imaging of the heart (i.e. an echocardiogram). A patient examination may take 15–45 min (Evans et al. 2010), depending on the amount of images, measurement and annotation required, as well as challenges posed by the patient's anatomy. Most exams are performed in outpatient clinics or hospital patient rooms; some are performed in other locations in the hospital. Handheld transducers (aka probes) used by CS tend to be smaller in cross-sectional area than those used in other types of sonography.

Published studies consistently report musculoskeletal (MSK) symptom prevalence of 50–80% in surveyed CS, which is similar to symptom reports for diagnostic medical sonographers (DMS) and vascular technologists (VT) (Claes, Berger, and Stassijns 2015; Evans et al. 2010; McCulloch, Xie, and Adams 2002; Smith et al. 1997; Vanderpool et al. 1993). The majority of studies of CS and other types of sonographers have been cross-sectional surveys, conducted to assess morbidity, describe work activities and identify risk factors that may contribute to the high prevalence of MSK symptoms. In one of the few studies to involve only CS, Smith et al. (1997) identified three factors that differed between survey respondents with and without MSK pain, including stature, number of exams performed each month and exam duration. From other studies of the general population of sonographers, factors associated with MSK pain in multiple studies include shoulder abduction, applying sustained pressure with the hand-held transducer, forceful gripping of the transducer and scanning larger patients (Friesen et al. 2006; Muir et al. 2004; Russo et al. 2002). Average push and grip forces on the transducer have been estimated to range from 1 to 8 kg, depending on the scan type and location (Burnett and Campbell-Kyureghyan 2010; Village and Trask 2007).

Recommendations for interventions to reduce the exposure of sonographers to risk factors for work-related MSK symptoms have been published in peer-reviewed

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journals (Muir et al. 2004), by professional societies (Australasian Society for Ultrasound in Medicine 2001; Society of Diagnostic Medical Sonography 2003) and by government agencies (Habes and Baron 1999). Horkey and King (2004) conducted a study of the impact of various recommended interventions in cardiac sonography. What is notable about the 19 interventions on their list is that none of them directly address the forceful exertions that are often necessary to achieve high-quality echocardiograms and are also associated with MSK pain, as described above. Also notable is the fact that new surveys of MSK pain in sonographers continue to be published (Claes, Berger, and Stassijns 2015), in spite of existing intervention recommendations, which suggests that these interventions are not being adopted or are in other ways insufficient to impact the prevalence of MSK pain in sonographers.

The objective of the current study was to involve CS in a participatory process of identifying problems they experience at work that they associate with physical stress and musculoskeletal discomfort and develop ideas, in partnership with them, for interventions that are biomechanically effective and viewed as useful, usable and desirable by the CS and feasible to implement by managers. This effort was part of a larger study, the goal of which was to develop interventions with and for five types of imaging technologists: CS, DMS, VT, mammographers and radiographers.

In part 1 of this paper, we describe the needs assessment and concept review phases of the study. In part 2 of this paper, we describe pilot studies and field trials of some intervention prototypes. The paper's main focus is CS, but the paper includes some elements of the study pertaining to VT and DMS, because a number of concerns and challenges are common to all three types of sonographers.

2. Part 1 – needs assessment and concept review

2.1. Methods

Data were collected from study participants in two sequential phases: needs assessment (phase 1) and intervention concept review (phase 2). Thirteen sonographers participated in both phases and 17 participated in one or the other of these two phases.

2.1.1. Phase 1: needs assessment

2.1.1.1. Study participants. Participation involved workbook preparation in advance of a data collection session that included a focus group discussion and an intervention idea generation collaborative activity. There were 20 participants (16 women, 4 men; with 6 months to 32 years of experience in sonography); each participated in one session. Two sessions were devoted to DMS (nine participants in total), one session to CS (five participants) and one to VT (six participants).

2.1.1.2. Procedures and data collection. Workbooks were designed to elicit information on the participant's background, organisation of their work tasks and descriptions of their work environment, equipment and patients. Preparing and submitting workbooks in advance of the session provided participants an opportunity for reflection and priming; reviewing workbook contents in advance allowed researchers to include examples of each participant's concerns in the discussion.

Each session consisted of four elements: introductions, review of some workbook entries and discussion of selected workbook photographs submitted by participants, (issues) card sorting and voting to identify participants' most important challenges based on issues they had just discussed and intervention idea generation. The latter element was conducted from the viewpoint of design as co-creation, in which researchers provide tools to non-designers to use to express their needs and solution ideas creatively. Sanders (2002) described this participatory methodology as a manifestation of 'a belief that all people have something to contribute to the design process and that they (non-designers) can be both articulate and creative when given appropriate tools with which to express themselves'.

2.1.1.3. Data analysis

Phase I data were analysed separately for each type of sonographer. Workbook entries were entered in spreadsheets to facilitate review, researchers made notes from audio recordings of the discussions and generative element presentations and photos and video were analysed for thematic and specific content. Through detailed review of these materials (grounded theory analysis), a document was created for each type of sonographer, which was organised by a number of major categories (such as Patient room design, Patient handling, Obesity and positioning, etc.), that emerged from the data. Within each category, every expressed need was listed, along with its source (audio recording, workbook entry, etc.), the interpretation of that expressed need, initial intervention ideas to address the need, an initial rating of the feasibility of prototyping and/or testing the intervention idea and the researcher's comments. Two researchers assessed data from each group of sonographers. Each researcher independently completed his/her analysis and then each pair of researchers worked together to develop an analysis for their sonographer group, based on consensus, which they presented to the research team for further analysis, discussion, and, finally, group consensus.

2.1.1.4. Intervention concept generation

The next step was to develop intervention categories (for example, reduce strains associated with portable exams – administrative controls; reduce strains associated with portable exams – engineering controls; address lack of arm support and awkward postures when scanning; etc.) along with a list of intervention concepts for each category and sonography group. Various types of brainstorming techniques, internet searches and literature searches were employed to generate intervention concepts. The next step was to refine and reduce the number of concepts to those that were most promising, viable and within the scope of the study. These concepts were then discussed with the sonographers in a concept review session (Phase 2).

2.1.2. Phase 2: concept review

2.1.2.1. Study participants. Six DMS, 12 VT, and 6 CS participated in this phase of the study (23 female, 1 male; 1–32 years of experience). Eleven participants were new to the study.

2.1.2.2. Procedures and data collection. Concept posters and some physical prototypes were presented to the participants who used evaluation forms and discussion to convey their opinions of the usability, usefulness and desirability of each concept, potential barriers they foresaw to using or implementing them, and improvement suggestions. Time was allocated for each concept, which included presentation of the concept to participants, question time and time for completing the evaluation form. CS and VT groups each reviewed 15 concepts and DMS reviewed 14. Hands-on interaction and role-playing were encouraged where prototypes were present. Once participants completed their evaluation form, the next concept was presented.

Usability items on the evaluation form addressed ease of use and ease of learning to use; usefulness items addressed predicted effects on sonographer's physical effort, fatigue, and efficiency and patient comfort; desirability items addressed level of interest in using the intervention by the participant and co-workers. Participants used a 5-point fixed response scale with a verbal anchor at each end ranging from strongly agree to strongly disagree to respond to each statement. Participants also provided an overall rating of each category, with a verbal anchor at each end, using a 1 (very poor) to 7 (very good) range. Example: 'My overall rating of its potential usability is ____'. At the end of the session, participants were asked to indicate which concepts should continue to be developed or pursued. They were each given six green voting dots to allocate to whichever concept(s) they chose.

2.1.2.3. Data analysis

Phase 2 data were analysed separately for each type of sonographer. Evaluation form entries were entered in spreadsheets to facilitate their review. Median values and spreads of scores were calculated for each statement. The number of green dots and barriers were counted and were normalised to provide counts per participant for each concept.

2.2. Results

2.2.1. Phase 1: needs assessment

Nineteen of the twenty sonographers reported experiencing work-related MSK discomfort. When asked to describe the most physically demanding exam or procedure they perform on a regular basis, and reasons that made the exams so demanding, these factors were repeatedly identified: repeated and/or continuous forceful pushing with the transducer (particularly for obese patients), patient position, awkward work postures and moving furniture in patient rooms to make room for the ultrasound equipment and sonographer. Estimates of percentages of their patients that were heavy or obese, as determined by the sonographers, ranged from 30 to 90% (VT and DMS) and 30–60% (CS).

The main themes that emerged during the four focus group discussions demonstrated some overlap between groups and some sub-specialty-specific concerns. Common issue clusters across all the groups of sonographers included portable exams, equipment design (keyboard, transducer), exam room design, patient room design, workload and time pressure, body strain and patient characteristics (primarily obesity). Unique issue clusters also appeared: exam table design (CS) and transvaginal exams (DMS). The needs assessment analysis for the CS is summarised in Table 1; needs in common with DMS and VT are so marked.

Brainstorming and other idea-generating activities yielded a total of 44 intervention concepts to address the interpreted needs of the CS. After categorising these concepts as either low-hanging fruit, blue sky, or somewhere in between, and either within the scope of the project, close, or out-of-scope, the screening analysis yielded 15 intervention concepts to present to the CS (see Table 2).

Results from the CS evaluation forms are summarised in Figure 1. For each concept, results include overall scores of potential usefulness, usability and desirability (scale 1–7), the number of "go forward" green voting dots received, and the number of barriers noted normalised to the number of participants.

Table 1. Results of needs assessment analysis of Phase 1 data from cardiac sonographers (CS).

Issue Category	Issues and needs
Ultrasound equipment	
Gel holder on ultrasound machine cart	• Current gel warmers for portable scans are inadequate. Should be able to access gel (bottles) easily and comfortably*
Ultrasound machine cart for portable exams	• Inadequate space to organise/store supplies for portable exams (gel, electrodes, cleaning wipes, gloves, etc.)* • Cart should roll easily (big and small machines); be stable so it does not tip over; small cart footprint for small machines* • Ultrasound machine (computer) on cart should be adjustable in height and orientation* • Back-up battery for work efficiency*
Ultrasound machine (computer) interface	• Poor design of menus (too many, not organised to support work)* • Poor design of keyboards (keys not clustered to support use; buttons and keys in awkward locations) increase sonographer's mental and physical workload and reduce efficiency* • Glare on display screen causes problems during exam*
Ultrasound machine (computer)	• Quick machine and software start-up is essential for stat echocardiograms
Transducer design	• Cord management (length, weight, cleaning)* • Lighter weight transducers, right-sized for sonographer's hand and type of exam* • Design should aid sonographer in grasping with less force, and without discomfort (indentations can hurt fingers)* • 3D transducers are too large and heavy*
Patients	
Heavy/Obese patients	• Must push harder with transducer to get image; requires more force from arm/shoulder and more grip force on transducer* • Smaller sonographers who scan right-handed have to reach very far to scan larger patient • Need equipment or other means to assist some heavy/obese patients to get into appropriate position for exam
Patient with large breasts	• Weight of the left breast is on top of the sonographer's hand while acquiring apical images. (Note: Breast weight can be approximated at 0.75–1% of body weight, though correlation with bra cup size is much stronger (Brown et al. 2012; Katch et al. 1980).)
Patient handling	• Need equipment or other means to assist some patients on/off exam table* • Once patient is on exam table, need equipment or other means to assist some patients with disabilities to get into appropriate position for exam
Environment	
Furniture	• Moving furniture in patient rooms is physically strenuous and inefficient*
Medical equipment	• In the patient's room, ventilators and other equipment that sonographers are not permitted to touch is often located where the sonographer or her equipment needs to be positioned, resulting in sonographer adopting awkward compensating postures to scan the patient*
Patient room design	• Small rooms require sonographer to move furniture away from bed* • Outlets – more are needed and in accessible locations (between hip and shoulder height)* • Lighting control – more access points and individual control* • Wide doorways facilitate movement of all equipment, including ultrasound* • Lack of appropriate seat for scanning, so sonographer stands during portable exams (can be 30–40 min long and one exam performed right after another)
Exam room design	• Doorway width should accommodate patient beds – eliminates need to transfer patient to exam table (reduced patient handling exposure, reduced risk of patient injury) *
Exam table/cart for patient	• Adjustability in height and access to heart improves exam quality, efficiency and comfort for patient and sonographer
Other	
Workload/scheduling	• Exam scheduling does not account for patient characteristics that can lengthen exam time*
Connectivity	• Need for reliable connectivity throughout hospital, to upload portable exams to server (for radiologist to interpret); improved work efficiency* • Access to prior exams from anywhere in the hospital*

Note: Needs marked with asterisk (*) are shared with DMS &/or VT.

While many concepts were evaluated as having potential by the concept review participants, after analysing the results from the concept review sessions for each group of imaging technologists, an 'A' list of 10 most promising concepts were identified and pursued for the remainder of the study. In Part 2 of this paper, further work is described concerning two of the 'A' list items that address particular needs of the CS.

3. Part 2 – prototype development and pilot testing

Portable Seating received fairly high scores from the CS, and was thought to be readily implementable by the researchers and therefore was chosen as one of the 'A' list items. The transducer positioner and holder and the system to assist with pushing the transducer concepts were not as highly rated by the CS and posed significant design challenges. However, together, they addressed fundamental exposure problems associated with upper extremity MSK symptoms in CS: prolonged pinching, forceful exertions, awkward scanning postures and static postures. The development of both concepts into functional, testable prototypes was a collaborative effort between the researchers and the CS, sometimes involving informal solicitation of ideas and feedback, and other times more structured evaluation in the form of field testing or more controlled laboratory-based assessment.

3.1. Portable seating

3.1.1. Rationale

CS perform ultrasound examinations of patients' hearts throughout the hospital, not just in a cardiology clinic. In the clinic, CS typically sit when performing these somewhat lengthy exams (15–45 min). However, when they take an ultrasound machine out of the clinic, to perform an examination of a patient in a hospital room, the emergency department, ICU, procedure room or other location in the hospital, the scan is performed while the sonographer stands. A CS may perform several portable exams before returning to the clinic, which could mean that she is on her feet for several hours without a break. Sometimes a chair is available in a patient's room, but these chairs are not ideal for scanning, because they are not height adjustable, may have arm rests that keep the sonographer at a distance from the patient or may be in use by visitors.

Through focus group sessions and subsequent informal and more formal interactions with the CS, a portable chair system was developed consisting of a holder that was mounted to a specific model of cart-mounted ultrasound machine and a folding, height-adjustable chair. The CS chose the chair from among four stable, lightweight, height-adjustable folding chairs that the research team identified as being potentially mountable to a portable ultrasound machine cart. The CS also provided important feedback and suggestions on design of the holder, which went through several iterations before being judged acceptable by the CS.

3.1.2. Prototype evaluation

A pilot field study involving six CS was conducted for a period of three weeks. Chair holder attachment kits were installed on carts of two portable (laptop-size) ultrasound machines that were being used daily for portable exams conducted outside of the clinic. A portable chair was positioned in each holder. Prior to data collection, potential CS research participants were given a demonstration explaining how the portable chair system worked, as well as how to complete the chair use data forms. Informed consent was provided by the CS who volunteered to participate in the field study.

The research participants were asked to consider using the portable chair when opportunities for use occurred. They were asked to describe situations where the chair could or could not be used. Data forms were completed when the CS returned to the clinic. Blank data forms were kept on the machine, for easy access. Completed forms were deposited in a locked dropbox in the clinic breakroom.

The CS were asked to provide the following basic information on the data form: date, number of patients scanned in that specific run and the location of the run. Then, the research participants were asked to mark whether or not they had opportunities to use the portable chair on the run. If they did not use the chair, they were asked to write down the barriers to use. If they did use the chair, they were asked to evaluate the usability, usefulness and potential barriers in using the chair, relevant to that run. After the data collection period ended, a focus group session was conducted to collect the participants' feedback in greater depth and detail.

3.1.3. Outcome

Research participants reported scanning 1–7 patients in a run. Runs took them throughout the hospital, including patient rooms, ICU, SICU, MICU and the Cardiac Catheterization Lab. Overall, the research participants gave positive feedback on the portable chair system; average usability and usefulness ratings (1–5 scale) were 4.9 and 4.8, respectively. The portable ultrasound machine cart was still easy to steer with the chair mounted on it. It was reported that the chair was helpful during scanning, post-scan image analysis and while waiting during procedures. During the scan, the portable chair was used in places where chairs were not available or were occupied by family members or other health care staff members. The chair reportedly reduced awkward scanning postures, as well as providing a more comfortable seated scan. The portable chair was viewed as sturdy and provided sufficient height adjustment for shorter and taller CS (participant height ranged from 157 to 188 cm). The portable chair was also used after scanning, while the CS were post-processing images acquired during an examination. In addition, the portable chair was reported to be used during procedures that required several steps, of which the heart sonogram was just one. While other steps of such procedures were occurring, the CS was able to sit while waiting for the time when he/she was needed to perform the heart sonogram.

There were also situations when the portable chair was not used. These included instances of short scanning time period, when performing a stat echocardiogram procedure, as well as when there was not enough space to set up the chair. There were also comments provided concerning power cord management. Specifically, the upper part of the chair holder system was attached to a part of the machine cart that the CS normally used to store the power cord. This problem was identified early in the field trial and corrective action was taken. In the focus group that followed the field trial, research participants mentioned that the corrective solution worked well and power cord management ceased being an issue for them.

The run cards were also useful for capturing user experience. Examples of participants' comments:

Table 2. Concepts presented to the cardiac sonographers (CS) in the concept review session.

Concepts	Existing	New	Interpreted need
Devices to create space for transducer	1 & 1-new use **		Optimise scanning area access and create space for sonographer's hand and transducer when patient is not on specialised exam cart
Drop-out cart	Several		Provide space for the transducer, in order to reduce effort required to position transducer when cardiac ultrasound exam is performed in clinic
Patient torso support – inflatable wedge		1	Help patient roll onto side and maintain desired body position during exam
Breast support devices	1	3	Support weight of breast during exams
Devices to manage transducer ('probe') cord *	1	2	Keep cord from contacting patient's bed, floor; reduce inclination to wrap cord around sonographer's neck
External motor for ultrasound machine *	2 – new use **		Reduce effort required to move ultrasound for portable exams
Arm support devices for sonographer *	1	2	Reduce static loading in the shoulder while scanning
Transducer positioner and holder		3	Reduce requirement for sustained static pinch grip on transducer and static upper body posture during scans
System to assist with pushing transducer against patient		3	Reduce amount and duration of manual force exertion required during cardiac ultrasound scans
Textured material or rings to improve finger–transducer interface *		2	Reduce loading on sonographers by improving hand–transducer interaction
Portable seating or sit/stand support	Several – new use **		Enable sitting and/or sit/standing during portable exams
Anterior torso support for sonographer *	Several		Provide alternative postures for scanning during longer exams; provide support for torso; eliminate interference from chair arms
Wheels for furniture *	2		Facilitate moving furniture in the patient room
Patient transfer station in clinic *		1	Reduce manual patient transfers and reduce number of portable exams
Position support aids for patients *	3 – new use **		Provide means for patient to assist in positioning themselves on exam table (laying down, rising, moving into/changing position)

Notes: 'Existing' indicates the number of existing solutions that were presented. 'New' indicates the number of new solution concepts that were presented.
**Indicates new application of an existing product.
*Potential to also benefit DMS &/or VT.

> I scan right-handed. Didn't use the chair during the scans, but did use it during post processing. Nice to sit after a tough scan.

> chair is perfect for the small rooms in the hospital. I even use it in the hallway at the computer for data entry.

> pt A: this was a stat echo - no time for setting up chair.—— pt B: it worked great for b pt. I was in a small room the chair was perfect. No other chair could fit

The next two comments were from the same CS, and demonstrate the importance of giving users time to acclimatise to new tools and methods:

> Slows me down too much + not worth to set up. (28 August)

> Dialysis RN sitting in chair, I was able to use the portable chair, very nice. (6 September)

3.1.4. Current state of this intervention concept

As a result of the positive response the portable chair system received from the CS who participated in the field study, the portable chairs have become fully incorporated into the work methods of the CS at the participating hospital. The portable chair system underwent two more rounds of design improvement after the field study. The goal was to eliminate the holder mounted on the ultrasound cart, in order to make it possible to attach the chair to any portable ultrasound cart that has two handles (one fore and one aft). The field tested system and the current version of the system are shown in Figure 2. Modifications were also made to the chair, to strengthen the parts of it that provide the continuous height-adjustability feature.

3.2. Articulating support arm system for transducer

3.2.1. Rationale

The objective for this intervention was to reduce exposure to four risk factors associated with upper extremity MSK symptoms in CS: prolonged pinching, forceful exertions, awkward scanning postures and static postures. The four identified issues were then translated into design specifications. After the concept review session a functional prototype was developed based on discussions with the cardiac sonographers. Several existing articulating arms, used for other purposes, were investigated. An articulating arm manufactured by Civco Medical Solutions (Kalona, Iowa; Model number 810–200) came closest to the solution concept the design team envisioned. It is an articulating arm connected by ball joints, and can be locked in position. It

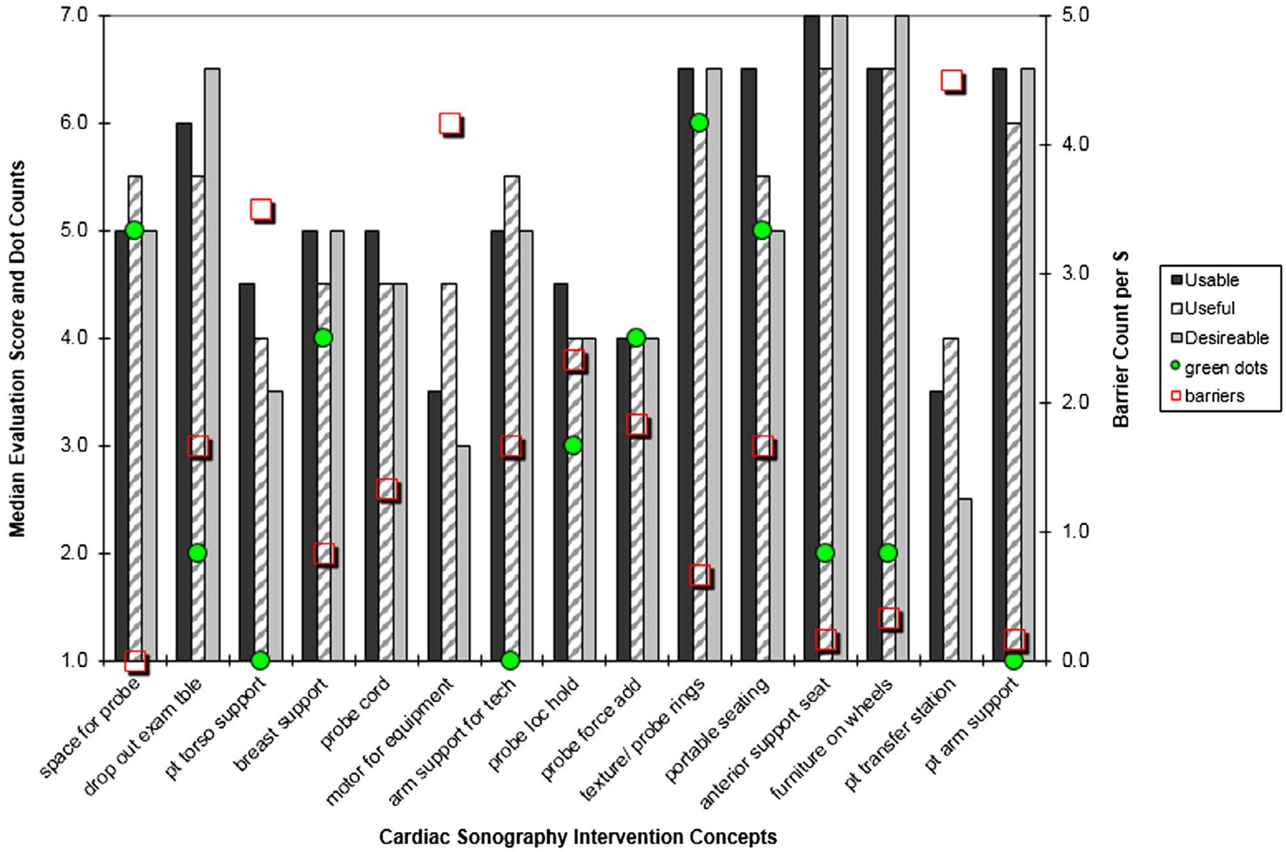

Figure 1. Cardiac sonographers' evaluations of intervention concepts.

is currently marketed for holding an ultrasound transducer in a fixed location during ultrasound-guided medical procedures. A new transducer holder and a new mounting stand were fabricated by the research team to facilitate dynamic use in an echocardiography clinic setting. The intervention is intended for echocardiographers who scan with the left hand. (Note: This is the preferred method, because right-handed scanning requires the sonographer to wrap his/her right arm around the patient, which requires pronounced shoulder abduction, effortful reaching and requires that the patient's back faces the sonographer.) The prototype system was designed to meet the following product specifications:

(1) Reduce the duration of pinch gripping: the end effector of the articulating arm holds the transducer, thus reducing the need to grip the transducer continuously.
(2) Reduce overall duration of force exertion: by utilising the locking feature of the articulating arm, the need to maintain the pushing force manually at all times is reduced.
(3) Reduce awkward upper extremity postures: by utilising the locking mechanism, the sonographer can reposition him/herself into a more neutral posture from an awkward posture that may have been required to initially position the transducer in the correct location; the sonographer can also perform small adjustments to the transducer via the articulating arm, rather than reaching across his/her own body with the right hand to grasp the end of the transducer held by the left hand.
(4) Minimise the need to maintain static posture of the left (scanning) arm: once the scanning window is found and a quality image is obtained the locking mechanism can be engaged to hold the transducer in position, minimising the need to sustain the posture of the left arm.

The articulating arm solution also supports the cord of the transducer, and as such addresses concerns related to cord management (Tables 1 and 2). The prototype system appears in Figure 3.

Two rounds of pilot testing were conducted. Both rounds were conducted in an ultrasound clinical setting and involved six experienced CS scanning healthy male adults who volunteered to serve as patients. Two of the CS participated in both pilot sessions, which were conducted several months apart.

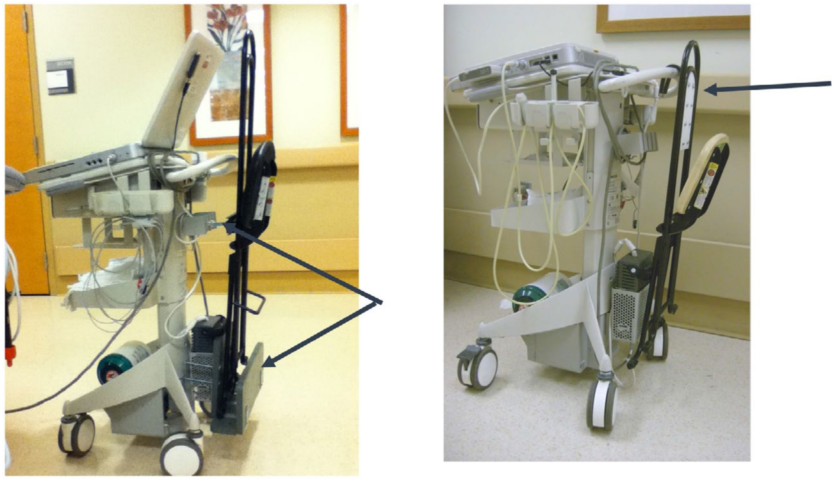

Figure 2. Field-tested portable seating system (left) and current seating system (right).
Notes: Arrows in left view point to holder portion of the seating system that was mounted on the ultrasound cart. Arrow in the right view points to a hook system that is permanently attached to the chair which now serves as means of holding the chair on the cart.

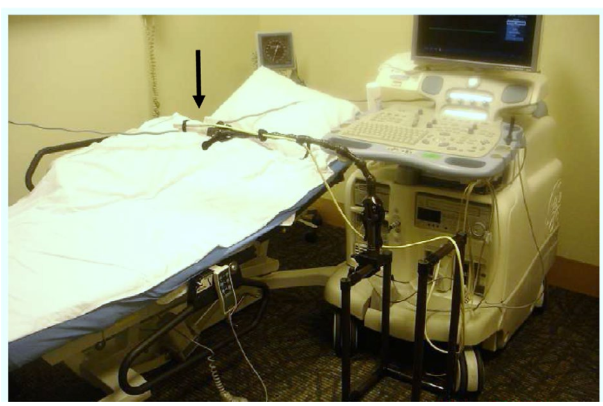

Figure 3. Ultrasound transducer (marked by arrow) and cord are suspended above exam table, while mounted on the articulating support arm with locking mechanism engaged.
Notes: The cardiac sonographer sits facing the ultrasound machine, with his/her right leg in between the two supports of the stand that supports the articulating arm and the left leg between the exam table and support stand.

3.2.2. Pilot Test 1

3.2.2.1. Methods. The first pilot study was a proof of concept, with two male members of the research team serving as patients; neither would be considered nor was classified as overweight (BMI < 25). The professional experience of the participating CS ranged from 1 to 20 years (cumulative experience = 82 years). Two were male and four female; two of the women had participated in a previous phase of the study. The CS were asked to obtain four particular scans, first as they normally would and then repeat all four scans using the articulating support arm system (ASAS). Before using the ASAS, each CS was shown how to use the locking mechanism of the arm and given a few minutes to become familiar with the device before using it to obtain images.

The sonographers were asked to think aloud and make comments while scanning in order to provide insight into how such a device might fit into the work system and issues or concerns they had. In addition to recording their verbal comments, data collected in the first pilot study included video recordings of the sessions, scanned sonographic images for quality assessment, the sonographer's verbal expression of level of exertion and written assessment of usability, usefulness and desirability of the articulating arm system using a form similar to the form used during the concept review session, but including several detailed items about each element of the ASAS (transducer holder, articulating arm, locking mechanism).

Image quality was assessed by two highly experienced cardiovascular credentialed sonographers who were blinded to the imaging method. The sonographers provided individual assessments that took into account anatomical structures within the heart, display of pathologic function, proper display of colour Doppler and M-mode display. Their independent results were then compared to determine and, if necessary, resolve any inter-observer differences.

3.2.2.2. Results. In general, CS were observed performing scanning tasks within a reasonable time frame when using the ASAS, and did not need much time to familiarise themselves with the operation of the device. In addition, while performing the scanning procedures, the CS verbally expressed that they were able to obtain comparable image quality when scanning with and without the device. They manipulated the ASAS with ease and did not appear

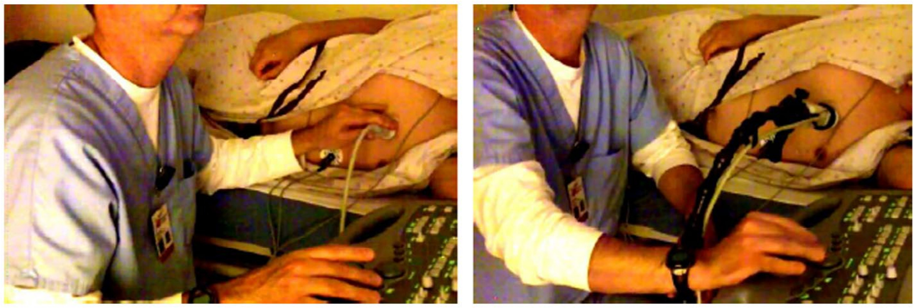

Figure 4. Cardiac sonographer making measurements of an acquired image while holding the transducer in place with his left arm and hand (left); left hand of CS is resting while he takes measurements of the image, because the articulating support arm system is maintaining necessary transducer position and force (right).

to have any difficulties moving the arm. In fact, the flexible arm and light weight of the device pleasantly surprised some of the participants. Their verbal comments included 'It turns really easy' and 'it's easier to use than I thought it would be'. This is important, as limiting the range of motion would result in loss of fine tuning manipulation, which would compromise image quality. Overall, the design of the device was intuitive, even at this initial prototype stage.

Based on observation, scanning with the device appeared to reduce the duration of pinch gripping, forceful exertion, awkward postures and static postures. A typical work posture when performing a left-handed scan is depicted in Figure 4 (left). In addition to prolonged pinching, the CS has to push the transducer against the patient's chest. Greater pinch force is required when the ultrasound gel migrates to the gripping surface of the transducer. Additional force is also required if the patient is obese. By utilising the locking mechanism, the ASAS maintained the location of the transducer and the requisite pushing force against the patient's chest. As anticipated, this provided an opportunity for temporary breaks from pinching and pushing exertions during the measurement phase of the exam (Figure 4, right). Ratings of perceived exertion (on a 0–10 scale, presented verbally, where 0 = no exertion at all and 10 = maximum possible exertion) ranged from 4 to 6 without the device and 2–3.5 with the device. The participants' responses to several detailed items on the evaluation form suggest the reasons for these reduced exertion ratings. Median scores for items about their perceptions that the ASAS would 'reduce the total amount of time I ________ during a scanning procedure' were as follows: grip transducer, 5.0, am pushing with transducer, 5.0, work in awkward postures, 4.5, work in a fixed posture, 5.0 (where 1 = strongly disagree and 5 = strongly agree).

Regarding image quality, for three scans (Apical 2 and 3 chamber 2-d, and Apical 4 chamber Doppler), 17 of 18 images collected while using the ASAS were judged to be as good or better than the images acquired without the device. For the fourth scan (Parasternal short axis (PSAX) M-mode) 3 of the 6 images collected using the device were judged to be of lesser quality than images made without the device.

In comparison to average overall ratings (1–7 scale; very poor - very good) of usability, usefulness and desirability from the concept review session (4.5, 4.2, 3.9, respectively), ratings were markedly higher from the CS using the functional prototype in the pilot study (6.2, 6.2, 6.1, respectively). Ratings for specific items provide useful information concerning design improvements. For example, some participants did not agree that it was easy to determine the correct orientation of the transducer in the prototype probe holder. The responses to some items revealed some concerns about potential effects of the device on patients including the possibility of the device making the exam more physically uncomfortable for some patients and the possibility of patients being intimidated by the device.

Having confirmed that high-quality images could be obtained with the articulating support arm system, the next step was to determine if the system could be used to acquire high-quality images in a more representative sample of patients.

3.2.3. Pilot Test 2

The second pilot study was conducted to determine if the intervention would work with larger patients, who are typically more representative of patients seen in a cardiology clinic. Parhar (2006) reported that ultrasound imaging quality tends to be reduced in obese patients 'due to acoustic noise that occurs when the ultrasound beam echoes from the surrounding fatty tissue'. As a result, the sonographer has to push the probe deeper into the skin, exerting higher forces to acquire quality images for these patients. Higher transducer grip force was demonstrated in a lab-based study that involved experienced CS scanning patient models who represented 5th, 50th and 95th percentile patients by body weight (Bastian et al. 2009).

Mean grip force during left-handed scanning increased by about 9% of maximal grip force with each increment in patient size.

3.2.3.1. Methods. One male and five female CS participated in the study. Their professional experience ranged from 1 to 25 years (cumulative experience = 62 years). Five healthy male adults each weighing over 90 kg (200 lbs) and with no affiliation to the study volunteered to act as patients. Based on BMI, three were classified as obese and two as overweight. Actor-patients ranged from under 30 to over 45 years of age. Before participating in the study, all participants reviewed and signed IRB-approved consent forms.

The CS were asked to obtain four particular scans and measurements, first as they normally would and then repeat all four scans using the ASAS. In advance of the scanning session, each CS was given time to become familiar with the ASAS, including how to use the locking mechanism. Two CS scanned the same actor-patient and all the others scanned a unique actor-patient. After scanning the actor-patients, four CS confirmed that their pilot study patient would be considered average or typical in size relative to patients they see in practice. Actor-patients did not report experiencing less comfort or more discomfort when the ASAS was used in comparison to when it was not used; this result addresses an important potential concern raised by some CS in the first pilot study.

Objective data collected during the study included electromyographic (EMG) data from the extrinsic finger flexor group, middle deltoid and trapezius muscles of the left arm and image capture data to measure trunk lateral flexion and rotation and left arm shoulder abduction and external rotation. Before the actor-patient entered the exam room, Delsys™ (Natick, MA) single differential electrodes were positioned on the CS's shaved and alcohol-cleaned skin. A Motion Monitor™ data acquisition system (Innsport, Chicago, IL) was used to collect the EMG data, which were sampled at 1000 Hz, bandpass filtered between 20 and 500 Hz and notch filtered at multiples of 60 Hz. EMG data from a reference exertion that simulated pushing a transducer against a patient's chest with 50 N of force was used for normalising the EMG data collected during the scanning tasks. Tenth and 50th (median) percentile values of the normalised EMG data were used to assess static and median levels of activity in the muscles. At the conclusion of the session, the CS completed the same usefulness, usability and desirability evaluation form that was used in the first pilot study.

Images were evaluated by a physician who is board certified in Cardiovascular Medicine and Echocardiography. PSAX M-mode and Apical 3 Chamber Doppler images were graded as good, fair or poor. Apical 2 and 4 chamber 2-D images were graded on a 1 = poor, 3 = good, 5 = excellent scale using standardised myocardial segmentation (Cerqueira et al. 2002). Ejection fraction was measured from the Apical 4 chamber view. The physician was blinded to condition when performing the image evaluation.

3.2.3.2. Results. There was no statistically significant difference between grades for scans made with and without the ASAS, based on results from the sign test. The sign test with ties included (Marshall 2014) was used because, for each CS, the majority of image segment scores were identical between the two conditions (from 63 to 84%). Only one CS did not show improvement in any image segment score with the ASAS, however, the cardiologist noted that the patient had 'Overall technically difficult echo windows. Would have used contrast clinically'. There was no pattern in the difference (larger vs. smaller) between ejection fraction values with and without the articulating arm (average absolute difference was 5.7%).

Performing each scan was divided into three stages (tasks): orienting the transducer to the desired view ('window searching'), optimising the image and making measurements. During the window searching stage for the apical views, 10th and 50th percentile trapezius m. activity tended to be lower when using the ASAS (Sign test, $p < 0.002$ and $p < 0.001$, respectively), while 10th and 50th percentile flexor m. group activity tended to be higher with the ASAS (Sign test, $p < 0.049$ and $p < 0.002$, respectively). During the optimise stage, 10th and 50th percentile activity in all three muscles was reduced after the locking mechanism was engaged during that phase (p values ranged from 0.039 to 0.0005). While making measurements, 10th and 50th percentile activity for all three sampled muscle areas tended to be lower when using the ASAS ($p < 0.013$ for deltoid and flexor m. and $p < 0.0001$ for trapezius m.). Figure 5 illustrates the difference in muscle activity level before and after the ASAS locking mechanism was activated during a scan.

By visual inspection, similar effects on muscle activity were seen for the parasternal view scans, but the small sample size precluded statistical analysis. Parasternal EMG data were not analysed with apical EMG data because of differences in hand and arm posture when acquiring images from those two locations.

Postures were most notably affected across the group of sonographers during the measure phase of scanning. For the apical view scans, spine rotation, external shoulder rotation and shoulder abduction were reduced 6–8 deg ($p < 0.03$), and for the parasternal view shoulder abduction was reduced by 11 deg ($p < 0.0022$) when using the ASAS. These differences may appear small, but Palmerud et al. (2000) demonstrated the sensitivity of intramuscular

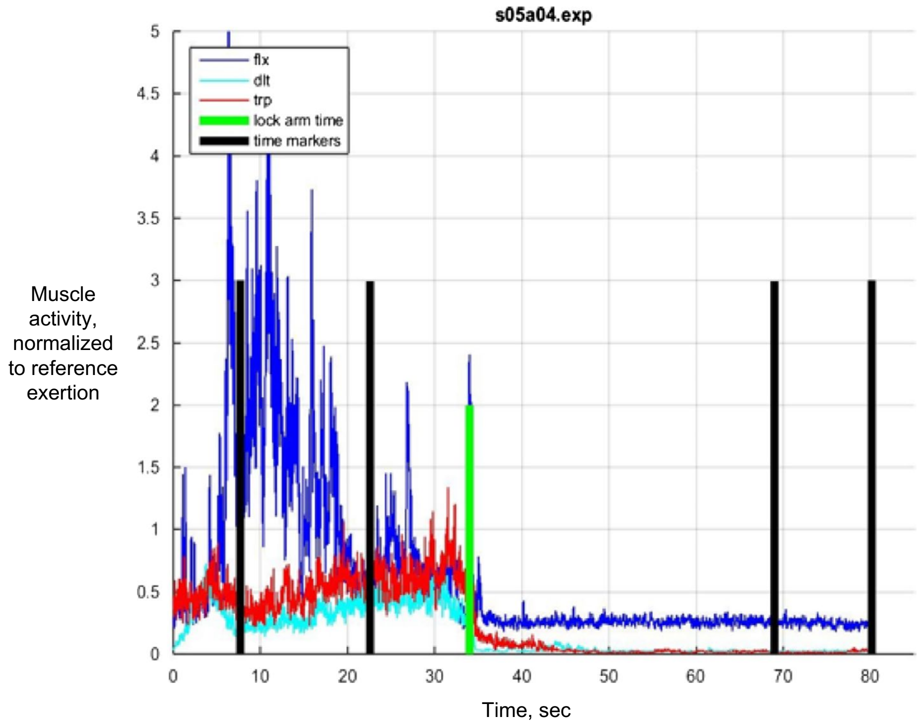

Figure 5. Using the articulating support arm system, this example shows a decrease in activity in the extrinsic finger flexor m. group, deltoid and trapezius m. during the optimisation phase after the locking mechanism is activated marked by vertical green line at about 33 s.

pressure (IMP; which can affect blood flow in muscle and tendon, as well as nerve function and physiology) in the supraspinatus and infraspinatus muscles to small changes (15 deg. increments) in arm elevation. Reduced force (muscle) exertion combined with a small reduction in shoulder abduction could result in a decrease in IMP below levels that have been shown to be problematic regarding development of muscle fatigue. Lateral spinal flexion was statistically ($p < 0.028$), but not practically greater (2 deg.) when using the ASAS (main effect, across all three scan phases).

Perceptions of usefulness, usability and desirability of the ASAS were, again, positive overall, with the exception of one individual. Average scores (1–7 scale; very poor – very good) for five of the participants were 5.6, 5.6 and 5.8, respectively, but were all 2's for the one exception. Interestingly, on the evaluation form this CS responded 'disagree' to the item 'I am able to get quality images with this device', while the cardiologist's evaluation showed no difference between quality of the images acquired by this CS with or without the ASAS; both received an average score of 2.8, which equated to 'good' in the rating system used by the cardiologist. The CS responses on the prototype's evaluation form provide direction for improvement, including designing the end effector of the ASAS to be comfortable to hold, providing more flexibility in the articulating arm and providing a way to make fine orientation adjustments at the transducer (distal) end of the ASAS.

4. Conclusion

One of the primary goals of this study was to identify areas of need and opportunity for intervention to reduce the exposure of sonographers to risk factors that contribute to MSK symptoms and disorders, health conditions that are prevalent in this sector of health care providers. This paper presents several areas of need and opportunity. The other primary goal of the study was to develop intervention concepts and some testable physical prototypes. This paper presents examples of several intervention concepts for cardiac sonographers, as well as descriptions of the development and evaluation of two interventions, one of which is currently in use in practice and the other which shows great promise, but requires further engineering. A key component of this research has been the continued engagement of end users, which has ensured that the interventions address users' needs and requirements. Opportunities abound for development of engineering controls to reduce MSK risk factor exposure in sonographers. Through this study, we hope to encourage other engineers and ergonomists to move beyond surveying sonographers about their problems and move into researching solutions to address their problems.

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