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Collaborating with radiographers to address their work-related musculoskeletal discomfort

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ABSTRACT

The prevalence of musculoskeletal (MSK) symptoms in radiographers is high, similar to other healthcare occupations that involve high levels of physical exertion (e.g. patient handling; grasping and moving equipment). Reports of interventions to reduce MSK discomfort in radiographers are limited. A participatory approach was used to investigate daily challenges, needs, and opportunities for developing interventions to address exposures to many of the risk factors that contribute to MSK symptoms in radiographers. In this paper, we present the expressed needs of experienced radiographers (including assistance with patient handling, security, supportive design of equipment and work spaces), along with their evaluations of several intervention concepts intended to address some of those needs. We also report results from tests of three prototype interventions stemming from this participatory process that demonstrate the potential for new engineering control concepts to reduce the physical effort associated with some of the most common tasks radiographers perform.

1. Introduction

Radiographers or Radiologic Technologists (RTs) are medical professionals who perform diagnostic x-rays in clinic settings, rooms of hospital patients, and hospital emergency departments. They may also work in therapeutic areas of application including fluoroscopy and lithotripsy. RTs spend significant portions of their work time positioning patients and equipment and working with computers (interacting with images on a picture archiving and communication system (PACS) and electronic patient medical records). This occupation is forecasted to grow faster than the anticipated US national average (Bureau of Labor Statistics, 2017), so it is critical to consider how to educate more RTs, and how to maintain the health of those already in the profession. Research shows that the prevalence of musculoskeletal (MSK) discomfort in RTs is quite high, at 60–75%, similar to other healthcare professionals such as nurses (Bos et al., 2007; Kumar et al., 2004a; Lorusso et al., 2007). RT work elements identified as stressful to the back include forceful exertions associated with patient handling and cassette re-positioning (Kumar et al., 2004b) and lack of an ergonomic work environment (Bos et al., 2007). Activities identified as stressful to the upper extremities included one-handed cassette handling and cassette re-positioning (Kumar et al., 2004b).

Forceful efforts and awkward postures can be observed when positioning a cassette during a portable exam (Fig. 1a), when supporting a patient during a fluoroscopy procedure (simulated in Fig. 1b), when moving a patient from a gurney onto an x-ray table (simulated in Fig. 1c), or when positioning a patient on an x-ray table. Kling and West (2015) described several factors that contribute to the physical workload of RTs, including being short-staffed, time pressure, fixed-base imaging equipment that does not mesh with portable patient lifts, and elevated fixed-height tables that require RTs to assist patients on and off. Patient weight and the degree to which a patient can assist or cooperate can also affect the effort required from the RT.

Reports of interventions to reduce MSK discomfort in radiographers are limited. Loose (2011) identified several preparatory steps that could reduce the effort of positioning a cassette under a patient during a

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portable exam. These included providing a chux (thick, reinforced cloth pad) under the patient (for lifting the patient), setting the head of the bed at 30 deg, putting the cassette in a plastic bag to reduce friction, and if the patient is on an air mattress, fully inflating that mattress. If present, a ceiling lift can be used to raise the torso when positioning a cassette. Slide boards (aka transfer boards) and inflatable air transfer devices can also reduce the physical effort required when performing lateral transfers between an x-ray table and gurney.

Given the limited attention that has been directed towards reducing work-related MSK symptoms in radiographers, a participatory ergonomics process was initiated for the purpose of generating intervention concepts to target some of the risk factors associated with their MSK symptoms. A similar approach was effectively used in working with mammographers (Sommerich et al., 2016b), cardiac sonographers (Sommerich et al., 2016a), and diagnostic medical sonographers and vascular technologists (Sommerich et al., 2019). The current study was designed in three parts described in Sections 2 to 4 of this manuscript: 1) needs assessment and intervention concept development, 2) intervention concept review, and 3) intervention prototype development and pilot assessment (Fig. 2). This research was approved by the university's institutional review board for human subjects protection. Informed consent was obtained from all study participants prior to their participation.

2. Part 1 – needs assessment and intervention concept ideation

Part 1 and Part 2 research activities occurred at what Sanders and Stappers (2013) describe as "the fuzzy front end" of the design process. As the primary subject matter experts, RTs were invited to participate in interactive sessions designed to 1) elicit their needs for finding new ways to work that could reduce their exposure to risk factors for MSK injuries and 2) evaluate concepts to achieve those new ways to work.

2.1. Part 1- methods

Radiographers were recruited from local outpatient clinics and hospitals through flyers, visits to staff meetings, and word of mouth. The needs assessment session took place in a meeting room adjacent to a radiology teaching space that provided ready access to functional radiographic equipment for the generative component of the session, during which participants would be invited to collaboratively make 'things' (very rough prototypes) to express their ideas about interventions to address some of the needs they would have discussed in the earlier part of the session. Seven radiographers (6 female, 1 male) participated in this session. Their experience in radiography (performing x-ray exams) ranged from 6 to 37.5 years, and collectively totaled 138 years.

Needs assessment data were provided through workbooks completed by the participants (n = 7) and discussion and creation of intervention artifacts ('things'/rough prototypes) during the 2 h session (n = 6 of 7). The workbook was expressly designed for this study; it incorporated several sensitizing elements described by Sanders and Stappers (2013). Prior to the session, participants completed the workbook through which they could describe the physical aspects of their work, schedules, and characteristics that could make some patients more challenging to image. The workbook contained a two day diary for recording exam details, including type, duration, anything that made the exam challenging, and any physical discomfort the radiographer experienced

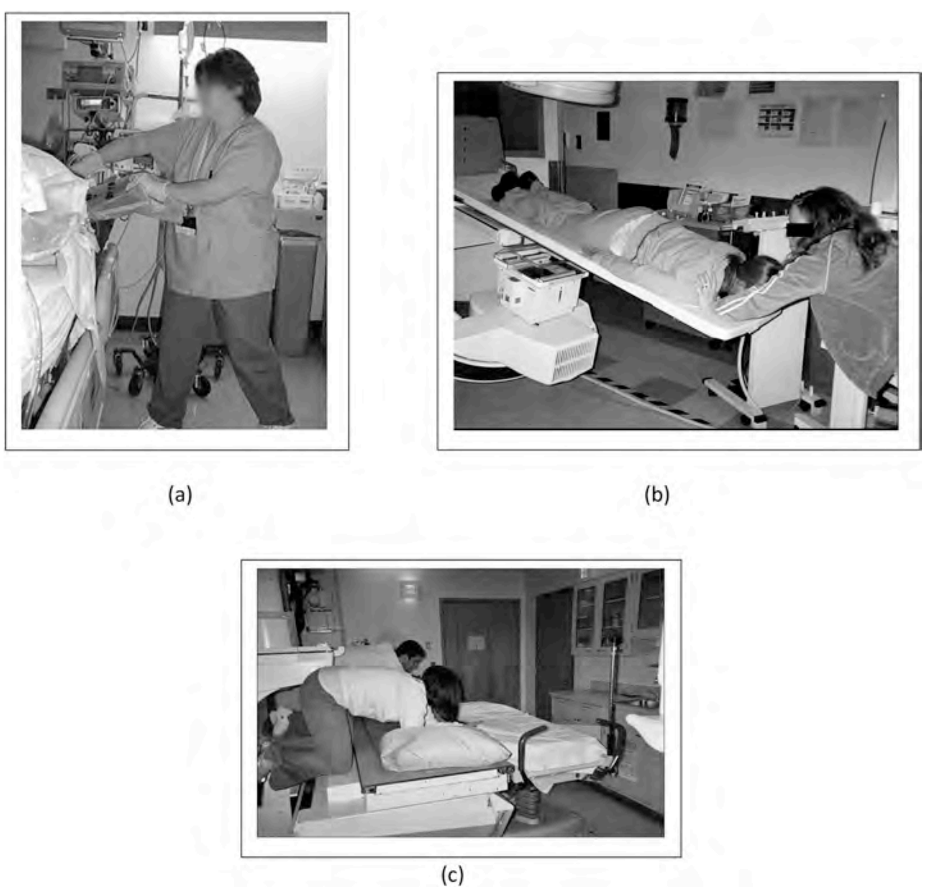


Fig. 1. Common, physically stressful tasks performed by radiologic technologists. (a) Positioning a receptor under a patient during a portable exam; (b) supporting a patient to keep patient from sliding off the fluoroscopy table (demonstration); (c) lateral transfer of patient from gurney to x-ray table (demonstration of position, patient would be on gurney).

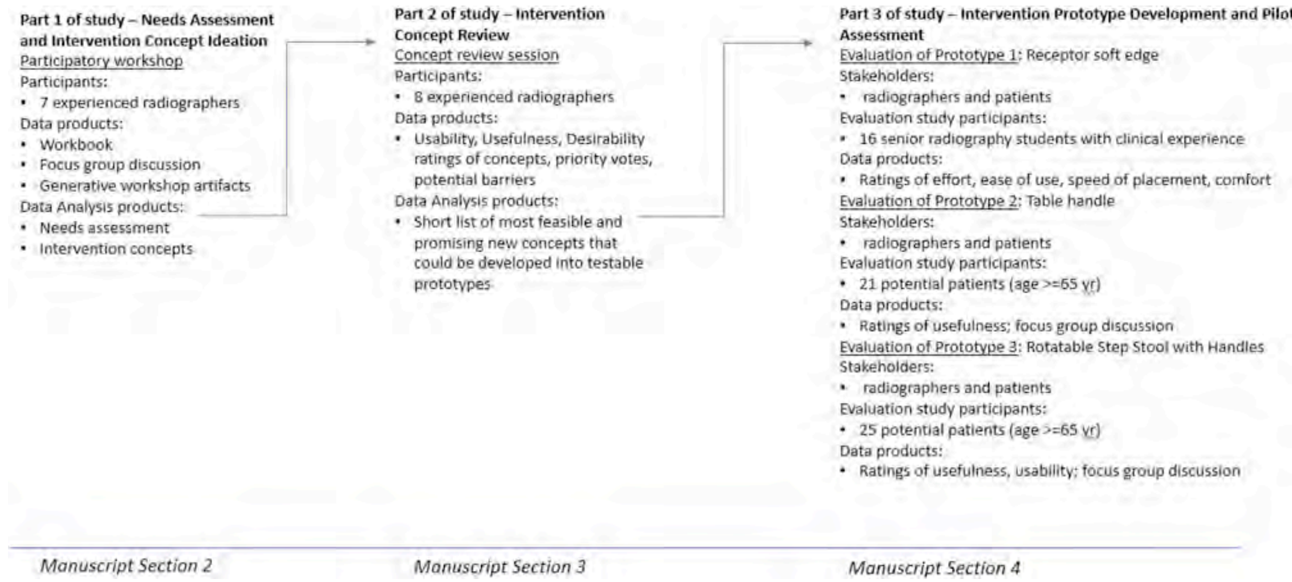


Fig. 2. Organization of this study.

during the exam. The workbook also contained a section for photos, taken by participants, of equipment or exam rooms they liked or found problematic and anything else they wanted to convey about their workspaces. Participants were asked to annotate photos with explanatory text. Completing workbooks in advance of the session primed participants for session engagement and completed workbooks provided examples for the researchers to use to spark discussion during the session.

After introductions, the session began with a moderator-guided discussion about some of their workbook content (responses to some select workbook questions: participants' experience as a radiographer and the most physically challenging type of exam they perform regularly; some of the photos provided by participants: those depicting issues raised by multiple participants, issues in the literature, or issues that seemed particularly challenging based on annotations provided by the participants). Two researchers took notes on large 'issues notecards' that participants subsequently sorted into categories and labeled with themes. Participants then identified their most significant challenges, from the issues they had just discussed, and determined which issues they wanted to address while working in small breakout groups during the latter portion of the session which was designed to aid the participants in generating intervention ideas to address the issues they had just been discussing. The latter element was conducted from the viewpoint of design as co-creation between end users and designers, engineers, and ergonomists. Sanders and Stappers (2013) described this approach as "a way to explore ideas, dreams and insights of the people who will be served through design". At the end of the generative part of the session, one radiographer from each of the small breakout groups presented and demonstrated the group's results (i.e. 3-D mock-ups/rough prototypes that embodied their intervention ideas). When that radiographer finished presenting his/her group's ideas a discussion ensued, during which the other radiographers and the researchers asked questions and contributed additional ideas and suggestions. Presentations were video- and audio-recorded.

Afterwards, workbook data were transferred to spreadsheets to aid review, researchers made notes from audio recordings of discussions and generative element presentations, and visual data (participants' annotated photos and video of the intervention artifact presentations) were all analyzed for thematic and specific content. Through this qualitative analysis process, a document was created that was organized by several major categories that emerged from the data. Within each category, all expressed needs were listed, along with their sources (annotated photo, generative session, etc.), interpretations of the expressed needs, intervention ideas to address the needs, and preliminary ratings of feasibility of prototyping or otherwise testing the ideas. Two researchers performed this initial assessment of the data from all of these sources. Each conducted an independent analysis, then they worked together to combine their results. Those results were presented to the research team for further examination and discussion. The team organized the results into intervention categories (e.g., 'patient handling', 'equipment handling'), into which preliminary intervention concepts and additional concepts generated by the team were placed. Brainstorming techniques, internet searches, and literature searches were employed to generate additional intervention ideas. The next step was to refine and reduce the number of concepts to those that were most promising and within the study's scope (i.e., those that could directly affect RT musculoskeletal health). Those concepts were then discussed with radiographers in a concept review session (Part 2).

2.2. Part 1 - results

All of the radiographers who participated in the needs assessment session reported experiencing work-related musculoskeletal discomfort. The average number of non-portable exams they reported performing during a typical day ranged from 5 to 12, and the number of portable exams ranged from 10 to 40. When asked to describe the most physically demanding exam or procedure they performed on a regular basis, portable exams of the abdomen or extremities were listed by four of the seven RTs, and when asked why, the explanations included patient weight and lack of assistance with positioning patients (from other staff, patients, or lifting aids). Other challenging contexts included a patient on a ventilator (equipment near the bedside limits access to the patient and attachments to the patient require additional care when handling the patient) and overnight exams (fewer staff available means less assistance).

Regarding working with challenging patients, responses ranged from 20 to 80% of patients being elderly; challenges included the need to provide various amounts of assistance to get patients on and off the x-ray table and positioning body parts for patients who cannot assist or hold required positions. Challenges associated with heavy patients, who constituted 25–80% of the participants' patient load, also had to do with the need to assist these patients in getting into position on the x-ray table (lying down, shifting, turning onto one side), and the difficulty of positioning a cassette under a heavy patient during a portable exam.

Fifteen to 70% of their patients were estimated to have some degree of physical impairment and these patients also required physical assistance (from the RT) to get on and off the x-ray table and get into position. Some of these patients may remain in a wheelchair for the exam, which adds physical and cognitive complexities to acquiring quality radiographs for these patients. Consistent with the workbook contents, the main themes that emerged from the discussions with the RTs were room design, table design, digital receptor design, patient handling, portable exams, and paperwork. The RT needs assessment, based on analysis of all the session-related data, is summarized in Table 1. The research team's idea-generating activities yielded a total of 23 intervention concepts to address the interpreted needs of the radiographers. Seventeen were determined to be within the scope of the study and were presented to the RTs in the concept review session (see Table 2).

3. Part 2 – intervention concept review

3.1. Part 2 – methods

Two male and six female radiographers participated in the review session (5–35 years of experience radiography performing x-ray exams; 173 years in total), including two RTs who participated in Part 1. One at a time, each concept was presented, discussed, examined, and then participants completed an evaluation form, before the next concept was presented. Illustrative posters and some physical prototypes were

Table 1
Results of needs assessment analysis of Part 1 data from radiographers (RTs).

Issues Category	Issues and needs
Portable exams	Receptor holders located at the back of the machine are difficult to access First generation digital receptors are heavy Digital receptor with cords - cords are a trip hazard Portable machines require a lot of space (can require significant physical effort to position these machines in smaller rooms, such as in ICU) Poor visibility of surroundings when pushing a portable machine with a fixed (non-telescoping) vertical tube column High level of physical effort is required to position a receptor under a patient who is lying in bed; patient weight and acuity are important contextual factors Batteries for driving portable x-ray machine may not last; RTs can get hurt trying to push machine when battery abruptly fails Older portable machines do not provide a means for the RT to quality check the radiograph before leaving patient's room, leading to repeating the whole acquisition process if the image is not satisfactory ('walk of shame')
Patient handling	Significant physical effort can be needed to lift and physically maneuver patients for radiographic images Significant physical effort can be needed to assist patients to sit up on x-ray table from recumbent position. Need easy-to-use, effective means for keeping patient from sliding down the table during myelogram; current manual methods can expose RTs to radiation and require RTs to hold awkward and stressful positions.
Room design	Improve security for radiographers working alone Improve visibility of patient to monitor for sentinel event
Equipment design	Reduce the need to physically manipulate equipment (tube and digital receptor) within the x-ray room, to reduce stress on RT's arms and shoulders – can be particularly challenging for shorter RTs Lack of access to both sides of an x-ray table can make patient handling more difficult (also may interact with room design) Need means for ambulatory patients to be able to easily sit on x-ray and procedure tables without physical assistance (effort) from RTs
"Paper work" (medical records)	Computer workstations are not well designed; monitor placement can require RTs to look up to view (requiring repeated or prolonged neck extension)

Table 2
Concepts presented to the radiographers in the concept review session.

Concept	Approaches	Interpreted need
Step stool	Alternative step stool and turning aids: • Step stool with adjustable width surrounding handrail • Rotating step stool with surrounding handrails • Step stool with surrounding handrail and embedded spinner	Means to assist elderly and physically impaired patients on and off x-ray and procedure tables that do not lower sufficiently; patient safety and reduced strain on RTs
Wheelchair Transfer station	Provide space with a ceiling lift in clinic, to lift patient in wheelchair onto an air transfer device on a gurney; from gurney patient can be easily transferred laterally onto imaging table using air transfer device	Reduce equipment-unassisted manual patient transfers
Wheelchair – patient assist devices	Provide equipment-assisted patient transfers between wheelchair and x-ray table for patient in wheelchair, who can significantly assist with his/her transfer onto x-ray table that lowers sufficiently • Transfer board • Sit-to-stand assist device	Reduce equipment-unassisted manual patient transfers
Lateral transfer device – in clinic	Utilize patient transfer device for lateral transfer to and from X-ray table: • Air transfer device • Slide board	Eliminate need for radiographers to get onto x-ray table to transfer patient
Patient support handle	Provide positioning aids to patient: • Handle attached to x-ray table • Trapeze handle above table	Provide means for patient to assist in positioning themselves on x-ray table (laying down, rising, moving into/changing position); enabling for patients and reduced strain on RTs
Fluoroscopy exam assist	• U-shaped bolster to comfortably support patient's head and shoulders • Provide handles on each side of x-ray table for patient to grasp	Eliminate need to manually support patient when table is in Trendelenburg orientation
Mirrors in clinic	Install convex or flat mirrors for improved remote observation of patient & equipment	Keep patient and equipment in sight; Improve patient position compliance during imaging
Mirrors in patient room	• Add convex globe mirror on the portable x-ray machine • Provide 'periscope' type device to view patient from outside the room	Keep patient and equipment in sight; Improve patient position compliance during imaging
Wheeled stand for receptor	Provide a wheeled stand to support weight of digital receptor when moving it between locations in clinic	Reduce the effort required to handle heavy digital receptor
Integrated stand for receptor	Provide articulating arm on a wheeled stand to orient and support weight of digital receptor when moving it between locations in clinic	Reduce the effort required to handle heavy digital receptor
Pocket storage for receptor	Image receptor management for CR generation portable machines: • Metal side pocket • Saddle bags	Reduce risk of damage to receptor; provide options for storing receptor
Furniture on wheels	Furniture on wheels and with handles:	Facilitate the moving of furniture in the patient room

(*continued on next page*)

Table 2 (*continued*)

Concept	Approaches	Interpreted need
	• Choose new furniture with these features • Retrofit existing furniture with wheels and handles	to accommodate portable x-ray machine
Soft edge frame (receptor positioning aid)	A frame, placed around the receptor, with contoured edge designed to facilitate pushing the receptor underneath the patient	Reduce strain on radiographer when positioning receptor under/behind patient during portable exam
Hollow transfer board (receptor positioning aid)	Hollow transfer board with space within for positioning receptor - for use in obtaining radiographs of patients in Emergency Department	Reduce strain on radiographer when positioning receptor under/behind patient
Transfer sheet and rod (receptor positioning aid)	Roll edge of transfer sheet around long rod; grasp rod and lift sheet as lifting aid to lift and support extremity when positioning receptor underneath	Reduce strain on radiographer when positioning receptor under patient when imaging an extremity
Inflatable wedge (receptor positioning aid)	For portable exams; develop an inflatable wedge to place behind patient, to reduce effort to position receptor	Reduce strain on radiographer when positioning receptor under/behind patient
Air support used as receptor positioning aid	In patient room, position air support lateral transfer device under patient, to reduce effort to position receptor; receptor is positioned between device and mattress	Reduce strain on radiographer when positioning receptor under/behind patient

created to assist the RTs to envision and understand how each ideated solution could be used. Participants were encouraged to interact with the prototypes, raise questions, discuss, and make suggestions or other comments prior to and while completing their individual evaluations of each concept.

The evaluation form included items addressing potential usability (anticipated ease of use and ease of learning to use), usefulness (anticipated effects on physical exertion, fatigue, patient comfort, and task efficiency) and desirability (potential interest, from participating RTs and their co-workers, in using the ideated intervention). Usability, usefulness, and desirability (UUD) items (15 in total) were each rated using a 5 point response scale (Strongly Agree to Strongly Disagree). Participants also gave an overall potential rating, from 1 to 7 (very poor to very good), for each UUD dimension. Participants also provided information about potential barriers to development or adoption that they could foresee. At the end of the session, each participant was given six votes to indicate which concepts should be made a priority.

Afterwards the evaluation form responses were entered into a spreadsheet. Median scores were calculated for each item and each dimension. For each concept, the number of priority votes were counted and the number of barriers were counted and normalized to provide counts per participant.

3.2. Part 2 - results

Results from the RTs' reviews of the concepts are summarized in Fig. 3. They include overall scores of potential usability, usefulness, and desirability, and numbers of priority votes and potential barriers.

Following analysis of the concept review results, the research team identified a short list of most feasible and promising new concepts that could be developed into testable prototypes for further evaluation within the remaining timeframe of the project.

4. Part 3 - intervention prototype development and pilot assessment

Intervention concepts that were investigated further, through development of functional prototypes and testing by potential users, included a soft edge frame (receptor positioning aid), a support handle

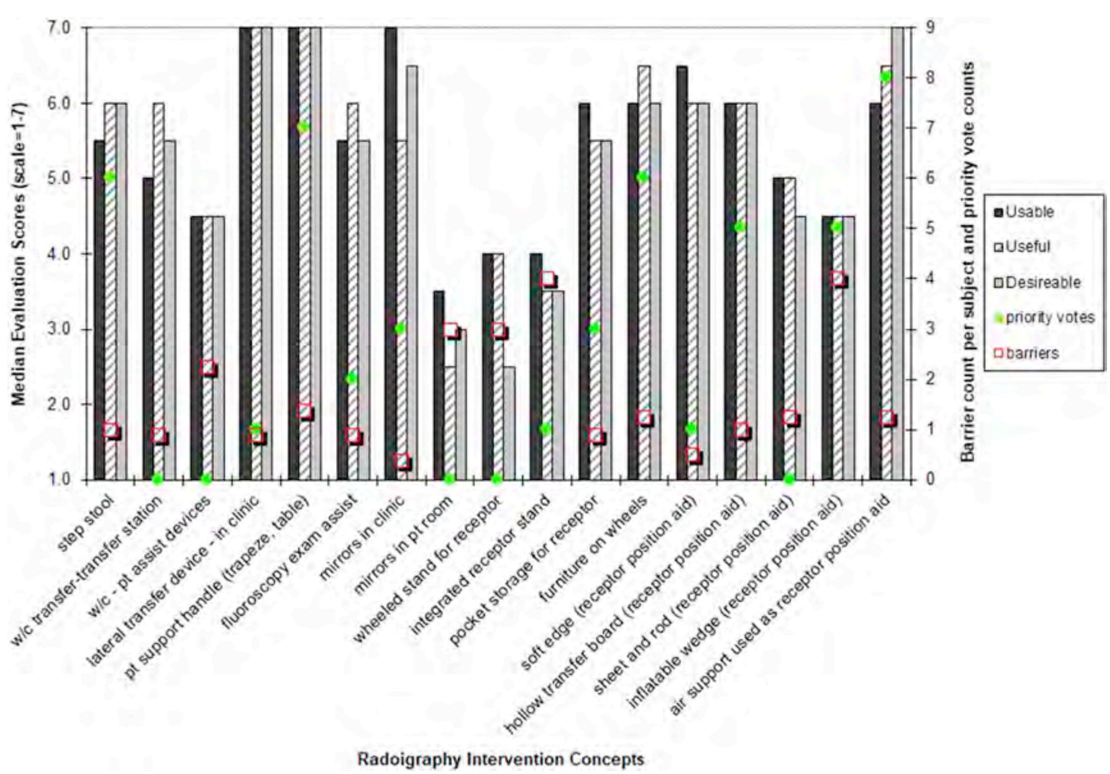


Fig. 3. Radiographers' evaluations of the intervention concepts. Evaluation scores refer to overall assessments of usability, usefulness, and desirability. The number of priority votes received from participants can be contrasted with the number of barriers to use or implementation anticipated by participants.

for patients to use when on the x-ray table, and a novel step stool. The support handle and the step stool are intervention concepts that address some of the patient handling and positioning tasks performed by RTs in a hospital's radiology department or outpatient clinic setting. Both concepts were designed to provide enabling support to patients while reducing physical strain on RTs. Both concepts received favorable median scores from the RTs, in terms of usability, usefulness, desirability, and numbers of priority votes (support handle: 7,7,7,7,; step stool: 5.5,6,6,6; respectively; Fig. 3). The receptor soft edge frame also received favorable scores for usability, usefulness, desirability (6.5, 6, 6, respectively), though was not considered a priority by the participants. However, given the large number of portable exams that hospital-based RTs perform, the research team wanted to investigate the potential to reduce some of the physical effort associated with that aspect of the RTs' work, as well.

4.1. Prototype 1 - receptor soft edge

Brief background. Radiographers who image the abdomen or chest as part of a portable exam need to place an x-ray receptor (or CR cassette) underneath or behind the patient to capture the x-rays and create the radiographic image. In the needs assessment session conducted at the beginning of the study (Part 1), the RTs described the receptor placement task as requiring considerable push force partially due to the shape of the cassette. Meittunen et al. (2004) measured push forces of 18–27 kg for an RT performing the task alone without assistance, a not uncommon situation. RTs in the current study also expressed strong concerns for not injuring the skin of elderly or other patients who have very fragile skin, or interferring with lines or tubing when placing and positioning the cassette under patients who are attached to equipment, such as a ventilator. The straight, blunt edges of current cassette and receptor designs can cause skin discomfort for patients as it is pushed underneath or behind the patient and can result in skin tears; the blunt edges contribute to the considerable force required to slide the cassette or receptor underneath a patient in preparation for image acqusition.

From intervention concept to prototype. The soft edge concept is a frame with a rounded edge designed to soften the leading edge and sides of the image receptor or cassette, to reduce the force required to push the receptor behind the patient and reduce discomfort and risk of injury to a patient's skin. The frame would be made of radiolucent material and designed such that it would be easy to place the receptor in and remove it from the frame. A prototype was developed that allowed testing of the effects of the soft edge frame in a controlled setting (see Fig. 4).

Functional prototype assessment. The prototype soft edge frames for a computed radiography (CR) cassette and digital receptor (DR) were assessed by 16 senior radiography students who participated in an evaluation session in which they role-played both as radiographer and patient. In their role as radiographer, participants compared use of a simulated CR cassette and a simulated DR with and without a soft edge frame for two common portable exam tasks: placing the cassette or digital receptor underneath a patient for an abdominal scan and placing it behind a patient for a chest x-ray. The simulated CR cassette weighed 1.7 kg, the simulated DR weighed 5 kg; the frames for each weighed 0.5 and 2.7 kg, respectively. The CR cassette was 46 cm W x 38 cm L x 1.3 cm D; the DR was 45 cm W x 58 cm L x 2.5 cm D. Both of these were modeled from contemporary equipment. Each participant role-played and provided separate evaluations of each condition through the perspective of the patient and the radiographer. Role playing is a familiar activity for these students as they learn to position patients in their simulation labs. The students also drew upon their two years of radiology clinic experience while performing and evaluating the positioning tasks for this study.

As the radiographer, each participant utilized a 1 to 5 Likert scale to assess the ease of handling a cassette (or receptor) and speed of placement and used a CR-10 Borg perceived exertion scale to rate overall physical effort (Borg, 1998). As the patient, each participant used a Borg CR-10 pain scale to rate any discomfort they experienced in each condition. Test condition order was counter-balanced across pairs of students.

The results of this evaluation session demonstrated that use of the soft edge frame tended to be rated more favorably than the unframed cassette or receptor, in terms of ease of handling, operational speed, and physical effort required (Fig. 5 a-d). 65% of the perceived effort ratings when using the CR cassette were lower with the soft edge frame and 13% were lower without the frame. Corresponding results when using the digital receptor were 70% and 23%, respectively. Only a small percentage of participants did not perceive the soft edge as at least somewhat useful, and 75% would like to have it available to use (Table 3). In their role as the patient, participants tended to report experiencing less discomfort when the soft edge frame was used, in comparison to when not used (Fig. 5a and b).

4.2. Prototype 2 – patient support handle

Brief background. Many patients need assistance when laying down, sitting up, or rolling over on an exam, x-ray, or procedure table. RTs and sonographers (Sommerich et al., 2019) described the physical challenges they encounter in assisting patients as they lie down, sit up, or move into a different posture for an imaging procedure. X-ray, fluoroscopy, lithotripsy, and fixed height exam tables do not have anything for patients to hold onto for stability. Therefore, patients hold onto or need assistance from a healthcare staff member or accompanying family member to get situated on the table. Short (15 cm) handles are attached to x-ray tables in some rare instances to provide patients something to grasp to hold a position during image acquisition, but the short length and location on the table limits the usefulness of such handles to that specific function.

From intervention concept to prototype. Concepts for a trapeze handle located above the table and a handle attached to the table were both initially considered. However challenges associated with the attachment point for a trapeze handle eliminated that concept from further consideration. There were also challenges with developing a means to

Fig. 4. (a) Simulated standard computed radiograph (CR) cassette, (b) the same with a soft edge frame around the cassette.

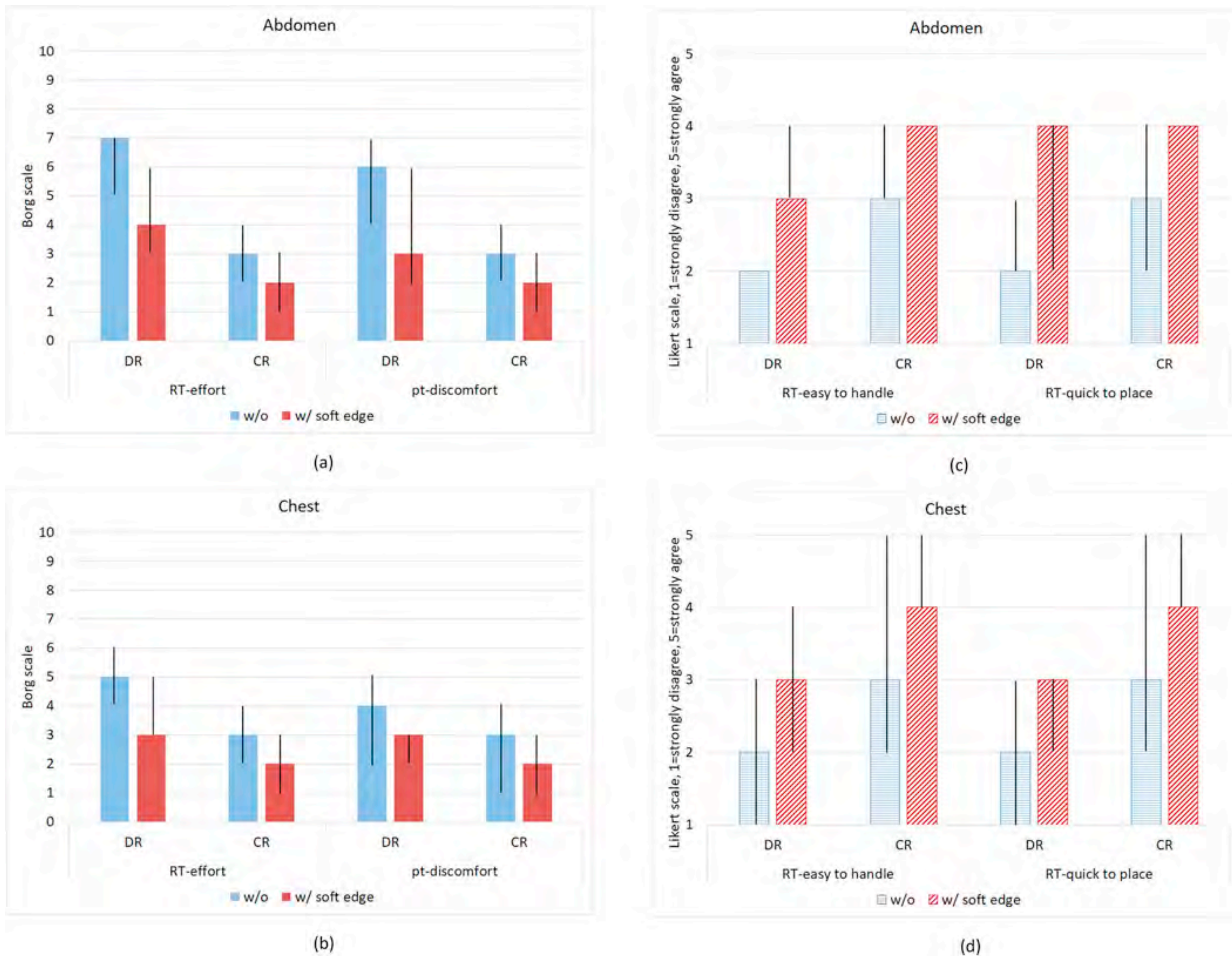


Fig. 5. Median values of ratings from soft edge testing in simulation laboratory setting; IQR indicated by vertical line (no visible line means IQR values equal median). The first two graphs provide Borg scale ratings of RT effort and patient (pt) discomfort for the abdominal placement (a) and chest x-ray placement (b). The second two graphs show median Likert scale ratings from the RTs for ease of handling of the cassette (receptor) and the extent to which they agreed that it could quickly be placed under the patient, for abdominal (c) and chest (d) placement.

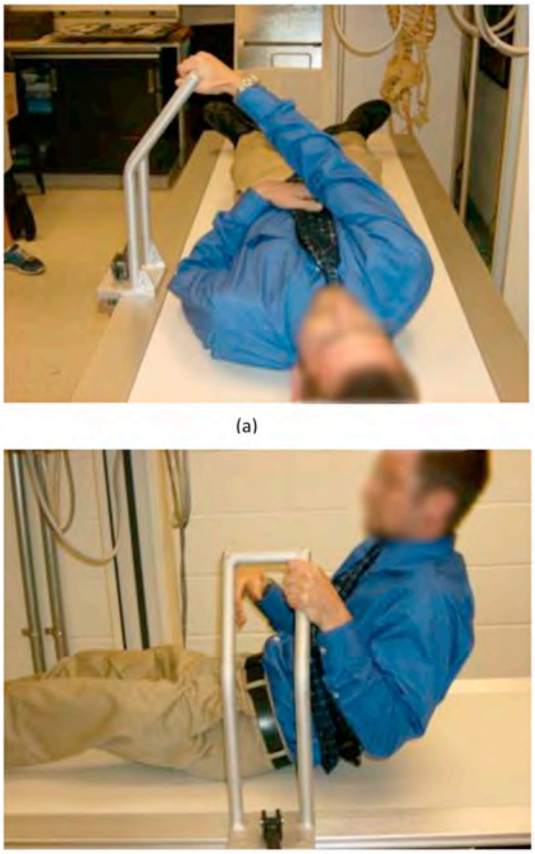
Table 3
Soft edge usefulness and desirability assessment.

Assessment item	CR cassette	Digital receptor
I think the soft edge frame is useful.	Yes: 56% Somewhat: 31% No: 13%	Yes: 25% Somewhat: 56% No: 19%
I would like to have the soft edge frame available to use.	Yes: 75% Somewhat: 6% No: 19%	Yes: 75% No: 25%
I think my colleagues would like to use the soft edge frame.	Yes: 25% Maybe: 56% No: 19%	Yes: 31% Maybe: 44% No: 25%
I think the soft edge frame benefits __the technologist __the patient __neither.	RT: 13% Patient: 19% RT + pt: 56% Neither: 13%	RT: 13% Patient: 44% RT + pt: 19% Neither: 25%

attach a handle to the table. The design specifications for the prototype required that the handle have a quick clamp-on mechanism suitable for retro-fit on existing x-ray tables, be sturdy and stable, and easily reachable by a supine patient. Fig. 6 shows two views of the prototype handle attached to an x-ray table. The handle is attached to the table with a lever clamping mechanism that can be quickly adapted to different table thicknesses by means of a large adjusting knob on the underside of the lower clamp plate. The handle can be grasped at different places depending upon whether the patient is lying down, rolling over, or sitting up and depending on the size and flexibility of the patient and where the handle is placed on the table relative to the patient.

Functional prototype assessment. Two user testing sessions were conducted, one at a community center and one at a retirement facility, to obtain use data from potential patients who might benefit from availability of such a support handle. In total, 21 individuals, all 65 years of age or older, tested the handle. In this protocol each participant was asked to perform three tasks: 1) lie down on a hard surface, 91 cm high table (simulating a fixed height table for procedures involving imaging, such fluoroscopy and lithotripsy, and older styles of x-ray equipment), 2) turn over on their side, and 3) sit up as they would at the completion of an exam. This procedure was competed twice, the first time without the prototype handle and second time with the prototype handle. After completing the second task with the support handle each participant was queried, via short survey followed by a short group discussion, as to the usefulness of the handle when lying down, rolling over, and sitting up.

All participants indicated the handle was helpful when changing


(a)

(b)

Fig. 6. An end view (a) and side view (b) of the prototype support handle attached to an x-ray table via a quick-clamp mechanism.

positions on the table and when sitting up. Most participants also found the handle helpful for lying down. Results are presented in Fig. 7, which includes photos that provide examples of how participants performed each task without and with the support handle. During the group discussion, one participant explained liking the human connection they felt when a person assisted them to sit up or lie down. However, more common were comments such as these: with the handle "I'm independent", "rather do it on my own" with the handle, "I'm a handle person!", "handle is useful; keep it on the table". One participant suggested that the handle should be made to feel smoother, and less metallic. Another participant suggested that the handle might have to be taller/longer for larger patients.

4.3. Prototype 3 - rotatable step stool with handles

Brief background. Many patients need help stabilizing themselves when using a step stool to get on or off a fixed height exam table or fixed height imaging or procedure table. In addition to stepping up on the stool, getting on the table requires the patient to make a 180° turn so he/she can sit on the exam table. In these situations, the imaging technologist often experiences significant biomechanical loads as patients hold on to or lean on the imaging technologist during the table mounting or dismounting process. This situation is made more challenging when patients are ill, experiencing lower extremity joint pain, are on balance-distrupting medication, are under the influence of anesthesia (during or after a procedure), and/or are overweight.

Standard step stool designs have a small foot print, which provides only a small surface on which the patient can turn around, and provide nothing to hold on to for assisting patients as they attempt to maintain their stability. Single handle step stools are unstable and can easily tip if the patient pushes on the handle before stepping on the step. Other kinds of patient handling equipment, such as standing aids and portable lifts that utilize a sling, are not suitable for this use because they have stabilizing legs that must go underneath or straddle the target location where the patient will be seated (Kling and West, 2015).

From intervention concept to prototype. The goal was to create a stable step stool with supportive handles for patients of various heights and shapes to grasp while mounting the step stool. Rather than asking the patient to turn around, the step stool was designed to be rotatable. By being rotatable the step stool's design eliminates the need for a patient to turn around on the step stool, thus reducing fall risk and restoring independence to many patients who now require assistance to mount and dismount an exam or procedure table using current step stools.

Several initial design concepts had been discussed with the imaging technologists who participated in the concept review process. An early functional prototype had been developed for evaluation by the imaging technologists during the concept review session; second and third generation functional prototype designs were evaluated by community dwelling older individuals (n = 21 and n = 4, respectively), who served as representatives from the patient population that might require use of a step stool in a clinic or other setting. These prototypes provided a means for patients to easily grasp the stepstool and stabilize their posture while getting on and off the step stool and the exam or imaging procedure table, as well as while being rotated 90 deg. by the imaging technologist. After mounting the step stool, the brake was released by a researcher (playing the role of radiographer) and the step stool and the patient were then rotated (slowly) in order to position the patient such that his/her back was to the table. Once the brake was activated then the participant could simply sit down on the table, using the handles of the rotatable step stool for support while doing so. The generation 2 prototype was made from an exisitng sit-stand device (ReTurn by Romedic), which had a foot-controlled brake lever; CREFORM (Greer, SC) tubing and connectors were used to create additional handles and a wooden box was placed on the standing platform to form the step. The generation 3 prototype was an original design, not created from modifying an existing device; a dead man's brake incorporated into the handle was grasped by the user who was moving/steering the patient, in order to allow the step stool to move.

Functional prototype assessment. The 21 older adults who participated in the table handle assessment also participated in the assessment of the generation 2 step stool; 4 other individuals, also age 65 or older from the same community center, participated in the later assessment of the generation 3 step stool. In the evaluation protocol the investigators asked each participant to get on and off a 91 cm high simulated exam/imaging procedure table using a standard (no handle) step stool (Fig. 8a), a one handle step stool (Fig. 8b), and the generation 2 or 3 rotatable prototype step stools shown in Fig. 8c and d, respectively. After completing each task the participants were asked if they felt safe and stable on the step stool they just used, and whether or not they felt apprehensive (uneasy) when using the step stool. After using all of the step stools (no handle, one handle, and rotatable), each participant was then asked if he/she felt dizzy or uneasy or scared while being turned on the rotatable step stool. These questions were asked because during the concept review process some of the imaging technologists expressed these concerns for their patients during the discussion of the various step stool concepts. Finally, the step stool participants took part in a brief group discussion prior to the end of the prototype evaluation session.

In the evaluations of both generation 2 and 3 rotatable step stools, 100% of the participants reported they felt safe and stable while using the new prototype step stools (Fig. 9). However, a few participants responded that being turned on the rotatable step stool made them feel dizzy ('yes' = 10%, 'maybe a little' = 14%) and 10% responded that they felt uneasy or scared while being turned on the rotatable step stool. During the discussion, a few participants raised some concerns about lack of space to accommodate the rotatable step stool if it was to be used in a patient exam room at their doctor's office.

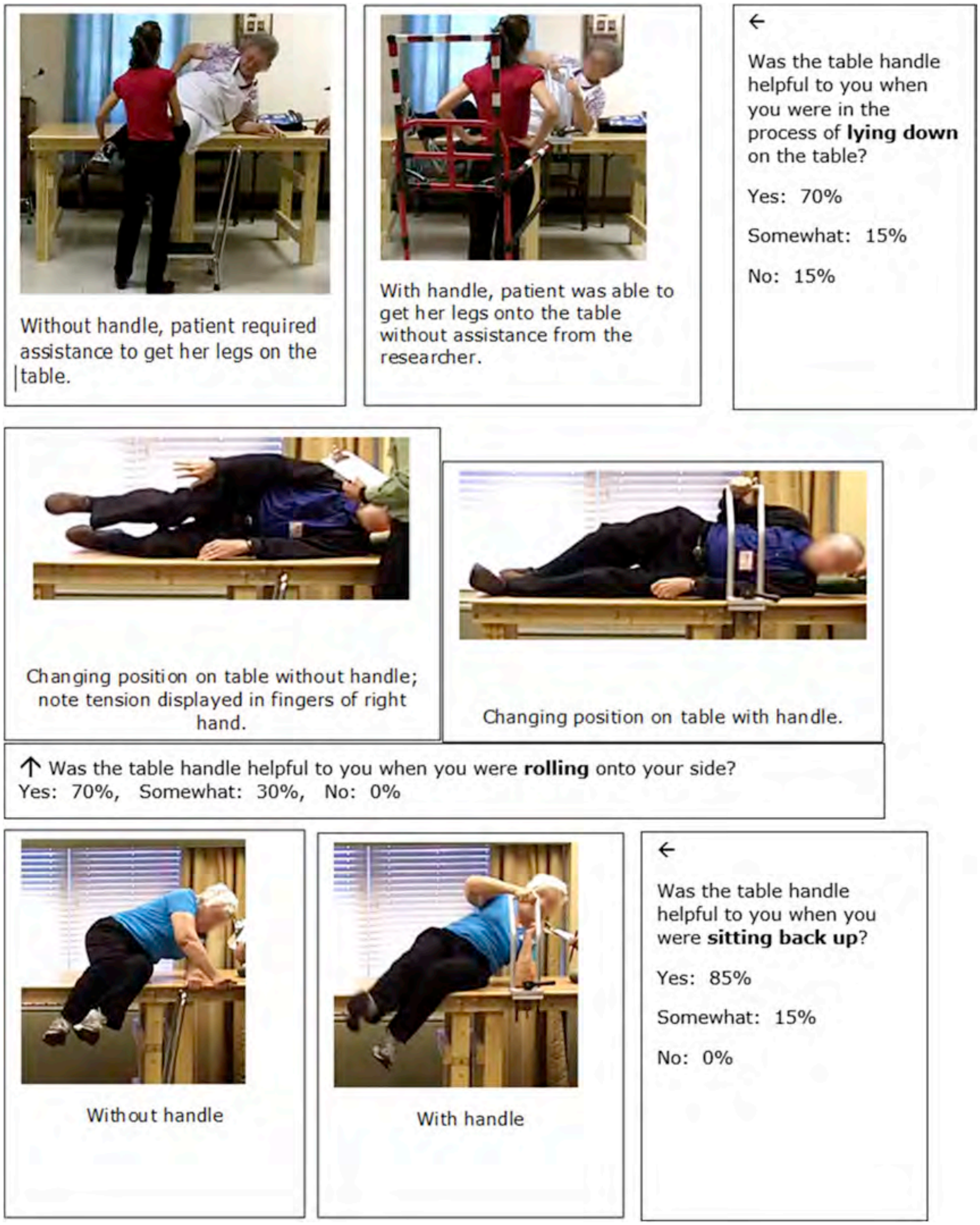


Fig. 7. Support handle assessment. Subjective assessments of the helpfulness of the table handle in supporting participants (potential patients) in going from sitting on to lying down on the table (top row), going from one position to another while lying on the table (as in side lying to supine or vice versa) (middle row), and sitting back up from lying on the table (bottom row).

5. Discussion

A participatory design approach was used to engage experienced radiographers in a research project to generate and evaluate new ideas for engineering controls that could reduce RTs' work-related exposure to MSK injury risk factors. Consistent with prior research (Bos et al., 2007; Kumar et al., 2004a; Lorusso et al., 2007), this study identified patient handling activities, including those involved in performing portable exams, as aspects of RT work that posed high risk for injury, and thus were targeted for intervention. The collaborative design research process generated new concepts for addressing several patient handling activities performed by RTs. These included a 'soft edge frame' to reduce physical effort of RTs and discomfort for patients, during portable exams, when putting a cassettte/receptor underneath a patient lying on a hospital bed; a rotatable step stool with handles to provide stabilizing support for patients when getting on/off exam tables, reducing the need for RTs to provide that physical support, thereby improving safety for patients and RTs; and a removable handle to attach to the x-ray table that patients could use to assist in positioning themselves on the table, thereby reducing some of the RTs' patient handling exposure. Functional prototypes were created and pilot usability tests were conducted on three concepts, all of which were shown to provide benefits to RTs

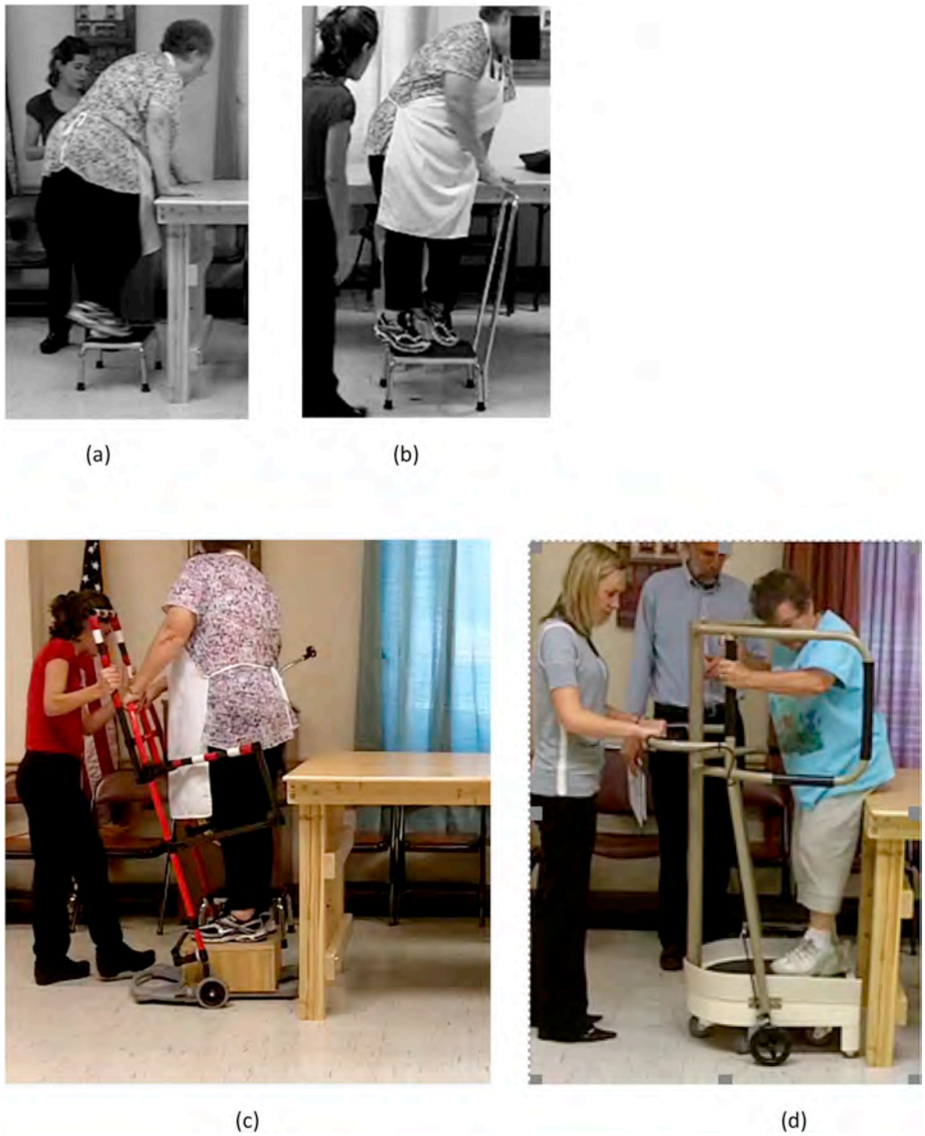


Fig. 8. Step stools evaluated by community dwelling older adults. (a) standard step stool, (b) single handle step stool, (c) second generation rotatable step stool prototype, (d) third generation rotatable step stool prototype.

and patients.

Eliminating hazards and substituting less hazardous tools and materials for those that are more hazardous are preferred methods of addressing workplace hazards, over administrative controls alone. However, there are few reports in the literature of such interventions that address the needs of radiographers (people who perform x-ray exams). Pais et al. (2012) provides a rare example of a published hazard analysis coupled with information about the design and implementation of two engineering controls for radiographers (inclined a formerly horizontal worksurface used when labeling cassettes, to reduce repeated trunk and neck flexion; in place of viewing the patient through a poorly placed window, a camera and visual display were added to the RT work console, to reduce repeated trunk and neck rotation and extension). The design of radiographic equipment continues to evolve in important ways that can reduce some of the physical stress experienced by RTs. For example, newer x-ray tables are height-adjustable and some can be positioned very low to the floor, to enable patients to more easily sit down and stand up from the table, or transfer themselves if using a wheelchair. Then, when preparing to acquire an image, the RT can raise the table so that he/she can work in a more upright posture when positioning the patient and equipment. If, however, the RT leaves the table at the low height and bends over the patient when feeling for landmarks, then only a partial benefit of the design improvements of the equipment are realized. New equipment must be accompanied by training and potentially also changes in procedures to realize the full benefits for patients and staff. Another important advance is in the design of digital receptors. Two key improvements are weight reduction (from 7 to 8 kg when they first came out, down to 3–5 kg currently) and wireless capability (eliminating the cord, a potential trip hazard). However, the weight is still not trivial when considering the RT may be grasping it with a one-handed pinch grip while pushing it under the patient, and simultaneously lifting the patient with the other hand to make room for the receptor (Fig. 1a). In spite of technological advancements in the design of radiographic equipment, repeated, forceful physical exertions, including lifting and moving patients, equipment, and furniture in patients' rooms continue to be risk factors to which RTs are exposed daily. This is reflected in the needs analysis (Table 1) and in many of the new concepts (Table 2) that resulted from working collaboratively with the highly experienced RTs who participated in this study.

An essential component of this research was engagement of end users (RTs and potential patients), which ensured that the interventions

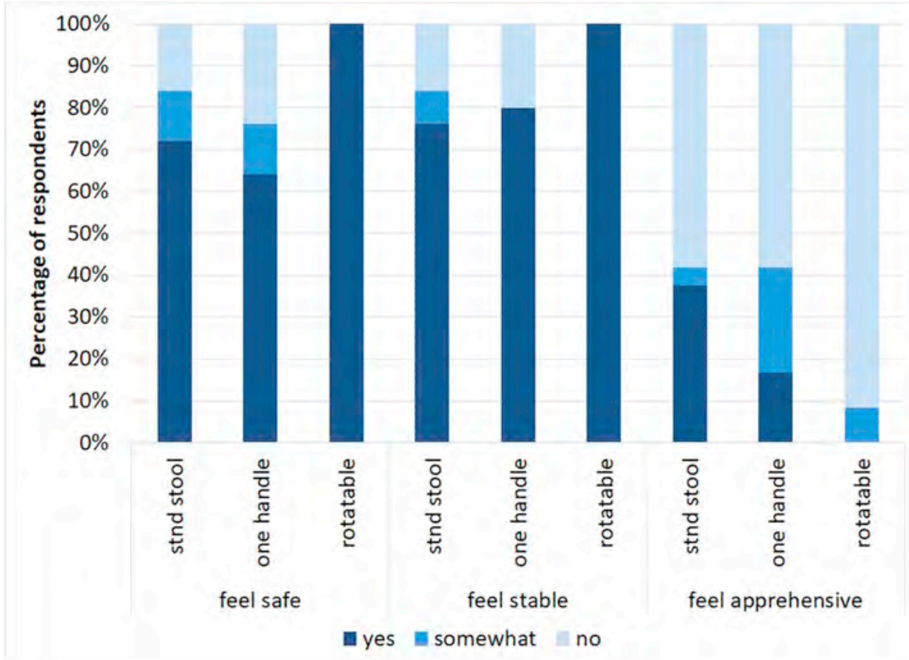


Fig. 9. Participants' perceptions of safety, stability, and apprehensiveness in using the standard (no handle) step stool, a one handle step stool, and prototype rotatable step stools.

address users' needs and requirements (Sanders and Stappers, 2013; Ulrich and Eppinger, 2008). This study demonstrates a model of collaboration between engineers, ergonomists, designers, and radiographer-subject matter experts, that yielded several promising engineering and administrative control concepts to reduce the radiographers' exposures to MSK symptom risk factors. While a good and necessary starting point, it is important to understand that successful intervention also requires engagement of hospital administrators, in their roles as financial decision-makers and establishers of their organization's safety culture. It also requires engagement of radiography equipment designers, to ensure their equipment includes design elements that facilitate more of the RTs' patient handling activities. Further, engagement of patient handling equipment designers would also be valuable, because portable sling type lifts and patient stand-assist equipment is typically not designed to interact with x-ray tables. Attempting to use such equipment, not designed for radiology clinic environment and use context, could increase, rather than decrease, the risk of injuries to patients and RTs.

The key limitation to this study is that after piloting the prototype interventions, the project ended with dissemination activities rather than with further development of intervention concepts. In spite of the strong interdisciplinary collaboration among the researchers and the RTs, partnerships were lacking with equipment manufacturers that could take the concepts further. As such, this study is classified as Developmental Research, 'research that informs intervention development', in Goldenhaur and colleagues' model of the intervention research process (Goldenhar et al., 2001). As pointed out by Taylor (2018), university labs typically do not have the resources to translate their discoveries into commercial products. Lutchen (2018) wrote about the mutual benefits to establishing formal, long-term collaborations between companies and univerisities, with companies gaining involvement at the early stages of univerity research, and society benefiting from the products that stem from these collaborations.

6. Conclusion

A primary objective of this study was identifying needs and opportunities for interventions to reduce the exposures to risk factors that contribute to the high prevalence of work-related MSK discomfort and injury in radiographers. This paper presents several areas of intervention need and opportunity. The other primary objective was development of intervention concepts and testable prototypes. This paper presents several intervention concepts and describes the testing of three prototype concepts for reducing radiographers' exposure to forceful exertions associated with their physical interactions with patients. This study draws attention to the great need to intervene with targeted solutions to the unique patient handling challenges faced by RTs on a daily basis.

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Disclosure statement

None of the authors have any financial interest or benefit to declare in any regard in relation to the study described in this manuscript. Each author is obliged by our institution to declare any actual or apparent conflicts of interest, annually, as part of the university's protection of human subjects process.

Declaration of competing interest

None.

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Appendix. Median scores from Part 2 of the study, the Intervention Concept Review, for items used to evaluate specific aspects of usability, usefulness, and desirability for concepts that were subsequently developed into prototypes and evaluated in Part 3 of the study

	Scoring scale: 1 = Strongly Disagree … 5 = Strongly Agree		
I. Usability	Receptor Soft Edge	Patient Support Handle	Rotatable Step Stool
1. I think this new approach would be easy to use, especially with the targeted patient groups.	4.5	5.0	4.0
2. I find this new approach unnecessarily complex.*	1.0*	1.0*	1.5*
3. I think that I would need assistance to actually use this new approach.*	1.0*	1.0*	2.5*
4. I imagine that most people would learn to use this new approach very quickly.	4.5	5.0	5.0
5. I think this new approach would be very cumbersome to use.*	1.0*	1.0*	1.0*
6. I would need to spend a lot of time practicing with this new approach before I could use it on patients.*	1.0*	1.0*	1.0*
II. Usefulness			
1. I would rather use this new approach than our traditional approach.	4.5	5.0	5.0
2. I believe that using this new approach would be more comfortable for the patient.	4.5	5.0	5.0
3. I believe that using this new approach would make my work easier physically.	4.0	5.0	5.0
4. I believe this new approach will help me perform my work tasks more efficiently.	4.0	5.0	4.0
5. I believe this new approach will reduce my physical fatigue at the end of each work day.	4.0	5.0	4.0
III. Desirability			
1. I would really benefit from the use of this new approach.	4.0	4.5	4.0
2. I would like to try this new approach as soon as you can get me a workable version.	4.0	5.0	5.0
3. I think some of my co-workers will want to use this new approach.	4.0	5.0	5.0
4. I really need this new approach for a select group of my patients.	3.5	4.5	4.0

* Items worded as problems with usability; expect scores <2.5 if these items were not seen as potential problems by study participants.

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