An Ergonomic Evaluation of Convex Probe Designs Using Objective and Subjective Measures

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Abstract. Use of a convex probe suitable to the hand and operating motion of the probe can contribute to prevention of sonographers from musculoskeletal disorders at work. The present study presents an ergonomic evaluation process customized to convex array ultrasound probe design. Various convex probe designs were evaluated by a mix of nine sonographers and medical doctors in terms of EMG activities of the upper extremity muscles, motion ranges of the upper extremity joints, and subjective satisfaction measures. A randomized controlled testing was administered for the probe designs in a simulation workstation at a designated speed of tilting, pushing, and rotating of convex probe. The subjective satisfaction results were found effective to identify preferred design features in detail, while the EMG and motion analysis results to identify a preferred probe design overall in terms of muscular load at the hand and postural comfort of the forearm.

Keywords: Convex Probe Design, Ergonomic Evaluation, Preferred Design Feature

1 Introduction

A high prevalence of musculoskeletal symptoms among sonographers has been reported due to elevated exposure to adverse work conditions. Previous studies [2, 4, 5, 6] reported significant prevalence rates of musculoskeletal pains among sonographers at the neck (43% ~ 86%), shoulder (29% ~ 84%), upper back (15% ~ 77%), lower back (33% ~ 71%), elbow (5% ~ 57%), and hand/wrist (33% ~ 64%). Risk factors of the musculo-skeletal pains with sonographers include repetitive motion, awkward posture, static muscle contraction, excessive force exertion, prolonged duration of scanning, improper design of device and workstation, insufficient rest, and manual handling of patients [1, 2, 3, 9].

An ergonomic evaluation is needed to identify the desirable design features of an ultrasound probe which can effectively reduce the physical workload of ultrasound task. An ultrasound probe produces sound waves that bounce off body tissues and makes echoes and also receives the echoes and transmits them to a computer for a sonogram. The most common types of ultrasound transducer include linear, convex, phased-array, and endocavity transducers. Few studies have been conducted for the ergonomic design and evaluation of an ultrasound probe to reduce the postural and muscular loads of ultrasound task. Paschoarelli et al. (2008) ergonomically designed a linear array ultrasound probe by adding an ergonomic grip and a rotation mechanism at the base of the probe for adjusting their contact areas to the breast to reduce wrist motions during a breast ultrasound scanning task. The proposed probe was compared with two existing probes in terms of wrist motion and subjective satisfaction and concluded that the new probe resulted in less average movement of the wrist, more time within the safe motion range of the wrist, higher acceptance, and lower discomfort than the existing probes. However, detailed features of their proposed probe such as size, shape, and weight were not analyzed in their study.

The present study was intended to identify preferred design features of a convex array ultrasound probe, commonly used for examinations of the abdomen, OB-GYN, and peripheral vasculature, by an ergonomic evaluation. Designs of convex probe in different sizes and shapes were evaluated in a lab environment while simulating ultrasound tasks by health professionals in terms of muscular load, motion, and subjective satisfaction. Preferred design features were suggested for convex probe based on the ergonomic evaluation results.

2 Materials and Methods

Participants

Health professionals (age = 44.6 ± 10.1 years; work experience in sonography = 16.9 ± 9.2 years; hand length = 167.0 ± 6.8 cm) including sonographers and physicians having no history of musculoskeletal disorders participated in the convex probe evaluation. The mean and variance of the participants are not statistically different from those of the corresponding Korean population [7] at $\alpha = .05$. The participants provided informed consent and their participation was compensated.

Apparatus

An EMG measurement system, a motion analysis system, and a subjective satisfaction questionnaire were used in a simulated workstation of sonography (Figure 1) for the ergonomic evaluation of convex probe design. The participant sitting on a stool (height adjustment range = 440 ~ 580 mm).

Simulated motions of pushing and rotation with a convex probe while applying a force of 20 ± 4 N on a silicon abdominal phantom (200 mm from the table) placed on a conventional examination table (length × width × height = 1800 × 730 × 650 mm). The motions of the upper body (wrist: flexion/ extension, ulnar/radial deviation, and pronation/ supination; elbow: flexion/extension; shoulder: flexion/ extension, abduction/adduction, and internal/external rotation; neck: flexion/extension, right/left bending, and right/left rotation; back: flexion/extension, right/left bending, and right/left rotation) were measured by 10 infrared cameras of the Osprey motion analysis system (Motion Analysis Corp., Santa Rosa: CA, USA; frame rates: 50 Hz). The outliers of motion measurements collected with a repetition in a probe task cycle were filtered

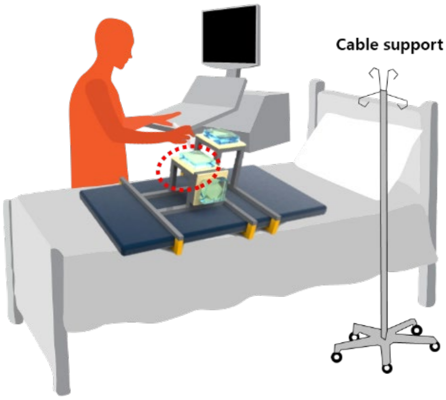

Fig. 1. Sonography simulation workstation.

and synchronized, and then the proportion of motion measurements within a comfortable range of motion for each joint motion was calculated as shown in Figure 2. Next, the muscle activities of the right upper limb and shoulder (thenar muscle, flexor carpi ulnaris, flexor carpi radialis, flexor digitorum, and extensor digitorum) were measured by the wireless EMG system Telemyo DTS (Noraxon, Scottsdale: AZ, USA; frame rates: 1,000 Hz). Noises of EMG were removed using a bandpass filter (10 Hz of lower cut-off frequency and 400 Hz of upper cut-off frequency) and then the filtered EMG signals were rectified, smoothed (time window = 400 ms), and normalized (%MVC) by EMG signals measured at his/her maximum force exertion. Lastly, a subjective questionnaire was used to assess the level of satisfaction with the size, curvature, and shape of the head and grip of a convex probe design in terms of fit to the hand, postural comfort, natural probe manipulation, effective force application, and even pressure distribution using a 7-point scale (-3: very dissatisfied, 0: neutral, 3: very satisfied) compared to a reference probe design designated.

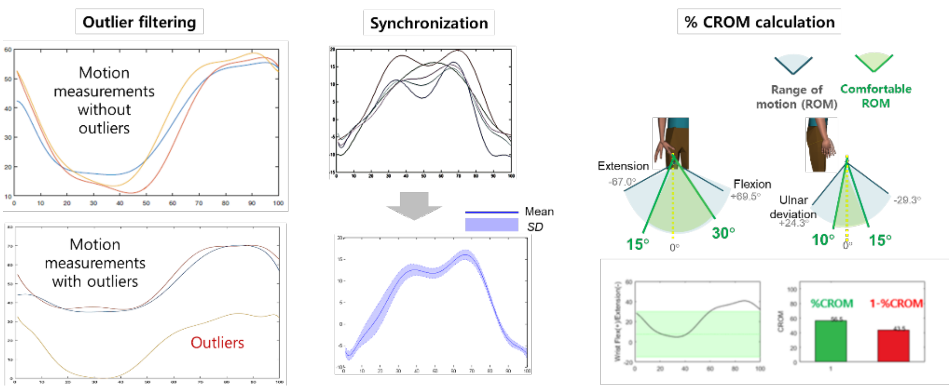

Fig. 2. Analysis process of %CROM (comfortable ROM).

Design of Experiment

A three-way (probe design × task × grip) within-subject (nested within hand size) design was used for the convex probe design evaluation. Probe design (three probe designs), task (push and rotate), grip (narrow and wide grips), and hand size (small, medium, and large hand size groups) were fixed-effects factors and subject was a random-effects factor in the present study. The three convex probe designs (existing design: ED; benchmarking based design: BM; and hand-data based design: HD; Figure 3) were prepared using a rapid prototyping machine. Note that the BM and HD designs were developed based on the result of a benchmarking on five convex probe designs and that of the relationship analysis of probe design variables and hand dimensions in a preferred grip as shown in Figure 4, respectively. The order of probe design was randomized and balanced across the participants.

Procedures.

The convex probe design evaluation was conducted for two hours per participant in four phases: (1) preparation, (2) practice, (3) main experiment, and (4) debriefing. In the preparation phase, the purpose and procedure of the evaluation were explained, informed consent was obtained, clothing for experiment was worn, electrodes and reflective markers were attached to designated locations on the body, EMG signals of the upper limb and shoulder muscles at the maximum voluntary contraction were collected, and the height, weight, hand length, and hand width of the participant were measured. In the practice phase, the participant was familiarized with the evaluation procedure. In the main experiment phase, while pushing and rotating tasks with each of the convex probe designs were simulated using narrow and wide grips at a designated speed by a metronome, the muscle activities and motions of the upper body were measured. After completing the convex probe simulation tasks, the BM and HD designs were compared with the ED design using the satisfaction questionnaire. Finally, in the debriefing stage, the preferred design characteristics of the probe designs were surveyed.

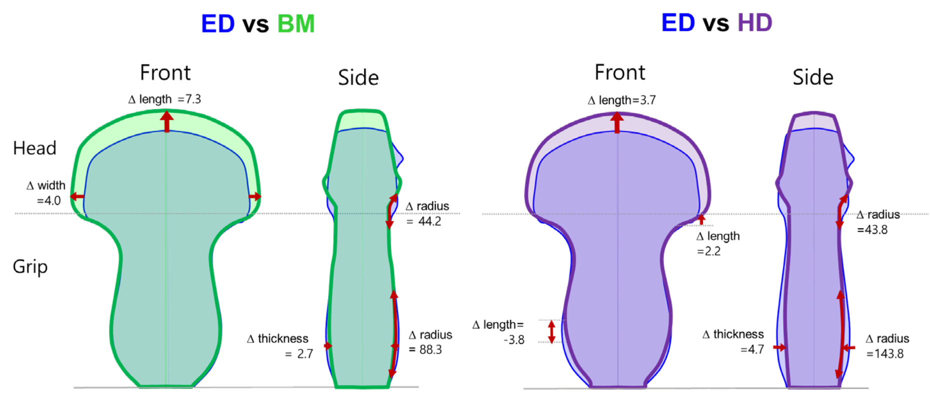

Fig. 3. Convex probe designs (existing design: ED; benchmarking based design: BM; and hand-data based design: HD).

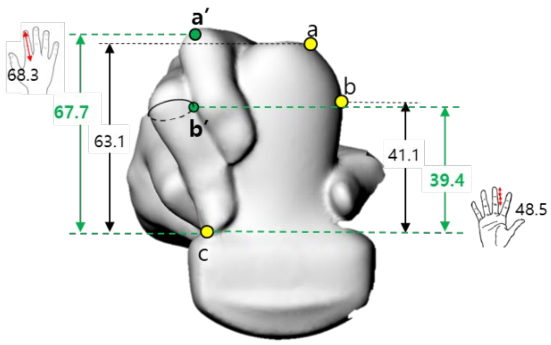

Fig. 4. The relationship analysis between probe design variables and hand dimensions in a preferred grip with a convex probe.

Statistical analysis.

Significant factors on EMG, joint motion, and subjective satisfaction were analyzed by ANOVA and then post hoc pairwise comparisons were conducted for significant factors at α = 0.05. Statistical analysis was performed using MINITAB 14 (Minitab Inc., State College, PA, USA).

3 Results

Muscular Load

ANOVA and post hoc analyses indicated that the BM and HD designs required slightly decreased (Δ < 1.4%MVC) muscle activities at the FCU, FCR, flexor, and extensor muscles and relatively largely decreased (Δ < 3%MVC) muscle activities at the thenar muscle compared to the ED design. The largest decrease (Δ = 3.6%MVC) in muscle activities was observed at the thenar muscle with the HD design when conducting the push task with the wide grip as compared with the other experiment conditions such as push with narrow grip, rotate with narrow grip, and rotate with wide grip for the ED and BM designs (Figure 5).

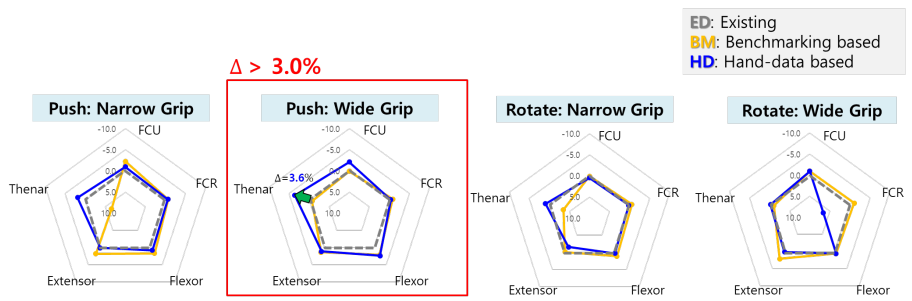

Fig. 5. Comparison of convex probe designs in terms of decrease in %MVC.

Table 1. ANOVA on adequacy of grip shape.

Sources	SS	df	MS	F_O	P-value
Probe design	58.475	3	19.4917	51.22	**<0.01***
HS	0.225	2	0.1125	0.16	0.857
Subject(HS)	5	7	0.7143		
Error	10.275	27	0.3806		
Total	73.975	39			

Comfortable Motion.

ANOVA analyses could not find any statistical differences in %CROM for the upper body by probe design. No post hoc analysis conducted due to the insignificance of probe design.

Subjective Satisfaction.

ANOVA analyses identified that probe design was significant at $\alpha = .05$ for all the satisfaction measures as shown in Table 1. The mean differences with the ED design for the satisfaction measures ranged from -.1 to 1.6 for the BM design and from 0 to 1.8 for the HD design as shown in Figure 6.

4 DISCUSSION

An ergonomic evaluation process customized to convex array ultrasound probe design was established in the present study. A simulated sonography workstation consisting of an examination table, a stool with a height adjustment function, a cable support, and a silicon phantom with a load cell underneath the phantom was prepared. Tasks (push, rotate, tilt, and slide), grip types (narrow and wide grips), a range of force application, and a speed of probe manipulation were specified and controlled in a syste-

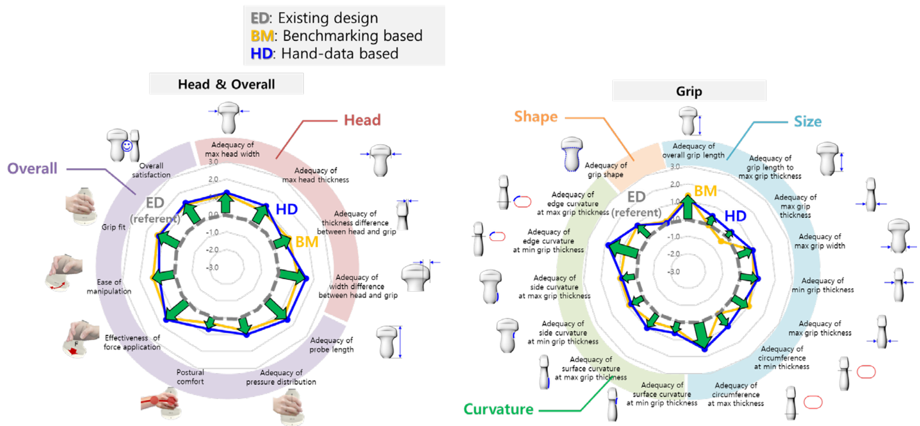

Fig. 6. Comparison of convex probe designs for the satisfaction measures.

matic manner. Lastly, the measurement and analysis protocols of muscle activities, body motions, and satisfaction were established.

The satisfaction assessment method was found effective, cost-efficient, and sensitive to identify the effects of a preferred convex probe design in the present study, while the EMG and motion analysis methods were found specific to identify the effects of a preferred convex probe design in terms of muscular load at the hand and postural comfort of the forearm. The satisfaction assessment method could detect the effects of various probe design features with higher sensitivity than the EMG and motion analysis methods when comparing the three convex probe designs with each other. Next, the EMG analysis method could detect the effect of the probe design based on hand data with higher specificity by identifying a significant decrease in the thenar muscle for pushing with a wide grip out of the five hand-forearm muscles for the experimental conditions of task and grip. Lastly, the motion analysis method was found the least sensitive method in detecting the effects of probe design features because the design changes in probe design in the present study were not large enough to significantly affect the motion of the upper body.

The convex probe design evaluation results suggested that a systematic application of hand data along with a preferred grip posture be effective to develop an ergonomic probe design for better fit and comfort. Of the three convex probe designs, the hand-data based design was found most preferred in terms of satisfaction and muscular load. The hand-data based design was developed by identifying the relationships between probe design variables and hand dimensions in the hand and probe image from scanning the hand posture with the most preferred probe.

Acknowledgements

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