An Ergonomic Grip Design Process for Vaginal Ultra Sound Probe Based on Analyses of Benchmarking, Hand Data, and Grip Posture

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Abstract. The present study presents a systematic design process for the ergonomic design of a vaginal probe based on benchmarking, hand data, and grip posture analyses. Five existing vaginal grip designs were compared with each other using subjective measures to identify preferred design features for a new probe grip design. An in-depth analysis of the relationships between grip design variables and hand dimensions was conducted along with the consideration of preferred grip postures of vaginal probe and hand measurements. Two novel vaginal probe grip designs were proposed based on the analysis results of benchmarking, hand data, and grip posture. A validation experiment showed a significant improvement of the hand-data based vaginal grip design compared with the existing designs in terms of subjective satisfaction and wrist flexion.

Keywords: Ergonomic grip design · Grip design process · Ultra sound probe

1 Introduction

The ergonomic design of an ultrasonic probe is needed to improve its usability and prevent work-related musculoskeletal disorders (WMSDs) among health care professionals engaged in sonography. Ultrasonic probe is a device that sends and receives ultrasound signals to the human body during ultrasound examination. Previous studies have reported that 65% to 91% of sonographers experience pains and WMSDs at the neck, shoulder, chest, lumbar, elbow, and wrist [4].

The risk factors of WMSDs experienced by ultrasound technicians include repetitive motion, inadequate posture, static muscle contraction, use of excessive force, prolonged work of ultrasound scanning, and improper design of ultrasound equipment and working environment [1, 3]. Ergonomically designed ultrasound probes can improve ease of use, ease of manipulation, use of proper force, and satisfaction, which can contribute to the prevention of musculoskeletal disorders among sonographers [2, 6].

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An ergonomic evaluation study is conducted to evaluate the physical workload of a sonographer quantitatively during ultrasonic operations and assess the risk of WMSDs. Subjective satisfaction questionnaires, posture and motion analyses, and muscular load (EMG) measurements are collected to evaluate the motion and muscle load during ultrasonic scanning task. Body postures and motions at the shoulder, neck, elbow, and wrist are measured and analyzed by video analysis systems, electrogoniometers, and optoelectronic motion capture systems. The muscular load of an ultra sound probe use is analyzed by measuring EMGs of middle trapezius, supraspinatus, infraspinatus, flexor carpi ulnaris, left extensor digitorum, and left deltoideus anterior muscle [3, 12–14].

Although studies have been conducted to evaluate the workload of ultrasound probe scanning, more research on the preferred design characteristics of the probe handle and the optimal shape based on human body dimensions and grip postures is needed. Burnett and Campbell-Kyureghyn [3] and Village and Trask [14] measured motion, EMG, grip and push forces during ultrasonic operations and analyzed the differences between tasks in physical workload, but the preferred designs of probe were not identified in terms of usability. In contrast, Mazzola et al. [11] and Paschoarelli et al. [12] proposed an ergonomic probe shape and compared the proposed design with those of the existing probes; however, they did not present the design rationale of the proposed design and the corresponding detailed design features in probe size, shape, and weight. The application of anthropometric data of a target population under consideration in the product design process enables to develop a design with better usability [7, 9, 10].

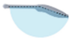
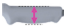
The present study developed a systematic handle grip design process based on benchmarking, hand data analysis and grip posture analysis to improve the usability of a vaginal probe. An improved grip design in terms of usability were proposed and then verified by an ergonomic evaluation in the study. The characteristics of the probe design were analyzed by the benchmarking of existing vaginal probe designs and the preferred design features of the existing designs were analyzed by satisfaction evaluation and an optimal handle grip circumference was derived by applying the hand data of Koreans. The vaginal probe design developed by the ergonomic grip design process in the present study was evaluated in terms of motion, muscular load, grip posture, and subjective satisfaction by ultrasonic probe users in a laboratory environment.

2 Development of Grip Design Process

2.1 Design Analysis of Vaginal Probe

To determine the effect of vaginal probe design on usability, probe designs in different sizes and shapes were analyzed as illustrated in Table 1. Probe designs were scanned using the Artec Eva 3D scanner (Artec Group Inc., Luxembourg) and six probe design dimensions of length, circumference, and angle were measured using the CAD software Alias Automotive 2012 (Autodesk, Inc., USA). The length of vaginal probe and the thickness of the middle grip largely varied with ranges of 307.6–350.8 mm and 32.1–42.6 mm, respectively. The shape of vaginal probe was largely classified into two types, straight (180°) and bent (163.7°–164.0°), by the angle between the head and the grip angle in the side view.

Table 1. The design dimension analysis of vaginal probe (illustrated).

Image			Vaginal probe designs					
Design dimension		Unit	Range	A type	B type	C type	D type	E type
Overall length		mm	307.6–350.8	Small	Large	Medium	Medium	Large
Head-grip angle		° (deg.)	163.7–180.0	Straight	Curved	Straight	Curved	Straight
Grip length		mm	127.3–142.8	Small	Large	Medium	Medium	Large
Thickness of frontal grip		mm	30.3–38.1	Medium	Large	Small	Small	Small
Thickness of middle grip		mm	32.1–42.6	Medium	Large	Medium	Medium	Small
Circumference of middle grip		mm	103.7–118.2	Medium	Large	Medium	Medium	Small

2.2 Design Evaluation for Vaginal Probe

The subjective satisfaction evaluation of five vaginal probe designs was performed to identify the preferred design characteristics of vaginal probe. Seven obstetrician-gynecologists (age = 48.0 ± 11.8 years; career = 19.3 ± 11.3 years; stature = 163.0 ± 5.3 cm) with no history of musculoskeletal disorders and having experience of ultrasonographic examination with vaginal probe for more than 5 years were recruited. The hand length (167.3 ± 6.5 mm) of the participants was statistically similar with the hand length (170.4 ± 7.3 mm) of 20–40 years old female group of Koreans (n = 2,067) from the 6th anthropometric research report (Size Korea, 2010) in terms of mean and variance (t[2, 072] = 1.12, $p = 0.26$ for mean difference; F[6, 2066] = 1.26, $p = 0.58$ for variance difference). The vaginal probe designs were evaluated according to length and angle appropriateness, form suitability, pressure dispersion appropriateness, grip comfort, and overall satisfaction using a 7-point scale (1: very unsatisfied, 4: neutral, 7: very satisfied).

Based on the results of the subjective evaluation of the five vaginal probes, the preferred design characteristics of vaginal probe grip were identified. A probe design with the overall length for medium size and the grip length for medium or a large size design was preferred. The straight type of vaginal probe was preferred to the bent type. A probe design with a small size of the frontal grip and a small or medium size of the middle grip was preferred.

2.3 Grip Design Based on Grip Posture and Hand Dimensions

The natural use posture with a vaginal probe grip was analyzed and the human body size data of the fingers were selected to design a preferred handle grip size. Vaginal probe grip postures were identified as two types: normal grip, where the finger and handle are orthogonal based on the power grip; the twisted grip for the inclined finger grip direction. D3 link length and palm-touch link length were selected for the hand dimensions as those related to the circumference of the middle grip.

The preferred grip circumference can be determined as shown in Fig. 1 by the sum of the deformed D3 link, palm-touch link, and clearance and the length deformation due to the twisted angle when the grip posture is changed. In the case of the vaginal probe grip, the D3 link length decreased to 60% of the straight posture as shown in Table 2, and palm-touch link, and clearance were 25% and 10% of the D3 link length, respectively. The preferred grip circumference is determined by the sum of the deformed-D3 length, the palm-touch link length, and the clearance for the normal grip is determined by summing the twisted length with the normal grip circumference at the time of the twisted grip.

The circumferences of vaginal probe grip at the contact points of fingers were derived by applying the finger length ratio and the finger length difference based on the circumference of the middle finger contact point from the index finger to the little finger. US anthropometric measurements data [5] were used for finger length ratio analysis, and the D2, D4, and D5 link length ratios were 99%, 97%, and 78% of the D3 link length, respectively. The optimal grip size for each finger was derived by applying the D2–5 link length ratio to the D3 link length based on the preferred circumference of the vaginal probe grip at the middle finger contact point (103.7 mm).

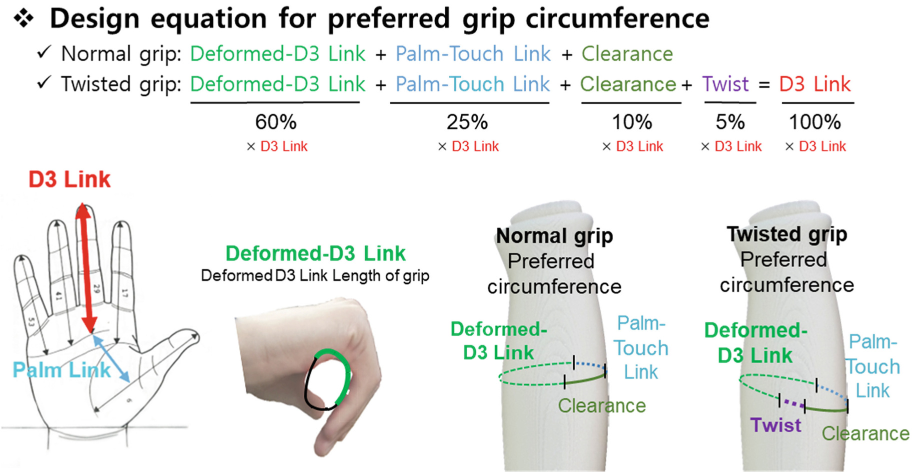


Fig. 1. Design equation of preferred grip circumference.

Table 2. Hand link length deformation analysis.

Participants	S1		S2		S3	
Item	Measurement (mm)	Ratio (%) vs. D3 link	Measurement (mm)	Ratio (%) vs. D3 link	Measurement (mm)	Ratio (%) vs. D3 link
D3 link	98.0	–	96.0	–	106.0	–
Deformed-D3 link	60.0	61.2	58.0	60.4	65.0	61.3
Palm-touch link	24.0	24.5	24.0	25	27.0	25.5
Clearance	9.0	9.2	8.0	8.3	11.0	10.4
Twist	4.0	4.1	4.0	4.2	6.0	5.7
Total	97.0	99.0	94.0	97.9	109.0	102.9
Error rate	1.0%		2.1%		2.9%	

2.4 Design Development for Vaginal Probe

The improved design of the vaginal probe grip was proposed with a benchmarking-based improvement (BM) grip and a hand data-based improvement (HD) grip as shown in Fig. 2. Based on the results of the subjective satisfaction assessment, the BM grip was designed by applying the medium size of overall length and the grip length, the shape of the bend, the small size of the frontal grip area and the medium size of the middle grip area. The HD grip was designed with the grip circumference corrected by applying the optimal grip design formula based on the overall characteristics of the BM grip.

3 Validation of Proposed Grip Design

3.1 Method

Participants

13 female sonographers (age = 44.6 ± 10.1 years; career = 16.8 ± 9.2 years; stature = 162.8 ± 5.0 cm) without having a history of musculoskeletal disorders and an experience of use of a vaginal probe for 5 years or above. The mean hand length (168.5 ± 6.8 mm) of the participants was found statistically similar with the hand length (170.4 ± 7.3 mm) of 20–40 year-old female group of Koreans (n = 2,067) from the 6th anthropometric research report (Size Korea, 2010) in terms mean and variance ($t[2078] = 0.94$, $p = 0.35$ for mean difference; $F[12, 2066] = 1.15$, $p = 0.58$ for variance difference).

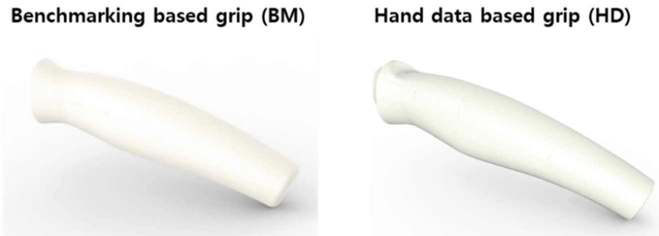


Fig. 2. Proposed vaginal probe grip designs.

Apparatus

The validation experiment of vaginal probe was performed with a medical phantom using two newly proposed probe grips (BM and HD grips) and an existing product. The most preferred probe grip design in terms of subjective satisfaction was selected as superior design product (SP grip, superior probe grip) and the new probe grip designs based on benchmarking and hand data analysis were evaluated along with the SP grip design. For the evaluation of vaginal probe, a phantom for evaluation, which was inspected by the medical staff, was used to implement an environment similar to the actual inspection task. The evaluation phantom was designed to induce a similar vaginal probe task by application of the depth (26 mm) and position guides (engraving depth: 2.0–6.5 mm).

An optical motion analysis system, an EMG measurement device, and a subjective evaluation questionnaire were used to measure changes in wrist motion, muscle activities of the arm and wrist, and subjective satisfaction during the vaginal probe test. The motion analysis system Osprey (Motion Analysis Corp., Santa Rosa: CA, USA; frame rates: 50 Hz) with 10 infrared cameras was installed at various heights around the participants. For the motion analysis 14 reflective markers (front head, rear head, right acromion, left acromion, offset, lateral epicondyle, medial epicondyle, right anterior superior iliac spine (ASIS), left ASIS, sacrum, radius, ulna, 5th metacarpal, and 2nd metacarpal) were attached to the body as shown in Fig. 3. The local coordinate system was defined at the neck, shoulder, waist, elbow, and wrist centers, and the angles of the each body parts (shoulder: flexion/extension, abduction/adduction, internal/external rotation angle; neck: flexion/extension, right/left bending, right/left rotation angle; back: flexion/extension, right/left bending, right/left rotation angle, elbow: flexion/extension angle; wrist: flexion/extension, ulnar/radial deviation, internal/external rotation angle) were measured while using a vaginal probe. The trajectory of the measured reflective marker was filtered using a fourth-order Butterworth filter (cut-off frequency = 5 Hz) to remove noise effects. EMG measurements were performed using the wireless EMG system Telemyo DTS (Noraxon, USA), and nine muscle loads (trapezius, deltoid, extensor digitorum, pronator teres, flexor digitorum, biceps, supinator, FCU, FCR) were measured when using the vaginal probe. Noise of EMG signal was removed using a bandpass filter (lower cut-off frequency: 10 Hz; upper cut-off frequency: 400 Hz) and after rectification, a signal smoothing was performed using root mean square (time window: 400 ms) for amplitude analysis (Fig. 4).

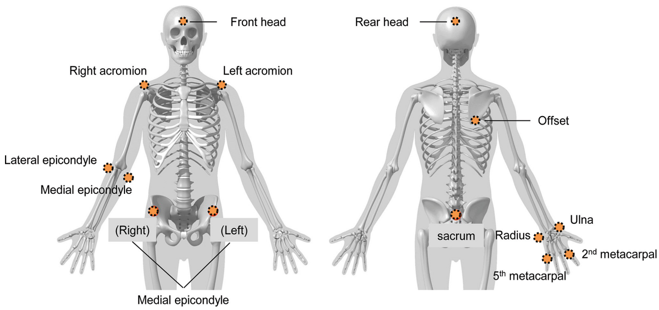


Fig. 3. Reflective markers attached to the whole body.

Subjective satisfaction of each proposed grip was assessed compared to the reference probe grip using a 7-point scale to measure the size (length, thickness, width), angle, and curvature adequacy, form fitness, posture and strength adequacy, grip comfort, and overall satisfaction of vaginal probe (−3: very dissatisfied, 0: neutral, 3: very satisfied).

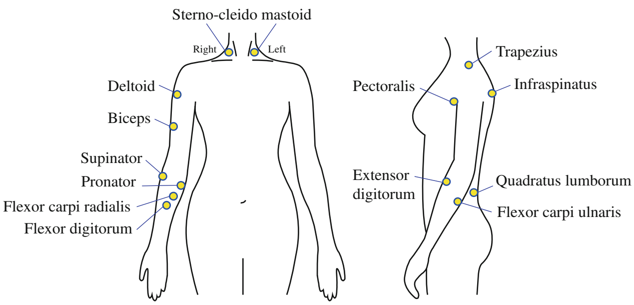
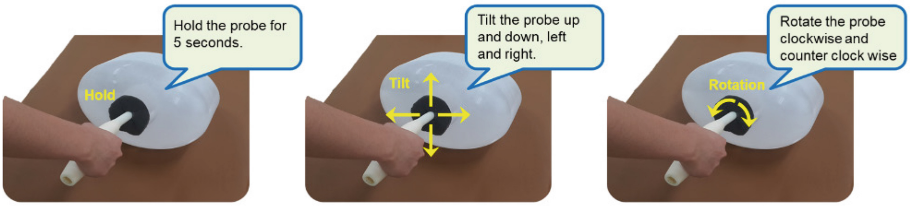


Fig. 4. Attachment of EMG electrodes.

Experiment Procedure

The verification experiment of the effectiveness of vaginal probe design was performed by four steps: (1) preparation of test and body size measurement, (2) measurement of EMG and body motion, (3) evaluation of subjective satisfaction, and (4) post-survey. In the experiment preparation and the human body measurement step, the experimental purpose and method were explained to the participants and informed consent was obtained. The height, weight, hand length, and hand width of the participant were measured after the participants changed with experimental clothing provided, reflective markers, EMG electrodes, and a radio signal transmitter module were attached to the body of the participant. The MVC (maximum voluntary contract) of the participant was measured prior to the experiment. In the main experiment, during the repeated three times of hold, rotate, vertical tilt, and lateral tilt movements, the participant's EMG and body movements were measured simultaneously while the participant was sitting.

A hold motion was performed by holding the probe for 15 s after power grip and insertion into the phantom as shown in Fig. 5a, and rotation motion was performed 90° clockwise from the center of the probe insertion direction in the power grip posture as shown in Fig. 5b. Next, vertical tilt and lateral tilt motions were performed by tilting 30° up/down and left/right in power grip posture as shown in Fig. 5c. The duration of task was controlled from 10 to 15 s per motion and the evaluation and task among the probes were randomized to minimize learning and fatigue effects. In the subjective satisfaction evaluation stage, the satisfaction level of each of the five grip designs (existing three preferred design and the two new designs) was relatively evaluated to the reference probe grip using the evaluation questionnaire based on task performance experience. Finally, a post-survey was conducted on the preference design characteristics of the probe.



(a) Hold (b) Tilt (c) Rotate

Fig. 5. Use tasks of vaginal probe in ergonomic assessment.

Statistical Analysis

Statistical differences in EMG, body movement, and subjective satisfaction according to vaginal probe design characteristics were analyzed by paired t test at $\alpha = 0.05$. Statistical analysis was performed using MINITAB 14 (Minitab Inc., State College, PA, USA).

3.2 Results

Motion

The improved grip based on hand data (HD grip) was found to improve the wrist motion efficiency in terms of flexion/extension and radial/ulnar deviation compared with the existing superior probe (SP grip). As shown in Fig. 6, the ratio within the average comfortable range of motion (CROM) of the HD grip and the BM grip were 13.5% and 10.3% higher than that of the SP grip in the flexion/extension of the wrist motion, respectively. In the radial/ulnar deviation of the wrist motion, the ratio within the average CROM of the HD grip was 2.5% higher than the SP grip, but there was no statistically significant difference. The ratio within the average CROM of the BM grip was 5.1% lower than the SP grip.

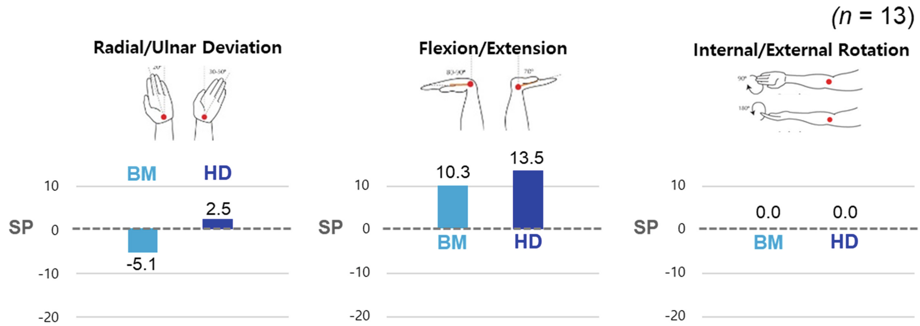


Fig. 6. Comparison of vaginal probe designs in ratio (%) of motion in CROM (comfortable range of motion).

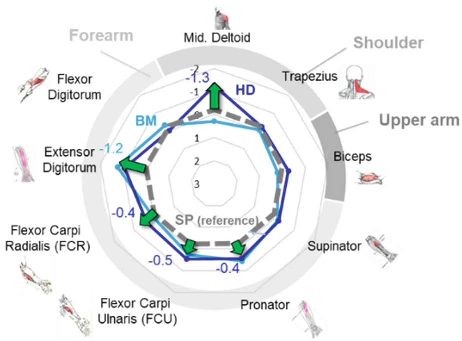


Fig. 7. Comparison of vaginal probe designs by percentage of MVC (%MVC).

Electromyography

The muscle loads of the HD grip and the BM grip were .5% and .2% lower than those of the SP grip, but no statistically significant difference were found. As shown in Fig. 7, % MVC of the HD grip was 1.3%, 0.9%, 0.4%, 0.5% and 0.4% lower in deltoid, extensor digitorum, pronator, FCR and FCU than the SP grip and decreased by 0.5% on average, respectively. When using the BM grip, the % MVC was 1.2% and 0.6% lower in extensor digitorum and pronator than the SP grip, respectively, and decreased by 0.2% on average.

Satisfaction

The HD grip was found to have improved subjective satisfaction with length, curvature and overall usability in comparison with the SP grip. The subjective satisfaction rate of the HD grip and the BM grip were 13.3% and 10.0% higher than that of the SP grip, respectively. As shown in Fig. 8, the subjective satisfaction of the HD grip was improved by 18.3% (Mean = 0.6 point) in length aspect, 15.4% (Mean = 0.5 point) in curvature aspect, and 9.1% (Mean = 0.3 point) in overall usability compared to the SP grip. The subjective satisfaction of the BM grip was increased by 16.5% (Mean = 0.5 point) in length aspect, 15.4% (Mean = 0.5 point) in curvature aspect, and 7.7% (Mean = 0.2 point) in shape aspect compared to the SP grip.

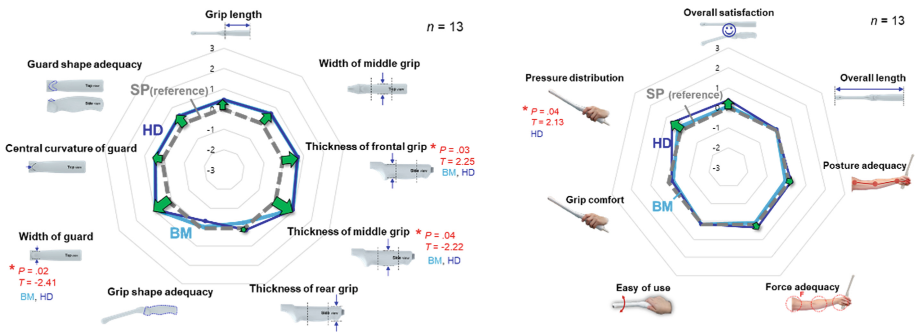


Fig. 8. Comparison of satisfaction evaluation for vaginal probe designs.

4 Discussion

The present study proposed an ergonomic grip design process which includes benchmarking, hand data, and grip posture analysis and developed an improved grip design. A preferred design of vaginal probe was derived using the evaluations of length, circumference, and angle. The proposed vaginal probe was favored in terms of subjective satisfaction with the medium size of the overall length, the shape of the bent, the small size of the frontal part of the grip, and the small or medium size of middle grip part. A design formula using the link length of the middle finger, the link length of palm-touch, clearance, and twisted length based on the preferred circumference of the middle finger contact point and design alternatives were developed based on the benchmarking results and hand data application.

The new design (HD grip) developed through the ergonomic grip design process was found better the most preferred existing design of vaginal probe (SP grip) in terms of motion efficiency and subjective satisfaction. The proposed probe design was evaluated by an ergonomic evaluation protocol, and the comparison of the existing and proposed designs were evaluated in terms of motion, muscular load, and subjective satisfaction for vaginal probe tasks. The HD grip increased 13.5%, 0.5%, and 13.3% in wrist flexion and extension, overall force, and subjective satisfaction, respectively, compared to the SP grip. The BM grip also showed increases in wrist flexion and extension efficiency, overall force, and subjective satisfaction by 10.5%, 0.2%, and 10.0%, respectively. These positive results of the proposed designs support the effectiveness of the proposed grip design process. Both the BM and HD grips were designed to be inversely tapered so that the movement of the wrist flexion required when holding and tilting the wrist could be less than that of the SP grip designed as a tapered shape and the ratios within the average CROM were relatively high.

When the hand data of a particular population under consideration are applied to the proposed design process, the optimal grip design which reflects human body dimension characteristics of the target population can be derived and the design process can be applied to the design of another handle grip. In this study, a vaginal grip design equation was developed by considering the preferential grip circumference of Koreans and hand dimensions characteristics of the Korean and American. The grip design equation proposed in this study can be used to design other race-specific optimal grip designs by applying different racial hand dimensions characteristics (e.g., the length per finger), hand dimensions (e.g., D2–D5 link length, Palm-touch link length, and twisted length, clearance) and grip posture characteristics (twisted length, clearance). Meanwhile, the grip design process of the ultrasound probe proposed in this study is expected to be useful not only in the ultrasonic probe, but also in the ergonomic design of various products which the user grasps and manipulates (e.g., vacuum cleaner handle, tool handle).

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