Development of a Flexible System for Measuring Muscle Area Using Ultrasonography

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Development of a flexible system for measuring muscle area using ultrasonography

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Abstract—Muscular strength can be estimated by quantification of muscle area. For this purpose, we developed a flexible measuring system for muscle area using ultrasonography. This method is completely safe and is particularly suitable for elderly people because the subjects are not required to perform any muscular contraction during measurement. The ultrasound probe is installed on a mechanical arm, and continuously scans fragmental images along the body surface. A wide-area cross-sectional image is then constructed using the measured images.

The link mechanism is very flexible, enabling the operator to measure images for any body posture and body site. Use of the spatial compounding method reduces speckle and artifact noise in the resultant cross-sectional images. The operator can observe individual muscles (extensor, flexor muscle, etc.) in detail.

We conducted experiments to evaluate the performance of the system. In the experiments, the position of the ultrasound probe was calculated with high accuracy according to the link posture. In addition, a high degree of correlation was verified between MR images and those of the developed system. We observed a reduction in noise due to use of the spatial compounding method, and propose a new calibration method for correcting the measured muscle area, which were slightly deformed by the contact pressure of the ultrasound probe. Finally, we examined the relation between muscular area and muscular strength in young and middle-aged subjects. The results of these experiments confirm that the developed system can estimate muscular strength based on muscular area.

Index Terms—Ultrasonography, Body composition, Elderly people, Muscle area.

I. INTRODUCTION

Japanese society is aging rapidly, with the numbers of bedridden elderly becoming a serious issue[1]. Evaluating the activities of daily living (ADL) is very important for preventing people from becoming bedridden. Muscular strength is an index for evaluating ADL; however, measurement of muscular strength can be unreliable in the elderly because voluntary muscular contraction is difficult for those with arthritis or osteoarthritis. There is a particular need for a reliable measurement method in the elderly who require nursing care.

Previous attempts to estimate muscular strength were based on muscle area. For example, Gadeberg et al.[2] found a correlation between maximal isokinetic muscular strength and the volume of ankle dorsiflexors and plantar flexors. Reed et al.[3] reported the relationship between muscle mass and

muscular strength in the elderly; however, the measurement accuracy of their bioelectrical impedance method changed due to differences in polar contact conditions. MR imaging and X-ray CT can be used to quantify muscle area[4],[5], but these devices are only widely available in medical institutions. In addition, X-ray CT has a serious drawback in that the subjects are exposed to radiation.

In previous research, we developed a cross-sectional image measurement system using ultrasound to evaluate muscle area[6]–[7] (Fig. 1(a)). This system used ultrasound probes to measure fragmental images of the extremities from several angles; a whole cross-sectional image was then composed from these images. To confirm the validity of the system, we conducted an experiment in which we measured the thigh muscle area of a number of subjects and reported the change in muscle area with aging[7]; however, two important problems in the system prevented its application to the elderly and disabled.

The first problem of the previous system was related to configuration of the measuring system. We installed several ultrasound probes in the wall of a water tank; to measure the ultrasound image, the subject was required to insert his/her extremity into the tank. Water is a suitable medium to fill the gap between the ultrasound probes and the extremity, and it regulates the matching of acoustic impedance; however, it is possible that the area for measurement may be limited by the diameter of the water tank. Moreover, unnatural posture was sometimes required for the subject to insert his/her extremity into the tank, and the measured image was sometimes insufficient because of attenuation of the ultrasound signal by the water.

The second problem was related to image processing. The previous system measured only about 10 fragmental images, providing limited information for construction of the whole cross-sectional image. In addition, image processing was somewhat rudimentary, selecting only the brightest pixels from the layered fragmental images; consequently, there was insufficient clarity in the composite image, which sometimes prevented identification of the tissue boundaries.

The present study was performed to address these two problems. In this study, we developed a flexible system for evaluating muscle area in which an ultrasound probe installed at the end of a mechanical arm scans freely along the body surface. This system enables the muscle area of the elderly and disabled to be measured in arbitrary postures, even while sleeping or sitting, because the flexible mechanical arm considerably extends the areas and body shapes that can be measured. In addition, beneficial information can be extracted from a

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Fig. 1. Overview of the ultrasound system.

large number of continuous fragmental images, and image quality is improved because the ultrasound probe is in direct contact with the body surface and causes less attenuation of the ultrasound signal.

The only problem identified with the new system is that the measured muscle area is slightly smaller than that measured by MR imaging: strain caused by the slight pressure of the ultrasound probe against the body surface during measurement results in decreased total image size and circumference. To overcome this limitation, it was necessary to develop a calibration method based on image circumference for muscle areas.

The remainder of this paper is organized as follows. Section 2 describes the components of the system, and Section 3 provides details of the verification experiments, and discusses the availability and validity of the system. Finally, the conclusions are presented in Section 4.

II. SYSTEM COMPONENTS

Figure 1(b) presents an overview of how measurements are obtained using the developed system. An ultrasound probe is attached to the end of a mechanical arm that can be moved freely along the body surface. The figure shows measurements being obtained in an elderly person in the recumbent position. This system is lightweight, compact, and portable.

Table I lists the specifications of the system. The system consists of two parts: a measurement unit that includes an ultrasound system and a mechanical arm, and image composition software used to create a cross-sectional image from fragmental images.

A. Measurement unit

A diagram of the mechanical arm is shown in Fig. 2. The mechanical arm is made of stainless steel and has a maximum of four degrees of freedom. The arm is made of four links with four joints; the length of the links and the number of joints can be changed according to the subject's body shape and size. A ball bearing in each joint enables smooth rotation. The mechanics fold up to a size of 150(W) × 105(D) × 830(H) mm and weight approximately 8.0 kg (including a counter-balance). The counter-balance is installed in the first link to

TABLE I
SPECIFICATIONS OF THE SYSTEM

Measurement unit	Link mechanism		
	First link	270-450	mm
	Second link	105-373	mm
	Third link	75-147	mm
	Fourth link	65	mm
	Weight	Approx. 8.0	kg
Ultrasonographic device			
	Probe type	Linear	
	Transmission freq.	5.0	MHz
	Elements	128	
	Field of view	80	mm
Image composition software	Image size	500 × 500	mm
	Gradation	256	
	CPU	2.80	GHz
	Memory	512	MB
	OS	Windows XP

Fig. 2. Composition of the link mechanism. The ultrasound probe can move on the same plane.

support the weight and maintain the balance of the links. It weighs 3.0 kg and can be detached from the first link for transportation. The length of each link can be adjusted: the first link from 270 to 450 mm, the second from 105 to 373 mm, and the third from 75 to 147 mm. The length of the fourth link is fixed at 65 mm. We determined the range of the lengths based on the database of the National Institute of Advanced Industrial Science and Technology[8], Japan. As shown in Fig. 2, the employed coordinate system is defined such that the joint axis of the first link is the origin (0, 0), and the counterclockwise direction is forward.

A block diagram of the system is shown in Fig. 3. An ultrasound imaging device (HS-1500, Honda Electronics Co., Ltd., Aichi, Japan) is used to measure the fragmental images. The ultrasound probe (HLS-338M) is a linear model with 5.0 MHz central frequency and 80 mm measurement width. Four high-resolution 2000 [P/R] encoders (UN-2000, Mutoh

Fig. 3. Block diagram of the system.

Engineering, Inc., Tokyo, Japan) are used to measure the joint angles. The fragmental images and joint angles are transferred to a personal computer (PC) via an image capture board (NI PCI-1411, National Instruments Japan Corp., Tokyo, Japan) and counter board (NI PCI-6602, National Instruments Japan Corp.). The two interface boards are inserted into an I/O expansion box (ECH(PCI)BE-H2B, CONTEC Co., Ltd., Osaka, Japan) connected to a laptop PC (WindowsXP, Pentium 4 2.80 GHz) through a PCMCIA bus.

B. Image composition software

Previous studies have investigated many different techniques for image composition[9]–[14]. In the medical field, Whatmough et al.[9] attempted the compilation of ultrasound images from multiple source images based on the spatial compound method and evaluated the image enhancement effect, while Hoskins et al.[10] measured ultrasound images from laboratory mice, and composed liver and stomach images using the spatial compound method. Both of these studies reported a remarkable reduction in image noise, such as speckle and artifact, using the spatial compound method, compared with original images.

The system used in the present study adopts the spatial compound method to compose a clear cross-sectional image. We consider that this method enables delineation of tissue boundaries following enhancement and a reduction in image noise. The mean value of brightness was calculated from overlapping pixels among the fragmental images, and was used to determine the brightness of the pixels in the composition image.

The position of the probe (x_0, y_0) is calculated based on the joint angles obtained by the encoders in each joint:

Fig. 4. Example of an image obtained using the developed system, showing various tissue types.

Fig. 5. Schematic diagram of the accuracy experiment.

$$x_0 = l_1 \cos \theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) + l_4 \cos(\theta_1 + \theta_2 + \theta_3 + \theta_4); \quad (1)$$

$$y_0 = l_1 \sin \theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3) + l_4 \sin(\theta_1 + \theta_2 + \theta_3 + \theta_4), \quad (2)$$

where, $\theta_1, \theta_2, \theta_3, \theta_4, l_1, l_2, l_3$, and l_4 are the joint angles and the link lengths as illustrated in Fig. 2. The parameters θ_2, θ_3 , and θ_4 are defined as the relative angles between two links, but θ_1 is defined as the angle from the x-axis; l_4 includes the length of the probe.

III. EXPERIMENTS

Figure 4 is an example of an acquired image. The image is approximately 150 mm in diameter, and is composed of 100 fragmental images integrated using the spatial compound method. In this example, speckle noise and image artifacts are remarkably reduced, while subcutaneous fat, muscles, and bone are clearly visible.

A. Evaluation of measurement accuracy

We evaluated the accuracy and reproducibility of the measured positions. A schematic diagram of the experiment is shown in Fig. 5. A measurement target of 300×200 mm was

Fig. 6. Accuracy of the measured position which shows error between true values and measurement values.

TABLE II
ACCURACY OF THE MEASURED POSITION WHICH SHOWS ERRORS IN AREA MEASUREMENT.

True value (cm ²)	Measurement value (cm ²)	Error (%)
25.0	24.6 ± 0.28	1.52
100.0	99.9 ± 0.28	0.11
225.0	223.6 ± 2.33	0.61
400.0	396.1 ± 1.16	0.97

placed at 300 mm from the origin of the mechanical arm. The target area was covered with 7×5 measurement points located at intervals of 50 mm. The regions and positioning were adjusted with respect to the practical example of the male abdomen.

The ultrasound probe was detached from the mechanical arm during the experiments. We touched the tip of the fourth link to each target and measured the joint angles for each; the target positions were then calculated using the measured angles. Measurements were obtained 12 times for each target; the maximum and minimum measurement values were disregarded and the positions were calculated based on the remaining 10 measured values.

Figure 6 shows errors between true values and measured values. The root-mean square error was 1.11 mm for the X-axis and 0.94 mm for the Y-axis, with reproducibilities of ± 0.87 mm (X-axis) and ± 0.72 mm (Y-axis).

Furthermore, area errors were examined. Four square areas which have a 50, 100, 150, and 200 mm side from the origin position (300, 0) were defined in Fig. 5, and the true values, measurement values, and errors for each area were calculated. Table II shows that area errors between the true values and the measurements were 1.52, 0.11, 1.59, and 0.97% for the four areas, respectively. These results verify the measuring accuracy of the mechanical arm.

Fig. 7. Overview of the image composition experiment.

Fig. 8. Changes in standard deviation for various number of frames averaged at each pixel. (i) and (ii) are 2.0 frames at high and low contrast, respectively; (iii) and (iv) is 7.0 frames at high and low contrast, respectively.

B. Evaluation of image composition

This section discusses the noise reduction and contrast enhancement achieved using the spatial compound method adopted in the developed system. Noise reduction and contrast enhancement were evaluated using a soft phantom made of a low-contrast material (agar) and a high-contrast material (polyurethane); Fig. 7 shows an overview of the phantom.

Fragmental images were scanned at 0.5, 1.0, 2.0, 3.0, 4.0, and 5.0 frames/sec, equal to 2, 3, 4, 5, 6, and 7 pieces for composition, respectively; the total scanning time was approximately 15 sec for each measurement. The phantom was warmed to about 36°C to approximate the temperature of the person's body.

After the images of the phantom had been composed, noise reduction and contrast enhancement were quantified by

Fig. 9. Change in separability with changing number of frames averaged at each pixel.

calculating the standard deviations of the brightness values in high/low-contrast areas, and the separability[15] between them, in both areas. Separability η is defined as

$$\eta = \frac{\sigma_B^2}{\sigma_W^2 + \sigma_B^2}. \quad (3)$$

Here, the variance within subgroup σ_W^2 and the variance between subgroups σ_B^2 are calculated as

$$\begin{aligned} \sigma_W^2 &= n_1\sigma_1^2/N_T + n_2\sigma_2^2/N_T; \\ \sigma_B^2 &= n_1(\mu_1 - \mu_T)^2/N_T + n_2(\mu_2 - \mu_T)^2/N_T, \end{aligned} \quad (5)$$

where, n_1, μ_1 , and σ_1^2 indicate the number of elements, mean, and variance, respectively, in group C_1 . Similarly, n_2, μ_2 , and σ_2^2 indicate the equivalent values in group C_2 ; N_T and μ_T represent the number of elements and the mean, respectively, for $C_1 \cup C_2$.

The experimental results are shown in Fig. 8. The standard deviation in the high/low-contrast areas decreases with increasing number of fragmental image to compose (Fig. 8a). Images (i)-(iv) in this figure show examples of image processing based on the spatial compound method, and confirm that the proposed method achieved high effective noise reduction with regard to speckle and artifact. In contrast, Fig. 8b shows the standard deviations for the same areas, calculated from all fragmental images before composition; it is clear that no change is observed with increasing number of fragmental images.

Figure 9 shows the separability between high- and low-contrast areas. Separability is limited between 0 and 1, and increases with increasing image contrast. The findings presented in Fig. 9 verify that separability increases remarkably with increasing number of fragmental images.

Next, we examined a line profile in the vertical direction, including the edge between high-/low-contrast regions, as shown in Fig. 7. Figure 10 shows changes in the line profile based on the spatial compound method. The dotted line indicates the profile on an original fragmental image before composition, and the dashed and solid lines indicate those on composition images from 2 and 7 pieces, respectively. The

Fig. 10. Image profile.

profile in the homogeneous speckle regions became smooth after composition due to the noise reduction effect of the spatial compound method. In contrast, the edge between the high-/low-contrast regions appeared slightly blurred, perhaps because the edge width was changed from 12 pixels to 16 pixels after composition. It can be considered that the mechanical error shown in Fig. 6 affects composition error.

The spatial compound method has the effect of noise reduction and edge emphasis on images. Noise reduction was confirmed in Fig. 8, Fig. 9, and as the homogeneous speckle regions in Fig. 10. However, we did not observe edge emphasis on the line profile in Fig. 10. The edge became rather blurred, suggesting that the edges on the fragmental images did not correspond completely due to error in the mechanical arm. In future development of the method, we would like to improve the accuracy of the measured position of the mechanical arm, and introduce an image registration step to align small features and structure boundaries prior to compounding.

C. Accuracy of the cross-sectional image

To examine the validity of the cross-sectional images, we compared the acquired images with MR images. In six men and four women, the thigh was measured at 50% of its length from the greater trochanter major. We attached a marker to the thigh of subjects and measured its position using both systems. Measurement was performed in the dorsal position, and was taken at the same location in all subjects. These data from these ten subjects were used only for area calibration, and were not used for any other experiments.

Cross-sectional images obtained at the same position by our system and by MR imaging are shown in Fig. 11. The original ultrasound image is shown, along with another ultrasound image in which the borderlines of each tissue have been manually delineated by the sonographer. Fat, muscle, and bone can be clearly distinguished in the cross-sectional image obtained by the developed system. Measurement in Figs. 12-18 were obtained by operators who were trained under basic guidance by a sonographer. The developed system enables even an inexperienced operator to adequately measure cross-sectional images after basic training. These figures indicate the accuracy and reproducibility of the system.

Fig. 12. Differences in thigh circumference measurement according to imaging modality.

A limitation of the developed system is that the obtained cross-sectional image tends to be smaller than that obtained by MR images. Figure 12 shows plots of circumferences measured from the ultrasound and the MR images. The ultrasound measurements were smaller than MR measurements in many subjects because of the slight pressure applied to the body surface by the ultrasound probe when measuring the cross-sectional image using this system. Therefore, it was necessary to devise a calibration method to correct the ultrasound image.

Figure 13 shows the correlation between the difference in thigh circumference and the difference in tissue area (between images obtained by MR and by our system). In the figure, the total thigh and fat areas show a strong correlation. Therefore, we proposed the following calibration function for the muscle area:

$$\begin{aligned}
 C_m &= C_t - (C_f + M_b) \\
 &= M_t - 7.6186 \times D_c - 0.2635 \\
 &\quad - (M_f - 4.5906 \times D_c - 11.1318 + M_b) \\
 &= M_t - M_f - M_b - 3.028 \times D_c + 10.8683, \quad (6)
 \end{aligned}$$

where, C_t , C_f , and C_m represent the corrected areas for total area, fat, and muscle, respectively, in the thigh. Similarly, M_t , M_f , and M_b indicate the measured areas of the total area, fat, and bone, respectively; D_c is the circumference error. The coefficients in the equation are derived from the regression function in Fig. 13.

We corrected the measurements of muscle area using this function. Figure 14 shows the correlation between muscle area calculated using our system and that calculated using MR imaging; the original and corrected values are plotted. The coefficient of the correction value is 0.983, with a significance level of 1%.

We then examined the validity of the visual distinction between the thigh extensor and flexor muscles, using the same images as in the experiment described above.

Figure 15 shows the correlation between muscle area calculated using the developed system and using MR imaging, as

Fig. 14. Correlation between muscle area calculated using our system and that calculated using MR imaging.

well as plots of the original and corrected values. The correlation coefficients of the corrected values are 0.968 (extensor muscle) and 0.988 (flexor muscle), with a significance level of 1%.

Muscle area can be accurately estimated based on the calibration function (6). MR images are not required in this equation, and it is sufficient to obtain the cross-sectional image measured by the developed system and the thigh circumference obtained using a tape measure. Moreover, we confirmed in the preliminary examination that error was less than 1% between circumferences obtained by a measure and those by MRI.

To evaluate the reproducibility of our system, we measured 24 subjects two times, at an interval of at least 1 day. The thigh was measured at 50% of its length from the greater trochanter major. We then compared the area measurements for the extensor muscle between the first and second images (Fig. 16), revealing a strong correlation between the two measurement times. The correlation coefficient was 0.996, with a significance level of 1%.

D. Application examples of the developed system

In this section, two examples of the field survey are introduced to discuss a potential application of the developed system. The developed system provides more objective and precise information based on visual images, compared with devices based on the impedance method. Various applications are expected in the medical and health-care fields.

First, we examined the relation between extensor muscle volume and maximum muscular strength. The subjects were 85 young (23.7 ± 3.2 years) and 41 middle-aged (52.4 ± 8.1 years) Japanese. Image measurement of the thigh was performed in the dorsal position. The thigh was measured at 50% of its length from the greater trochanter major. To measure maximum muscular strength, each subject rested his/her thigh on the seat of a chair and extended the right knee with maximum effort. A strain-gauge-type tension sensor (T.K.K.1269f, Takei Scientific Instruments Co., Ltd., Nigata, Japan) was installed at the right ankle to measure the maximum force. Figure 17 shows the correlation between extensor muscle area

Fig. 11. Example of the cross-sectional images.

Fig. 13. Correlations between difference in circumference and difference in area (between the developed system and MR imaging) for each tissue type.

and muscular strength. The correlation coefficients were 0.677 (young) and 0.690 (middle-aged), with a significance level of 1%.

We then examined change in thigh muscle area with aging in the middle-aged and elderly. The subjects were 94 male (68.4 ± 9.6 years) and 167 female (69.8 ± 10.1 years) Japanese. The measurement parameters were as for the above experiment. Figure 18 shows the relation between age and muscle area. We confirmed a decrease of muscle area with aging in both sexes.

These results indicate the potential use of the cross-sectional

images as a simple screening test applied to our daily living. For example, there is a particular need for a safe and reliable measurement of muscular strength in elderly people who require nursing care because they tend to have high blood pressure, arthritis, and/or osteoarthritis, and voluntary muscular contraction is risky and/or difficult for them. The estimation of muscular strength based on muscle area is one example of an application expected for the developed system. Similar techniques are presented in previous studies using MR and X-ray CT[2]-[5], but our system has great advantages in terms of its portability, safety, and cost. The system can obtain

Fig. 15. Correlation between extensor and flexor muscle areas calculated using the developed system and using MR imaging.

Fig. 16. Reproducibility.

high quality data easily, without radiation exposure.

In addition, we attempted to conduct several large-scale field surveys: 1. Examining differences in muscle area between elderly people with independent ADL and those requiring long-term care, 2. Evaluating the decrease in muscle area with aging, 3. Setting of standard values of muscle area between generations. We will attempt to extend these results to useful applications in the near future.

Fig. 17. Knee extensor muscle area vs. muscular strength.

IV. CONCLUSION

This paper describes a newly developed muscle-area measuring system using ultrasound. In this system, an ultrasound probe installed at the end of a mechanical arm scans freely along the body surface. In particular, the muscle area of the elderly and disabled can be measured in arbitrary postures such as sleeping or sitting because the use of a flexible mechanical arm enables the measurement of many areas and body shapes. Using this new technique, high-quality images can be acquired based on the spatial compound method. Experiments confirmed the measurement performance of the developed system. We also proposed a new method for calibrating muscle area based on the circumference of the extremities. We consider that this system could be used for muscle evaluation in sports training and in the rehabilitation of elderly people. In future investigations, we aim to develop an automatic function for muscle, fat, and bone distinction in the measured image to improve the usefulness of the present measurement system in the practical setting.

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Fig. 18. Changes of thigh muscle area in the middle-aged and the elderly.

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