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Scale-Independent Stiffness Measurement of Upper Limbs with Lymphedema by a Circular Compression

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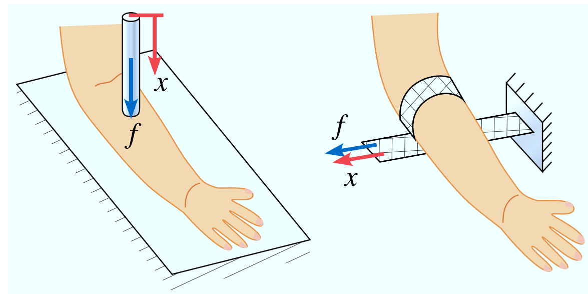
***Abstract*— Lymphedema caused by the dissection of lymphatic node for treating a breast cancer produces serious swelling on the limbs and reduces the quality of life of the patient. For quantitative assessing the disease, this study newly proposed the stiffness measurement method of upper limb with lymphedema. A measurement system, where a roll-up belt was installed to circularly compress the limb by pulling the belt was developed. Both the belt tension and displacement were measured during the compresson of limb. Scale-independent stiffness index was newly derived from the bulk modulus and applied the measured force and displacement. The stiffness index of upper limb with lymphedema was measured. The index of affected limb was larger than that of healthy limb in a patient.**



(a) Local measurement (b) Circular measurement

Fig. 1. Two approaches of measuring limb stiffness

I. INTRODUCTION

Lymphedema is often caused by the dissection of lymphatic node for treating cancer, especially breast tumor. In the progress of disease, an upper limb is getting heavy fatigue with pain and finally reaching elephantiasis where the limb is swollen over 30 cm in diameter, and the skin surface is extremely stiffen like a elephant skin. In order to delay the progress of edema, there is only a physical therapy such as lymphatic massage, instead of a radical treatment. Early diagnosis of the disease is the most important and the only way to keep a patient's quality of life normal.

A lot of studies which attempt to early diagnosis lymphedema have been reported. Richards et al. [1] have measured lymphatic flow in limbs. However, this measurement method has not been applied to lymphedema due to the irradiation of a radioactive agent for detecting flowing lymph. In clinical assessment, a medical doctor compares the stiffness and swelling of limb surface between left and right based on the palpation and circumference measurement, respectively [2]. However, in spite of patient's complaint, unfortunately, the disease is used to be overlooked when the crosswise differences of stiffness and circumference are too small to be recognized. If there is no crosswise difference in circumference, medical doctor has to certainly recognize a small difference in stiffness, and this is a main reason why the assessment is difficult. There have been lots of studies to mechanically measure the stiffness of living tissue to assessing disease quantitatively [3]–[6]. Yoshitoshi et al. [7] have been evaluate the stiffness of edematous skin based on the relationship between the displacement of skin surface and applied force by a contact probe. Kawahara et al. [8] have proposed non-contact type stiffness sensor with fluid force and optical displacement measurement instead of a contact probe. However, due to a local stiffness measurement as shown in Fig. 1 (a), these studies have some issues; (1) the measurement result has been disturbed by a local structure including blood vessels, muscles, and bones; (2) there is scale dependency on the measured stiffness where the stiffness of large object is apparently smaller than that of small one; (3) multiple measurement around the limb has been required for obtaining whole stiffness of limb.

To cope these issues, the goal of this study is the quantification of lymphedema based on the stiffness measurement of upper limbs. In this study, for evaluating the stiffness of upper limbs, a measurement system where a roll-up belt was installed to compress the limb circularly and detect the deformation as shown in Fig. 1 (b) was developed. And also, a scale-independent stiffness index applicable to the measurement system was developed based on the bulk modulus. To date, there is no investigation considering scale-independent stiffness-measurement of upper limbs with lymphatic edema by circularly compressing the limb.

II. METHODS

A. Development of a Stiffness Measurement System

Fig. 2 shows the schematic diagram of a stiffness measurement system. There are two requirements for the system development; (1) to measure the stiffness of object, both force applied to the object and its deformation should be obtained

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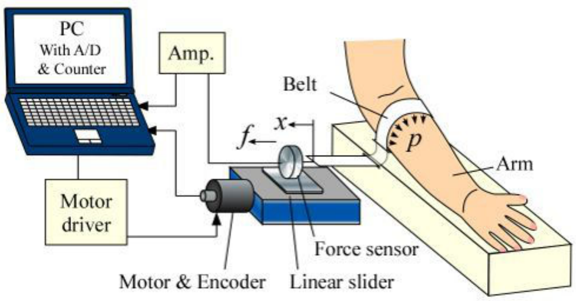
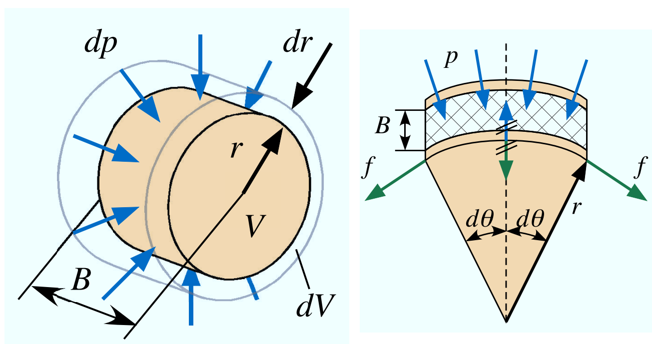


Fig. 2. A schematic diagram of a stiffness measurement system



(a) Overall (b) Miniregion

Fig. 3. The geometric relationships

as accurately as possible; (2) to detect the characteristics of whole circumferences of limbs, whole of limb is desired to be mechanically stimulated only in one time measurement. With considering both requirements, a stiffness measurement system was developed by using a roll-up plastic belt with a width of 10 mm. The one side of roll-up belt was fixed on the main frame of system as a fixed end, and the other side was attached to a force sensor bolted on the slider block of linear slider as a movable end. Total length and the width of belt were 232 mm and 12.5 mm, respectively. The ball screw of linear slider was allowed to install DC servo motor to drive the linear slider and measure the relative position of slider block on the ball screw via a rotary encoder embedded in the servo motor with a position resolution of 6 μm. Force sensor output was amplified by an analog amplifier circuit (Strain Amp., NEC Avio Infrared Technologies, Tokyo, Japan). Both force sensor and rotary encoder signals were acquired by a laptop computer via an analog input/output interface module (CSI-360112, Interface Corporation, Hiroshima, Japan) with a sampling rate of 1 ms. The resolution of force measurement was 0.14 N. DC servo motor was controlled with a position feedback by the computer via the interface module and motor driver circuit.

B. Formulation of a Scale-Independent Stiffness Index

In this section, assuming that both the tension and displacement of pulling belt was measured through an experiment, a scale-independent stiffness index is formulated based on the bulk modulus. In the case of measuring human upper limbs, stiffness evaluation has to be considered the personal or bilateral difference of limb size, because when the object is evaluated with an assumption that the relationship between an applied force and the deformation is able to be followed to Hooke's law as a linear spring without the length dimension, the stiffness of large object is apparently smaller than that of small one. This indicates that the stiffness of the linear spring model of Hooke's law is unable to be distinguished between a difference caused by lymphedema and scale dependency. On the other hand, the bulk modulus is scale independence because it is defined from an applied pressure and the volume difference of object.

Focusing the deformation of region compressed by pulling the roll-up belt during the measurement as shown in Fig. 3 (a), this study obtained the relationship between pressure and volume changes as follows:

$$dp = -K\frac{dV}{V} \tag{1}$$

where dp, K, V, and dV are pressure change, bulk modulus, the volume of compressed region, and its infinitesimal change, respectively. According to the geometric relationship around the compressed region, the right-hand side of (1) is transformed as follows:

$$\frac{dV}{V} = 2\frac{dr}{r} \tag{2}$$

Now, this study focus dp on the left-hand side of (1). According to a force balance between the tension of pulling belt and contact force caused by p on the infinitesimal area with a central angle of $2d\theta$ as shown in Fig. 3 (b), (3) was obtained.

$$2fd\theta = 2rd\theta Bp \tag{3}$$

where B is the width of belt. Solve (3) for p,

$$p = \frac{f}{Br} \tag{4}$$

where f and r are belt tension and object radius, respectively. The total difference of (4) for f and r is as follows:

$$dp = -\frac{f}{Br^2}dr + \frac{df}{Br} \tag{5}$$

Substitute (2) and (5) for (1),

$$-\frac{f}{Br^2}dr + \frac{df}{Br} = -2K\frac{dr}{r} \tag{6}$$

(6) is a first order differential equation, and the general solution is given by (7).

$$f = Cr - 2BKr\log r \tag{7}$$

where C is the constant of integration. Let the initial condition be $f(r_0) = 0$ where r_0 is the initial radius of object, the particular solution is given by (8).

$$f = 2BKr\left(\log\frac{r_0}{r}\right) \tag{8}$$

Solve (8) for K,

$$K = \frac{f}{2Br}\Big/\log\frac{r_0}{r} = \frac{\sigma}{\epsilon} \tag{9}$$

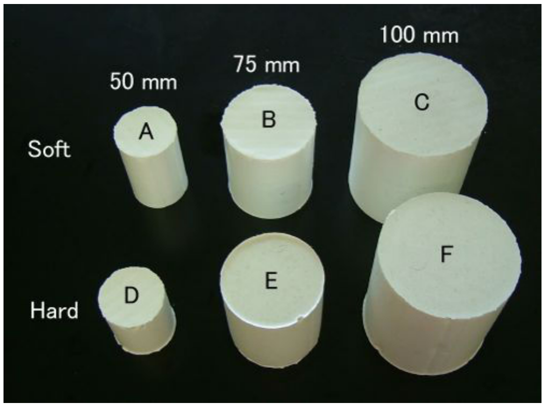


Fig. 4. Silicon models

TABLE I
SPECIFICATIONS OF SUBJECTS

Subject	Age	YAO	LE	Diameter [cm]			
				FR	FL	UR	UL
A	20's	–	-	22.0	22.0	21.5	22.0
B	50's	20	+	22.1	20.7	26.5	25.6
C	70's	2	-	34.4	26.1	37.1	32.6

YAO: years after operation, LE: lymphedema,
FR: forearm, right, UR: upper arm, right,
FL: forearm, right, UL: upper arm, right

where σ, ϵ are as follows:

$$\sigma = \frac{f}{2Br} \tag{10}$$

$$\epsilon = \log \frac{r_0}{r} \tag{11}$$

where $r = (l_b - x)/2\pi$. l_b and x are the length and the displacement of belt, respectively. Hense, the scale-independent stiffness index K is obtained from both a pulling force and a belt displacement modified by object scale such as r and r_0.

C. Validation of Scale Independency

Six different cylindrical silicon models with three diameter of 50, 75, and 100 mm and two different types of silicon stiffness were formed. Fig. 4 shows the overview of silicon models. Each silicon model was compressed by the roll-up belt with a pulling speed of 5 mm/s. The time-courses of both pulling force and the position of movable end were obtained by using the developed system. The formulated index K is calculated for each obtained data.

D. Stiffness Measurement of Upper Limbs

The clinical experiment was performed at Hiroshima University, Hiroshima, Japan, after approval by the ethics committee of Hiroshima University, and an informed consent was obtained from each subject before the experiment. The imformation of subjects are as follows:

- Subject A: female, healthy, lymphedema (-).
- Subject B: female, right-side operated, lymphedema (+).
- Subject C: female, right-side operated, lymphedema (-)

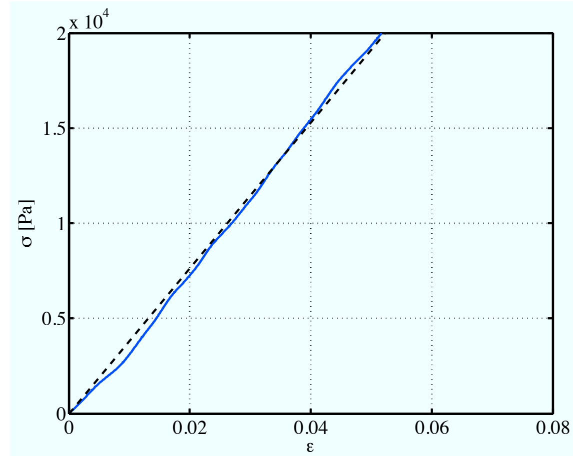


Fig. 5. Relationship between σ and ϵ

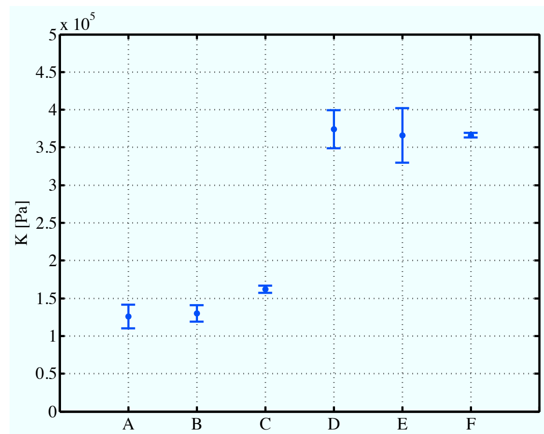
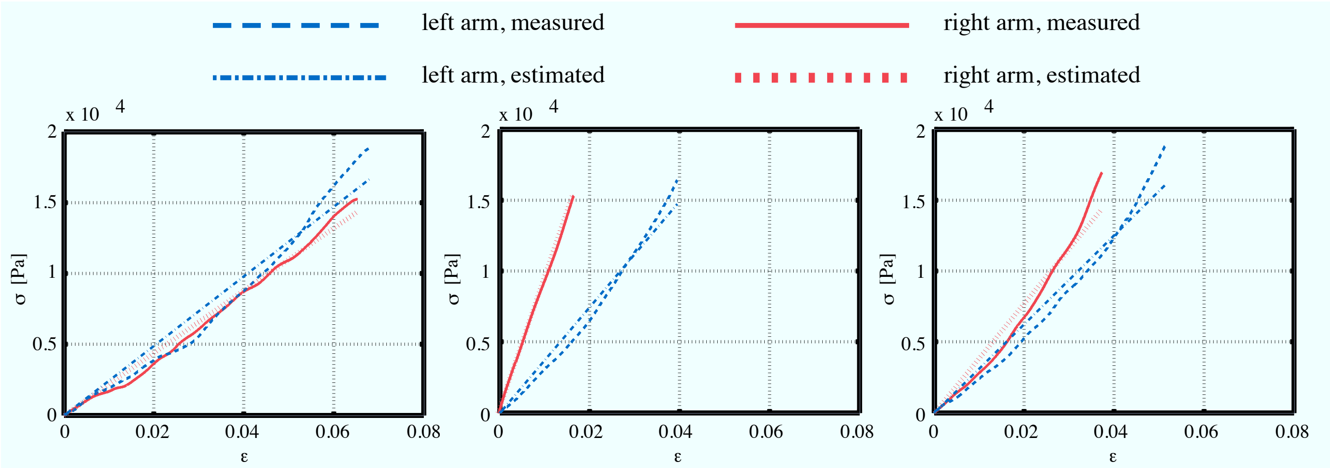


Fig. 6. Scale-independent Stiffness Indexes K of silicon models

TABLE I shows the detail information of subjects. After subject's upper limb was inserted into a loop of the belt, both right and left parts at 5 cm from the medial side of elbow to upper arm were compressed by the roll-up belt with a pulling speed of 5 mm/s and pulling force of 20 N. The time-courses of both pulling force and the position of movable end were acquired by the developed system. The formulated index K was calculated for each obtained data.

III. RESULTS AND DISCUSSION

The solid line in Fig. 5 shows a measured σ–ϵ line, which is the relationship between both scale-modified tension and displacement of belt, during the compression of silicon model E. The developed index E calculated by fitting the solid line with least-square method was 3.85×10^5 Pa. The dotted line in Fig. 5 shows the σ–ϵ line reconstructed from the calculated K, and both measured and reconstructed lines are nicely coincident. Fig. 6 shows the average values of K from the data in the experiments for six silicon models (A, B, . . ., and E). The scale bars in Fig. 6 show the standard deviations in each 5 times measurement. The standard deviations were small where the maximum deviations is less than



(a) Subject A (b) Subject B (c) Subject C

Fig. 8. Relationships between σ and ϵ

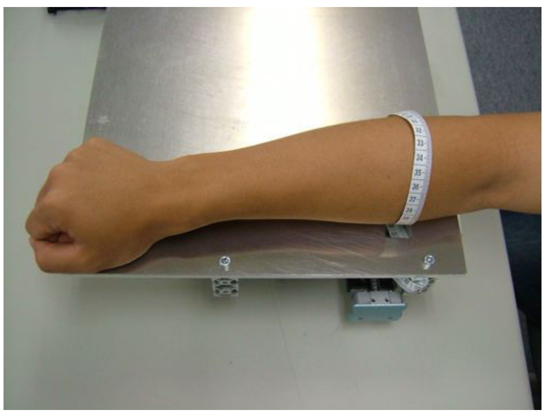


Fig. 7. An overview of stiffness measurement

10 percent in case of silicon model E. The average values in two groups in different stiffness silicon models (soft: A, B, C) and (hard: D, E, F) were able to be scale-independently measured, respectively.

Fig. 7 shows an overview of stiffness measurement for a upper limb of healthy male (example image). Subjects never felt any pain caused by the experiment. Fig. 8 shows the relationships between σ and ϵ in the measurement for each upper arm of subject A, B, and C. Both solid and dotted lines are the measured value and the reconstructed data by fitting the measured value with least-square method, respectively. There are nonlinear characteristics where the slope in large ϵ is larger than that in small one in each result unlike in case of a silicon model. The nonlinear characteristics were speculated that some layers with each different stiffness such as a skin, Subcutaneous tissue, muscles, bones were compressed one after another from softer tissue to stiffer one as pulling the belt. The values of stiffness indexes K of right and left upper arms in Subject B were 9.24×10^5, 3.73×10^5 Pa, respectively. This result indicates that the right upper arm with the operation is stiffer than than that of left healthy one. However, there are no differences in the circumference of upper limbs over the reference value of circumference for the lymphedema assessment (2 cm). There is some possibility of assessing the lymphedema in case of no circumference difference patient. The values of K of right and left upper arms in Subject C were 3.86×10^5, 3.13×10^5 Pa, respectively.

IV. CONCLUSION

This study newly proposed the stiffness measurement method of upper limbs for assessing lymphedema quantitatively. The scale-independent stiffness index was applied for measured data. Through the clinical experiment, the index of affected limb was found to be larger than that of healthy limb in a patient.

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