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A sensor to measure hardness of human tissue

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Abstract—**An innovative sensor is developed to evaluate hardness of human soft tissue. This sensor provides easy and accurate hardness measurements based on a unique sensing mechanism. Hardness of soft materials is often evaluated by using international standards of hardness such as IRHD (International Rubber Hardness Degree) and durometer hardness. However the conventional scales based on these standards requires a stable pressuring condition to the target. Therefore, these scales cannot be used for targets that are in motion or targets that require quick measurement such as human muscles during exercises and a liver exposed at a surgery. The prototyped sensor has a compact body and allows continuous hardness measurement with an arbitrary pressing force. This sensor always monitors the force exerted on the sensor and automatically eliminates the unintended effect from the fluctuation of the pressing force. Therefore, continuous time series of the hardness data is real-timely available. This paper reports results of a test as well as the detail of the mechanism and data processing technique of the latest version of the sensor.**

I. INTRODUCTION

Authors have been developing sensors to detect muscle hardness over the skin surface as a man-machine interface to control wearable devices to assist human motions [1][2][3]. Hardness information is very useful for estimating contraction level of muscles.

In the middle 1990's Yamamoto et al. developed a sensor that mechanically measures muscle hardness over the skin and they successfully controlled their exoskeletal devices to assist nurse's patient transferring operation by using their sensor [4]. However, their sensor is interfered by installation conditions and physical contacts from outside thus the sensor is not suitable for practical uses.

Authors have been developing a sensor to measure muscle hardness with different mechanism from that of Yamamoto's sensor. This sensor allows measurements of muscle hardness even under the fluctuation of installation pressures. Therefore the assisting devices work reliably and safely by using this sensor. One advantage of the hardness sensor is the easiness of installation on human body. This sensor is available even over the clothes unlike conventional surface EMG sensors. The assisting devices can be practical by using our sensor because of its excellent measuring accuracy and great convenience in use.

It is expected that this hardness sensor works well not only as a man-machine interface of assisting devices but also as a diagnostic tool of medical doctors. Many researchers are exploring a method to evaluate physical properties of human tissue for such medical purposes. Fischer firstly tried to measure physical properties of human soft tissue and make use of the data for diagnosis and treatments [5][6][7]. Neurogenic Technologies Inc. commercialized a scale, Myotonometer, and Leonard et al tried to use the scale for evaluating muscle condition of motoneuron disease patients [8]. Vain et al. tried to apply Myotonometer for evaluating level of rigor mortis [9][10]. Zheng and Mak developed an ultrasound indentation system with a pen-size, hand-held probe and tried to evaluate viscoelastic properties of lower limb soft tissues [11][12]. Many studies have been conducted to evaluate viscoelastic properties of various body parts such as breast, liver and prostate gland for diagnostic purpose.

It is highly expected that the developed hardness sensor is also applicable to the evaluation of the condition of human tissue. In this paper, the latest model of our sensor is presented. A new structural design is applied and size and weight of the sensor is dramatically reduced. A new data processing algorithm is also applied to this model and the accuracy of the measurement is greatly improved.

II. MECHANISM OF HARDNESS SENSOR

Fig.1 shows a sketch of our hardness senor for soft tissue. The sensing part of the sensor is composed of two pressure sensitive components. One is a flat disk (32mm in diameter) and the other is a button (4mm in diameter and 4 mm in height) in the middle of the disk to be indented to the target. The both components, the disk and the button are pressed to the target and receive reaction forces. The sensor measures the force loaded on the button, F_b and the total force loaded on the sensor, F_t by using pressure transducers. The hardness of the target is calculated from these two forces.

III. MUSCLE STIFFNESS SENSOR

This sensor is originally developed as a man-machine interface of wearable devices for assisting disabled. We call this sensor "MSS (Muscle Stiffness Sensor)". The level to which the muscle is stiffened is evaluated by using this sensor. The activation level of the muscle can be estimated from the stiffness information. The assisting device reads the user's intention of motion from the muscle activation level and actuates its motors so that the user can accomplish intended motions such as picking up a pen or standing up with his/her partially paralyzed limbs under the assistance of the device.

Fig.2 and Fig.3 show a photo and a cross-sectional drawing of the MSS. The main structure including a button and a disk is made of industrial plastic. The disk part is composed of two circular plates and a doughnut-shaped airbag. The airbag is sandwiched between two plates. One of the plates to be contacted to the skin has a button in the middle. Force on the button is directly measured by a strain gauge transducer (PS-C, KYOWA ELECTRONIC INSTRUMENTS Co., Ltd.). And the total reaction force loaded on the sensor is estimated from airbag pressure. Another strain gauge transducer is used for detecting the airbag pressure. This sensor is specially designed to be compact and lightweight because the assisting device is supposed to be used in daily life. The compactness and lightness are very important requirements for this sensor to make the system practical. Signal amplifiers are needed in addition to this sensor. The signal conditioning circuit can be incorporated to the sensor. The dimension of the disk part is 32mm in diameter and 8mm in thickness. The curvature

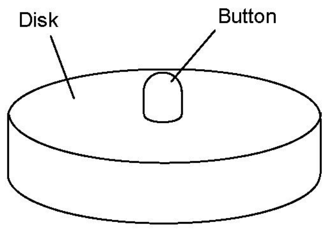

Figure 1. Sketch of hardness sensor

Figure 2. Muscle stiffness sensor (MSS)

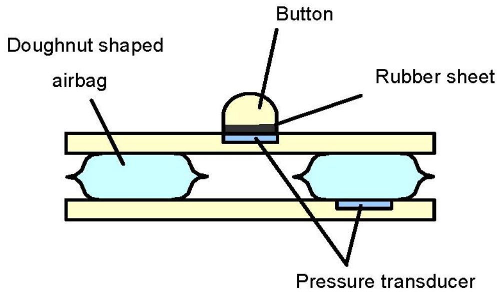

Figure 3. Cross-sectional drawing of MSS

radius, diameter and height of the button are 3mm, 6mm and 4mm, respectively. Total weight of this sensor is 5g.

IV. VISCERAL HARDNESS SENSOR

Authors are now trying to divert MSS to a diagnostic tool of internal organs at surgery as requested by medical researchers. A photo and a cross-sectional drawing of the sensor are shown in Fig.4 and Fig.5 respectively. Major part of the design is almost the same as one of MSS. Diameter of the button is larger than MSS because the internal organs such as liver are softer than skeletal muscles. By employing bigger button the measuring range is adjusted to soft target. In addition, this sensor includes signal amplifier circuits. The sensor has some volume to be easily held by doctors.

V. DATA PROCESSING ALGORITHM

Main advantage of this sensor is continuous measurement under arbitrary pressing force to the target. A new data processing algorithm is introduced to the latest version of the MSS to improve measuring precision. Fig. 6 shows recorded data of F_B and F_T in the measurement of 7 specimens made of silicone rubber with different hardness. Fig. 7 shows the measurement by using MSS. The hardness of these specimens is previously measured by a scale, durometer type E (HERDNESS TESTER Type GS-721N, TECLOCK Co., Ltd.) as shown in Fig. 8. It is observed that F_B increases as F_T increases linearly and the slope of each data can be considered as a constant value α. A y- interception β of the

Figure 4. Prototyped liver hardness sensor

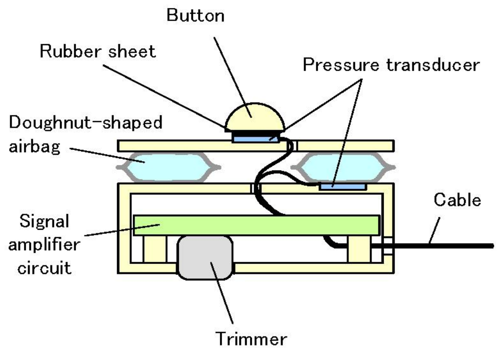

Figure 5. Cross-sectional drawing of liver hardness sensor prototyped

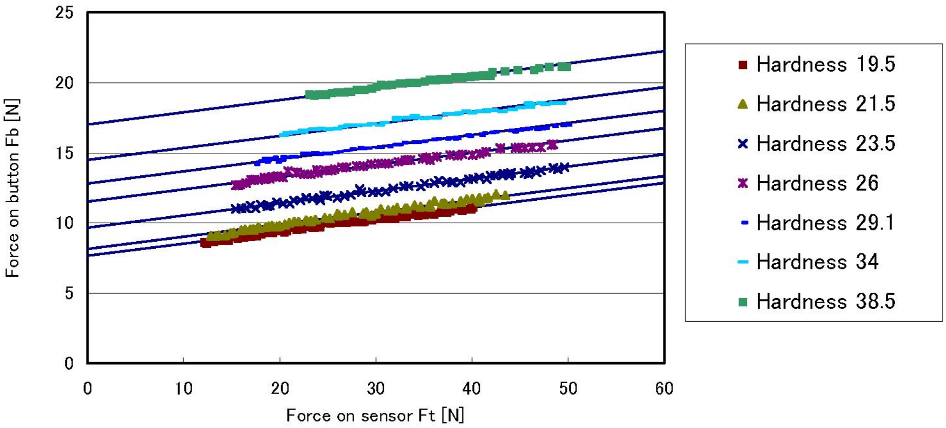

Figure 6. F_B - F_T relations obtained from the measurement with 7 specimens

Figure 7. Measurement of silicon specimens by using MSS

Figure 8. Measurement of silicon specimens by using a durometer scale

line reflects the hardness of the target tissue. The β is not influenced by fluctuation of pressing force F_T and is derived based on an equation, $\beta = F_B - \alpha F_T$. The slope α=0.086 is experimentally obtained. β can be converted to durometer hardness H based on an approximated curve reflecting the experimental relationship between β and H. Fig. 9 shows a plot of β-H relation. A quartic curve,

$$H = p\beta^4 + q\beta^3 + r\beta^2 + s\beta + t \qquad (1)$$

can be obtained based on a curve fitting technique. The coefficients of each term, p,q,r,s and t, are shown in TABLE I.

TABLE I. COEFFICIENTS OF EQUATION (1)

p	q	r	s	t
-0.0121	0.5938	-10.548	82.355	-217.18

VI. RESULTS

Fig. 10 shows an experimental result of the hardness measurement of a specimen with 30.1 durometer hardness by using MSS under fluctuating pressing force. The superiority of our developed sensor over the conventional hardness measuring devices is proved. Using our sensor, accurate hardness of the soft target can be measured even under the fluctuation of the pressing force. This feature of our sensor enables reliable measurements under unconditioned environments.

The standard deviation of the hardness data obtained by our sensor (shown in Fig.10) was 0.447. While the standard deviation of 10 times durometer measurement of the same specimen was 0.700 under controlled pressing force. It was demonstrated that the hardness could be measured with lower data variation by using the developed sensor even under fluctuating pressing condition than the case of measurement with durometer under controlled pressing condition.

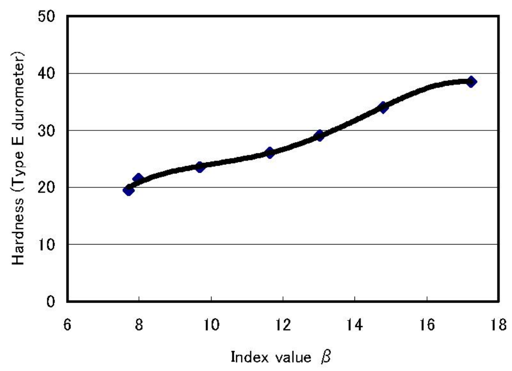

Figure 9. β-H relation experimentally obtained

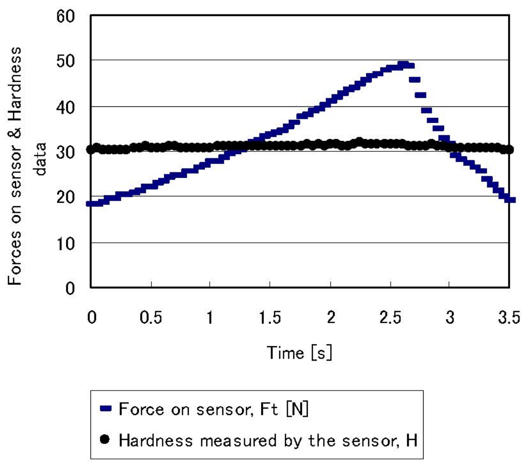

Figure 10. Measurement of a specimen (31.1 hardness) under the fluctuation of pressing force F_T

VII. CONCLUSION

An innovative sensor for hardness measurement of human tissue with new structural design and new data processing algorithm is proposed. The size and weight is largely reduced through the development thus practicability of the sensor is greatly improved. It was demonstrated that the sensor has superior measurement abilities through tests using silicon rubber specimens. Because of its high robustness against fluctuation of measuring condition (pressing condition) the sensor has wide variety of application fields such as sports science and welfare engineering.

In the field of medical diagnosis, it is expected that this hardness sensor can play a great role as a new method of quantitative palpation of organs such as breast, liver, pancreas and lung. We are now preparing for the clinical test to measure hardness of organs with medical researchers.

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