WCCI 2012 IEEE World Congress on Computational Intelligence
June, 10-15, 2012 - Brisbane, Australia FUZZ IEEE

An Automated Calibration by Using Fuzzy Control for a Measurement System of Lachman Test

Shogo Kawaguchi, Kouki Nagamune
Graduate School of Engineering, University of Fukui
Fukui, Japan
kawaguchi@me.his.u-fukui.ac.jp

Daisuke Araki, Tomoyuki Matsumoto, Seiji Kubo, Takehiko Matsushita, Ryosuke Kuroda, Masahiro Kurosaka
Graduate School of Medicine, Kobe University
Kobe, Japan

Abstract—**Lachman test is one of a manual tests for examining the anterior cruciate ligament (ACL). A medical personnel discriminates degree of the ACL injury by the feeling of stress on the finger. This method is subjective and dependent on the skill of medical personnel. Hence, a measurement device for Lachman test has been developed. This measurement system consists of finger braces and force sensors on each fingers. However due to low accuracy of the system, improvement of current device has been proposed by calibrating the finger braces for different finger thickness. The calibration made for the device was successfully detect the true force applied to the finger braces. Nevertheless, the system was only able to measure low load with high accuracy. Future works are already in progress to improve the resolution of A/D converter and to measure the force distribution during Lachman test with high accuracy using the force sensor.**

Keywords-Lachman test, Force Sensor, Anterior Cruciate Ligament

I. INTRODUCTION

Lachman test is a manual test used to examine the Anterior Cruciate Ligament (ACL) of the knee where there is a suspicion of ACL tear for a particular patient. The Lachman test is recognized by most authors as the most reliable and sensitive clinical test for the determination of ACL integrity, superior to the Anterior Drawer test commonly used in the past. To perform the test, patient is put on supine position on the examination table. The knee of a patient is flexed about 20 to 30 degrees and the leg is externally rotated [1]. A medical personnel should place one hand at the back of tibia and the other hand on the thigh. It is important that the thumb is placed on the tibial tuberosity. By pulling anteriorly on the tibia direction, an intact ACL should prevent forward translational movement of the tibia on the femur ("firm endpoint") as shown in Fig. 1. Anterior translation of the tibia associated with a soft or a mushy endpoint indicates a positive test. More than about 2 mm of anterior translation compared to the uninvolved knee suggests an ACL tear ("soft endpoint"), as does 10 mm of total anterior translation. The measurement of ACL movement can be made with an instrument called as "KT-1000" [2-4]. However, this instrument cannot be used to determine if a knee is experiencing an ACL tear [5]. This test can be performed either in the field such as during sports event or in a normal clinical condition whenever a patient presents with knee pain. In either situation, ruling out fracture is important in the evaluation process. Also when evaluating the integrity of the ACL, it is important to test the integrity of the Medial Collateral Ligament (MCL), because this is a common ligament tear in the ACL injury as well. Some studies have reported the stress during Lachman test [6], however, they could not obtain the force data dynamically.

In previous studies, quantitative measurement of Pivot Shift test by three-dimensional electromagnetic sensors have been conducted [7, 8]. However, there are no literature found on a quantitative force measurement of medical personnel fingers during Lachman test. This study set the goal to develop a quantitative measurement system of Lachman test with force sensors. The system could enable us to analyze a mechanism of the "endpoint" that indicates a degree of injury of the ACL.

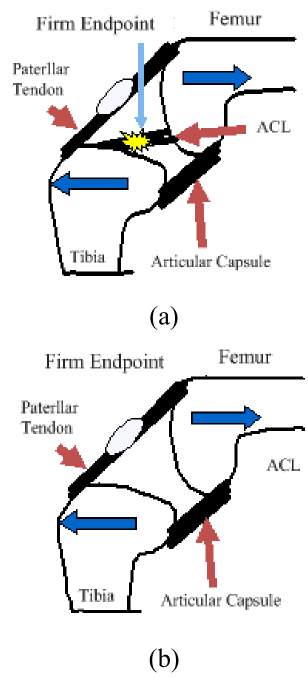


Figure 1. Mechanism of Lachman test. (a) Firm endpoint. (b) Soft endpoint.

II. METHOD

This paper explains mainly on the principle of the measurement system, because this is a pilot study an automated calibration method of the developed system.

A. *Force Sensor*

Force sensors were constructed using conductive rubber (sili-us Fuso Gomu Co. Ltd.). The thickness of this conductive rubber was set to 0.05 mm. The rubber was then cut to the specified dimensions of 6.0 (mm) x 7.0 (mm) x 0.1 (mm). Then, a set of pattern for the sensor was made by using an extension board (ICB-075 san-hayato Co. Ltd.) which was placed copper on the entire surface. This process is made with thermal transfer printing method. The thermal transfer printing method is one of methods for etching the circuit board. First of all, design of the circuit (Fig. 2) was printed on the paper using a laser printer. Next, the circuit printed paper and copper foil of the extension board are attached to each other. The design was transcribed to the copper foil through heating by means of iron or laminating machine. To complete the circuit, etching liquid was used to dissolve the copper according to the pattern of sensors on the extension board.

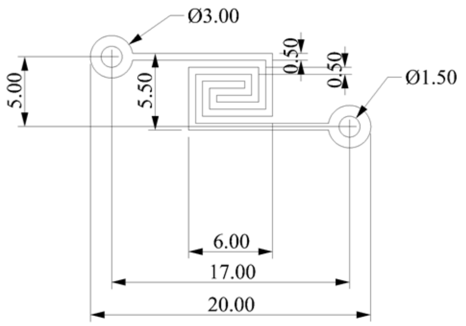


Figure 2. Design of the force sensor.

Next, the rubber and copper foils affixed to each other by using a laminating machine (LPD3213, Fujipura Co. Ltd.). Then, a profile of this sensor was modified to a curvy shape by thermal heating device (EH-NW80-K, Panasonic Co. Ltd.) as shown in Fig. 3. The resistance value of the sensor is varying between 100 Ω to 1 kΩ. The resistance value of the sensor is inversely linear with the load. Thus, the sensor has a lower value of resistance whenever the load is increased.

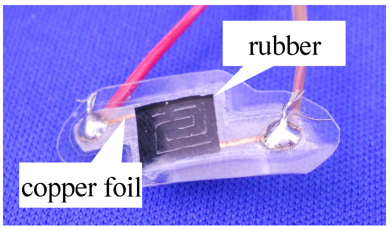
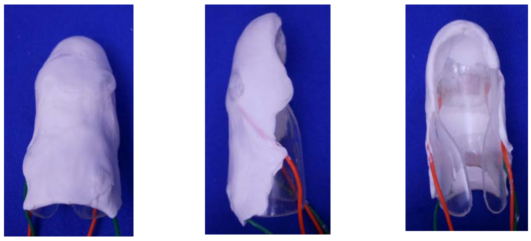


Figure 3. Real sensor.

Finger braces (Sawamura prosthetics and orthotics service Co. Ltd.) were used for fixing the force sensors to each fingers. Then, each finger braces was attached with two force sensor. The finger brace was molded by using thin thermoplastic (JJ-210, Daicel Finechem Co. Ltd.). Henceforth, a finger brace with two sensors was called as "Finger Force Sensor" as shown in Fig. 4.



(a) (b) (c)

Figure 4. Finger force sensor. (a) Front. (b) Left. (c) Rear.

This measurement system had ten finger force sensors. The built of this finger force sensors was designed to fit on any fingers securely. Channel 0 (Ch 0) and channel 1 (Ch 1) were set to the thumb of the right hand. Channel 2 to 9 were set to the other finger in same way. The same procedures were made for the left hand where channel 10 and 11 were set to the thumb and channel 12 to 19 to the rest of the fingers.

B. *Measurement Circuit*

1) Force Sensor in the AC Circuit

The conductive rubber has capacitance. The communication bus of the measurement circuit with PC is USB used by PIC micro computer (PIC18F4500 (Fig. 5), Microchip Co. Ltd). To cancel the capacitance of the conductive rubber, Pulse Width Modulation (PWM) was used by the micro computer. Because the microcomputer has many I/O ports and port of the USB, the measurement circuit includes many task such as the LCD to confirmation of the inside information, communication of the A/D converter and control of the digital potentiometer. The development of the firmware for this microcomputer was made by using overall development software (MPLAB, Microchip Co. Ltd) and C language. The USB communication method was implemented by using MCHPFSUSB Framework (Microchip Co. Ltd) and communication class of Microchip was used as the driver for the PC.

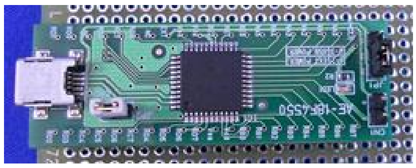


Figure 5. PIC18F4550.

Due to low current, PWM by PIC microcomputer cannot be passed to these sensors. Transistors were then used to provide current needed for the PWM. The circuit of one sensor is shown in Fig. 6. Low pin of the sensor is connected to variable pin of the digital potentiometer. One of three pins of the variable resistor part of the digital potentiometer was not connected. Another pin is connected to ground (GND). The sensor unit was made by two variable resistance. The resistance value of the sensor was decreased when the applied load was an increased. However, the resistance value of the digital potentiometer remains the same. This variable resistance were used for calibration of fingers due to different thickness of fingers for each person. Nevertheless, since the sensors was coiled to the finger braces, different thickness of fingers can cause noises. Hence, the calibration of the voltage value for different thickness of fingers was needed to decrease the noise.

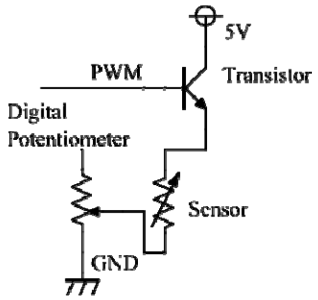


Figure 6. Circuit of one sensor.

2) Digital Potentiometer

This measurement system has 20 digital potentiometers (AD5220BN10, Analog Devices Co. Ltd.) for calibration of finger thickness. This digital potentiometer can change its resistance by input from digital signals. In this IC, there are three pins (clock (CLK), chip select (CS) and up/down (U/D)) as input and three pins of variable resistance as output as shown in Fig. 7. The decode part can operate as low level of digital at CS. In the U/D, Up and Down are high and low levels, respectively. The value of variable resistance moves up or down as number of Low level at CLK in accordance with U/D. The up/down counter is 7 bits. Accordingly, the resolution of the variable resistance is 128 positions. The initial positions of resistance is at the center. This IC has 10 kΩ of resistance thus first value of resistance is about 5kΩ.

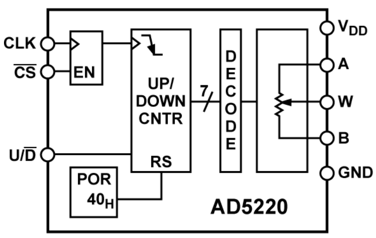


Figure 7. Digital potentiometer.

In the measurement circuits, there are 20 digital potentiometers. Then the circuit has a set of address select by using decoders unit 74HC154 and 74HC155 (Fig. 8). 74HC154 is a decoder of 4 inputs and 16 outputs while 74HC155 has 2 inputs and 4 outputs. The CS of the digital potentiometer is negative logic. Outputs of both of 74HC154 and 74HC155 are low level logic. When the control of the digital potentiometer is not necessary, the circuit will be on high level at all outputs of address select circuit.

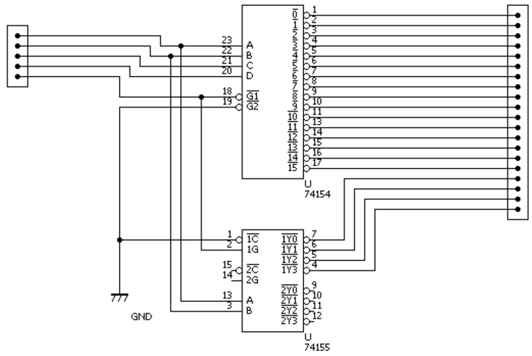


Figure 8. Address select circuit.

C. Fuzzy Control of the Calibration for Finger Thickness

The control of the calibration for finger thickness was used with Fuzzy control. The fuzzy knowledge was used by the voltage value.

- Knowledge 1 : When the value of voltage is low, the value of resistance should be decreased.
- Knowledge 2 : When the value of voltage is high, the value of resistance should be increase.

This knowledge was converted as following fuzzy IF-THEN rules,

- Rule 1 : IF a degree of Down is higher than Up, THEN the number of CLK is increased.
- Rule 2 : IF a degree of Down is lower than Up, THEN the number of CLK is decreased.

The variation of the resistance was in proportion to the CLK of the digital potentiometer. This fuzzy knowledge was to decide the number of CLK and U/D. If the number of CLK at the decrease position was smaller than one to increase, U/D was decided as up. In the opposite situation, U/D was decided down as shown in Fig. 9. However, when the maximum value of CLK is fixed, the intended value may diverge. To improve the convergence, the maximum value of CLK should be changed.

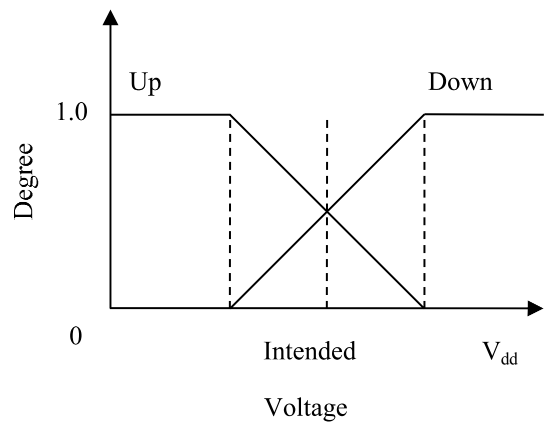


Figure 9. Membership of Fuzzy control.

For finger thickness calibration, amplitude of the voltage value for each channels was measured. If the amplitude were high, maximum number of CLK will be decreased.

D. Measurement System

The measurement system has two A/D converters (AGB65 - ADC (Fig. 10), Asakusagiken Co., Ltd.). The A/D converter has 16 channels port. The input range is from 0 to 5 V. The resolution can be selected either 8 bits or 12 bits by using command for this A/D converter. For use of this system, 8 bits A/D converter was selected. The speed of the communication can be selected either 9600 or 115200 bps by using the hardware switch. This A/D converter has two RS-232C bus. Two A/D converters were connected together for this system to achieve 32 channels of conversion ports. The 20 channels were dedicated for force sensors and 6 channels were assigned to acceleration sensors. Two acceleration sensors (KXM52－1050, Kionix Co., Ltd) were used for the system. The output of this sensor is in the form of analog signal. The range of the sensor is ±2 gravitational acceleration. In this system, two sensors were fixed to the femur and tibia by using braces.

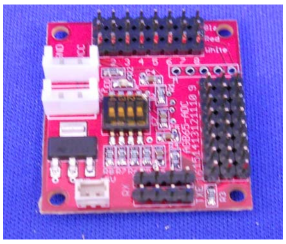


Figure 10. A/D converter.

TABLE I. SPECIFICATION OF A/D CONVERTER

Communication Bus	RS-232C
Faculty	Input
Input channel number	Single end 16 channels
Input range	0～5 V
Resolution	8 bits/12bits

The circuit box (Fig. 11) comprises of several I/O ports such as USB, Finger Force Sensors and acceleration sensor ports. The circuit box also includes power select switch and a unit of LCD display. The LCD was intended to check the status of current operation. The output voltage of the system was set to 5 V by using 3-terminal voltage regulator. A fan (40 mm x 40 mm) was fixed in the circuit box to maintain the temperature due the heat generated by the voltage regulator. In the circuit, six transistor arrays were used to cater 20 channels of the system. Address select can be operated in automatic or manual operation by using one switch. The selection of mode of operation was made by using bus buffer, 74HC125 and 75HC126. For the manual operation, address select of the digital potentiometer was controlled by DIP switch. U/D can be controlled by toggle switch while CLK by push switch.

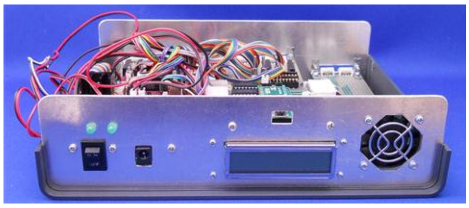


Figure 11. Circuit box.

III. EXPERIMENTS

A. Calibration for Finger Thickness

The calibration for finger thickness was made by inserting fingers on the Finger Force Sensors. Relaxed posture was required during the process of calibration because the value of the voltage did not converge if the medical personnel adds the stress to the fingers during calibration process. The term of the convergence was practically set to 2 % of the intended value.

B. Calibration for Relationship between Voltage and Load

This system should be calibrated before measuring the load data. A mechanical testing device was developed by using an electroactuator (PWA II Cyllinder, Orientalmotor Co., Ltd.), a slider (ELSM6YE035MK, Orientalmotor Co., Ltd) and a load cell (Thin type load cell (multi-force sensor), Kyowa Electronic Instruments Co., Ltd) as shown in Fig. 12 (a). The frame of this device was made by aluminum. The device was controlled by a computer with custom made software (Fig. 12 (b)). Specification of the electroactuator is tabulated in Table II.

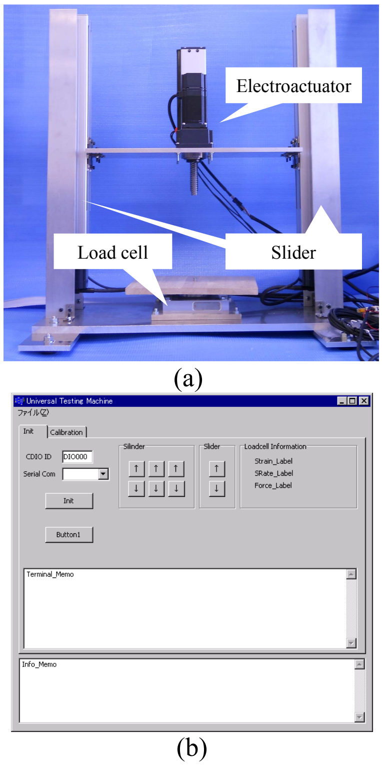


Figure 12. Mechanical testing system. (a) Mechanical testing device. (b) Custom made software

TABLE II. SPECIFICATION OF ELECTROACTUATOR

Stroke (mm)	Maximum Load (N)	Resolution (mm)
100	500	0.01

Calibration was performed for the each finger force sensors by using mechanical testing device (Fig. 13). A plastic lump was inserted into each finger force sensors as shown in Fig. 13. The plastic lump was used to prevent the finger brace from being bent due to the applied forces and cause the calibration to give inaccurate values. These finger force sensors were calibrated at different loads values of 20 N, 40 N, 60N, 80 N and 100 N. The load was vertically applied to the surface of the finger force sensor. The tip of the load cylinder of electroactuator was placed at the center of the conductive rubber of the sensor. The measurement was taken a few seconds after the load being applied to allow the voltage values to be in a steady condition. The same procedure was repeated by using real finger. The value in real finger was regarded as true value.

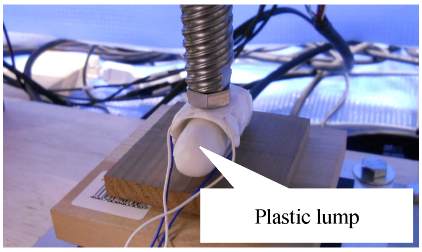


Figure 13. Calibration scene.

The calibration of finger thickness was verified by comparing the value measured using plastic lump and real finger. The load calibration by using real finger was assumed as the real value of relationship between load and voltage. In this experiment, radius of the plastic lamp was set to 10 mm. Meanwhile, the radius of real finger was 8 mm. The shape of the finger brace was extended when using with plastic lump but remains unchanged during experimented with real finger.

IV. RESULTS

A. Calibration for Finger Thickness

The result of the calibration for finger thickness is shown in Fig. 14. The result shows some variation in characteristic for different fingers. Ch 0 and Ch 1 were the sensors for the thumb. Ch 8 and Ch 9 were the sensors for the little finger. Meanwhile Ch 2 and Ch 3 represent the sensors for the rest of the fingers. The time at 0 ms was indicating the start of the calibration process. In this calibration, sampling rate was set to 50 Hz and the desired value was set to 3.92 V. The value in this measurement software was decided 200 because the resolution of the A/D convert was 8 bits, where 0 represents 0 V and 255 represents 5 V. The total time of calibration was stable within about 2 seconds. In Fig. 14, the measured final value was a little bit larger than the desired value. The difference in the measured value was due to some noises. For each channels, the same pattern can be seen where the changes of voltage were small at the start of calibration and gradually increase over time.

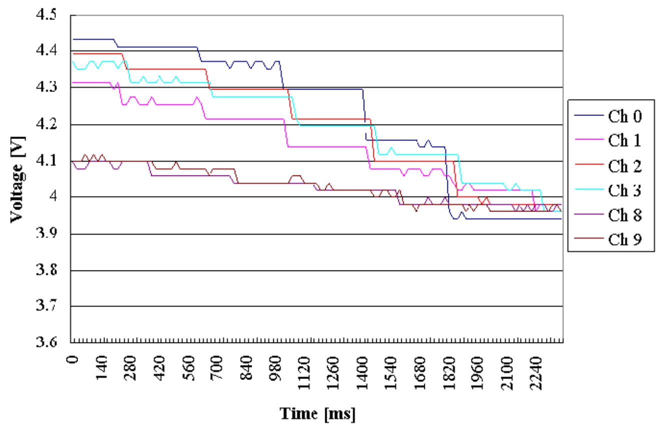


Figure 14. Result of the calibration for finger thickness.

B. Calibration for Relationship between Voltage and Load

Result of load lalibration is shown in Fig. 15. "lump_clb" represents the use of both of calibrations (finger thickness and voltage-load). "real_clb" is the value for calibration with real finger. "lump_none" is the calibration data without the calibration for finger thickness. "real_none" is the value for the real finger without calibration. The value of "real_clb" and "real_none" are considered to be true value. In Fig. 15, the patterns of "real_clb" and "lump_clb" were nearly the same. However the patterns of "real_none" and "lump_none" clearly differ from each other.

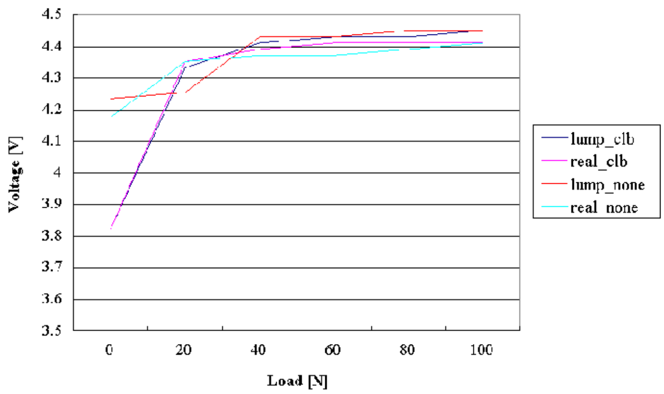


Figure 15. Result of load calibration.

V. DISCUSSION

In the calibration for finger thickness, the calibrating time taken until the system was converged was about 2 seconds. The time taken for the system calibration is considered to be good because during the calibration process, an examiner must not move their hand or otherwise the measurement of Lachman test cannot be performed due to the oscillation of the finger that prevent the system to achieve desired stabilization state.

Because the resolution of the A/D converter of this system was low, the range of the variables were also small. In the calibration for relationship between voltage and load, the patterns of true values and calibration are nearly same. Hence, the range of variable to differentiate between 60 N to 100 N was comparatively small and difficult to determine the real values between these forces. This case was considered as not very good for a sensor due to low range of variable to detect different resistance. This problem will be addressed in the future works by using a higher ADC resolution to enable the better measurement of voltage-load relationship. Generally, it can concluded that the calibrated values was more accurate as compared to the uncalibrated values for the finger thickness.

VI. Conclusion

A measurement system for the finger stress with force sensor during Lachman test was developed. Previously, the system was tested and resulted in low accuracy of measurement. Hence, the method of calibration for finger thickness was introduced. In this experiment, a sensor of the measurement system was measured for accuracy using the developed calibration method. The improvement of the measurement system includes fast calibration of finger thickness as well as higher accuracy of the sensor. This calibration of voltage-load relationship only required to be performed once and remove the necessity to repeat the same calibration for different examiners. Thus, giving advantage of saving time and at the same time helps the examiner easily uses the measurement system without the need to do extra technical works beforehand. Moreover, this method could also be applied to a situation where the relationship of voltage-load become off due to deterioration of the sensor. Besides the advantages of new method of calibration, unfortunately the method only works best for low loads and new problem came into sight as higher load was applied due to low range of variable from the AD converter. Future works will include the improvement of the resolution of A/D converter and to measure the force distribution during Lachman test with better accuracy of the force sensor. The relationship of voltage-load are also depending on the finger thickness. Hence, there is a need to study on the variation of finger itself to provide essential data for the calibration of voltage-load relationship.

Acknowledgment

This work was supported (in part) by the Support Program for Improving Graduate School Education from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] D. C. Fitzpatrick, M. B. Sommers, B. C. C. Kam, J. L. Marsh, M. Bottlang, "Knee Stability After Articulated External Fixation," *American Journal of Sports Medicine*, vol. 33, pp. 1735-1741, 2005.

[2] A. J. Schuster, M. J. McNicholas, S. W. Wachtl, D. W. McGurty R. P. Jakob, "A New Mechnical testing Device for Measuring Anteroposterior Knee Laxity," *American Journal of Sports Medicine*, vol. 32, pp. 1731-1735, 2004.

[3] K. Sun, S. Tian, J. Zhang, C. Xia, C. Zhang, T. Yu, "Anterior Cruciate Ligament Reconstruction with BPTB Autograft Irradiated Versus Non-Irradiated Allograft: a Prospective Randomized Clinical Study," *Journal of Knee Surgery Sports Traumatology Arthroscopy*, vol. 17, pp. 464-474, 2009.

[4] F. Gebhard, M. Authenrieth, W. Strecker, L. Kinzl, G. Hehl, "Ultrasound Evaluation of Gravity Induced Anterior Drawer Following Anterior Cruciate Ligament Lesion," *Knee Surgery Sports Traumatology Arthroscopy*, vol. 7, pp. 166-172, 1999.

[5] S.H. Wiertsema, H.J.A. van Hooff, L.A.A. Migchelsen, M.P.M. Steultjens, "Reliability of the KT1000 arthrometer and the Lachman test in patients with an ACL rupture," *The Knee*, no. 15, pp. 107-110, 2008.

[6] A. M. Rijke, C. J. Tegtmeyer, D. J. Weiland, F. C. McCue III, "Stress Examinaion of the Cruciate Ligaments: A Radiologic Lachman test," *Radiology*, vol. 165, no. 3, pp. 867-869, 1987.

[7] Y. Hoshino, R. Kuroda, K. Nagamune, M. Yagi, K. Mizuno, M. Yamaguchi, H. Muratsu, S. Yoshiya, and M. Kurosaka, "In Vivo Measurement of the Pivot-Shift test in the Anterior Cruciate Ligament–Deficient Knee Using an Electromagnetic Device," *American Journal of Sports Medicine*, vol. 35, pp. 1098-1104, 2007.

[8] R. Kuroda, Y. Hoshino, K. Nagamune, S. Kubo, K. Nishimoto, D. Araki, M. Yamaguchi, S. Yoshiya and M. Kurosaka, "Intraoperative Measurement of Pivot Shift by Electromagnetic Sensors," *Operative Techniques in Orthopaedics*, vol. 18, pp. 190-195, 2008.