Development of a Wearable Sensing Glove for Measuring the Motion of Fingers Using Linear Potentiometers and Flexible Wires

Yeongyu Park, Jeongsoo Lee, and Joonbum Bae, *Member, IEEE*

***Abstract*—In this paper, a wearable sensing glove for measuring the motion of the fingers is proposed. The system consists of linear potentiometers, flexible wires, and linear springs, which makes it compact and lightweight so that it does not interfere with the natural motion of the fingers. Inspired by the way wrinkles on finger joints are smoothed out when the finger is flexed, a flexible wire is attached to the back of each finger. As the flexible wire moves due to the motion of the finger, the joint angles are calculated by measuring the change in length of wire. Linear potentiometers with linear springs were used to maintain the tension of the wires in order to measure the wire length change consistently. Because the motion of the proximal interphalangeal (PIP) joint is dependent on that of the distal interphalangeal (DIP) joint, only two linear potentiometers were used for each finger. A compact sensing module including 10 linear potentiometers and springs was attached to a glove. The proposed system can widely be applied for the systems, which require to measure finger motions accurately, e.g., virtual reality or teleoperation systems. Such feasible applications were actually implemented and introduced in this paper.**

***Index Terms*—Finger motion measurement, human-robot interaction, wearable system.**

I. Introduction

THE HAND is one of the richest sources of tactile sensory data, enabling precise, and complex manipulation. Using the delicate manipulation ability of the hand, human–robot interaction systems which are operated by the hand have been actively researched for rehabilitation, virtual reality, entertainment, teleoperation, power assistance, and so on [2]–[5]. For the development of such systems, measurement of unconstrained hand motion should be preceded. Due to the small space and multifunctions of the hand, however, hand motion measurement systems have not fully been exploited yet.

Previously developed hand motion measurement systems can be categorized to glove and nonglove-types. As wearable glove-type systems, optical encoders, magnetic positioning sensors, fiber optic sensors, and flexible resistances have been applied [6]–[11]. But, because of the limited space and complicated anatomical structure of the hand, a compact and simple measurement system, which is able to measure unconstrained finger motion accurately, has not yet been developed. As nonglove-type systems, electromyographic (EMG) or infrared (IR) camera signals were applied [12], [13]. With the nonglove-type systems, general hand gestures such as rotating or pointing can be detected without wearing anything to the hand. But the nonglove-type systems may not be suitable to accurately measure the joint angles of the fingers.

In this paper, a novel wearable sensing glove for measuring the flexion/extension motion of fingers, which consists of linear potentiometers and flexible wires, is proposed. The proposed system was inspired by how the wrinkles on the finger joints are smoothed when the finger is flexed. Flexible wires are tied to the glove to detect the finger motions. As the flexible wires are moved by the finger motions, the joint angles are calculated by a kinematic model of the finger and the displacement changes of the wires, which are measured by the linear potentiometers. Each finger has three degrees of freedom in flexion/extension, but only two joint angles are needed to be measured using the relationship between the proximal interphalangeal (PIP) joint and the distal interphalangeal (DIP) joint. The potentiometers and return springs are attached to the glove as a compact sensing module. Performance of the proposed systems was verified by experiments, and the possible applications including virtual reality and teleoperation systems were actually implemented.

This paper is organized as follows. Section II reviews the skeletal structure of the hand. Section III details the concept and implementation of the proposed system. The performance of the motion measuring system is investigated experimentally in Section IV. Implementation of the proposed system is described in Section V, and the feasible applications are introduced in Section VI. Conclusion is presented in Section VII.

II. Skeletal Structure of the Hand

The hand is a complex combination of bones, muscles, and ligaments, which determine the direction and range of motion. Understanding the anatomical structure of the hand is necessary to accurately measure the motion of the fingers.

Motion of the hand is achieved via 19 bones, 19 joints, and 29 muscles [14]. Each finger (except the thumb) has three bones—a distal, middle, and proximal phalanx—and three

Manuscript received June 11, 2014; revised October 16, 2014; accepted November 23, 2014. Date of publication December 18, 2014; date of current version February 02, 2015. This work was supported by the Global Frontier R&D Program on Human-Centered Interaction for Coexistence funded by the National Research Foundation of Korea grant funded by the Korean Government (MEST) under Grant NRF-2012M3A6A3056354. Preliminary versions of this paper were presented at the IEEE/American Society of Mechanical Engineers (ASME) International Conference on Advanced Intelligent Mechatronics (AIM) 2014 [1]. Paper no. TII-14-0619.

The authors are with the Bio-Robotics and Control (BiRC) Laboratory, Department of Mechanical Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan 689-798, Korea (e-mail: ygpark@unist.ac.kr; galanthus@unist.ac.kr; jbbae@unist.ac.kr).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TII.2014.2381932

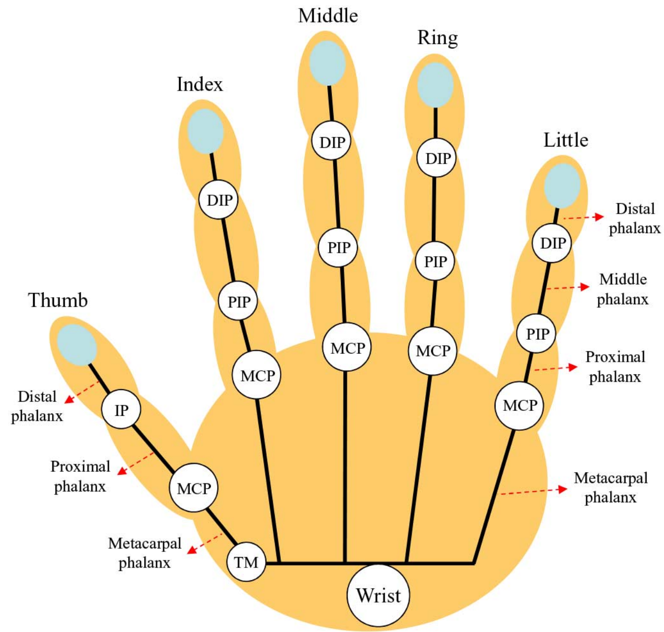


Fig. 1. Schematic diagram showing the anatomy of the hand.

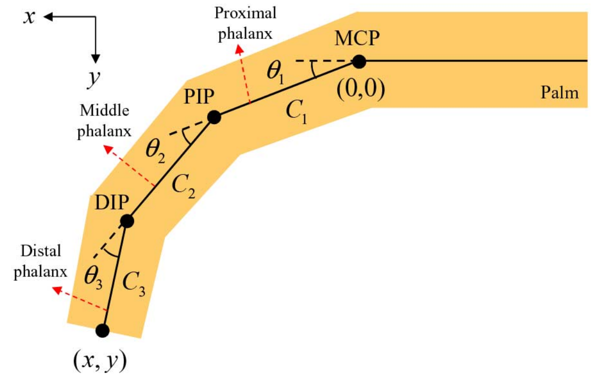


Fig. 2. Cross section of a finger.

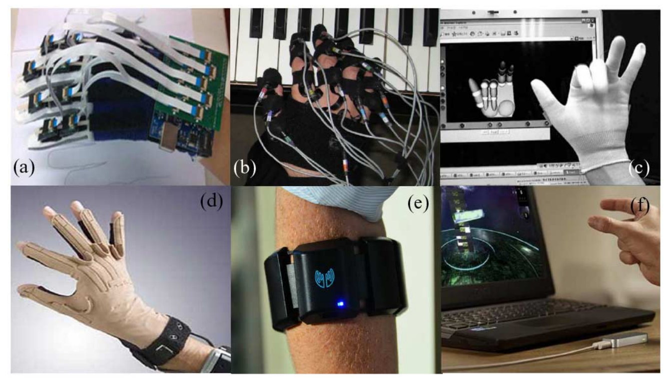


Fig. 3. Previously developed finger motion measurement systems. (a) Optical linear encoder based system [6]. (b) Magnetic three dimensional position sensor based system [7]. (c) Hetero-core fiber-optic nerves based system [9]. (d) CyberGlove [11]. (e) Myo gesture control [12]. (f) Leap motion [13].

joints—a proximal interphalangeal (PIP) joint, metacarpophalangeal (MCP) joint, and DIP joint, as shown in Fig. 1. The thumb has only two bones—the distal and proximal phalanx—and two joints—the interphalangeal (IP) and MCP joints. The metacarpal and phalanx bones meet the wrist at the carpometacarpal (CMC) joints. The IP joints, including the PIP and DIP joints, have one degree of freedom (DOF) for the flexion/extension, and the MCP joints have two DOFs for the flexion/extension and abduction/adduction.

Flexion/extension is typically required more frequently than abduction/adduction when manipulating objects. Thus, a finger flexion/extension motion measurement system that does not interfere with the natural motion of the fingers is desirable. Therefore, here, we focus on the flexion/extension of all five fingers.

III. Configuration of the Wearable Sensing Glove

A. *Concept of the Proposed System*

The cross section of a finger is shown in Fig. 2 during flexion/extension. Because the lengths of each finger element, C_1, C_2, and C_3, can be measured in advance, the position of the fingertips can be described as follows:

$$x = C_1\cos(\theta_1) + C_2\cos(\theta_{12}) + C_3\cos(\theta_{123}) \quad (1)$$

$$y = C_1\sin(\theta_1) + C_2\sin(\theta_{12}) + C_3\sin(\theta_{123}) \quad (2)$$

where θ_{12} and θ_{123} are the summation of θ_1, θ_2 and $\theta_1, \theta_2, \theta_3$, respectively. We only need these three joint angles to describe the flexion/extension of each finger. However, measuring the joint angles of the fingers is not straightforward due to the space limitations around each finger. In addition, the goniometric system should be sufficiently light and compact not to interfere with the natural motion of the fingers.

A number of approaches have been tried to measure the position of the finger joints accurately. A similar approach has been described using optical linear encoders (OLEs) [6], However, the encoders, which were attached to the fingers, and cables that were used for the encoders, which were thick and wide, inhibited the natural motion of the fingers, as shown in Fig. 3(a). Three-dimensional (3-D) magnetic positional sensors have been applied to measure the joint angles of the fingers [7]. As shown in Fig. 3(b), they could measure the motion of the fingers in 3-D space. But the required peripherals became obstacles for measuring the unconstrained motion accurately. Fiber optic sensors have been used for goniometry [9] in Fig. 3(c). The sensors were adhered to a glove for ease of use. However, the glove required that the optical sensors should be bent carefully to measure the joint angles. Furthermore, mobility was limited by the required peripherals, including a laser diode and an optical power meter. Flexible resistances have been applied to a commercially available sensing glove, called CyberGlove [11], as shown in Fig. 3(d). The glove measures not only flexion/extension but also abduction/adduction of the fingers and movement of the wrist. However, the resistances in the CyberGlove are flexible but not stretchable, thus it may disturb the natural motion of the fingers, which can be explained by Fig. 4. Also, it has the cost inefficiency comparing with other commercialized sensors such as Myo armband and Leap motion.

For nonglove-type finger motion sensing systems, EMG or infrared (IR) camera signals were utilized. Myo shown in Fig. 3(e) uses an armband to measure the EMG signals of

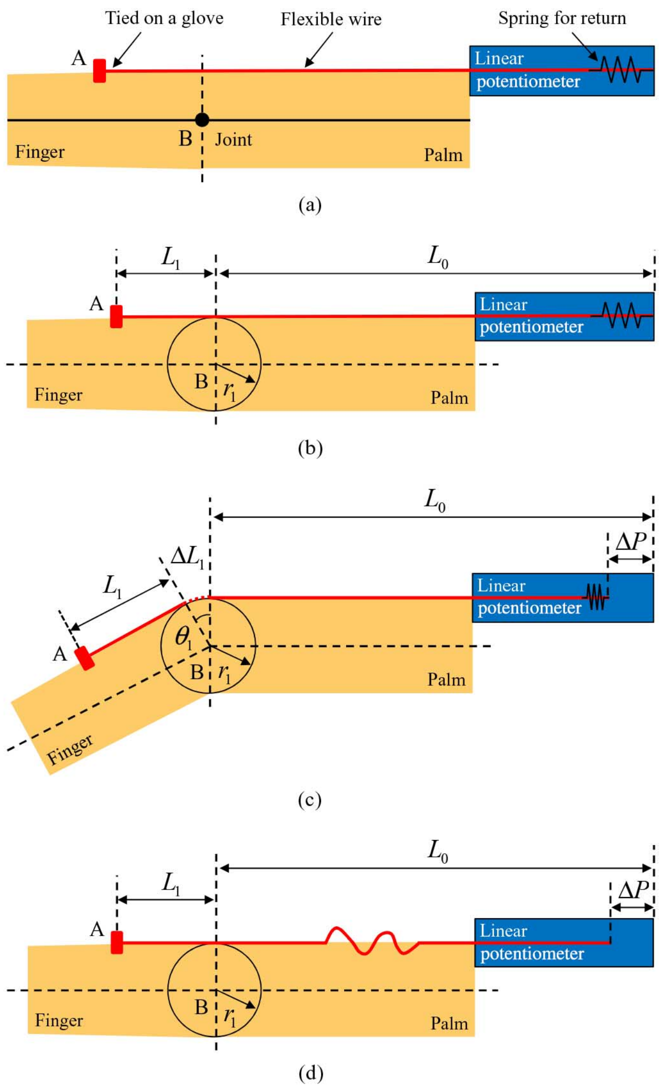


Fig. 4. Schematic diagram showing the concept of the proposed finger joint measurement system (one finger case). (a) Overview of the system. (b) Initial position of the finger. (c) Flexed finger. (d) Necessity of a return spring.

the forearm, and the hand gestures such as rotating or pointing are detected by the measured EMG signal patterns [12]. It can detect general hand gestures by the simple structure on the forearm without any constraints on the hand movement, but accurate finger joint angles cannot be measured. Leap motion uses IR camera signals which are measured by a compact sensor as shown in Fig. 3(f) [13]. Hand gestures can be detected without wearing any devices on the hand, but the hand should be placed within the camera range, which is less than about 1 m. Also, if the fingers are overlapped, the sensing accuracy is decreased.

In this paper, flexible wires and linear potentiometers with linear springs are used to measure the flexion/extension of the fingers. The concept of the proposed system is shown schematically in Fig. 4. For clarity, only one joint is explained in Fig. 4. A flexible wire (a fishing line was used in this paper) was attached to the finger by tying it to the glove, as shown in Fig. 4(a) (see point A in the figure). Since the motion of the finger joint can be considered as a rotation around a fixed joint (see point B in Fig. 4), the kinematics of one joint can be described as shown in Fig. 4(b). As the finger is flexed, the connected line moves because the wrinkles of the finger joint are smoothed out. The displacement ΔL can be calculated as follows:

$$\Delta L_1 = r_1 \theta_1 \tag{3}$$

where r_1 is the radius of the finger joint, which can be directly measured, and θ_1 is the joint angle. The change in length ΔL_1 is measured using a linear potentiometer and is equivalent to ΔP as shown in Fig. 4(c). Thus, the joint angle can be calculated as follows:

$$\theta_1 = \frac{\Delta P}{r_1}. \tag{4}$$

When the finger is extended [i.e., to the original position shown in Fig. 4(d)], the flexible wire returns to its initial position by the spring installed in the potentiometer. Without the spring, the flexible wire would be loose, as shown in Fig. 4(d), and the system would only be able to measure the finger flexion once.

B. Interdependency Between Finger Joints

Before we move to the multiple-joint case, the interdependence of the finger joints should be considered. It is well known that the DIP joint cannot move independently; the motion of the DIP joint depends on that of the PIP joint. The relationship between them has been usually approximated as follows [15]:

$$\theta_{\mathrm{DIP}} = \frac{2}{3}\theta_{\mathrm{PIP}} \tag{5}$$

where θ_{DIP} is the angle of the DIP joint and θ_{PIP} is the angle of the PIP joint. However, our experimental results in Section IV-B showed that the relationship could not be represented as a linear relationship, and the relationship was not identical for everyone. Thus, a more accurate relationship is required in order to measure both joint angles using only one measurement of the PIP joint. By obtaining an accurate relationship between the DIP and PIP joints, only two measurements are required for each finger, and the number of DOFs of the measurement system can be reduced. The relationship between the DIP and PIP joints was obtained experimentally and is discussed in Section IV-B.

C. Design of the Proposed System

Considering the interdependence of the DIP and PIP joints, the system was designed as shown in Fig. 5. Similar to the single joint case, the angle of each joint was measured using a linear potentiometer. Since the DIP joint angle can be obtained from the PIP joint angle due to the interdependence, only two potentiometers were used to measure the PIP and MCP joint angles.

Suppose the finger is flexed from the position shown in Fig. 5(a) to that shown in Fig. 5(b); the displacement of the attachment points ΔL_1 and ΔL_2 is given by the two linear potentiometers and the distance of moved tied points are as follows:

$$\Delta P_1 = \Delta L_1 \tag{6}$$

$$\Delta P_2 = \Delta L_1 + \Delta L_2. \tag{7}$$

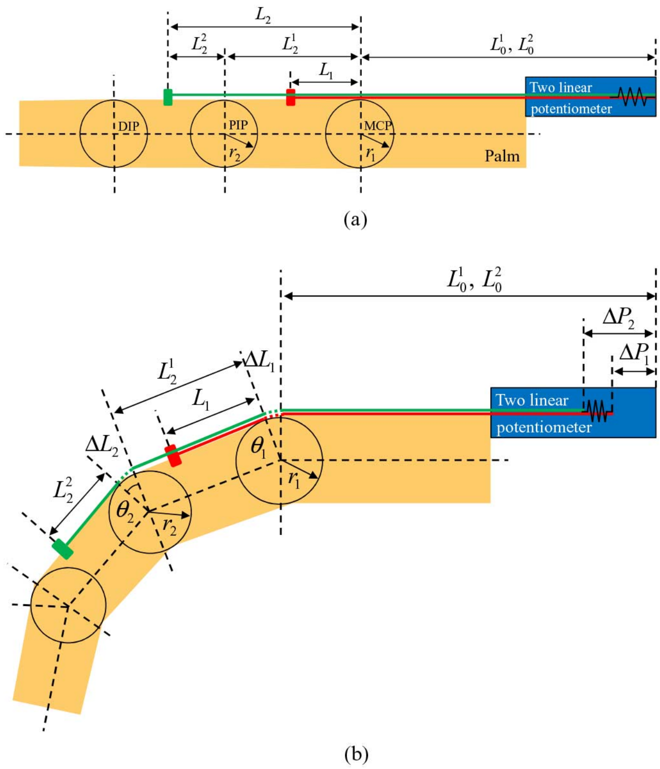


Fig. 5. Schematic diagram showing the concept of the proposed finger joint measurement system (multifinger case). (a) Schematic of the proposed system (multijoint case) and (b) flexed finger.

The joint angles can be calculated as follows:

$$\theta_1 = \frac{\Delta L_1}{r_1} \tag{8}$$

$$\theta_2 = \frac{\Delta L_2}{r_2}. \tag{9}$$

Thus, the joint angles can be obtained as follows:

$$\theta_1 = \frac{\Delta P_1}{r_1} \tag{10}$$

$$\theta_2 = \frac{\Delta P_2 - \Delta P_1}{r_2}. \tag{11}$$

The only required measurements are the changes in the distances of these attachment points, which were measured using flexible wires and linear potentiometers. One of the advantages of this system is that the flexible wire can be wound; thus, the wires do not have to be aligned with the fingers. Therefore, the sensing module containing the potentiometers and springs was located on the back of the hand, and the flexible wires were attached to the glove and connected to the sensing module, as shown in Fig. 6. Two flexible wires were used per finger to measure the angles of the PIP and MCP joints, and each wire was connected to the middle and proximal phalanxes. Thin cylindrical guides were attached to the glove to guide the wires. Also, the wires were slightly stitched to the glove between the guides as shown in Fig. 12. By these two guides, the wires were well aligned to the glove and not twisted each other. Thus, the wires move along the bones of the fingers, and the flexion/extention motions of the fingers can be accurately measured.

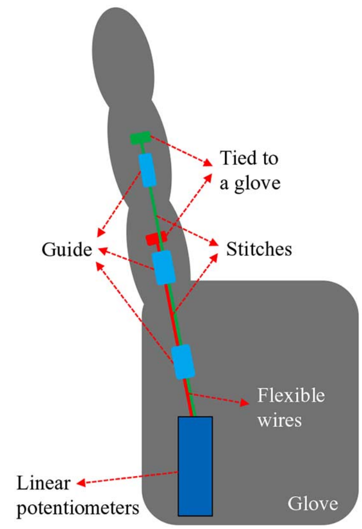


Fig. 6. Design of the proposed system.

IV. Experimental Verification

To verify the performance of the proposed system, measurements were obtained using the proposed system and were compared with those of small wireless inertial measurement unit (IMU) sensors attached to the fingers [16]. The IMUs were able to measure joint angles perpendicular to three axes; however, only the flexion/extension motion angle was compared to the potentiometer measurements.

A. Verification of the Concept

Prior to applying the system to a human hand, we investigated the performance using a wooden model hand. In this way, additional uncertainties due to the fit of the glove could be eliminated. The IMU sensors and a flexible wire were attached to the wooden hand, as shown in the left side of Fig. 7. The IMU sensor was attached directly to a wooden finger, and the flexible wire was connected to the wooden finger between the DIP and PIP joints, with the linear potentiometer and return spring. The potentiometer was located on the back of the wooden hand. Only the PIP joint of the index finger was flexed, whereas the MCP joint remained fixed. The measured potentiometer signal was converted to the PIP joint angle using (11). The experimental results are shown in Fig. 8(a). The two measurements were in good agreement, with an average error of approximately 0.65°. It is known that the sensing ability of human in the limb position is about 1° [17]. If the sensing accuracy of the wearable sensing glove is in this range, the wearable sensing glove may be considered as a satisfactory system. In the case of commercialized sensor, CyberGlove, the measurement error is specified as under 1°. Based on this specification, the proposed system can be considered as a suitable system to measure finger motions.

B. Relationship Between the DIP and PIP Joints

As described in Section III-B, the interdependence between the DIP and PIP joints was analyzed and the relationship

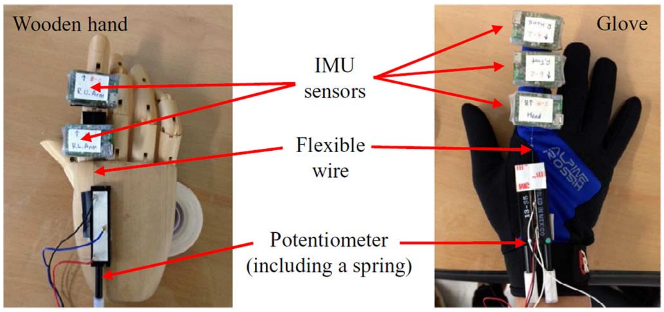


Fig. 7. Experimental setup.

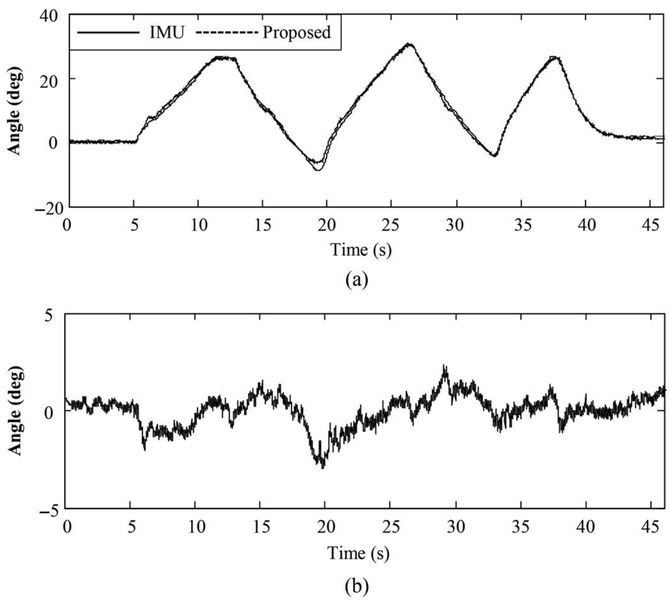


Fig. 8. Experimental results with a wooden hand. (a) Measured joint angles using both the IMUs and the proposed system. (b) Error between the two measurements.

between them was obtained from experimental measurements. The motion of the finger is composed by a combination of the flexor digitorum profundus (FDP) and the flexor digitorum superficialis (FDS) muscles [18]. The relationship between the DIP and PIP joints is often assumed to be linear [15]; however, the linear approximation may not be correct considering the complicated activation mechanism of the FDP and FDS muscles to control the DIP and PIP joints [19]. In this section, the relationship between the DIP and PIP joints is experimentally obtained to estimate the DIP joint angle by measuring the PIP joint angle only.

To obtain the accurate relationship between the DIP and PIP joints, five subjects (age: 24.4 ± 0.55, three males, two females) participated in the experiment. Three IMU sensors were directly attached on their index finger at distal, middle, and proximal phalanges. The participants were asked to flex and extend their fingers five times freely, and the relationship between the motion of the two joints was obtained using curve fitting.

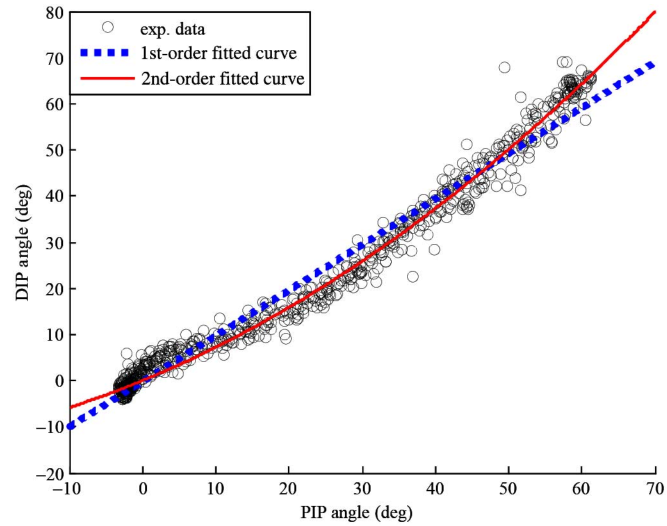


Fig. 9. Relationship between the DIP and PIP joints.

One of the representative results is shown in Fig. 9. As shown in the figure, the relationship might not be represented as a linear one; thus, the data were fitted by both first- and second-order polynomials as follows:

$$\theta_{\mathrm{DIP}} = 0.989\,\theta_{\mathrm{PIP}} - 0.230 \quad (12)$$

$$\theta_{\mathrm{DIP}} = 0.006\,\theta_{\mathrm{PIP}}^2 + 0.674\,\theta_{\mathrm{PIP}} + 0.104 \quad (13)$$

where θ_{DIP} is the angle of the DIP joint and θ_{PIP} is the angle of the PIP joint. The curve fitting result indicates that the angles of the DIP and PIP joints are not linearly interdependent, and that the second order fits better than the first order, in contrast to the well-known expression given in (5).

The experimental results from 25 trials are summarized in Tables I and II. As shown in tables, there exist individual variations in relationship between the DIP and PIP joints, but remains constant in each participant; standard deviation of five experimental results in each participant was small with an average of 0.036. Also, the relationships fit better to second-order polynomials than first-order polynomials. Higher than the second order were also tried to approximate the relationship, but the higher orders than the second had a very small effect to the relationship, i.e., the parameters of the higher orders were almost zero. Thus, the relationship between the DIP and PIP joint was approximated to the second order. In this paper, the second-order relationship between the DIP and PIP joints was individually obtained in advance, then it was used to accurately measure the three joint angles using only two joint measurements.

C. Joint Angle Measurement

The experimental setup for measuring joint angles of the fingers is shown in the right-hand side of Fig. 7. Three IMU sensors, to measure the DIP, PIP, and MCP joint angles, were attached to the index finger, and two wires were tied to the proximal and middle phalanx of the glove and connected with two potentiometers. In this experiment, the index finger was bent

TABLE I
EXPERIMENTAL RESULTS OF FIRST-ORDER FITTING

$\theta_{DIP} = a_0\,\theta_{PIP} + a_1$			
Subject	a_0	a_1	RMSE[a]
A	0.84	–23.8	10.08
B	0.69	–11.9	6.95
C	0.57	–6.34	7.24
D	1.09	–16.6	8.86
E	0.70	1.44	8.42

[a]Root-mean-square error.

TABLE II
EXPERIMENTAL RESULTS OF SECOND ORDER FITTING

$\theta_{DIP} = b_0\,\theta_{PIP}^2 + b_1\,\theta_{PIP} + b_2$				
Subject	b_0	b_1	b_2	RMSE[a]
A	0.011	–0.12	14.4	8.06
B	0.005	0.30	–9.46	6.22
C	0.004	0.17	–1.44	6.64
D	–0.001	1.16	–17.4	8.85
E	0.004	0.28	4.55	7.50

[a]Root-mean-square error.

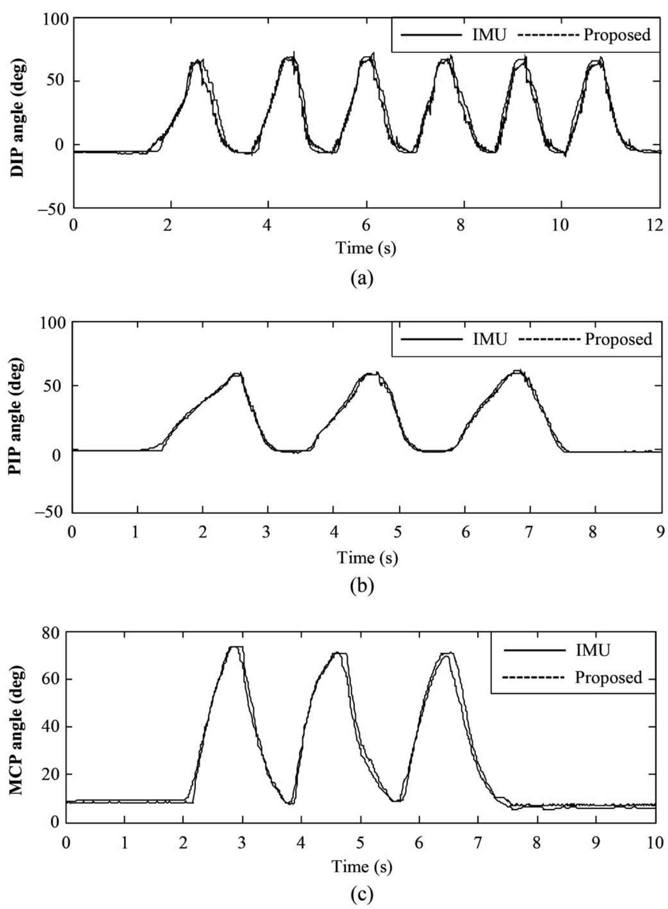


Fig. 10. Measured joint angles using the proposed system. (a) DIP joint. (b) PIP joint. (c) MCP joint.

back and forth several times as usual flexion/extension motions with the palm to be flat. The result of each joint angle measurement is shown in Fig. 10. The measured angles, converted from potentiometer measurement by (10) and (11), show great consistency between two different measurement methods; however, the DIP angle is slightly different, which might be caused by accumulated errors in measuring the PIP angle in IMU sensors and modeling the relationship between DIP and PIP joints.

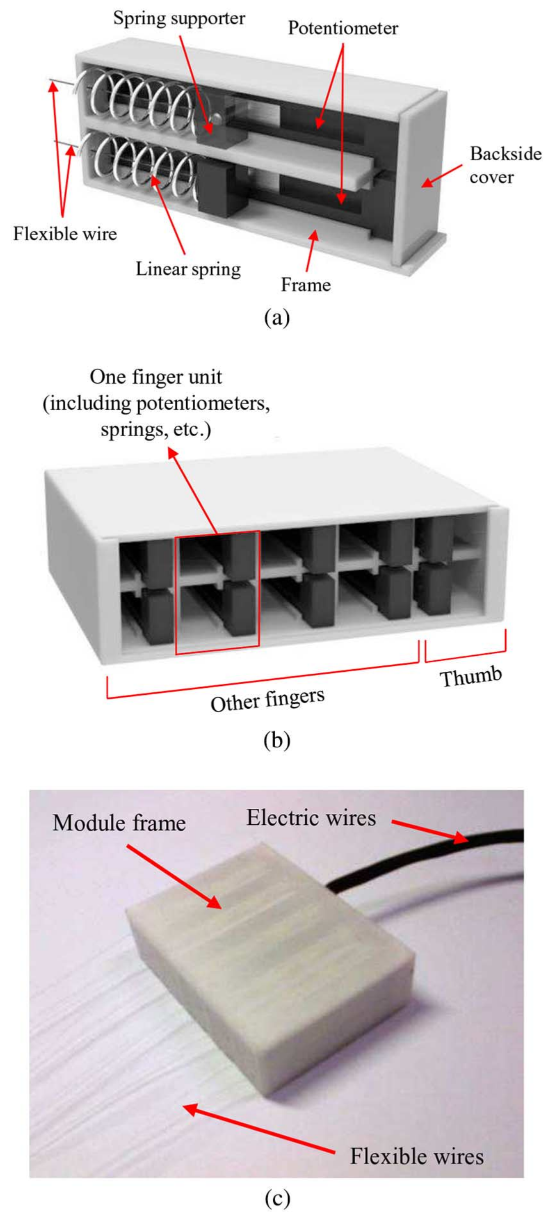


Fig. 11. Design of the sensing module. (a) Cross section of the sensing module. (b) Backside of the sensing module. (c) Manufactured sensing module.

V. IMPLEMENTATION OF THE WEARABLE SENSING GLOVE

The proposed system requires 10 potentiometers to measure the flexion/extension of five fingers simultaneously. Miniature linear potentiometers with a 20-mm stroke were used to create a compact and lightweight sensing module so as not to interfere with the natural motion of the fingers [20]. Two potentiometers were installed vertically, as shown in Fig. 11(a), to decrease the size of the sensing module. The lever of each potentiometer was

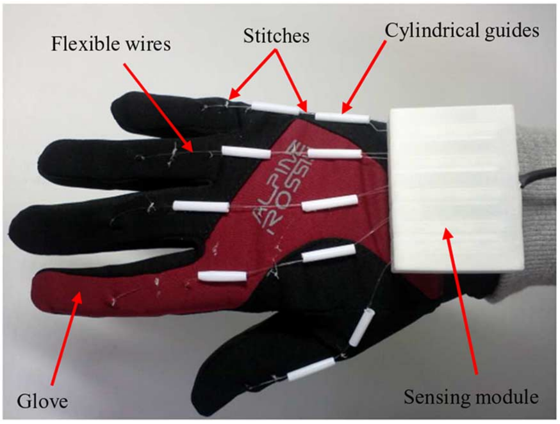
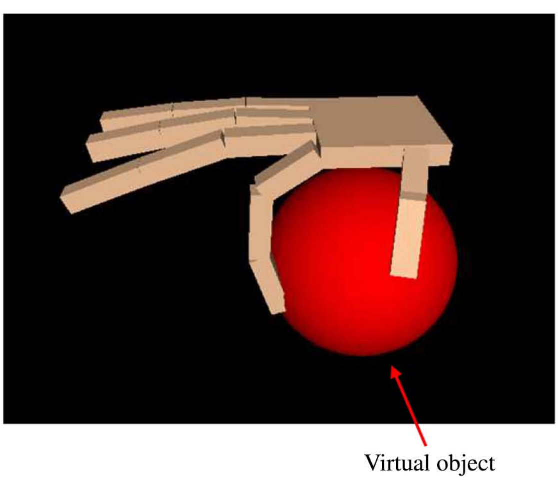


Fig. 12. Proposed wearable sensing glove.

(a)



(b)

Fig. 13. Interaction with virtual objects. (a) Vibrators attached to the sensing glove and (b) virtual object in the user-interface.

attached to a flexible wire, which was connected to the glove via a small opening in the frame. Manually designed linear springs were installed so that the potentiometer returned to its initial position when the finger was extended.

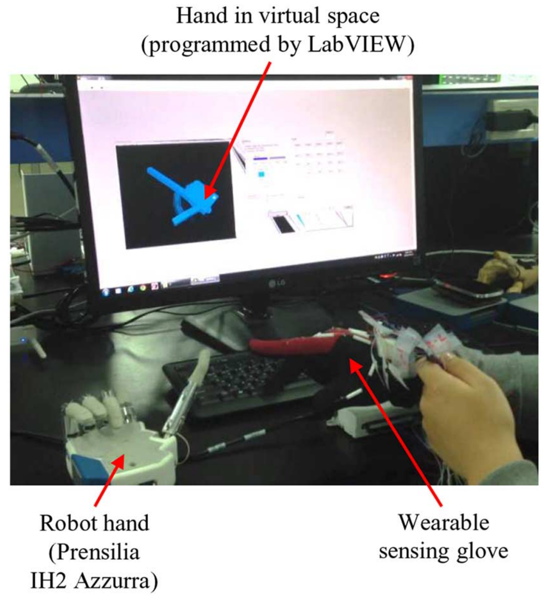


Fig. 14. Experimental setup for teleoperation of a robot hand.

The rear side of the sensing module, through which the potentiometers and springs were inserted, is shown in Fig. 11(b). The frame of the sensing module was fabricated from nylon material using rapid prototyping technologies. The size of the sensing module was $45 \times 61 \times 17.4$ mm and the mass was only 39 g; this may be considered sufficiently compact and lightweight not to interfere with the motion of the hand. The sensing module was attached to a glove as shown in Fig. 12, which can be easily worn by a user.

VI. Applications

The proposed sensing glove can widely be applied for the systems, which require to measure finger motions accurately. The feasible applications are interaction with virtual objects, teleoperation of a robot hand, and entertainment systems (e.g., playing a virtual piano in a console game with the measured finger motion). Some of the possible applications were actually implemented and introduced in this section.

A. *Interaction With Virtual Objects*

Since the fingers play a key role in touching and manipulating objects, the finger motions should be accurately measured to implement the virtual reality. The proposed sensing glove was applied to implement simple virtual reality. In this system, the virtual hand was moved by the measured finger motions, and the vibration feedback was provided to the user when the hand touched virtual objects. The frequency of the vibrators, which were attached to the fingertips, increased as the finger pushed the virtual object more. The virtual hand was modeled as a rigid linkage with 14 DOFs (two for the thumb and three for each finger) to express the measured finger motions by the proposed system. The vibrators attached to the proposed sensing glove are shown in Fig. 13(a), and the user-interface programmed by LabVIEW is shown in Fig. 13(b).

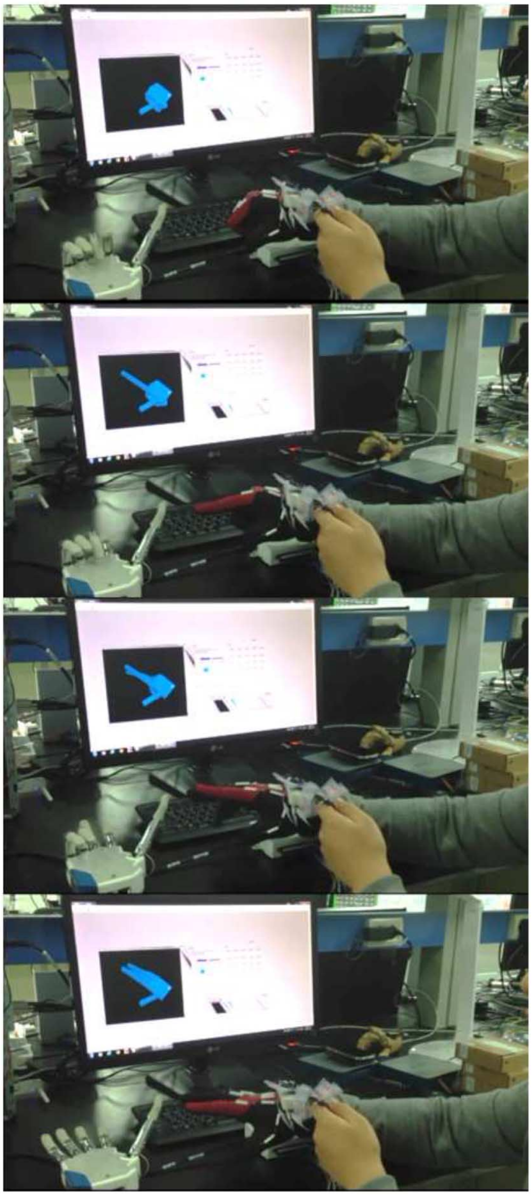


Fig. 15. Various postures of the robot hand.

B. Teleoperation of a Robot Hand

The proposed system can be applied to operate a robot hand in a remote place. In this experiment, a robot hand (IH2 Azzurra robot hand from Prensila [21]) was controlled by the sensing glove; the joint angles of the five fingers were measured using the proposed sensing glove, and the measured angles were then transmitted to the robot hand to mimic the motion of the fingers. The measured finger motion was displayed to the user by the virtual hand introduced in the previous chapter. The experimental setup is shown in Fig. 14, and the various postures of the robot hand are shown in Fig. 15. In this setup, the robot hand and the sensing glove were connected to the same PC, but the system can be extended to the teleoperation system if two systems are connected by the Internet in different places.

VII. Conclusion

We have described the wearable sensing glove utilizing linear potentiometers, flexible wires, and return springs. By measuring the change in length of the flexible wires in response to flexion or extension of the fingers, the joint angles could be obtained. A compact sensing module containing the linear potentiometers and springs was attached to the back of the hand, and connected to the fingers via flexible wires. The performance of the system was verified experimentally, and the feasible applications of the proposed system, i.e., interaction with virtual objects and teleoperation of a robot hand, were implemented and introduced.

Directions for future work include integration of proposed system to measure the motion of the fingers and an exoskeleton to interact with virtual objects [22]. The measured position of the fingers will be applied to generate accurate force feedback for intelligent interaction between a human user and virtual objects.

References

[1] Y. Park, J. Lee, and J. Bae, "Development of a finger motion measurement system using linear potentiometers," in *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatron. (AIM)*, 2014, pp. 125–130.

[2] S. Ueki, H. Kawasaki, S. Ito, and Y. Nishimoto, "Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy." *IEEE/ASME Trans. Mechatron.*, vol. 17, pp. 136–146, 2012.

[3] J. Iqbal, O. Ahmad, and A. Malik, "HEXOSYS II-towards realization of light mass robotics for the hand," in *IEEE Int. Multitopic Conf. (INMIC)*, 2011, pp. 115–119.

[4] Control VR. (2014). Control VR [Online]. Available: https://www.controlvr.com/

[5] K. Tadano, M. Akai, K. Kadota, and K. Kawashima, "Development of grip amplified glove using bi-articular mechanism with pneumatic artificial rubber muscle," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2010, pp. 2363–2368.

[6] K. Li, I.-M. Chen, S. H. Yeo, and C. K. Lim, "Development of finger-motion capturing device based on optical linear encoder," *J. Rehabil. Res. Dev.*, vol. 48, pp. 69–82, 2011.

[7] K. Mitobe *et al.*, "Development of a motion capture system for a hand using a magnetic three dimensional position sensor," in *Proc. SIGGRAPH'06 ACM SIGGRAPH Res. Posters*, 2006, p. 102.

[8] C.-S. Fahn and H. Sun, "Development of data glove with reducing sensors based on magnetic," *IEEE Trans. Ind. Electron.*, vol. 52, no. 2, pp. 585–594, Apr. 2005.

[9] M. Nishiyama and K. Watanabe, "Wearable sensing glove with embedded hetero-core fiber-optic nerves for unconstrained hand motion capture," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 12, pp. 3995–4000, Dec. 2009.

[10] M. Nishiyama, H. Sasaki, and K. Watanabe, "Restraint-free wearable sensing clothes using a hetero-core optic fiber for measurements of arm motion and walking action," in *Proc. SPIE*, 2007, vol. 6529, pp. 652 91Y–1.652 91Y–8.

[11] CyberGlove Systems. (2013). *Cyberglove II* [Online]. Available: http://www.cyberglovesystems.com/

[12] Myo Gesture Control. (2014). *MYO Gesture Control Armband* [Online]. Available: https://www.thalmic.com/

[13] Leap Motion. (2014). *The Leap Motion Controller* [Online]. Available: https://www.leapmotion.com/

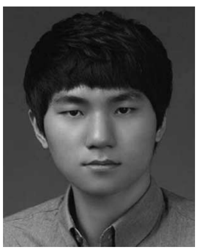
[14] D. Neumann and E. Rowan, *Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation*. Philadelphia, PA, USA: Mosby, 2002.

[15] H. Rijpkema and M. Girard, "Computer animation of knowledge-based human grasping," *ACM Siggraph Comput. Graph.*, vol. 25, pp. 339–348, 1991.

[16] e2box. (2014). *Ebmotion Studio* [Online]. Available: http://www.e2box.co.kr/

[17] E. Samur, *Performance Metrics for Haptic Interfaces*. New York, NY, USA: Springer, 2012.

[18] A. D. Nimbarte, R. Kaz, and Z.-M. Li, "Finger joint motion generated by individual extrinsic muscles: A cadaveric study," *J. Orthopaed. Surg. Res.*, vol. 3, pp. 1–7, 1991.
[19] J. Leijnse, P. Quesada, and C. W. Spoor, "Kinematic evaluation of the fingers interphalangeal joints coupling mechanism-variability, flexion-extension differences, triggers, locking swanneck deformities, anthropometric correlations." *J. Biomechatron.*, vol. 43, pp. 2381–2393, 2010.
[20] ALPS. (2014). *Linear Potentiometer (Model: Rdc1022a05)* [Online]. Available: http://www.alps.com/
[21] Prensilia. (2014). *IH2 Azzurra Robotic Hand* [Online]. Available: http://www.prensilia.com/
[22] I. Jo and J. Bae, "Kinematic analysis of a hand skeleton structure," in *Proc. Ubiquit. Robots Ambient Intell. (URAI)*, 2013, pp. 457–458.



Yeongyu Park (S'14) received the B.S. degree in mechanical and advanced materials engineering from the Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea, in 2014. Currently, he is pursuing the Ph.D. degree in mechanical engineering at UNIST.

His research interests include wearable hand exoskeleton systems and human–machine interaction systems.

Jeongsoo Lee received the B.S. degree in mechanical and advanced materials engineering from the Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea, in 2014. Currently, he is pursuing the Ph.D. degree in mechanical engineering at UNIST.

His research interests include wearable hand exoskeleton systems and rehabilitation systems.

Joonbum Bae (S'07–M'12) received the B.S. degree in mechanical and aerospace engineering (*summa cum laude*) from Seoul National University, Seoul, Korea, in 2006, and the M.S. and Ph.D. degrees in mechanical engineering from the University of California at Berkeley, Berkeley, CA, USA, in 2008 and 2011, respectively, where he also received the M.A. degree in statistics in 2010.

He joined the School of Mechanical and Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea, in 2012, where he is currently the Director of the Bio-Robotics and Control (BiRC) Laboratory. His research interests include modeling, design, and control of human–robot interaction systems, and biologically inspired robot systems.

Dr. Bae was a finalist of the Semi-Plenary Paper Award at the American Society of Mechanical Engineers (ASME) Dynamic Systems and Control Conference in 2012, and a finalist of the Best Poster Paper Award at the International Federation on Automatic Control (IFAC) World Congress in 2008. He received a Samsung scholarship during his Ph.D. studies.