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Design framework for a seamless smart glove using a digital knitting system

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Abstract

The wearable electronics integrated with textile-based devices is a promising strategy to meet the requirements of human comfort as well as electrical performances. This research presents a design and development framework for a seamless glove sensor system using digital knitting fabrication. Based on the performance requirements of glove sensors for controlling a prosthetic hand, desirable design components include electrical conductivity, comfort, formfit, electrical sensitivity, and customizable design. These attributes are determined and achieved by applying appropriate materials and fabrication technologies. In this study, a digital knitting CAD/CAM system is utilized to meet the desired performance criteria, and two prototypes of the seamless glove sensor systems are successfully developed for the detection of both human and robotic finger motions. This digital knitting system will provide considerable potential for customized design development as well as a sustainable production process. This structured, systematic approach could be adapted in the future development of wearable electronic textile systems.

Keywords: Framework for wearable electronics, Seamless glove sensor, Digital knitting CAD/CAM system, Finger motion detection

Introduction

Electronic textiles can provide several advantages, including enhanced accessibility, comfort, and durability, flexibility, and stretchability in diverse fields such as sensors and actuators, energy generators, transistors, and capacitors (Bae et al. 2014; Choong et al. 2014; Nassour and Hamker 2019; Ryu et al. 2018). Electronic textiles are also soft and offer close contact between electronics and the skin, which is challenging for bulky and planar film-based devices. The ubiquitous nature of textiles provides an ideal medium for a wearable sensor platform to monitor physiological activities and environments. Various approaches have attempted to embed conductive materials into textile structures, including coating or printing on the textile surface (Li et al. 2020; Uzun et al. 2019), stitching patterns with conductive thread with a sewing machine or embroidery machine (Shin et al. 2018), and developing woven or knitted electronic textiles with functional yarns (Fan et al. 2020; Wu et al. 2018). The knit structure of these textiles is composed of consecutive rows of interconnected yarn loops that give the material flexibility for outstanding fit, high elasticity, and excellent elastic recovery (Trangsirinaruenart and Stylios 2019). The combination of elastane fiber with conventional yarns provides loop dimensions of shape, length, and width that are crucial parameters of the physical, mechanical and dimensional properties of knitted fabrics (Azim et al. 2014; Sitotaw 2018).

In recent years, data gloves with various sensor units have been introduced as an essential wearable platform for applications in virtual/augmented reality interfaces (He et al. 2019; Zhu et al. 2020) and health monitoring, including of physical rehabilitation for post-stroke patients (Heo et al. 2020; Kim et al. 2019; Wang et al. 2020). However, existing glove systems have multiple drawbacks, such as lack of robustness and washability with the integration of rigid electronics onto a glove platform, the need for multiple complicated processes such as attachment of a sensory unit, and the bulkiness of the system. Several efforts have been made to integrate functional fiber sensors into textiles to provide flexibility and mobility. However, there are still limitations to large-scale deployment, including the relatively high cost and manufacturing time (Ou et al. 2019). Additionally, a customizable design for shape, size, and fit are critical to ensure conformal contact between the textiles and body. With the development of computer-aided design (CAD), a digital CAD knitting system can facilitate design development with various 3D shapes for custom-fit and embedded patterns using various materials. CAD also allows us to modify the dimensions and structure through user-centered interfaces and visualize virtually simulated images. In future production, a seamless manufacturing process would enable economical utilization of materials and energy without waste. Accordingly, programmable and reconfigurable engineering design approaches with a structured methodology, which describes interrelationships among requirements, design parameters and characteristics, must be established in wearable electronic textile development.

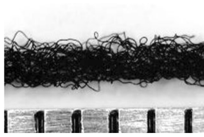
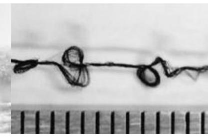
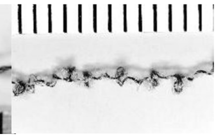
In this study, we present a systematic structured design and development framework for a seamless smart glove as a motion sensor platform using the computer-aided digital knitting process modified from the previously developed wearable motherboard design and development framework (Park and Sundaresan 2001; Rajamanickam et al. 1998). The requirements of the wearable glove sensor system are determined, and the specific sensing and comfort properties are consolidated into five design components. Based on the design components, the appropriate materials and the fabrication technology are applied. Digital knitting technology is utilized for the development of the glove sensory system through a programmable and automated process for creating a seamless three-dimensional (3D) glove. Finally, two prototype seamless glove sensor systems worn on the human hand and robotic hand are demonstrated.

Methods

Materials

For the seamless glove sensor system, textured nylon and spandex with polyester were used for the base glove shape, and the conductive yarns with textured nylon were used as the sensor unit. The selected conductive yarns were silver-plated and unplated nylon 66 44/12 filaments wrapped around 20 dtex of a single spandex fiber

Table 1 Yarn specifications with enlarged images

	Bulk continuous filament yarn for base	Bulk continuous filament yarn for sensor	Spandex with filament	Conductive filament
Images				
Fiber content	Nylon	Nylon	Polyester + Spandex	Nylon + silver-plated nylon + Spandex
Yarn count (tex)	24.6	23.9	10	4.4

with a linear resistance of less than 125 Ω/in (Marktek Inc., Chesterfield, MI, USA). The specifications of the selected materials are shown in Table 1.

Framework development

A structured methodology for the design and development of a seamless glove sensor system was adopted from the Georgia Tech Wearable Motherboard™ (Park and Sundaresan 2001; Rajamanickam et al. 1998) and further modified to create a novel glove sensor platform to meet specific end-user requirements. The developed framework for the glove sensor should focus on designing the embedded sensor component (ESC) of the sensor and the customized design component (CDC). While the ESC is related to selecting adequate conductive materials, knitting structure, and patterns, the CDC determines personalized design factors such as the location and dimension of the sensor units based on the user specifications. Thus, this framework is useful not only in mass production, but also in customized fabrication.

Fabrication of a smart glove using CAD/CAM

The seamless digital knitting machine (15 gauge; 60-cm width; Shima Seiki SWG041N$_2$, Wakayama, Japan) was utilized to fabricate the knitted glove. The knitting software included with the knitting machine, Apex3 design system, offers a pre-programmed glove shape and design options such as adjustment of measurements. The custom-sensor design and the structures can be specified by drawing the designated color operation, representing a different knitting operation in the automation software.

Characterization

A performance evaluating process was conducted to understand the fundamental characteristics of the sensor under stretching and bending conditions. The relative change in resistance upon deformation of the knitted textile sensor was characterized utilizing a universal strain testing machine (Teraleader, Daejeon, Korea), as shown in Fig. 1a. Both sides of the sensor were clamped and pulled via a programmed periodic load. The embedded inverter circuit described in Fig. 1b simultaneously measures the resistance of the sample while mechanical change is applied. It compares the reference resistance R_{ref} and the sample resistance R_{sample} by detecting the difference between the voltage input

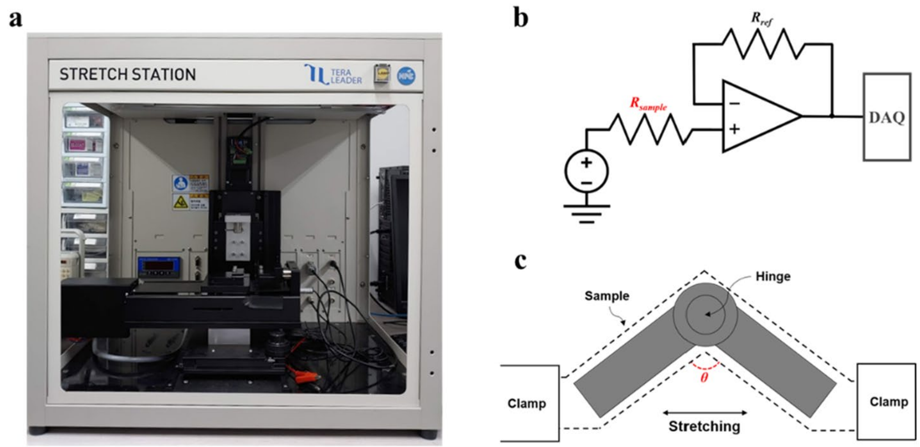


Fig. 1 **a** A universal strain testing machine for textile sensors, **b** its embedded inverter circuit for measuring resistance, and **c** the bending frame

to and output from the op-amp in the circuit, which is depicted as a triangular shape in Fig. 1b. Then, the measured data were collected by the data acquisition system (DAQ).

The strain testing machine has a built-in function to elongate samples linearly; the built-in testing bed can be directly used for sample characterization under tension. However, to measure the bending characteristics, it is necessary to use an additional tool, as shown in Fig. 1c, to convert the linear input load to an angular one. We placed the bending tool inside the tubular sample then measured the internal angle θ while exerting the same tension as the stretching experiment; thus the angle θ is measured in descending order, from a larger angle (nearly 100°) to a smaller angle (nearly 0°).

Results and discussion

Design and development framework

To develop the framework for a smart glove system, we closely worked with researchers in bio-robotics labs to understand the user needs and required performances. One major requirement was customization in the development of embedded sensor units and the glove shapes. To meet the user specifications, customization properties were added into the framework and achieved through digital fabrication technology.

Analysis of performance requirements and properties

Figure 2 presents the design and development framework of a seamless knitted smart glove using a digital knitting system modified from the wearable motherboard (Park and Sundaresan 2001; Rajamanickam et al. 1998). The user performance task for the wearable glove sensor system was to detect finger gestures and wrist motion of the human hand using embedded textile-based strain sensor units. The detailed and specific set of performance requirements are as follows: functionality, wearability, durability and stability, manufacturability, customized design, and connectivity. The functionality of the smart glove sensor system required that it be able to detect finger and wrist motion with the embedded sensor unit. Wearability required that it be lightweight, breathable, conformable to the skin, comfortable to wear, and easy to assemble with peripheral devices

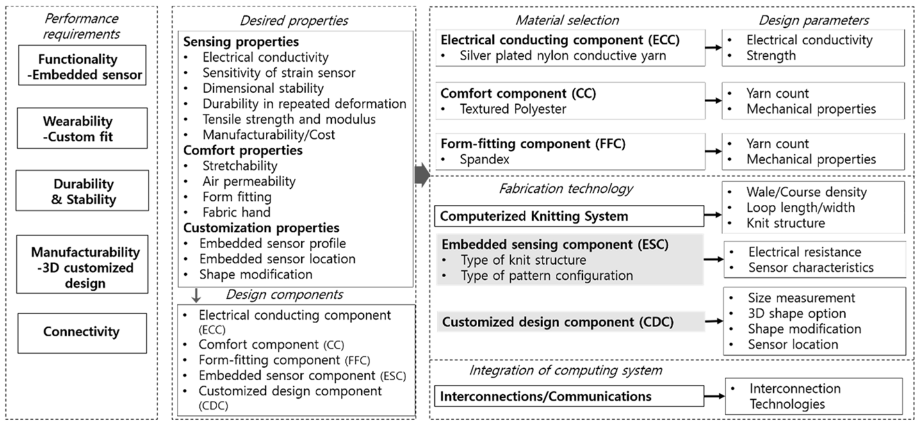


Fig. 2 Design and development framework for a wearable smart glove system

such as a circuit board. Another critical requirement was the durability to endure repeated deformation with a stable electrical signal. A wearable glove system will eventually be manufactured in large quantities over a range of sizes and designs. In particular, glove design elements should be programmable in the manufacturing process, such as the three-dimensional shapes for the hand, design variation for peripheral units, and the location, profile, and dimension of sensor units. Ultimately, the developed glove sensor should be able to connect to microcontroller units to compute the acquired data.

The identified essential performance requirements for the wearable glove sensor systems were then translated and categorized into appropriate sensing and comfort properties. Based on these properties, we determined specific design components for the wearable glove system (electrical conducting, comfort, form-fitting, electrical sensing, and customized design). These design components can be achieved through appropriate choice of materials and fabrication technologies.

Materials selection and specification

The selected materials and specifications for the glove sensor system are described in "Materials" section. For the electrical conducting component, silver-plated yarn with non-conductive yarn was chosen due to the excellent balance between conductivity and resistance. This yarn formed the piezoresistive sensor to detect the angle of the finger joint and wrist as a strain sensor. Not only the resistance of the materials, but also the knitted sensor geometry and knit structure affect bulk electrical properties. The comfort component is related to the total hand quality, such as softness, smoothness or roughness, air permeability, moisture absorption and stretchability. The texturized nylon selected for the base materials had irregular crimps on the filament and provided warmth and absorbency with trapped air, as well as being soft, flexible, and having high extensibility and excellent comfort properties. For form-fitting, elastomeric fiber was inserted both in the sensor unit and the base glove area, leading to improved form-fit for the user, and more importantly, placement of the sensor unit at the designated area during dynamic movement. While a knitted piece can be somewhat elastic due to the interlocking loop structure, the fabric does not return to its original shape quickly after stretching. To address this issue, we used spandex yarn to create an elastic fabric with low hysteresis, a high degree of stretchability, dimensional stability, durability, and shape retention ability.

Computerized knitting system for fabrication

Digital knitting technology was utilized for the development of the glove sensory system through a programmable and automated process for creating a seamless three-dimensional (3D) glove. The digital knitting machine consists of a two-bed system with multiple yarn carriers, which enable knitting of a two-layered tubular shape with various yarns. The knitting machine is combined with the CAD software, which allows a user to observe, select, and modify the dimensional structural design parameters with visualized results.

Figure 3 illustrates the automatic software, Apex3 (Shima Seiki), including the pre-set glove shapes, the detailed design options, and the manipulation of measurements. Detailed design selection like 3D shape or thumb type and size measurement was closely related to the form-fitting component. The embedded sensor component referred to the type of knit operations, including knit, tuck, transfer, or miss, as well as the sensor placement and configuration. Flat drawing tools for assigning knit structure and color were utilized for determining the embedded sensor component, such as sensor location, conductive path configuration, and knit structure. The knit structure applied for both the base glove and the sensor unit was single jersey, employing the plating technique, where the conductive yarn appears on the backside of the surface. For the sensor configuration, two different conductive profiles, a rectangular shape and a rectangular horseshoe shape, were developed and placed on the figure joint areas and wrist joint area. The customized design component included hand size adjustment for different users, and an opening on the hand back for easy assembly with a circuit board. Advanced design manipulation was limited to the pre-set shape offered by the automation software. However, the development of the machine programming language allowed for extended freedom in design.

Characterization of a knit textile sensor

First, we evaluated the electrical resistance on single-wale and two-wale types of embedded knitted sensor units, as well as the relative change in resistance with respect to the applied strain. Table 2 shows the average initial resistances of the fabricated glove

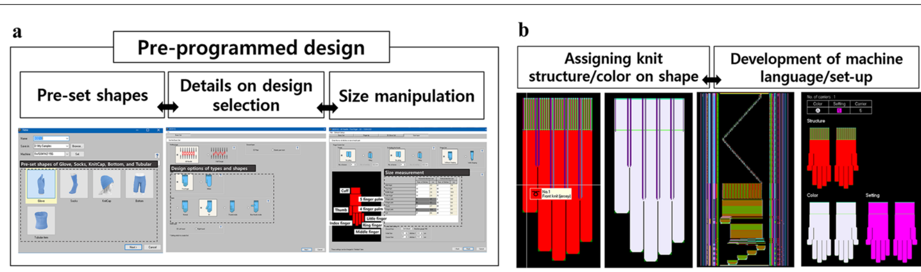


Fig. 3 Automated software system for design manipulation. **a** Pre-programmed shapes of the Glove, Socks, KnitCap, Bottom, and Tubular shape, including design options and hand measurements, and **b** assignment of knit structures and patterns with the development of machine language for knitting

Table 2 Average initial resistance of the samples

Rectangular shape	Initial resistance R_0 (Ω)	Standard deviation σ
Single wale	892	235
Two wales	451	88

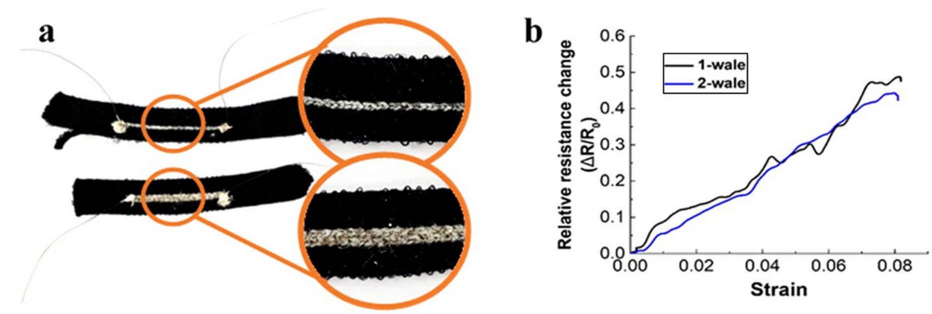


Fig. 4 a Two samples wired: single-wale and two-wale conductive area; **b** sensitivities of the two samples

sensors with conductive areas with one- and two-wale rectangular shapes. Since their initial resistances were different, further experiments were conducted to determine which one was more suitable for the glove sensors: producibility and sensitivity.

We connected electrical wires to the fabricated, seamless glove sensors along the wale direction, as shown in Fig. 4a. Since they were wired along the wale direction, each of the wales were electrically connected in parallel; the single-wale sensor showed a higher initial resistance R_0 than that of the two-wale (Li et al. 2009; Xie et al. 2019).

Due to the specifications of the digital knitting machine, a knitted sensor with conductive yarns in two or more wales yielded a more stable output than knitting in a single wale, causing a smaller standard deviation of the average initial resistance. Although their initial resistances are different, their relative resistance changes from strain, i.e. sensitivities, showed similar characteristics, as seen in Fig. 4b. The relative resistance changes of the samples show a linear characteristic with a constant gauge factor. However, as the extended loops start to show more contact areas the relative resistance change undergoes gradual flattening, decreasing the gauge factor. Since the glove sensors with conductive areas in single- and two-wale rectangular shapes show similar sensitivities, all the further characterizations were conducted with the single-wale sample.

To investigate the electrical performance of the embedded knit sensor, the relative changes in resistance with respect to the applied strain and bending angle were measured. When the glove sensor was released from the exerted load, it exhibited nearly the same characteristics with the stretch case, as shown in the hysteresis loop in Fig. 5a under stretching and (b) under bending. These linear characteristics of resistance change were also observed in experiments with gradually increasing step loads, with the results presented in Fig. 5c for stretching and Fig. 5d for bending. By

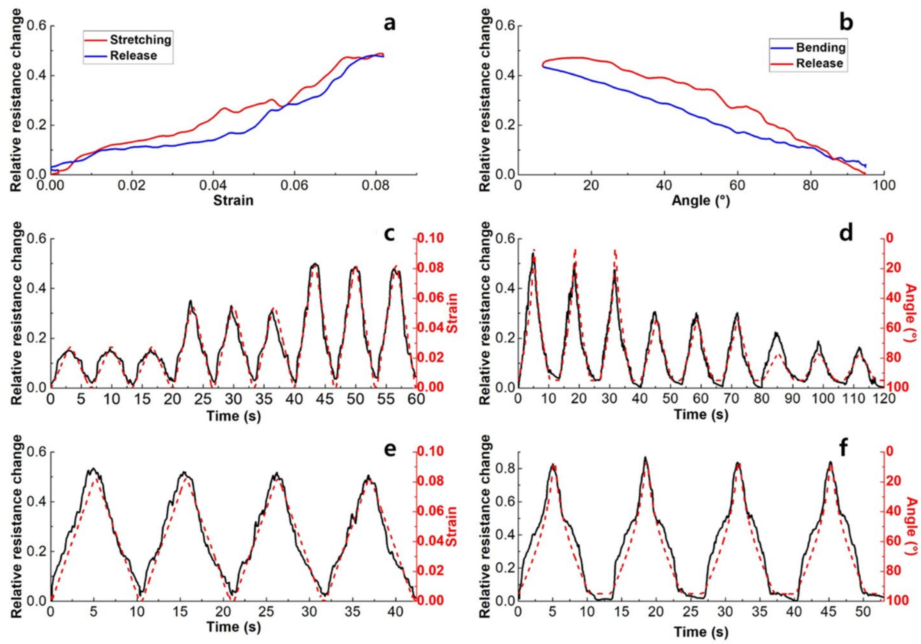


Fig. 5 Sensor characterization: **a** Hysteresis loops for stretching and **b** bending; Step responses for **c** stretching and **d** bending; and Response times for **e** stretching and **f** bending

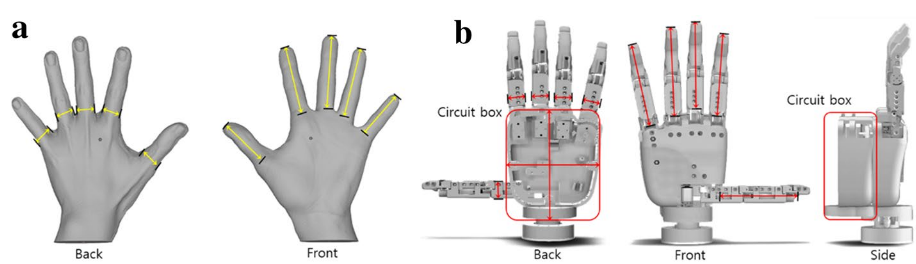


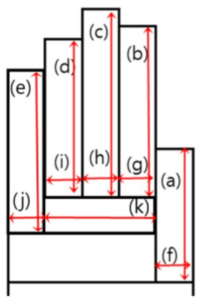
Fig. 6 Size measurements for **a** human hand and **b** robotic hand

comparing the measured response data with the input load, the response time can be calculated, as shown in Fig. 5e and f for stretching and bending, respectively. The average response time for the developed glove sensor was found to be 130 ms.

Fabrication of seamless glove sensor prototypes

Based on the results from extensive analysis of the framework, we explored two seamless glove sensor systems for the human hand and robotic hand and evaluated the sensor characteristics. During the initial procedure to customize glove design, accurate and efficient hand dimensions from a user were extracted from 3D scanned images, which were captured from a 3D scanner (DRAKE, THOR3D, Russia). Similarly, robotic hand measurements can be obtained from the 3D drawing in the 3D CAD system shown in Fig. 6. A previous study proved that there is no significant difference in hand measurements between the 3D scanning method and direct measurement systems (Yu et al. 2013).

Table 3 Size input parameters and the measurement for the human hand and robotic hand



No.	Dimension	Human hand (mm)	Robot hand (mm)
(a)	Thumb (vertical)	51	86
(b)	Index finger (vertical)	65	82.9
(c)	Middle finger (vertical)	72	98.14
(d)	Ring finger (vertical)	63	86.5
(e)	Little finger (vertical)	43	77.54
(f)	Thumb (horizontal)	16	16.1
(g)	Index finger (horizontal)	15	16.1
(h)	Middle finger (horizontal)	14	16.1
(i)	Ring finger (horizontal)	13	16.1
(j)	Little finger (horizontal)	11	17.1
(k)	3 finger palm (horizontal)	9	NA
NA	Circuit board (x × y)	NA	100.4 × 84

Table 3 shows the total measurements of five fingers for both human and robotic hands, including the vertical and horizontal dimensions of each finger and the additional width of three fingers, specified as the size input parameters in the digital knitting software. The size of the circuit box on the robotic hand back was determined.

On the 15-gauge knitting machine used, there were 15 needles/inch on the front and back beds, and the number of stitches was pre-set at $7.8 \times 8.7/\text{cm}^2$ (wale × course) using the software. However, the actual number of stitches for the base glove was observed to be $9 \times 14/\text{cm}^2$ (wale × course). The elastane yarns in the knit structure caused deformation of the loop shape due to their elasticity; therefore, the loop length became shorter, and the density, particularly in the course direction, increased dramatically (Sadek et al. 2012; Sitotaw 2018). The glove knitted with spandex provided a comfortable shape, fit, smoothness, elasticity, and excellent elastic recovery.

Figure 7 illustrates the sensor units in the automatic software, the virtually knitted simulations, and the physical prototype photographs for the human hand and robotic hand. In the CAD software, the sensor units were placed on the front side of the hand for detection of bending and motion in the five fingers and wrist. There are various conductive profiles possible for strain sensors, such as rectangular, oval, diamond or horseshoe shape. Among these cases, two of the most popular choices are introduced in Fig. 7: conductive profiles of a rectangular horseshoe shape for a human hand glove and a rectangular shape for a robotic hand. Extra conductive rectangles were also added on the palm as textile electrodes for attaching external pressure sensor units. By using the intarsia knitting technique, the various sensor profiles could be knitted with conductive yarns

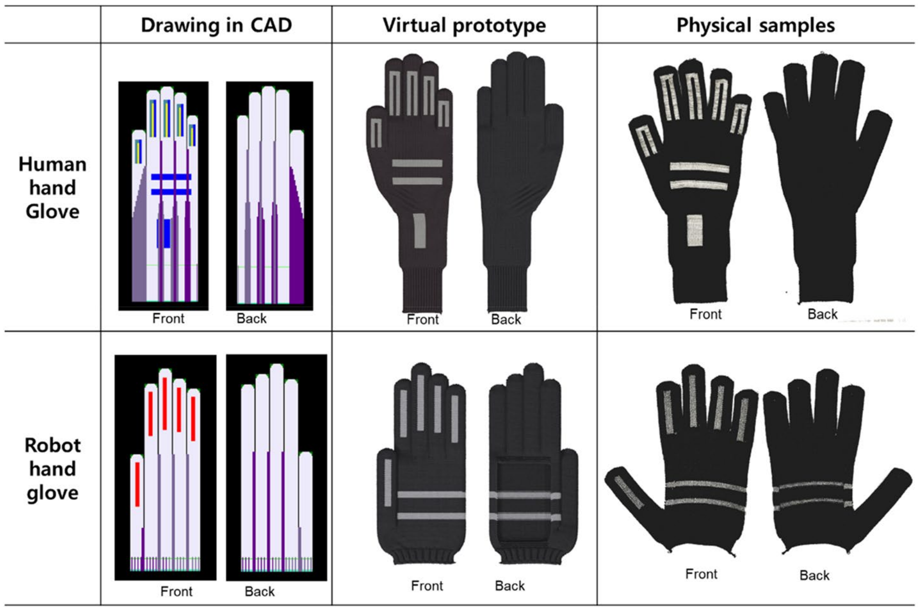


Fig. 7 Glove design with sensor units, the simulated virtual front and back gloves, and knitted prototypes for the human hand and robotic hand

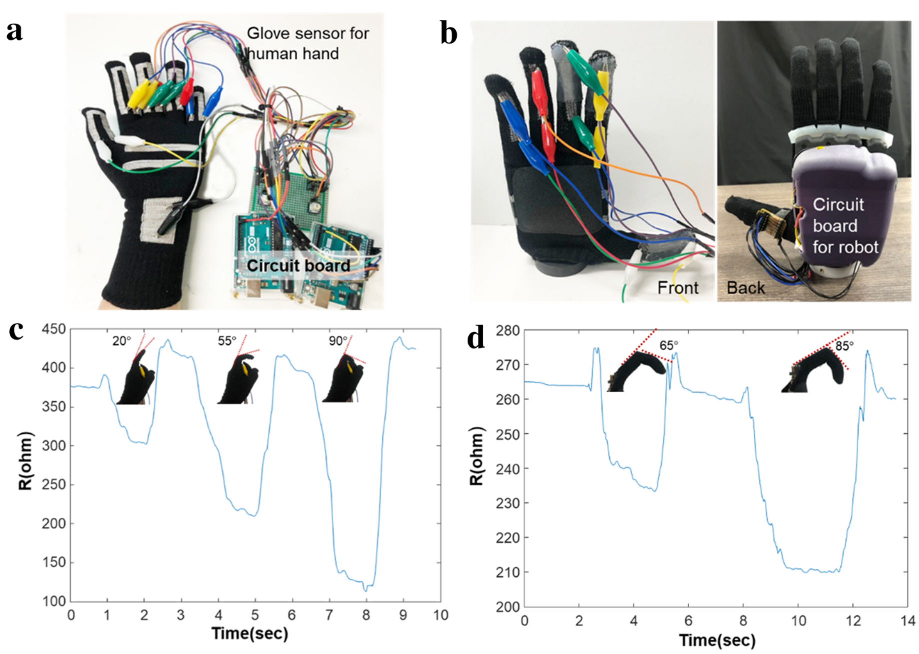


Fig. 8 Prototypes of **a** the human hand glove system and **b** the robotic hand glove sensor and the electrical signal in change of the finger bending motion of **c** the human and **d** the robotic hand

in the designated areas. It should be noted that automatic software processing was limited to the standard pre-set shapes; therefore, the opening for the circuit box on the back of the robotic hand with two-line electrodes was manipulated during the development stage (Fig. 3b, right image) with the machine programming language. The successfully developed opening with the additional textile electrodes are shown in the virtual simulation. Finally, seamless glove sensors for a human hand and robotic hand were fabricated with the digital knitting machine mentioned in "Fabrication of a smart glove using CAD/CAM" section.

Figure 8a and b show two prototype seamless glove sensor systems worn on the human hand and robotic hand. The intended application of the seamless glove sensor for the human hand is for the glove to be worn on one healthy hand in order to control a prosthetic hand on the opposite side (Sebelius et al. 2006). The seamless glove sensor for the robotic hand detects the robotic finger motion and acquires the applied force by moving the robotic finger. We observed that both gloves fit well in size and assembly with the circuit board for both human hand and robotic hands.

To evaluate the electrical signal of actual finger motion, we attached the wires to the finger sensor, which was connected to the circuit board with an Arduino microcontroller for detecting resistance change during finger motion. The electrical resistance of the change in angle related to the finger bending motion is presented in Fig. 8c and d. Although we used bulky crocodile clips for performance evaluation, the wires and the circuit board can be embedded within the glove when it is ready for out-of-the-lab deployment or mass production.

Conclusions

In summary, we established a structured framework for the design and development of a seamless glove sensor system fabricated using digital knitting technology that can detect the motion of human and robotic hands. The framework was validated by designing and fabricating a seamless glove sensory system to meet performance requirements. The integration of digital knitting technology shows excellent potential for customized design solutions and textile-based sensor construction in wearable electronic applications. This approach will provide further opportunities in both freedom of design and rapid prototype development as well as a sustainable manufacturing process. With appropriate usage in materials and fabrication technologies, systematic approaches such as this can be incorporated into diverse wearable electronic textile systems.

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Authors' contributions
All authors read and approved the final manuscript.

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Availability of data and materials
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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References

Azim, A. Y. M. A., Sowrov, K., Ahmed, M., Hassan, H. M. R. U., & Faruque, Md A A. (2014). Effect of elastane on single jersey knit fabric properties-physical & dimensional properties. *International Journal of Textile Science, 3*(1), 12–16. https://doi.org/10.5923/j.textile.20140301.03.

Bae, J., Lee, J., Kim, S., Ha, J., Lee, B. S., Park, Y., et al. (2014). Flutter-driven triboelectrification for harvesting wind energy. *Nature Communications*. https://doi.org/10.1038/ncomms5929.

Choong, C. L., Shim, M. B., Lee, B. S., Jeon, S., Ko, D. S., Kang, T. H., et al. (2014). Highly stretchable resistive pressure sensors using a conductive elastomeric composite on a micropyramid array. *Advanced Materials, 26*(21), 3451–3458. https://doi.org/10.1002/adma.201305182.

Fan, W., He, Q., Meng, K., Tan, X., Zhou, Z., Zhang, G., et al. (2020). Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring. *Science Advances, 6*(11), eaay2840. https://doi.org/10.1126/sciadv.aay2840.

He, T., Sun, Z., Shi, Q., Zhu, M., Vera Anaya, D., Xu, M., et al. (2019). Self-powered glove-based intuitive interface for diversified control applications in real/cyber space. *Nano Energy, 58,* 641–651. https://doi.org/10.1016/j.nanoen.2019.01.091.

Heo, J. S., Shishavan, H. H., Soleymanpour, R., Kim, J., & Kim, I. (2020). Textile-based stretchable and flexible glove sensor for monitoring upper extremity prosthesis functions. *IEEE Sensors Journal, 20*(4), 1754–1760. https://doi.org/10.1109/JSEN.2019.2949177.

Kim, M. K., Parasuranman, R. N., Wang, L., Park, Y., Kim, B., Lee, S. J., et al. (2019). Soft-packaged sensory glove system for human-like natural interaction and control of prosthetic hands. *NPG Asia Materials, 11*(1), 1–12. https://doi.org/10.1038/s41427-019-0143-9.

Li, L., Au, W., Wan, K., Wan, S., Chung, W., & Wong, K. (2009). A resistive network model for conductive knitting stitches. *Textile Research Journal, 80*(10), 935–947. https://doi.org/10.1177/0040517509349789.

Li, Q., Wang, Y., Jiang, S., Li, T., Ding, X., Tao, X., et al. (2020). Investigation into tensile hysteresis of polyurethane-containing textile substrates for coated strain sensors. *Materials and Design, 188,* 1–10. https://doi.org/10.1016/j.matdes.2019.108451.

Nassour, J., & Hamker, F. (2019). Enfolded Textile Actuator for Soft Wearable Robots," *2019 IEEE International Conference on Cyborg and Bionic Systems (CBS)*, Munich, Germany, pp. 60–65, https://doi.org/10.1109/cbs46900.2019.9114425.

Ou, J., Oran, D., Haddad, D. D., Paradiso, J., & Ishii, H. (2019). SensorKnit: Architecting textile sensors with machine knitting. *3D Printing and Additive Manufacturing, 6*(1), 1–11. https://doi.org/10.1089/3dp.2018.0122.

Park, S., & Sundaresan, J. (2001). Adaptive and responsive textile structure (ARTS). In T. Xiaoming (Ed.), *Smart fibres, fabrics and clothing* (pp. 226–245). Cambridge: Woodhead.

Rajamanickam, R., Park, S., & Sundaresan, J. (1998). A structured methodology for the design and development of textile structures in a concurrent engineering framework. *Journal of the Textile Institute, 89*(2), 44–62. https://doi.org/10.1080/00405009808658682.

Ryu, H., Park, S., Park, J. J., & Bae, J. (2018). A knitted glove sensing system with compression strain for finger movements. *Smart Materials and Structures, 27*(5), 055016. https://doi.org/10.1088/1361-665X/aab7cc.

Sadek, R., El-Hossini, A. M., Eldeeb, A. S., & Yassen, A. A. (2012). Effect of Lycra extension percent on single jersey knitted fabric properties. *Journal of Engineered Fibers and Fabrics, 7*(2), 11–16. https://doi.org/10.1177/155892501200700203.

Sebelius, F., Eriksson, L., Balkenius, C., & Laurell, T. (2006). Myoelectric control of a computer animated hand: A new concept based on the combined use of a tree-structured artificial neural network and a data glove. *Journal of Medical Engineering & Technology, 30*(1), 2–10. https://doi.org/10.1080/03091900512331332546.

Shin, Y.-E., Lee, J.-E., Park, Y., Hwang, S.-H., Chae, H. G., & Ko, Y. (2018). Sewing machine stitching of polyvinylidene fluoride fibers: programmable textile patterns for wearable triboelectric sensors. *Journal of Materials Chemistry A, 6*(45), 22879–22888. https://doi.org/10.1039/C8TA08485H.

Sitotaw, D. B. (2018). Dimensional characteristics of knitted fabrics made from 100% cotton and cotton/elastane yarns. *Hindawi, 2018,* 8784692. https://doi.org/10.1155/2018/8784692.

Trangsirinaruenart, O., & Stylios, G. (2019). A novel textile stitch-based strain sensor for wearable end users. *Materials, 12*(9), 1469. https://doi.org/10.3390/ma12091469.

Uzun, S., Seyedin, S., Stoltzfus, A. L., Levitt, A. S., Alhabeb, M., Anayee, M., et al. (2019). Knittable and washable multifunctional Mxene-coated cellulose yarns. *Advanced Functional Materials, 29*(45), 1905015. https://doi.org/10.1002/adfm.201905015.

Wang, B., Takahashi, N., & Koike, H. (2020). Sensor glove implemented with artificial muscle set for hand rehabilitation, *Ahs'20: Proceedings of the Augmented Humans International Conference*, 11, 1–4, doi.org/https://doi.org/10.1145/3384657.3384791.

Wu, H., Guo, H., Su, Z., Shi, M., Chen, X., Cheng, X., et al. (2018). Fabric-based self-powered noncontact smart gloves for gesture recognition. *Journal of Materials Chemistry A, 6*(41), 20277–20288. https://doi.org/10.1039/C8TA08276F.

Xie, J., Jia, Y., & Miao, M. (2019). High sensitivity knitted fabric bi-directional pressure sensor based on conductive blended yarn. *Smart Materials and Structures, 28,* 035017–035025.

Yu, A., Yick, K. L., Ng, S. P., & Yip, J. (2013). 2D and 3D anatomical analyses of hand dimensions for custom-made gloves. *Applied Ergonomics, 44*(3), 381–392. https://doi.org/10.1016/j.apergo.2012.10.001.

Zhu, M., Sun, Z., Zhang, Z., Shi, Q., He, T., Liu, H., et al. (2020). Haptic-feedback smart glove as a creative human-machine interface (HMI) for virtual/augmented reality applications. *Science Advances, 6*(19), eaaz8693. https://doi.org/10.1126/sciadv.aaz8693.

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