ACCURACY PREDICTION OF WEARABLE FLEXIBLE SMART GLOVES

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Abstract:
This article aimed at providing a new biomechanical three-dimensional dynamic finite element model of the hand–glove combination for exploring the distribution of the overall continuous dynamic contact pressure of the hand with the flexible glove in the state of grabbing an object, and further predicting the accuracy of sensors of wearable smart gloves. The model was validated by garment pressure experiments at eight muscle points. The results showed that the pressure value measured with three flexible gloves was highly consistent with the finite element simulation value. Based on the model, the distribution of dynamic pressure between the soft tissue of the hand and the fabric in the process of flexing the fingers and grabbing external objects were predicted accurately and effectively, which indicated that the model with high accuracy could be applied to evaluate the accuracy of the pressure value collected by sensors of smart gloves. In addition, the model had been confirmed that it has a certain application value. The findings could help to provide a reference for dynamic continuous monitoring equipment or other intelligent wearable devices, and promote the development of the intelligent clothing industry in the future.

Keywords:
Smart gloves, finite element analysis, grabbing action, contact pressure, accuracy assessment

1. Introduction
The advancement of flexible electronic technology provides development opportunities for the development of wearable flexible intelligent devices. Nowadays, there is a growing awareness of the exploitation of sensor equipment that can be flexible, stretched, wearable, and track the complex motion of the human body [1–4]. Flexible sensors can collect, process, and feedback on the relevant information of the human body through technologies such as textiles, materials, artificial intelligence, and the Internet. In particular, wearable smart products applied in the field of textile and clothing have specific functions such as human health monitoring [5], information transmission [6], communication [7], human–computer interaction [8], and other functions. Wearable smart gloves combined with flexible sensors provide an effective way to monitor, collect, and analyze the data of the hand, which has a significant impact on many application areas such as clinical medicine [9], human–computer interaction [10], bionic manufacturing [11], and product design [12]. For instance, small flexible capacitor sensors can detect micro gestures from small posture changes [13]; height stretching sensors can control the movement of the robot’s finger [14]; capacitance sensors can accurately rebuild the hand posture based on neural network algorithms [15]; and knitting pressure blocking gloves can identify the type and method of grabbing [16]. A multimode sensor system combined muscle activity with sensitive array [17] or flexible equipment with measuring strain and stress [18] also helps achieve gesture classification.

In the actual application scenario, the contact pressure between gloves and the soft tissue of the hand is important information that the pressure sensor needs to collect when wearing smart gloves and interacting with external objects. Although flexible sensor technology has developed rapidly in recent years, the flexible pressure sensor used in smart gloves is still defective in terms of signal stability, recognition accuracy, and response speed. Specifically, the relative position of the sensor and the hand is prone to change during the process of exercise, which makes it difficult to measure the pressure of glove–hand interface accurately. In addition, the number and location of the layout of the pressure sensor are limited, so the information detected is scarce, the signal acquisition system of the pressure sensor is too complicated to improve the stability of the signal acquisition, and the materials for manufacturing flexible pressure sensors are expensive. These factors are considered as the main limitations that affect the accuracy of the pressure collection.

The finite element numerical simulation method is one of the most commonly used methods in clothing pressure prediction. With the development of three-dimensional (3D) modeling technology, a 3D biomechanical model can be established, and the contact pressure, contact area, stress, and strain on the interface of the garment and the human body can be calculated accurately through digital simulation. Much research has focused on establishing finite element models for simulating the pressure between the garment and skin. Lin et al. [19] simulated the process of wearing tight pants to the lower limbs and the knee flexing movement to analyze the dynamic relationship between the tights and the skin surface. Dan and Shi [20] explored the displacement and pressure distribution of the waist-wearing elastic pantyhose during walking by the finite element simulation method. Chen et al. [21] studied the changes in the pressure of medical pressure socks on human
legs with the finite element model. Hong et al. [22] established a finite element model of a standard female body bust section to find the linear equation between the pressure on the chest, the strain of the vest, and the fabric’s Yang’s modulus. Sun et al. [23] predicted the breast-shaping effect of the bra and the pressure distribution of the skin by establishing a finite element contact model of female ultra-elastic breasts and steel ring bras. With the establishment of the finite element simulation model, the interface pressure distribution of a certain part of the human body can be understood. Nevertheless, the current research focused on the impact of the pressure caused by tight functional pressure garments on the human body. The exploration of continuous dynamic pressure on garment–skin interface in interaction between the human body and external objects is still unclear.

The signal output by wearable smart gloves that is based on sensor technology in actual detection applications is closely related to human body surfaces, dynamic parameters, and materials itself. However, there is no clear criterion for the accuracy of the output signal, which puts forward a huge challenge for the development of wearable smart gloves. In addition, the accuracy of the glove system needs to be tested before the wearable smart gloves are produced, which helps to evaluate whether gloves are suitable for investment. Currently, it is rarely measured by the entire glove system in terms of repetitiveness and accuracy. At the same time, it lacks a standard performance evaluation method, which also becomes an obstacle to the industrialization of wearable smart gloves.

Based on the aforementioned issues, there is an urgent need for a set of calibration measurement accuracy data to assess the reliability of the data collected by smart gloves. The purpose of this study is to establish a combined 3D biomechanical model of the hand and glove. The simulation model can output the continuous dynamic pressure of the glove–palm interface in real time. The distribution of the contact pressure obtained by the numerical simulation can be applied to evaluate the accuracy of the pressure sensor of smart gloves, overcome the limitations of current smart gloves in applications, and provide data reference for the accuracy of data collection of wearable flexible smart gloves. At the same time, it helps to improve the evaluation system of wearable flexible smart gloves. The numerical simulation method can also be extended and applied to the accuracy evaluation of other wearable intelligent textiles to promote the further development of the industry of smart e-textiles.

2. Methodology

2.1. Establishment of a finite element model of hand

In this research, a 3D solid model of the hand was established by cropping operations based on an open-source 3D anatomical male human digital model, and the process of reconstruction of the model of the hand was as follows: Geomagic Studio 2012 software was used for smooth processing on the model surface, and eventually converted polygon facial slices into NURBS curved surfaces suitable for creating complex curved shapes. Then, each component model of the hand was introduced in the Solidworks 2019 software to reaggregate. Since the complex geometric surfaces of the bones and soft tissue in the hand model and the high requirements for the mesh quality, Hypermesh 2019 software was chosen to carry out 3D meshing. Finally, the 3D geometry model of the hand was obtained, as shown in Figure 1, which consists of soft tissue and an internal skeleton. Furthermore, as we were concerned with the contact pressure at the glove–palm interface rather than the internal response of the hand, the ligaments and tendons of the finger joints were not considered to simplify the model.

2.2. Establishment of a finite element model of the glove–hand combination

A combined glove–hand model was further constructed for predicting the glove–palm surface contact pressure, which included the hand, the glove, and a cylinder. The model of the cylinder was obtained in the part module in the Solidworks 2019 software (Figure 2a). As the base layer of the wearable flexible smart glove is a light-fitting glove, the 3D shell glove fabric geometry model was constructed based on the built hand model by shell extraction operation in Solidworks 2019 software (Figure 2b). In the end, a combined model of the hand-wearing gloves was established (Figure 2c).

The 3D geometric model of the hand was preprocessed. Then, the complete combination model was introduced into the Abaqus 2020 software for finite element simulation, including the definition of material attributes, the selection of grid types, loads, constraints, and the setting of boundary conditions. The process of

Figure 1. The 3D geometry model of the hand. (a) The bone of the hand and (b) the soft tissue of the hand.
reconstruction of the finite element model of the glove–hand combination is shown in Figure 3.

2.2.1. Materials

The bones are composed of cortex and pine bone, both of which have viscoelastic and anisotropic mechanical characteristics. Some scholars have given various material parameters to the cortical and pine bones, respectively. In theory, it is closer to the authenticity characteristics of human bone materials that define bones as nonaverage materials. However, the particularity of biomass is that as an active organization, its material parameters will change under different mechanical effects. Within a specific range, the cortex and pine bone have the characteristics of linearly elastic material. Because of previous studies on the mechanical properties of the human body [24–27], bones of the hand were defined as a homogeneous, linearly elastic material in the simulation. Therefore, this study characterized the bones as an average linearly elastic material to simplify calculations.

In addition, the mechanical properties of soft tissues are more complicated. Scholars believe that it can be regarded as a homogeneous linearly elastic body when observing the changes.
Due to the substrate of wearable smart gloves being flexible textile gloves, the three light-fitting gloves were experimentally measured as the material properties of the glove fabric. Concretely, the quality and thickness of fabric samples were measured by electronic balance and thickness instrument, and the density values were calculated through the ratio of quality and volume. The stretching rate of glove fabrics generally does not exceed 30% when wearing gloves for grasping movements. Therefore, the single-axis stretching experiments were used to test the mechanical performance of fabric samples. According to the stretching experimental data, the tensile stress–strain curves of the three fabrics in the wale and course direction can be obtained from an excellent linear relationship within the range of 0–30%. In terms of the slope of the straight line is Young’s modulus, and the ratio of horizontal and vertical strain is Poisson’s ratio of the fabric. The glove mainly occurs in the vertical stretching and deformation at the grip movement. Correspondingly, the stress produced during the stretching process is primarily related to the mechanical behavior of the fabric in the wale direction. Hence, only the tensile properties of the fabric in the wale direction were considered in the simulation (Figure 4), and the material of the glove fabrics model used in the simulation can be regarded as the linear elastic and isotropic material. The material parameters of each component of the finite element model are shown in Table 1.

2.2.2. Mesh

The types of bones and soft tissues of the hand were defined as a four-node linear tetrahedron element (C3D4) combined previous researches and needs of the study. The meshing density of the bones was 2 mm, and the soft tissue was 1 mm (Figure 5a). The mesh elements used for the glove fabric model were four nodes of curved shell (S4R) with limited membrane strain (Figure 5b). The glove model consisted of 30,902 elements with a minimum mesh size of 1.5 mm. The type of cylinder was defined as the eight-node linear six-sided element (C3D8R), and there were 38,400 elements in the model with a minimum mesh size of 2 mm (Figure 5c).

2.2.3. Load and boundary conditions

The reference points were defined on the internal bones, and all nodes on the bone were coupled to the reference point, which was convenient to describe the kinematic information and exert mechanical load on the hand. Furthermore, as multiple joints in

Table 1. The material parameters of each component in the finite element model

<table>
<thead>
<tr>
<th>Part</th>
<th>Density (kg/m³)</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>1,950</td>
<td>14,000–20,000</td>
<td>0.3</td>
<td>Ref. [24–27]</td>
</tr>
<tr>
<td>Soft tissue</td>
<td>1,100</td>
<td>0.177</td>
<td>0.4</td>
<td>Ref. [28–31]</td>
</tr>
<tr>
<td>Gloves (fabric 1)</td>
<td>453</td>
<td>0.457</td>
<td>0.304</td>
<td>Ref. [32]</td>
</tr>
<tr>
<td>Gloves (fabric 2)</td>
<td>336</td>
<td>0.288</td>
<td>0.379</td>
<td>Ref. [32]</td>
</tr>
<tr>
<td>Gloves (fabric 3)</td>
<td>468</td>
<td>0.320</td>
<td>0.329</td>
<td>Ref. [32]</td>
</tr>
<tr>
<td>Cylinder</td>
<td>1,040</td>
<td>2</td>
<td>0.39</td>
<td>Ref. [33]</td>
</tr>
</tbody>
</table>
the fingers have a subordinate relationship during exercise, the local coordinate system was established at each joint, so that the finger bones can be rotated under each local coordinate system. The local coordinate system of the finger joints of the hand finite element model is shown in Figure 6.

Joint displacements were applied to each joint for gripping motion simulation, and a static measurement method was used in this article to determine the rotation angle of each joint hinge in the gripping posture. The joint angles of each finger measured from human experiments were applied to the joint local coordinate system of the hand finite element model as load conditions [33].

3. Experimental verification of finite element model

To verify the accuracy of the pressure of the simulation prediction, the garment pressure on the palm of the hand was measured with the hand wearing the glove, and compared with the pressure that predicted by the finite element prediction.

3.1. Experimental materials

Ideally, the wearable flexible smart glove combined the sensing system with an ordinary textile glove. In alignment with the manufacturing principles governing smart gloves and the imperative for validating the effectiveness of the combined glove–hand model in this study, three light-fitting gloves available in the market were selected through pre-experiments, identified as fabric 1, fabric 2, and fabric 3. The style of the three glove fabrics is shown in Figure 7, and their specific parameter is shown in Table 2.

The grasping object should have a simple geometric shape to avoid unnecessary factors that may increase complexity of the results. Therefore, a cylinder was chosen as the grasping object, and the diameter and height of the cylinder were set to 60 and 200 mm, respectively, to avoid the uncomfortableness. The cylinder was made of Acrylonitrile Butadiene Styrene by a 3D printer (Shanghai Dianxiang Automation Equipment Co., Ltd., Dianxiang, DX-750s, China).

3.2. Selection of feature points

The measurement location of the soft tissue of hand was determined by existing theory and pre-experiments. Based on biomechanical studies of the finger joints, it is clear that muscle attachment points can be used as an important area for garment measuring. Furthermore, it can be concluded that the curvature of the body is an important factor in garment pressure. Eight points were finally determined as the pressure test point, with the specific locations shown in Figure 8: A (flexor pollicis longus), B (flexor disitorum profundus of index finger),

Figure 5. (a) The mesh of the hand, (b) the mesh of the glove, and (c) the mesh of the cylinder.

Figure 6. The local coordinate system of the finger joints of the hand finite element model.
3.3. Measurement of the finger joint angle

Angles of 14 joints of fingers in the grabbing position were measured by an angular gauge when the hand reached a stable grip on a cylinder in this study. To minimize the error, each joint was measured three times to ensure that the error in each measurement did not exceed 5°, and the measured joint angles of each finger joint in the gripping position are shown in Table 3.

3.4. Garment pressure test experiment

The AMI3037-10 airbag contact pressure test system was used for garment pressure testing, which includes airbags, pressure converters, and data collectors. The measurement principle of the sensor is to measure the pressure between the two planes. Pressure sensors are both flexible materials, so that they will change with the changes in the fingers during the test. Then, the pressure-sensitive area of the sensor is relatively small compared to the surface area of the grasped object, so the fit with the surface of the cylinder is relatively high during the force transmission process, and the force used to deform the sensor can be ignored in the method of transmission. In addition, the sensors were calibrated before the test to eliminate the system error. Under this premise, it can be considered that the attached sensor’s impact on the inherent mechanical elasticity of the human skin will be reasonably small and will not affect the measurement results. The measurement accuracy is high enough to capture continuous dynamic garment pressure. Except for considering that the built finite element model of hand is based on the right hand of a healthy adult man, the hand dimensions of the selected subjects should be consistent with the model. Five healthy men (average age 22.9 ± 1.1 years, height 174.6 ± 6.3 cm, weight 63.7 ± 8.1 kg, and body mass index 20.5 ± 1.5 kg/m²) were recruited for this study, and all subjects were free of hand injury.

The pressure experiment was performed in a climatic chamber at a temperature of 25 ± 1°C and a relative humidity of 65 ± 2%. In turn, five subjects were asked to wear three light-fitting gloves with different fabric compositions. The airbag probe of the AMI airbag pressure sensor was placed on the eight test points of the right hand. The instrument was set to zero after wearing glove fabrics, and then subjects gripped at the same joint angle as the model. As shown in Figure 9, all subjects gripped the cylinder with the right hand, and it was still motionless after reaching the stability of grasping. The posture was maintained for 10–15 s for pressure records, and then, this step was repeated five times to obtain the average value.

Table 2. The fabric parameters of the three gloves

<table>
<thead>
<tr>
<th>Number</th>
<th>Material parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric 1</td>
<td>92% nylon, 8% spandex</td>
</tr>
<tr>
<td>Fabric 2</td>
<td>85% polyester, 15% spandex</td>
</tr>
<tr>
<td>Fabric 3</td>
<td>70% cotton, 30% spandex</td>
</tr>
</tbody>
</table>

Figure 7. The style of the three glove fabrics: (a) fabric 1, (b) fabric 2, and (c) fabric 3.

Figure 8. Location of pressure test points on the hand.

C (flexor disitorum profundus of middle finger), D (flexor disitorum profundus of ring finger), E (flexor disitorum profundus of little thumb), F (musculus flexor policis brevis), G (thenar), and H (hypothenar).
For the sake of verifying the effectiveness of the model, the position of each finger and the flexion angle of the joint in the experimental gripping posture were kept the same as the simulation when the gripping posture was finally achieved. The grip postures of experimental and simulation results are shown in Figure 10. Obviously, the comparison of the posture in the experiment and simulation shows significant similarity.

### 3.5. Pressure collection of sensors of wearable smart gloves

To predict the accuracy of the pressure sensor of wearable smart gloves, a film flexible sensor commonly used in smart gloves on the market (flexible film pressure sensor ZNS-01 smart glove piezoresistive multipoint sensing pressure sensor) was selected and placed on the palm of the hand, and then the flexible glove was worn for cylindrical grasping, as shown in Figure 11. The contact pressure collected by the film flexible sensor can be compared with the simulation value, which is conducive for the accuracy assessment of the finite element model.

#### 4. Results

##### 4.1. The stress distribution of gloves and soft tissues

The Abaqus 2020 software was used to complete the numerical simulation of the hand gripping a cylinder while wearing a flexible glove fabric in this research. The display dynamic analysis was adopted to simulate the dynamic flexion process of the finger. What’s more, the joint displacement was applied to the “hinge” connector to drive the model, and the specific joint angles were measured in previous experiments. A set of eight pressure test points was set up in advance to output the contact pressure at the glove–palm interface in the visualized module.

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**Table 3. The angles of the joints of fingers under the grabbing posture**

<table>
<thead>
<tr>
<th>Finger joints</th>
<th>Thumb (°)</th>
<th>Index finger (°)</th>
<th>Middle finger (°)</th>
<th>Ring finger (°)</th>
<th>Little thumb (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distant interphalangeal point</td>
<td>24.06</td>
<td>17.19</td>
<td>25.78</td>
<td>20.05</td>
<td>34.38</td>
</tr>
<tr>
<td>Middle interphalangeal point</td>
<td>36.67</td>
<td>63.03</td>
<td>74.48</td>
<td>68.75</td>
<td>74.48</td>
</tr>
<tr>
<td>Proximal interphalangeal point</td>
<td>73.91</td>
<td>103.13</td>
<td>117.46</td>
<td>111.73</td>
<td>97.40</td>
</tr>
</tbody>
</table>

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**Figure 9.** Garment pressure test experiment: (a) the fixation of the airbag pressure sensors, (b) the state of the glove was worn on the hand, and (c) the action of grasping the cylinder.

**Figure 10.** Comparison of the gripping posture: (a) finite element simulation and (b) experiment.

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http://www.autexrj.com/
The material properties of fabric 1, fabric 2, and fabric 3 were assigned to the shell finite element model of the glove respectively to observe the effect of different mechanical properties of different glove fabrics on the interface pressure. The stress distributions of gloves and soft tissues are shown in Figures 12 and 13, respectively.

In the process of grip with a glove fabric, dynamic deformation of the fabric occurred due to external force with the finger movement. The mechanical properties of different glove fabrics correspond to different fabric compositions. Generally, the greater the Young’s modulus, the less likely the material to deform, and the stronger the rigidity of the material, the greater the hardness, so that the smaller the Young’s modulus, the greater the deformation produced and the less stress the fabric is subjected to. It is shown in Figure 12 that the lowest stress was distributed on fabric 1, and the minimum stress was between the center of the palm and the bottom of the glove, about $3.273 \times 10^{-5}$ MPa; the stress of fabric 2 was the highest due to the minimum Young’s modulus, at approximately $5.364 \times 10^{-2}$ MPa, and the strain was also the largest correspondingly, about 18.63%. Owing to the convex surface of the thenar and its greater curvature, the stress and strain of the area corresponding to the glove were higher than the surrounding...
area, with a maximum stress of approximately $7.564 \times 10^{-4}$ MPa. The stress distributed in immediate areas was between $6.383 \times 10^{-5}$ and $7.271 \times 10^{-4}$ MPa. The maximum stress of fabric 3 was concentrated at the location of the thumb side of the glove, about $4.112 \times 10^{-2}$ MPa, followed by the distal area of the thumb and index finger, the proximal area of the ring and middle finger of the glove, all with stress magnitudes floated between $7.382 \times 10^{-4}$ and $3.471 \times 10^{-3}$ MPa, and the lowest stress distributed between the center of the palm and the little thumb side of the glove, at approximately $5.934 \times 10^{-5}$ MPa.

In conclusion, the overall stress distribution trends of three glove fabrics were consistent, which meant that the model established had the effectiveness of biomechanics. Simultaneously, the effectiveness of the glove–hand combination finite element model was also verified.

The interaction force from the cylinder to the glove fabric was further transferred to the soft tissues through the glove after a stable gripping position had been achieved. As shown in Figure 13, the stress distribution of soft tissue with three flexible glove fabrics has a high consistency and the stress suffered by soft tissue is smaller than the glove as a whole. To be specific, the maximum stress occurred in the proximal area of the fingers and the area attached to the musculus flexor pollicis brevis. It can be known that the stress of soft tissue wearing fabric 2 glove was the highest, followed by fabric 3 and fabric 1, respectively, which is related to the material mechanical properties of the fabric. The maximum stress of soft tissue wearing fabric 1 was $1.099 \times 10^{-2}$ MPa, the stress of soft tissue wearing fabric 2 was $2.035 \times 10^{-2}$ MPa, and the stress of soft tissue wearing fabric 3 was $1.769 \times 10^{-2}$ MPa. Secondly, stress analysis was conducted on specific areas: the distal region of the index finger, the proximal regions of the middle finger, ring finger, and little finger. The stress values for soft tissue with fabric 1 ranged from $2.104 \times 10^{-5}$ to $1.149 \times 10^{-4}$ MPa, fabric 2 exhibited stress levels within the range of $4.535 \times 10^{-5}$ to $7.646 \times 10^{-4}$ MPa, and fabric 3 showed stress levels ranging from $3.432 \times 10^{-5}$ to $3.511 \times 10^{-4}$ MPa. Furthermore, it was observed that the stress in the area under the palm of the hand was the lowest.

4.2. The distribution of continuous dynamic contact pressure

There was no contact between the hand and the cylinder until 0.6 s, the grip movement was over to reach a stable grip state when the time reached 1 s. The dynamic flexion process of grasping action was quantified and analyzed in Figure 14, to gain a clearer understanding of the changes in the contact pressure between the glove and the hand, which shows the contact pressure cloud diagram of action similar to that of the hand gripping a cylinder while wearing the fabric 1 glove during the course of 0, 0.6, 0.7, 0.8, 0.9, and 1 s.

It can be seen from the figure that the fingers were completely stretched when the grip movement had not begun, and the contact pressure between the palm and the glove was 0 MPa. With the increase of the flexion angle, the stress of the area where the musculus flexor pollicis brevis attached to the soft tissue was increasingly concentrated. It was because muscles were passively stretched in the movement of the finger flexion. As a result, the greater the curvature at the point of attachment of the muscle, the greater the stretching and deformation of glove fabrics at the corresponding location, the stress of the soft tissue and the glove increased, and the contact pressure also increased. At the same time, as the gripping action was carried out, the distance between the cylinder and the palm got
closer, and the palm was squeezed by the external objects to produce greater deformation, leading to the increased pressure in the contact area. The maximum contact pressure on the palm reached $1.412 \times 10^{-3}$ MPa when a steady-state gripping posture was reached. Besides, the maximum contact pressure in the finger flexing process occurred in areas where the musculus flexor pollicis brevis attached.

5. Discussion

5.1. Model verification

Within the aim of verifying the effectiveness of the finite element model, the data obtained from the AMI airbag pressure sensor were compared and analyzed for relative errors with the

![Figure 14. The cloud diagram of the contact pressure of the finger flexing dynamic grip process in the state of wearing the fabric 1 glove.](http://www.autexrj.com/)
The comparison of the contact pressure between the finite element simulations with measured values of wearing fabric 1 glove is shown in Figure 15(a). It was manifested from the finite element simulation results that the contact pressure at the hypothenar was the smallest, about $2.601 \times 10^{-5}$ MPa, and on the contrary, the location where the musculus flexor pollicis brevis attached was subjected to the highest pressure at approximately $1.412 \times 10^{-3}$ MPa. The finite element simulation results were analyzed based on the average of the measured contact pressure while wearing the fabric 1 glove, and the relative errors of each test point were as follows: A (flexor pollicis longus): 10.77%; B (flexor digitorum profundus of the index finger): 12.87%; C (flexor digitorum profundus of middle finger): 15.21%; D (flexor digitorum profundus of ring finger): 15.17%; E (flexor digitorum profundus of little thumb): 3.76%; F (musculus flexor pollicis brevis): 6.39%; G (thenar): 4.83%; and H (hypothenar): 5.26%. Figure 15(b) compares the measured values of wearing the fabric 2 glove with the simulated values, and the contact pressure of each test points ranged from $7.211 \times 10^{-5}$ to $1.651 \times 10^{-3}$ MPa. Figure 15(c) depicts a comparison between the measured values of wearing the fabric 3 glove and the simulated values. The hypothenar had the smallest relative error of 2.57% and the largest relative error of 15.21% was found on the flexor digitorum profundus of index finger.

In a word, it can be seen that the relative errors of contact pressure between the simulated and measured during dynamic gripping while wearing the three flexible gloves were within a reasonable range. Among them, the relative error at the key point of the muscles was a maximum of 15.59% and a minimum of 2.57%. Nevertheless, the relative errors of the flexor digitorum profundus of index, middle, and ring fingers were large because the force-generating habits were different for each experimental subject when grasping the cylinder. Furthermore, due to the challenges encountered in accurately pinpointing the muscle measurement points during the in vitro garment pressure testing experiment, a certain level of discrepancy was observed between the simulated and measured values. Despite this, the contact pressure values measured by the three flexible gloves exhibited a consistent trend of change with the finite element simulation. Notably, the finite element predictions for the eight test points aligned well with the experimental measurements, indicating a high degree of accuracy in the finite element model. Moreover, the simulated results for each test point were mostly within the average ± standard deviation of the results obtained for the five subjects in the experiments, so the model could be proved to have operational stability.

5.2. Accuracy prediction model of the smart glove

As shown in Figure 16, the pressure value of all test points changed significantly, and the trend of overall contact pressure of the eight test points was on the rise during the finger flexing. Concretely, the contact pressure of the area attached to the flexor digitorum profundus of five fingers was almost no change within 0.6–0.9 s and the increase in the trend became gentle. With the increase of the flexion angle, the fingers began to contact the cylindrical surface, so that the contact pressure increased sharply in 0.9–1 s. The contact pressure in the attachment area of the musculus flexor pollicis brevis gradually increased at the beginning of the grip until it reached a pressure maximum of $1.463 \times 10^{-3}$ MPa at 0.8 s, after which the contact pressure remained between $1.264 \times 10^{-3}$ and $1.412 \times 10^{-3}$ MPa. The overall contact pressure in the region of the thenar and hypothenar was relatively small, and the pressure values fluctuated slightly with the flexion of the fingers. With a slow increase in the overall trend, the pressure value reached the maximum when fingers reached a stable gripping position.

Referring to the results of the simulation, it can be concluded that the contact pressure was the largest at the location of the attachment position of the musculus flexor pollicis brevis, and the magnitude of the contact pressure curve over time was also greater. Hence, with the aim of making the data comparison curve more obvious, the data of contact pressure at point F were extracted in the postprocessing module of Abaqus software to read the change with finger flexion. Finally, the pressure dispersion point diagram of the change over time was obtained. Then, the simulation data were linearly filed by the Origin software, and the simulation linear regression model was established, as shown in equation (1). The equation is a linear regression model of the contact pressure at the point F over time when the fingers were flexed at a uniform rate of 1 s until the gripping action was complete and a stable grip on the cylinder was achieved after wearing the glove.

$$y = 0.0145x + 0.8154,$$  \hspace{2cm} (1)

where $x$ is time (s) and $y$ is the contact pressure (MPa) at the attachment point of the musculus flexor pollicis brevis. The Pearson test and Spearman nonparametric test were used to quantify the correlation between experimental measurements and simulations. The descriptive and correlation statistical tests were run under SPSS27 software. The statistical results obtained are shown in Figure 17. It can be seen that
there was a significant Pearson correlation ($R = 0.950$, $N = 50$, $P < 0.001$) and the Spearman rank correlation ($R = 0.874$, $N = 50$, $P < 0.001$) between the simulated and measured pressure values. The prediction pressure distribution was generally consistent with the experimental results, which proved that the model could characterize the accuracy of the sensor of wearable flexible smart gloves.

Apart from this, the mean absolute error (MAE) was selected as a representation indicator of a linear regression model, and the

Figure 15. Comparison of contact pressure of simulated and measured values: (a) the situation of wearing fabric 1 glove, (b) the situation of wearing fabric 2 glove, and (c) the situation of wearing fabric 3 glove.
Experimental and simulated values of continuous dynamic pressure during gripping were analyzed for relative errors. The difference between the experimental and simulated results was evaluated through the MAE calculated by equation (2). The smaller the value, the smaller the error between the two. Considering the confirmed effectiveness of the biomechanical model established, which accurately predicts continuous dynamic garment pressure, it can be utilized to assess the precision of the pressure sensor in collecting pressure values. In the end, the resulting MAE for the sensor was calculated to be 0.066, the value was small enough to explain that the smart glove pressure-sensitive resistance flexible film pressure sensor has high accuracy during data collection.

\[
\text{MAE} = \frac{1}{n} \sum_{j=1}^{n} |A_j - E_j|
\]  

where \( n \) is the number of data points; \( A \) (MPa) is the contact pressure predicted in the simulation; \( E \) (MPa) is the contact pressure tested in the experiment; and \( j \) is the time serial number. As a consequence, MAE corresponds to the average absolute value error between the measured and predicted values.

Figure 16. The contact pressure simulation results during the finger flexing process in the action of grabbing the cylinder with fabric 1 glove: (a) the contact pressure at point A, (b) the contact pressure at point B, (c) the contact pressure at point C, (d) the contact pressure at point D, (e) the contact pressure at point E, (f) the contact pressure at point F, (g) the contact pressure at point G, and (h) the contact pressure at point H.
finite element simulation prediction model can be used to characterize the accuracy of the collection signal of the sensing materials, which will be significant to promote the development, optimization, and effect prediction of flexible intelligent wearable devices. What is more, it can be combined with textile materials, measurement technology, and sensor technology to further expand into a variety of practical applications, such as bionic manufacturing, clinical medicine, rehabilitation auxiliary tools, virtual interaction, and other fields.

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