Sensing performance of knitted strain sensor on two-dimensional and three-dimensional surfaces

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HIGHLIGHTS

• Demonstration of a new method of using a three-dimensional surface to evaluate the sensing performance of the knitted sensor.
• A larger strain sensing range closer to the actual sensing strain of the human body.
• Capability of the knitted strain sensor for detection of human gait movements.

GRAPHICAL ABSTRACT

Abstract

Flexible strain sensors and their sensing performance have been attractive in human motion detection applications. In this project, a knitted strain sensor was designed and fabricated via the technology of weft-knitting a nylon/nylon-wrapped spandex/silver-coated yarn into a knitted garment. Locations of sensor areas were customized to form a whole piece of knitted garment popular for today's applications in elastic tight-fitting activewear. The sensor provides electrical resistance data as a wearable sensing device for detecting body motions. A new method of using a three-dimensional curved surface to evaluate the sensing performance of the knitted strain sensor was proposed. Compared with the method of two-dimensional test, the three-dimensional test method was closer to the actual human sensing situation when the knitted sensor is worn. The strain sensing range of the three-dimensional curved surface was 120%, twice the sensing range of the two-dimensional surface. This research indicated that this three-dimensional surface testing method could be effectively applied in the sensing performance evaluation of fabric strain sensors.

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1. Introduction

Textile strain sensors have broad application prospects in the field of human body motion detection, especially when sensing performance has been widely concerned [1,2]. However, most strain sensors so far have only involved two-dimensional sensing performance testing, and few studies have been conducted on three-dimensional sensing performance [3]. Therefore, the current testing method for fabric strain sensing performance cannot fully reflect the three-dimensional sensing mechanism in the applications of human motion detection.

Strain sensors can detect the bending deformation of the flexible material through the change of the electrical signal [4–8], and it has been widely used in human activity detection and health monitoring [9–13]. It is expected that these sensors will act on the human body like skin, satisfying multi-dimensional responses to strain changes in all directions [14]. Stretchable strain vector sensor, made from large areas of parallel and vertical graphene [15], can simultaneously detect...
the direction and amplitude strain vector, and thus can detect multidirectional human actions [16,17]. In actual sensing applications, the accuracy of motion detection will be greatly affected if it only meets the sensing needs in the two-dimensional direction and ignores the sensing changes on the three-dimensional surface when the strain sensor detects human motion [18–20]. It is also a challenge to determine the sensing performance of the three-dimensional curved surface for various strain sensors [21,22].

In order to solve this problem, there has been a method of sensitivity sensing in multi-scale directions, which can apply to various mechanical deformations including stretching, bending, and pressing [23]. When the sensor is attached to the human body, it can monitor the large strain of joint movement [24,25]. The induction mechanism of knitting and other types of strain sensors is affected by various complex deformations forces, resulting in corresponding changes in their resistance including tensile deformation [26–28]. Many researchers have studied the unidirectional and bidirectional tensile deformation of the fabric [29,30]. A method for testing the elastic knitted fabric poisson ratio and modulus was proposed based on an orthotropic theory and strip biaxial tensile test [31]. Most of the reported strain sensor testing methods only involve strain sensor testing on two dimensions [32,33]. A stretchable hydrogen sensor based on crumpled graphene is sequentially stretched and twisted by uniaxial and biaxial prestrain to evaluate its sensitivity. This two-dimensional test method cannot fully reflect the true deformation on the three-dimensional level. In addition, the sensor can be adapted to various deformations by changing the structure of the sensor [34–36]. A new carbon nanotube/flexible fiber-shaped strain sensor can be applied to various bending and twisting deformations through a double helix structure [37]. It exhibits good sensing performance and can well detect subtle and drastic human movements [38]. Some pressure sensors similarly have the problem of detecting the performance of 3D surfaces [39,40]. Most of the detection instruments used are plane pressure detectors [41], which cannot fully characterize the curved surface pressure problem in practical applications. For example, a triboelectric sensing textile, constructed with core–shell yarns, tests its sensor performance under a pressure linear motor [42]. In addition, the pressure sensor is transferred to the surface of the fabric through the silver nanofiber, and the compression test is performed through the load of the tensiometer [43]. A 3D nanoporous electrode by constructing conductive percolation networks was created as a strain sensor. The 3D structural platform allows a strain sensor with a widened detection range to captures human motions, including phonations and joint movements [44].

No testing standard available is another issue in the assessment of sensor performance at a three-dimensional level. When strain or pressure sensors are mostly used in applications of human body detection, the unidirectional or bidirectional sensing performance at the two-dimension level is mostly used as sensing indicators [45]. However, in actual 3D deformations including bending and squeezing, it will be affected by complicated forces from all directions [46]. Therefore, it is necessary to analyze the electrical signal changes in the strain sensor when the three-dimensional surface is stressed. Its sensing performance like sensitivity and stability in the detection of human motion also needs to be analyzed.

In this work, a highly stretchable knitted strain sensor based on nylon/spandex-covered by silver-coated yarn was developed. Weft-knitting full-shaping technology is used to position and knit the strain sensor into sportswear, which can provide data generation as a wearable sensing device for detecting body motions through the change in electrical resistance when the fabric is stretched or compressed. According to the needs of human motion detection, locations of sensor areas are customized to form a whole piece of knitted garment popular for today’s applications in elastic tight-fitting activewear, sportswear, and casual wear. In particular, this work proposes a new method for the evaluation of strain sensors for 3D surface sensing performance. It is demonstrated that the 3D sensing properties are closer to the real sensing strain on human body surface and the sensing range is wider than tensile stress on a two-dimensional surface. Moreover, by obtaining characteristic values of resistance signals from the knitted strain sensor, gait movements of the human body can be detected.

2. Materials and experimental methods

2.1. Materials

The conductive yarn used for strain sensing is a commercial silver-coated nylon filament yarn (40 dtex 12f) purchased from Bangcai Textile Company (Shaoxing, China). The metalized nylon filament yarn is surface-coated with silver particles. The yarn normalized electrical resistance is 12.5 Ω/cm, with a resistivity 0.1±0.05 Ω-m and tensile strength 5.6 cN/dtex. An ordinary nylon filament yarn (75 dtex 36f) and nylon-covered spandex yarn (50 dtex spandex filament covered by 20 dtex nylon staple fiber) were used as received for making knitted base fabric (legging fabric). The electrical resistance of ordinary nylon yarn is beyond the maximum value of our test equipment and is thus treated as an insulating material.

2.2. Strain sensor fabric preparation

Knitted sensing leggings fabric were manufactured on a single circular knitting machine (SMM-102 MP2, Pitch 0.907 mm, E28, Diameter 15 in., Santoni Spa, Italy). At the technical face of the fabric, the base structure of the legging fabric was plain knits formed by the nylon yarn and spandex yarn. An ordinary nylon filament yarn (75 dtex 36f) was used to form the face side of a knitted fabric base. Backside of this knitted fabric base was formed by a spandex yarn (20/50 dtex covered spandex). The silver-coated nylon yarn was knitted into the fabric as plating stitch to create conductive loops in multiple zones (Fig. 1). The fabric loop density is 26 wales/cm (PA) × 17 courses/cm (PB). In this study, ten sensors were designed to form a real strain sensing area around the knee joint to cover the knee joint deformation area. Based on previous experimental research results, each sensor was knitted to be 5 cm long and 1.5 cm wide [47].

The selected weft knitting method features with simplicity and quickness. Depending on actual wearing needs, it is necessary to knit a certain area of conductive yarn as strain sensors in a different row or column direction, or even conductive sensing areas in a curved or arbitrary pattern. This cannot be achieved by weaving and warp knitting [3,33]. The sensing mechanism of the flexible knitted sensor is the change of loop contact points. When fabric loops are tightly connected, many resistance sensing paths are formed. When the fabric is...
deformed under external forces, resistance values of the fabric strain sensor change corresponding to a decrease or increase of the loop contact points.

2.3. Strain sensor signal acquisition and analysis

A digital multimeter (Victor 4105A low resistance tester) was used to test resistance signals from the ten sensors. An acquisition software program was developed to process the real-time resistance signals in the test. The software used the Bluetooth 4.0 protocol for data transmission and communication. It can transmit 20 resistance values per second. An A/D conversion device with an external contrast resistance of 100 Ohm was used to convert analog signals into digital signals. The resistance value of each sensor was calculated using the properties of a series circuit. This acquisition software can simultaneously collect data from five channels related to five sensors. Gauge factor (GF), also called sensitivity coefficient, is usually used to evaluate the sensitivity of strain sensors, which can be estimated by the following Eq. (1):

\[ GF = \frac{R}{R_0} \frac{\varepsilon}{\varepsilon} \]

where \( R \), \( R_0 \), and \( \varepsilon \) represent the test resistance, initial resistance, and strain, respectively.

2.4. 2D and 3D surface tensile sensing performance tests

In order to study the sensing properties of a three-dimensional surface fabric sensor, a universal testing machine (Instron Model 5966) was used to evaluate the two-dimensional stress properties of the knitted fabric samples with the yarn strain sensors. According to the ASTM D5035 standard test method for breaking force and elongation of textile fabrics, the tensile properties of the knitted fabric samples were tested with a setting of 100 mm/min for tensile rate and 100 mm for gauge length and the stress-strain properties were measured by stretching the samples to reach a strain of 140%. Initial strain responsiveness was tested by stretching the samples to produce a 10% strain at a speed of 500 mm/min. Sensing stability and repeatability were tested with 3000 stretching cycles at a speed of 250 mm/min. Resistance

| Sum of squares | df  | Mean square | F    | Sig. |
|----------------|-----|-------------|------|------|
| Between groups | 2588.312 | 5 | 517.662 | 21.522 | 0.26 |
| Within groups  | 315,907.799 | 13,134 | 24.053 | 13,139 | |
| Total          | 318,496.110 | 13,139 | | |

Table 1:
ANOVA result for assessing tensile speed influence on strain sensor resistance.
responsiveness was assessed under 50% strain with tensile speeds in the range of 50–250 mm/min. Two ends of a resistance testing hardware unit (MCU) were connected to the fabric strain sensors to simultaneously record the resistance and strain data under cyclic loads, as shown in Fig. 2a.

To better understand the fabric strain sensor performance under a 3D deformation, a fabric bursting test was used to evaluate strain sensor responses to all-direction large tensile strains produced by a large bursting pressure, according to the standard test method of ASTM D3787 for bursting strength of textiles (ball burst test). The sample was fixed by insulating clamps on the universal tensile testing machine with a setting of 100–600 mm/min for bursting speed and 10–40 mm for bursting depth.

2.5. Body gait detection

The real wearing of the legging fabric with the strain sensor was conducted to test the resistance change when the leg stands and bends. The resistance change of the knee joint at different angles (90–150°) was tested. Measured resistance signals reflected characteristics of four kinds of motion (walking/running/climbing steps/descending steps) under human gaits.

3. Results and discussion

3.1. 2D tensile properties and electrical conductive property

In the two-dimensional tensile test of the fabric, because the longitudinal elongation of the knitted fabric is greater than that in transverse direction and the longitudinal stretch meets the large strain range, the fabric sample was stretched in the longitudinal direction for uniaxial tensile test. Fig. 2b shows the two-dimensional longitudinal tensile test of the sensor (also see Supplementary Video S1).

The tensile property of the conductive knitted fabric is shown in Fig. 2c. According to the two-dimensional tensile stress-strain curves, where plotted three stress-strain curves represent three cyclic tensile measurements for the same test specimen, showing that the maximum strain range can reach 140% when the fabric structure is not damaged. The electrical resistance change of the strain sensor corresponding to the tensile strain is also determined, as shown in Fig. 2d. The initial electrical resistance of the strain sensor is about 5 Ω. During the whole stretching process, the resistance change is divided into three stages. The first stage is responding to a strain range of up to 60%, as depicted in Fig. 2e. In the first stage, due to gradual stretching of the knitted loops along the tensile direction, loop contact points in the strain sensor are reduced and the stress and relative resistance increase accordingly. Based on Eq. (1), the sensitivity coefficient \( GF \) decreases gradually.
from its initial value of 33.3 to yielding value of 25. In the second stage, the resistance increase flattens, because contact points among loops tend to increase with a larger stretching. At this time, the resistance of the sensor is at its maximum, and the stretch range interval is 60–90%. When the stretch range exceeds 90% until reaching 140%, the resistance change becomes the third stage where the knitted loops in the strain sensor are further straightened by stretching. The resistance shows a reversed proportional relation with the increase of tensile stress.

Further tensile tests were conducted to evaluate the response time, stretch speed effect, and long-term stability of the flexible knitted sensor. Fig. 2f shows the response time of the flexible knitted sensor strain stimulus. When the tensile deformation becomes 10%, the response time of the strain sensor is 400 ms when loaded at a high stretch rate of 500 mm/min. The fast response time of the knitted strain sensor is conducive to monitoring a series of small movements of limbs, such as muscle movements and facet joint movements.

The high durability of the knitted strain sensor is due to its high elasticity and firmly connected loops in the knitted structure. So, multiple stretches will not destroy its structural stability. In addition, as a strain sensor, stretch speed is also very important for the application of human body motion monitoring. Strain sensors with different tensile speeds at the same strain range of 50% were studied. Different tensile rates have little effect on relative resistance within the test speed range of 50–250 mm/min, which is appropriate to obtain a reliable response as indicated in Fig. 2g. One-way analysis of variance ANOVA was performed to verify this. From the ANOVA analysis result listed in Table 1, calculated probability of F value (21.522) is 0.26>α = 0.01,
indicating that tensile speed has no significant effect on the strain sensor resistance at the 99% confidence level. At the same time, the normal distribution analysis of the speed versus resistance is performed to prove that the speed probability meets the normal distribution (Fig. 3). The coefficient of skewness is 0.46; the variance is 27.54, and the standard deviation is 5.24.

Sensor stability is an important indicator of engineering applications, which can significantly reduce the cost of use. As shown in Fig. 2h, the strain sensor shows 3000 cycles of stretching and return at tations, which can signi

Fig. 2h, the strain sensor shows 3000 cycles of stretching and return at 38x315 tations, which can signi

Therefore, this bursting area increase could be a measure for the fabric all-direction tensile strain. If denoting the original circular area as \( A_0 \) and conical surface area as \( A \), the area increase rate \( \eta \) can be calculated by the following Eq. (2):

\[
\eta = \frac{A - A_0}{A_0} = \frac{\pi r^2 - \pi (r - \frac{D}{r})^2}{\pi r^2} = 1 - \frac{r - \sqrt{r^2 + D^2}}{r} - 1
\]

where \( r \) is the radius of the original circular area, \( l \) is the generatrix of the cone, and \( D \) is the depth of the bursting displacement.

3.3. Random-direction tensile strain

Fig. 5a is an illustration of the bursting test position. The three-dimensional deformation of the fabric during the bursting involves complex deformations such as bending, stretching, shear, compression, and friction between the fabric and the stainless steel ball. Fig. 5b shows the real picture of fabric bursting test. According to the research of Pei et al. [26], in the experiment of fabric three-dimensional surface, the average strain \( \varepsilon \) of fabric in a random direction is defined as Eq. (3):

\[
\varepsilon = \frac{L + S - r}{r} \times 100\%
\]

Among them, \( r = 22 \) mm is the inner diameter of the bursting ring clamp; \( L \) is the stretched length of the fabric without the contact arc with the stainless steel ball determined by Eq. (4):

\[
L = \sqrt{\left(\frac{D - \frac{d}{2}}{2}\right)^2 + r^2 - \left(\frac{d}{2}\right)^2}
\]

where \( D \) is the depth of the stainless steel ball to break the fabric and \( d = 25 \) mm is the diameter of the stainless steel ball. \( S \) is half of the arc length when the stainless steel ball is in direct contact with the fabric, expressed as Eq. (5):

\[
S = \frac{d}{2} \left( \arctan \frac{d/2}{L} + \arctan \frac{D - d/2}{r} \right)
\]

Fig. 5c shows the 3D surface stress–strain relationship. Fig. 5d shows the relationship between the resistance of the flexible knitted sensor

![Fig. 7. (a) Comparison of the relationship between resistance and strain in three cases; (b) The relation between resistance ratio and four movements strain; (c) Comparison of 3D surface and two-dimensional tensile sensor performance.](Image 38x548 to 289x741)

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and the average strain range. Due to the structural characteristics of the highly elastic spandex yarn, the surface strain of the fabric can reach more than 140%, and the resistance of the fabric increases linearly corresponding to the fabric strain within 120%.

In Fig. 5e, the monotonic characteristics of the sensor resistance can be observed. When the average strain of the sensor is less than 51%, the resistance changes monotonously. When the average strain exceeds 51%, there is hysteresis. This hysteresis reaction is due to the fatigue of the fabric when the stretch is too large. Fig. 5f shows the response time of the 3D surface sensor under strain stimulation. When the sample is stretched to 33% of the average strain at 400 mm/min, the response time is 350 ms. At the same time, sensor tests with different machine speeds under the same strain (20% strain) were also conducted. Different tensile rates have little effect on the relative resistance within the test speed range (100–600 mm/min), as shown in Fig. 5g.

According to Eqs. (2) and (3), combining the relationship between $\eta$ and $\varepsilon$, the bursting area increase rate and the average strain of the fabric deformation are both related to $r$ and $D$. After the two variables $r$ and $D$ are controlled separately, the relationship between $\eta$ and $\varepsilon$ is constructed. From Fig. 6, it can be seen that the variable factors of either $r$ or $D$ have a proportional function relationship within the application range. Either $\eta$ or $\varepsilon$ can explain the resistance change resulted from the 2D strain.

Comparing the two-dimensional tensile test with the 3D surface bursting test, the fabric deformation during the 3D surface test is closer to the tensile deformation during actual human motion and the range of strain is bigger in accordance with the linear increase of resistance (Fig. 7a). Two-dimensional stretching is unidirectional in most fabric tensile tests, but in actual applications, fabrics are subject to multidirectional stretching. For this reason, the 3D surface stretching is more suitable for practical applications. Due to a large strain deformation in all directions, the knitted strain sensor is more inclined to 3D sensing in the first 60% of tensile deformation. When the deformation is greater than 60%, the sensor performance is away from the 3D sensing and more resembling the 2D sensing. Using the 3D surface bursting test model, the maximum tensile strain of the strain sensor can reach 120% according to the corresponding relationship between the curved surface and the resistance change. This indicates that the 3D surface model meets the need for testing the movement of most joints of the human body. In Fig. 7b, the strain associated with different motions can be

![Fig. 8.](image-url)

(a) Knee joint upright-bending relative resistance relationship; (b) Knee joint resistance changes at different angles; (c) Correspondence diagram of resistance changes of legs under four kinds of sports.

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calculated based on the resistance change, the strain range of four movements is less than 60%, and the strain of up and down steps is obviously higher than running and walking (Smoothed curve). In contrast, the 2D tensile deformation model is only suitable for strain sensing with a maximum strain range of less than 60% in order for the strain sensor to maintain linear responsiveness. This feature can be used to select two different deformation methods for motion detection according to the types of deformation of different joints (Fig. 7c). The three-dimensional curved surface sensor can be used as a new method of testing strain or sensing the performance of pressure sensors. This method is closer to simulate the stress and deformation of the human body wearing.

3.4. Human motion monitoring

Joint motion is most basic and necessary for the detection of human body movements. To investigate how the knitted fabric strain sensors can be applied to wearable devices to monitor various movements of the human body based on their excellent flexibility, high sensitivity, durability, and wide working range, further study was conducted to use the knitted strain sensor to detect joint motions of the human body and to evaluate the sensor perceptivity. A knee joint is a typical representative as a joint with a large motion range. As shown in Fig. 8a, basic movements of the knee joints of legs were tested and corresponding relative resistance was recorded.

When the leg is straightened (at a 180° position), the relative resistance is 0.2. When the leg is bent to a maximum angle while walking (Position 90°), the relative resistance quickly rises to 3.8. Similarly, when testing dynamic changes of the leg bending angles, the corresponding relationship between the angle of the knee joint and the relative resistance is exhibited in Fig. 8b. It can be seen that as the medial angle of the left leg knee joint is changing from 180° to 90°, the fabric strain sensors are gradually stretched, resulting in a gradual increase in the relative resistance. A small fluctuation that appeared at each signal peak indicates a combinational effect by small muscles, joint jitter, and fabric hysteresis.

As shown in Fig. 8c for leg movements, the flexible knitted sensors simultaneously detect four knee movements in terms of walking, running, climbing steps, and descending steps (watch Supplementary Video S2). The knitting sensor extracts the eigenvector from the resistance signal to perform multivariate analysis. The figure shows that during walking, the resistance signal from the leg impulsively increases and decreases upon the strain sensor stretching/releasing cycle of deformation. At the beginning of running, the leg is bent greatly, and the resistance rises and falls rapidly and dramatically. During the same time period of running, the frequency of fluctuation is the highest. When climbing steps, the leg first moves both forward and upward with larger bending angle changes and the resistance increases rapidly and then decreases. Due to the larger bending amplitude of the leg movement, the maximum resistance is higher than that detected from walking. When the leg shifts to move forward and upward, the resistance rises rapidly and then decreases. An alternative resistance signal pattern can be obtained for the descending movement. Gait resistance changes further illustrate that actual wearing resistance change is more inclined towards 3D sensing.

4. Conclusion

In this study, a large-strain wearable knitted strain sensor based on the weft knitting process using silver-coated fiber and nylon/nylon-wrapped spandex material was presented. The locations of sensor were customized and knitted into the legging. The strain sensor shows good sensor performance under both 3D curved surface strain and two-dimensional tensile strain. The response in the two-dimensional surface is 400 ms, and the three-dimensional curved surface response is 350 ms. The sensor has stability under 3000 repeated loading cycles in a two-dimensional surface. We have proved that the working range of sensing strain can reach 120% in the case of three-dimensional deformation, which is greater than 60% of the working range of uniaxial deformation sensing in the two-dimensional surface. The three-dimensional curved surface should be more adapted to the actual sensing strain of the human body when sensing is less than 60%. Comparing the tests of three-dimensional with two-dimensional sensor performance, the three-dimensional sensor test is closer to the actual sensor deformation when the human body wears the sensor. This test method is more advantageous to be standardized. In addition, the knitted strain sensor is suitable for detecting human gait movements, such as walking, running, climbing steps, and descending steps. Therefore, the three-dimensional curved surface sensing test can become a new method for the assessment of strain sensor sensing performance.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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