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(Citation)
Journal of Ambient Intelligence and Humanized Computing,14(11):14623-14628

(Issue Date)
2023-11

(Resource Type)
journal article

(Version)
Accepted Manuscript

Joint Angle Measurement by Stretchable Strain Sensor

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ABSTRACT

Measurement of body motion is required in professional and amateur sports and in health-care services for the improvement and evaluation of human motion. This study proposes a method for measuring joint angles. The key device in this method is a stretchable strain sensor. The strain sensor stretches over 200% under strain with low elasticity and measures the amount of strain with high accuracy. The key advantages of the strain sensor are its thinness, light weight, and low elastic modulus. If the strain sensor is attached on human skin over a joint, it does not impede joint motion and can therefore measure the stretch of the skin. The proposed method estimates the joint angle from skin stretching based on simple mechanical models. In an experiment, the strain sensors were applied to knee and ankle joints. The average error between the estimated angles and reference joint angles measured by motion capture was within 5°.

Key Words: measurement, joint angle, strain sensor, wearable sensor.

1. INTRODUCTION

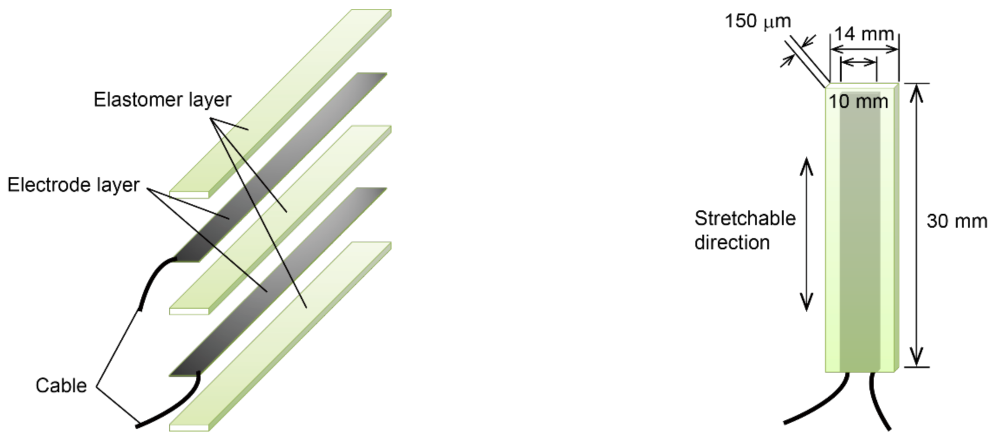
Measurements of human motion are required in professional and amateur sports and in health-care services. In sports science, data about motion trajectories and velocities are useful for physical therapy and training. In health-care settings, motion data is used for rehabilitation and diagnosis (Marin et al. 2017).

Various devices are used in studies of human activity recognition (Ferrández-Pastor et al. 2017; Lotfi et al. 2012). Camera-based methods are generally used to measure human motion precisely. However, camera-based methods limit the measurement area. A limited measurement area is not suitable for measurement of humans while performing exercise like walking, running, or playing football. To measure human joint angles, an angle sensor called goniometer is commercially available (Biometrics 2018). The goniometer is wearable and has high accuracy. However, the high cost of this sensor prevents widespread use. Recently, wearable sensors have been developed. A strain gauge using a conductive polymer composite has been used to measure the stretch of fabric (Cochrane et al. 2007). Curvature sensors have been proposed for angle measurements of finger joints (Otsuki et al. 2010; Kramer et al. 2011). These curvature sensors are flexible but not stretchable and might interfere with smooth motion. Conductive fiber sensors have also been reported (Gibbs and Asada 2005; Mattmann et al. 2008; Yamada et al. 2011). Tights including such fiber sensors have been used to measure knee and hip joints (Gibbs and Asada 2005). Fiber sensors embedded in a T-shirt have been used to measure motion patterns of the upper body (Mattmann et al. 2008). Fiber sensors distributed on a glove have been used to measure hand motions (Yamada et al. 2011). In addition, film-shaped sensors have also been developed (McAlpine et al. 2007; Lipomi et al. 2011; Chossat et al. 2013). A sensitive strain sensor has been used to measure the skin motion generated by heart beats (Pang et al. 2012). A film-shaped sensor has also been used to measure finger motion (Cai et al. 2013). These wearable sensors therefore have demonstrated potential to measure human motion. They could be arranged in the shape of a shirt, pants, or wearable bands. Almost all these examples have demonstrated only the variation of the sensor output during motion. Complete models for extracting motion measurements using film-shaped sensors have not yet been studied.

In this study, a measurement method based on a one-dimensional model for joint angles is proposed. The key device in the method is a flexible and stretchable strain sensor. The method uses a simple joint model. The joint model is composed of a single degree of freedom hinge joint and defines the relation between the joint angle and the length of the arc. In the experiment, the strain sensors are attached to knee and ankle joints. The experimental results reveal the errors between the estimated angles and the angles measured by the motion capture.

2. STRETCHABLE STRAIN SENSOR

The stretchable strain sensor discussed in this paper is made of three elastomer layers and two electrode layers, as shown in Figure 1. This simple laminated structure will be easy to mass produce. The sensor is 150 µm thick, weighs only about 1.1 g/cm3, and has low elastic modulus (0.8 MPa at 100% strain). Although the strain sensor shows a hysteresis loop during the initial stretch, the hysteresis loop disappears after the second stretching (Nakamoto et al. 2015a). The durability at 50% strain is more than 1000 cycles. The strain sensor responds to stretching velocity of more than 100 mm/s with no delay (Nakamoto et al. 2015b). If the strain sensor is attached to human skin, these characteristics of the strain sensor do not prevent human motion. In addition, the strain sensor is intended to be disposable. Therefore, the strain sensor has the basic characteristics needed for measuring human motion in terms of skin stretching.



(a) Components of the strain sensor include three elastomer layers and two electrode layers. The electrodes are made from a conductive material that stretches along with the elastomer layers.

(b) Dimensions of the strain sensor and stretchable direction for measurement of joint angles.

Figure 1: Structure of the strain sensor.

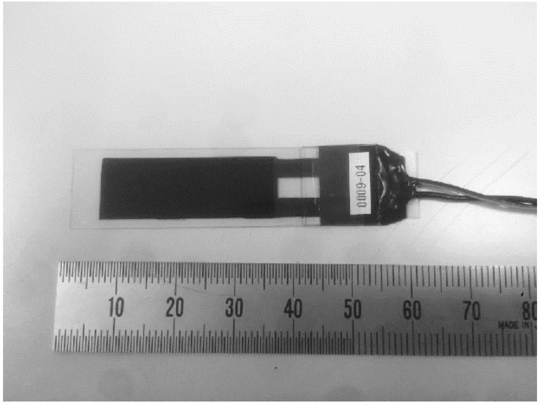
The strain sensor structure is a sandwich structure of two parallel electrodes and one elastomer. The structure works as a parallel-plate capacitor, the capacitance of which depends on the size of the electrode and the thickness of the elastomer layer. The height and width of the electrode and the thickness of the elastomer are written as h, w, d, respectively. The equation for the initial capacitance C_0 is

$$C_0 = \varepsilon_r \varepsilon_0 \frac{hw}{d}, \tag{1}$$

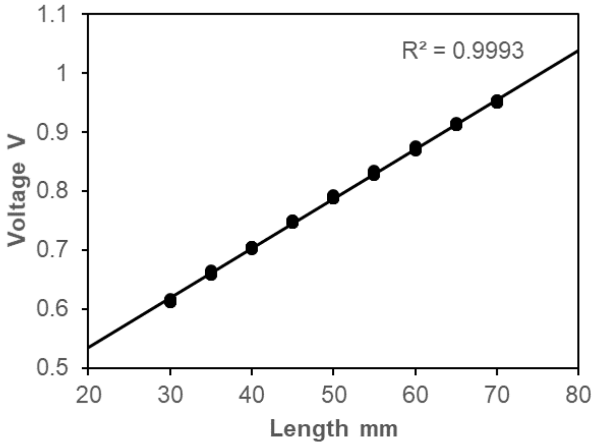
where ε_r is the relative permittivity of the elastic layer and ε_0 is the electric permittivity in a vacuum. We assume that Poisson's ratio for the elastomer is approximately 0.5 (Nakamoto et al. 2015a). If the height is stretched by a factor of n from h to nh, the width and the thickness change to $w/\sqrt{n}$ and $d/\sqrt{n}$, respectively. The capacitance C_n can then be rearranged as follows:

$$C_n = nC_0. \tag{2}$$

The capacitance C_n is directly proportional to n. If we assume that the height is the length of the sensor, the stretched length nh can be calculated from C_n, C_0 and h. Figure 2 (b) shows the relationship between the stretched length and the voltage as measured with a prototype sensor. The voltage was converted from the capacitance of the strain sensor using a CV converter (Nakamoto et al. 2015b). The line in Figure 2 (b) shows the line of best fit and its coefficient of determination is 0.99. The result shows that the length and the voltage are in a linear relationship. This relationship also shows good agreement with Equation (2). Therefore, the strain sensor has the potential to measure the length with small error.



(a) Prototype of the strain sensor.



(b) Relationship between stretched length and voltage.

Figure 2: Fundamental characteristics of the strain sensor.

3. JOINT MODELS FOR ANGLE MEASUREMENT

Rotation motion stretches the skin over the joint. The relationship between the stretch of the skin and the joint angle is diagrammed in Figure 3. As an example, Figure 3 (a) shows a joint model of a knee. If the knee joint is a rotational joint with one degree of freedom, the relationship between the stretch of the skin Δl and the joint angle θ [rad] is as follows:

$$\Delta l = r\theta, \tag{3}$$

where *r* is the radius of the joint. Equation (3) indicates that the joint angle θ is proportional to the skin length difference Δl. When a strain sensor attached to the knee measures the degree to which the skin stretches, the stretch of the skin is equal to the difference in length of the sensor as follows:

$$\Delta l = (n - 1)h \tag{4}$$

$$= (C_n / C_0 - 1)h \tag{5}$$

If we substitute Equation (5) into Equation (3), the joint angle has a linear relationship with the capacitance of the strain sensor. Hence, the joint angle is estimated from the capacitance using the following linear equation:

$$\theta = aC_n + b, \tag{6}$$

where *a* and *b* are the slope and intercept of the linear equation, respectively.

Figure 3 (b) shows a joint model for an ankle. In this case, rotation of the ankle joint does not stretch the skin over the ankle joint. If the terminals of the strain sensor are attached to the lower leg and the foot, rotation of the foot stretches and contracts the strain sensor. r' denotes the radius of the ankle joint as shown in Figure 3 (b). If the stretch of the strain sensor $\Delta l'$ is assumed to be nearly equal to the arc of the joint motion, the following equation is derived.

$$\Delta l' = r'\theta', \tag{7}$$

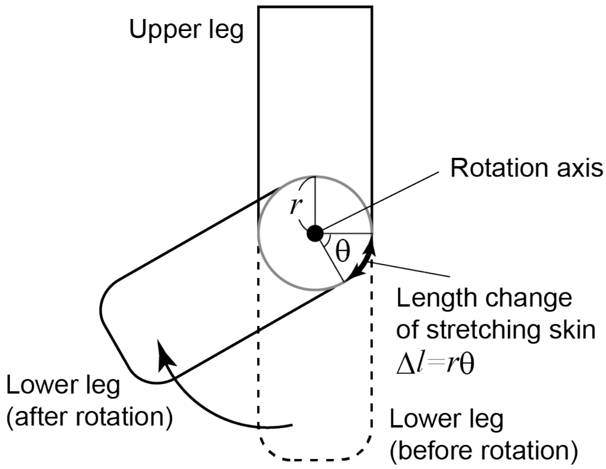
The stretch of the strain sensor is in a linear relationship with the angle of the ankle joint θ' [rad]. In the same manner as the knee joint, the angle of the ankle joint is calculated using a linear equation.

Therefore, the angles of the knee and ankle joint are expressed by linear equations using the variable of capacitance. In actual use, two data sets of angles and capacitances, for example, capacitances at 0° and 90°, would be used to calibrate the slope *a* and intercept *b* of the linear equation. The capacitance is measured as a voltage from the CV converter.

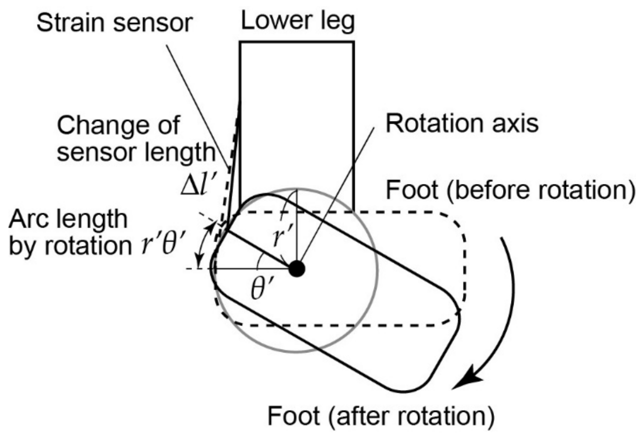
4. EXPERIMENTS

4.1 Knee measurement

An experiment using the prototype strain sensor was conducted to confirm the effectiveness of the proposed measurement method. Figure 4 shows a picture of the strain sensor attached to a knee joint. The terminals of the strain sensor were attached to the skin with tape. The initial hysteresis of the strain sensor was removed by stretching it in advance. A motion capture system (OptiTrack manufactured by NaturalPoint Inc.)



(a) Model of knee joint.



(b) Model of ankle joint.

Figure 3: Joint models.

was used to measure the angle of the knee joint for a reference. Positive angles indicate the direction of the knee's flexion. The sampling frequency was 60 Hz. A subject flexed his knee along interval chimes of 1.5 sec, and the interval was chosen as a low-impact activity for the human subject. The subject was a male of 22 years old. The test was repeated 10 times.

Typical experimental results are shown in Figure 5. The right axis shows the output voltage of the strain sensor. Higher voltage indicates a longer stretch of the strain sensor. The left axis shows the joint angle measured by the motion capture system. The joint angle estimated by the linear regression based on the output voltage is also plotted. In Figure 5, the strain sensor output voltage changed even at angles more than 90°. The coefficient of determination between the estimated and measured angles was 0.98. The maximum error was approximately 14.9° at the angle of 50°. The means and standard deviations of the errors between the estimated and measured angles are listed in Table 1. Since the error in the range between 40° and 60° was high, Table 1 also lists the means and deviations in this range.

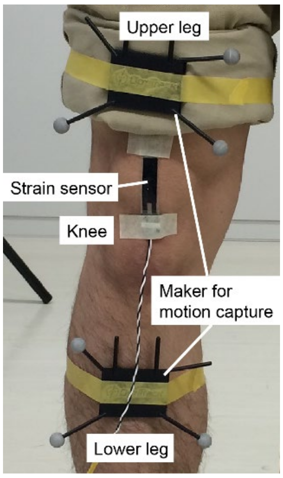


Figure 4: Knee joint with the strain sensor.

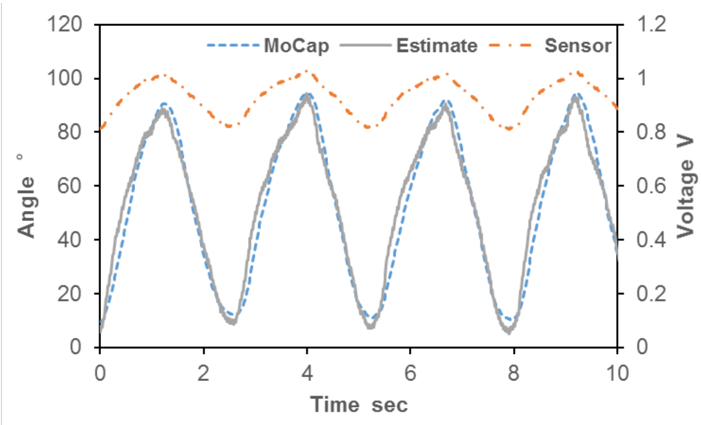


Figure 5: Relationship between time and angles of knee joint. The line, dashed line and dot-dashed line are estimate angle, measured angle by the motion capture and output voltage by the strain sensor, respectively.

Table 1 Mean and standard deviation of the errors between estimate and measured knee joint angles in 10 times experiments.

	All range	Range between 40° and 60°	
		Flexion	Extension
Mean [°]	4.4	8.9	1.7
Standard deviation [°]	3.6	2.3	1.3

4.2 Measurement of ankle joint

Figure 6 shows the strain sensor attached to a subject's ankle. The human subject rotated his ankle periodically to its possible flexion and extension angles. The markers for the motion capture system were mounted on the backs of the lower leg and heel. The joint angle estimated by the linear regression was based on the output voltage. Positive angles indicate the direction of plantar flexion. The other conditions were same as the tests with the knee joint.

A typical example of the experimental results is shown in Figure 7. Table 2 lists the means and standard deviations of the errors between the estimated and measured ankle joint angles. The maximum error was 8.2° and occurred at the maximum angle of dorsal flexion.

4.3 Discussion

When estimating the angle of the knee joint, the maximum error was 14.9º, indicating somewhat low accuracy. In Table 1, the mean error over the whole range of motion, however, is 4.4°, and the coefficient of 0.98 shows that the error of the measurements was small on average. The mean error of the flexion in the range from 40° to 60° was higher, at 8.9°. On the other hand, the mean error for extension angles was 1.7°. The sensor therefore responds differently to flexion and extension. The aspherical shape of the kneecap and the muscle shape under the skin affect the stretch of the skin which increases the mean error for the flexion motion. When the sensor was attached to the ankle, the standard range of motion was from -20° (dorsal flexion) to 45° (plantar flexion). The experimental results showed that the measurement range nearly covers the normal range of the ankle joint. The mean and standard deviation of the error were within 2°. The accuracy was within 5% over the whole range of motion. The error was high at the maximum angle of dorsal flexion. We consider that the linear model no longer applies at this extreme angle.

The proposed methods based on one-dimensional joint models have the potential to measure almost the whole range of motion for each joint. The relationship between the angle and the output voltage is linear. Although this study used linear regression, we can easily calibrate the parameters of the linear equation from two measurements. However, the one-dimensional model limits the sensor in that it cannot be applied to two- or three-dimensional joints and does not include the effect of the aspherical shape of the kneecap and muscle tissue. The estimated joint angles were inaccurate in the range between 40° and 60° of the knee joint.

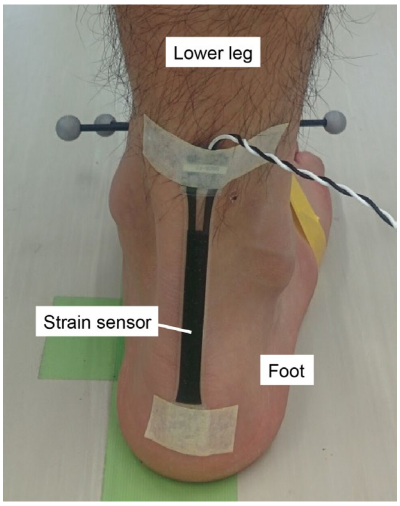


Figure 6: Ankle joint with the strain sensor.

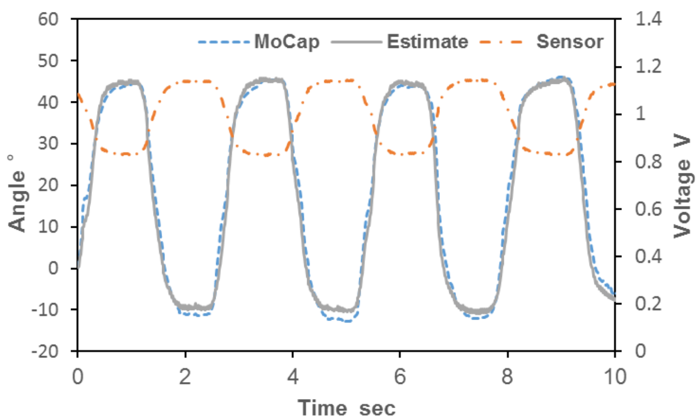


Figure 7: Relationship between time and angle of the ankle joint. The line, dashed line, and dot-dashed line show the estimated angle, angle measured by motion capture, and the output voltage from the strain sensor, respectively. The coefficient of determination is 0.98.

Table 2 Mean and standard deviation of the errors between estimated and measured ankle joint angles in 10 trials.

Mean	1.9º
Standard deviation	1.7º

To improve accuracy would require a more detailed model of the joint that includes the shapes of bones and muscles. Humans have three-dimensional joints such as the shoulder and hip joints. Three or more one-dimensional strain sensors could extend the measurements to three-dimensional joints with a more fully developed model of the joint. The other major limitation on the study was the lack of multiple human subjects. To confirm the consistency of measurement errors between individuals, we need to conduct experiments with more subjects.

5. CONCLUSION

In this study, a measurement method based on a one-dimensional model for joint angles was proposed. The key device in the method is a stretchable strain sensor. The strain sensor measures the stretching length of skin around a joint. A joint model composed of a hinge with only one degree of freedom defines the relation between the joint angle and the length of the limb arc. The effectiveness of the proposed method was demonstrated through the experiments measuring knee and ankle joints. The estimated angles were generally in agreement with the reference angles measured by motion capture. However, the proposed method was rather inaccurate in a specific range of joint angles.

Since the asymmetrical shape of the kneecap and the muscles under the skin affect the stretch of the skin, more human subjects are required for future testing. In addition, anthropometry data about these subjects should also be recorded. With higher-powered studies that allow us to develop the sensor more finely, we plan to use it to measure the motions in exercises such as running, jumping, and sport.

REFERENCES

Biometorics Ltd (2018) Goniometers. Biometerics Web. http://www.biometricsltd.com/goniometer.htm. Accessed 14 Jan 2018

Cai L, Song L, Luan P, Zhang Q et al (2013) Super-stretchable, transparent carbon nanotube-based capacitive strain sensors for human motion detection. Scientific Rep 3:3048. https://doi.org/10.1038/srep03048

Chossat JB, Park YL, Wood RJ, Duchaine V (2013) A soft strain sensor based on ionic and metal liquids. IEEE Sens J, 13:3405-3414. https://doi.org/10.1109/JSEN.2013.2263797

Cochrane C, Koncar V, Lewandowski M, Dufour C (2007) Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite. Sens 7:473-492. https://doi.org/10.3390/s7040473

Ferrandez-Pastor FJ, Mora-Mora H, Sanchez-Romero JL (2017) Interpreting human activity from electrical consumption data using reconfigurable hardware and hidden Markov models. J Ambient Intell Human Comput 8:469-483. https://doi.org/10.1007/s12652-016-0431-y

Gibbs PT, Asada HH (2005) Wearable conductive fiber sensors for multi-axis human joint angle measurements. J of NeuroEng and Rehabil 2005:2-7. https://doi.org/10.1186/1743-0003-2-7

Kramer RK, Majidi C, Sahai R, Wood RJ (2011) Soft curvature sensors for joint angle proprioception. Proc of 2011 IEEE/RSJ Int Conf on Intell Robots and Systems, 1919-1926. https://doi.org/10.1109/IROS.2011.6094701

Lipomi DJ, Vosgueritchian M, Tee BCK, Hellstrom SL et al (2011) Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. Nat Nanotechnol 6:788-792. https://doi.org/10.1038/nnano.2011.184

Lotfi, A., Langensiepen, C., Mahmoud, S.M. et al (2012) Smart homes for the elderly dementia sufferers: identification and prediction of abnormal behavior. J Ambient Intell Human Comput 3:205-218. https://doi.org/10.1007/s12652-010-0043-x

Marin J, Blanco T, Marin JJ (2017) Octopus: A design methodology for motion capture wearables. Sens 17:1875. https://doi.org/10.3390/s17081875

Mattmann C, Clemens F, Troster G (2008) Sensor for measuring strain in textile. Sens 8:3719-3732. https://doi.org/10.3390/s8063719

McAlpine MC, Ahmad H, Wang D, Heath JR (2007) Highly ordered nanowire arrays on plastic substrates for ultrasensitive flexible chemical sensors. Nat Mater 6:379-384. https://doi.org/10.1038/nmat1891

Nakamoto H, Ootaka H, Tada M et al (2015a) Stretchable strain sensor based on areal change of carbon nanotube electrode. IEEE Sens J, 15:2212-2218. https://doi.org/10.1109/JSEN.2014.2377022

Nakamoto H, Oida S, Ootaka H et al (2015b) Design and response performance of capacitance meter for stretchable strain sensor. Proc of 2015 IEEE/RSJ Int Conf on Intell Robots and Systems 2348-2353. https://doi.org/10.1109/IROS.2015.7353694

Otsuki M, Okuyama T, Tanaka M (2010) Characterization of a curvature sensor using a solid polymer electrolyte. Proc of the Int Soc for Optics and Photonics 75000L. https://doi.org/10.1117/12.858441

Pang C, Lee GY, Kim TI et al (2012) A flexible and highly sensitive strain-gauge sensor using reversible interlocking of nanofibres. Nat Mater 11:795-801. https://doi.org/10.1038/nmat3380

Yamada T, Hayamizu Y, Yamamoto Y et al (2011) A stretchable carbon nanotube strain sensor for human-motion detection. Nat Nanotechnol 6:296-301. https://doi.org/10.1038/nnano.2011.36