Wearable Wrist Joint Movement Detection using Two Sensitivity-Enhanced Plastic Optical Fibers*

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***Abstract*—We demonstrate two flexible, sensitivity-enhanced plastic optical fiber (POF) strain sensors embedded in a polyamide wrist brace for human wrist joint movement monitoring. The two sensors are, respectively, featured with a D-shaped side-polished zone of ~40 µm depth and ~30 mm length and etched periodic gratings with a pitch of 3 mm, which correspondingly exhibit around 46.8 and 17.8 times in normalized bending sensitivity by far larger than conventional commercial POF due to more sensitive strain-induced evanescent field interaction with the side-machined fiber. In terms of different detection sensitivity to bending angles, the two modified sensors are separately arranged at the back and side of the wrist and then enable to decouple wrist joint behaviors induced by flexion-extension and abduction-adduction motions. The application therefore shows a great potential for the developed sensors in wearable exercise rehabilitation of human joints.**

Keywords—plastic optical fiber; enhanced sensitivity; wrist joint motion; wearable sensor; exercise rehabilitation

I. Introduction

Flexible, sensitive and facile-fabricated strain sensors are highly desirable in future generations of wearable devices. Among these wearable devices, there are increasing application needs for the measurement of fast variations of the human joint movements due to sport monitoring, physical therapy and rehabilitation [1], such as dynamic measuring of lumbar curvature [2], finger joints [3] and limbs [4]. Devices used for this purpose are mechanical or electromechanical goniometers, which generally come into operation by using resistive potentiometers or strain gauges. However, conventional metal foilsand semiconductor-based strain gauges are incompetent to be utilized in wearable sensing owing to their poor mechanical compliance and limited workable range [5]. Compared to these electrical counterparts, fiber-optic sensors are increasingly used for human joint angles monitoring because of the advantages of small size, light weight, flexibility and immunity to external electromagnetic interference [6]. Types of optical fiber which have been reported to have been implemented in wearable sensors include flexible POF [7], fiber Bragg grating (FBG) [8], side-polished FBG [9, 10] and notched side-ablated polymer optical fiber on a fabric substrate [11]. For wearable systems, simple and miniaturized devices with small power consumption are necessary. Therefore, in comparison with other types of optical fiber wearable sensors, recently the development of POF sensors based on intensity modulation due to bending of optical fiber for healthcare monitoring has increased greatly [12, 13]. Moreover, since POF can possess yarn-like flexibility, much more flexible and drapable sensors can be fabricated and then incorporated into textiles [14]. For the particular case of determining joint angles, several studies have reported POF sensors to measure upper- and lower-limb angular movements [15]. However, regarding macro-bending effect, these conventional POF sensors usually demonstrate low bending sensitivity. In addition, to the best of our knowledge, few efforts are being made to characterize POF sensors for the use of wrist joint motion monitoring in the field of wrist rehabilitation exercise.

Herein, we report the facile construction of a flexible wearable optical fiber bending sensor using POFs that were treated by mechanical processing. Two side-processed sensors with a D-shaped side-polished zone of ~40 µm depth and ~30 mm length and etched fiber gratings with a pitch of 3 mm were respectively arranged at the back and inside of the hand so as to sense wrist joint movement behaviors induced by flexion-extension and abduction-adduction motions. More importantly, a wrist gesture motion was achieved with a mean error limit of 3.3 deg in the corresponding flexion-extension and abduction-adduction ranges of -20~+45 deg and -10~+30 deg, which is comparable to the reliably accepted movement evaluation performance of 5 deg according to the American Medical Association [15].

II. Sensor Fabrication

Figure 1 depicts the fabrication process of the sensitivity-enhanced POF sensors. A commercial POF with a central wavelength of 650 nm was selected to implement the side-machining process. As shown in Fig.1(a), the POF fiber was inserted into a plexiglass mounting fixture made by 3D printing technology to side-polish the fiber core with a D-shaped polishing zone of ~40 µm depth and ~30 mm length by using diamond sheets in different grit sizes of 9 and 3 µm. The residuals on polished surface were cleaned by ultrasound equipment. It should be noted that diameters of the original POF fiber and fiber core are 1 mm and 0.98 mm, respectively. Then referring to Fig. 1(b), another POF fiber was arranged in a fixture with an arc-shaped groove having a same diameter of 1 mm as the fiber. Then, periodic gratings were etched into the POF according to the molded grating structure with a pitch of 3 mm in a grating length of 30 mm. After that, the fabricated

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etched POF [Fig. 1(c)] and side-polished [Fig. 1(d)] POF samples were embedded in a polyamide wrist brace for human wrist joint movement monitoring, as illustrated in Fig. 1(e) and then used for subsequent wrist joint motion measurement to investigate their flexible bending deformation behaviors. It should be added that the fabricated sensor sample can be assembled onto polydimethylsiloxane (PDMS) substrate for wearable human-motion detection.

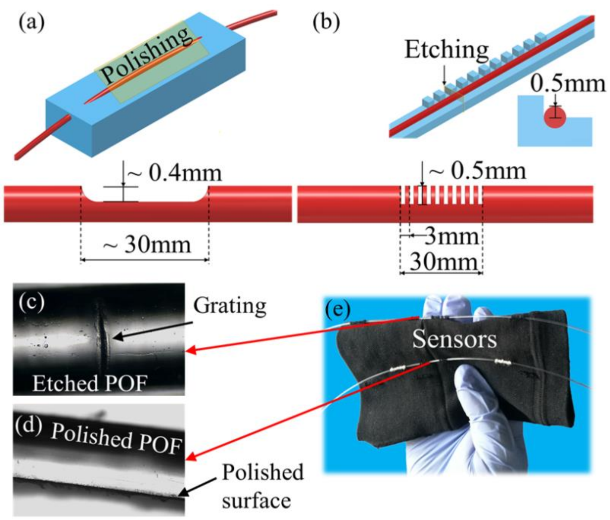

Fig. 1. Fabrication process of the sensitivity-enhanced POF sensors. (a) Side-polishing a POF. (b) Etching fiber gratings on the side-surface of a POF. (c) Etched fiber grating on the POF. (d) Side-polished fiber surface. (e) Picture of the fabricated sensors embedded into a polyamide wrist brace.

III. Experiment And Result Analysis

To verify the operational concept of the proposed two types of side-machined POF sensors, the wrist joint movement experiments were conducted, as depicted in Fig. 2(a). A semiconductor laser (QST-650) with a central wavelength of 650 nm guided the light into the developed sensors through an optocoupler. Then the power of transmitted light was received by a 1 MHz bandwidth photodetector with a conditioning amplifier. The output signals of sensors attached on the wrist brace were fed into an oscilloscope at a sampling frequency of 20 kHz to achieve the response characteristics. It is worth mentioning that the large-sized commercial laser in the experiment could be replaced by an on-chip superluminescent diode to implement portable wearable applications.

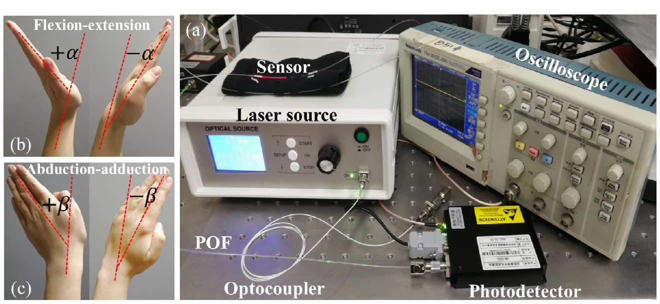

Fig. 2. (a) Experimental setup for wrist joint movement detection. Wrist joint (b) flexion-extension and (c) abduction-adduction motions.

In this way, the proposed optical sensors utilize a simple intensity-modulated scheme to detect human joint movement on the basis of reinforced light transmission losses due to amplified bending effect associated with the fiber curvature variations induced by wrist joint flexion-extension and abduction-adduction motions, as depicted in Figs. 2(b) and 2(c). Note that the angle α ranges from 0 deg, equivalent to a rest position, to -20 deg and +45 deg, which respectively correspond to the tested maximum wrist flexion and extension angles. Likewise, the angle β ranges from 0 deg to -10 deg and +30 deg, corresponding to the tested maximum wrist abduction and adduction angles, respectively.

Then the intensity change in response to fiber bending deformation imposed by wrist flexion-extension motions was measured to estimate the sensitivity-enhanced performance of the developed sensors. It should be pointed out that the three POF-based sensors were successively arranged at the same central position of the back of a hand wrist. It can be obviously found in Fig. 3 that compared with the extremely low normalized sensitivity of 0.0004/° for a conventional POF, the etched grating POF and D-shaped POF demonstrated higher sensitivities of 0.0187/° and 0.0071/°, respectively, which are around 46.8 and 17.8 times larger than the former. Furthermore, the etched grating POF was also superior to the D-shaped POF for monitoring flexion-extension motion, in consideration of the sensitivity of about 2.6 times higher than the latter. This phenomenon indicates that although the latter is characterized by the increase in light leakage due to the weakened guiding properties of POF, the structure of etched periodic gratings in POF contributes to the remarkable change in light loss for the reason of the double changes in the period of the index modulation and the effective refractive index. However, a good linear fitting response was achieved for the D-shaped POF, which was therefore placed at the back of the wrist in view of a large angle range for flexion-extension motion. As a result, the etched grating POF sensor was arranged at the side of the wrist, according to the wrist joint movement behaviors.

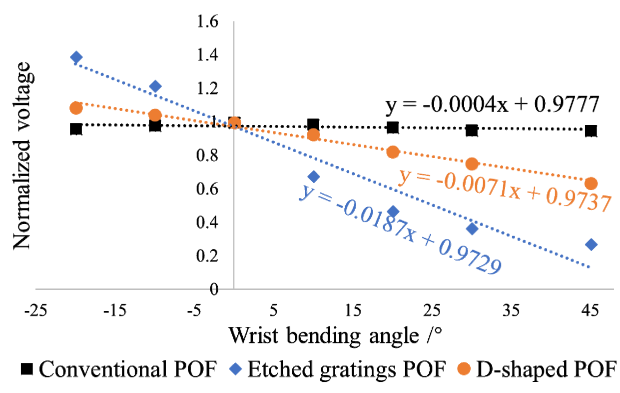

Fig. 3. Sensitivity to flexion-extension motion for conventional, D-shaped and etched grating POF sensors.

Figure 4 shows the cross-sensitivity to flexion-extension and abduction-adduction motions for the D-shaped and etched grating POF sensors mentioned above. In Fig. 4(a), the D-shaped POF demonstrated a more sensitive response to flexion-extension motion with a normalized sensitivity of ~0.0071/° in the tested angle range of -20~45 deg, in comparison to the response to abduction-adduction motion with a negligible response of ~0.0001/° in the tested range of -10~30 deg. Actually, a low goodness of fit (R^2=0.042) also implied a nonlinear behavior around 0.0001/°. In contrast, as shown in Fig. 4(b), the etched grating POF placed at the side of the wrist was more sensitive to abduction-adduction motion with a good normalized sensitivity of ~0.012/° over the aforementioned range, compared with the result in response to flexion-extension movement with a similar low sensitivity of ~0.0003/°. In other words, the flexion-extension and abduction-adduction motions could be decoupled by coordinating the use of the two types of POF sensors, along with corresponding appropriate mounting positions.

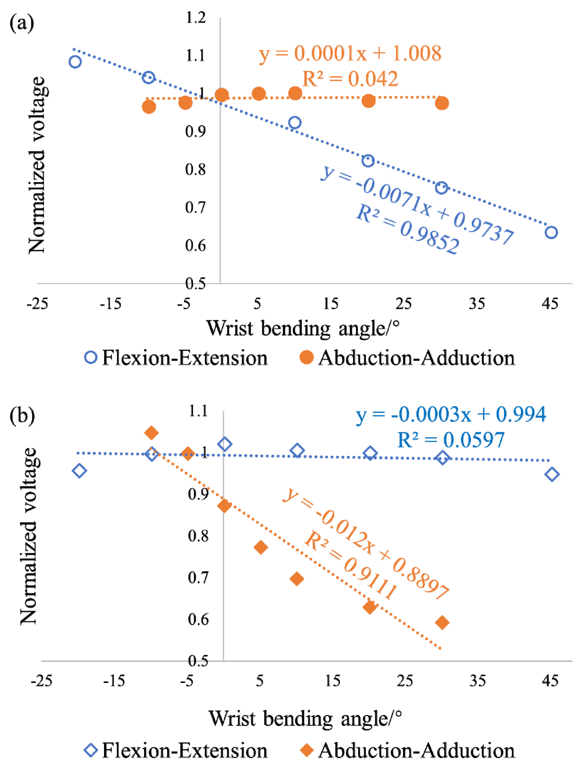

Fig. 4. Sensitivity to flexion-extension and abduction-adduction motions for (a) D-shaped and (b) etched grating POF sensors.

Then eight random measurement points concerned with wrist joint compound motions were labeled on a coordinate paper, where the angles α and β corresponding to horizontal and vertical coordinates were respectively extracted by the fabricated D-shaped and etched grating POF sensors. Figure 5 presents the reference and measured data, as labeled in hollow and solid points, respectively. According to Table 1, maximum absolute errors for α and β were -8° and 20°, respectively, occurring at point 3, which significantly differ from the calculated average values (-3.73° and 3.8°) based on 3σ principle. Hence the data at point 3 could be regarded as gross errors, which possibly resulted from the wrist joint jitters with large amplitude. In this case, the average values for the remaining 7 points were confirmed as -3.14° and 1.4°, respectively, with maximum absolute errors of -6° and 9°. In fact, the resulting average errors are lower than the commonly accepted movement evaluation performance of 5 deg [15]. Further research on side-machined POF sensor array is needed to monitor complicated human joint motions, in combination with data regression correction technology.

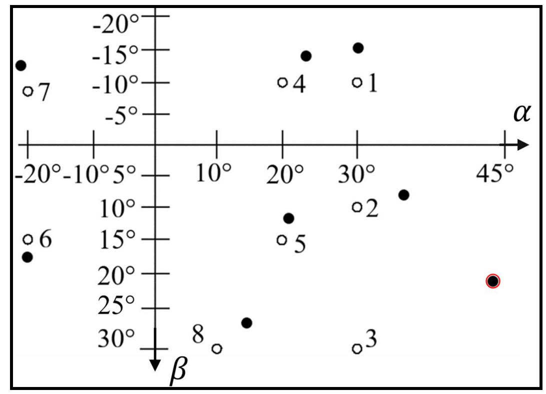

Fig. 5. Wrist joint motion moitoring using two side-machined POF sensors.

Table 1. Reference and measured angles related with wrist joint motions.

	Reference angle /°		Measured angle /°		Absolute error	
Point	α	β	α	β	α	β
1	-10	30	-16	30	-6	0
2	10	30	8	39	-2	9
3	30	30	22	50	-8	20
4	-10	20	-16	21	-6	1
5	15	20	12	21	-3	1
6	15	-20	18	-20	3	0
7	-10	-20	-14	-25	-4	-5
8	30	10	26	14	-4	4
	Average value (8 points)				-3.73	3.8
	Average value (7 points)				-3.14	1.4

IV. Conclusion

Two types of simple and sensitivity-enhanced POF sensors based on intensity modulation in the human wrist joint angle monitoring were presented by side-polishing POF or etching periodic gratings on the external surface of a POF. In comparison with the conventional POF, the fabricated etched grating and D-shaped POF sensors exhibited about 46.8 and 17.8 times larger normalized light power losses in response to flexion-extension motion. Moreover, the cross-sensitivity to flexion-extension and abduction-adduction motions was investigated by fixing the D-shaped and etched grating POF sensors at the back and side of the wrist, respectively, over the tested range of -20~45 deg and -10~30 deg. The normalized sensitivities obtained by the developed sensors in the corresponding measurement ranges were approximated as 0.0071/° and 0.012/°, respectively, as well as the ignorable cross-sensitivity between each other. The as-fabricated flexible wearable sensor scheme could be extended for applications of virtual reality and healthcare, in addition to exercise rehabilitation.

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