A multifunctional helical fiber operated in non-contact/contact dual-mode sensing aiming for HMI/VR applications

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ABSTRACT

The demand for information exchange between humans and machines or virtual spaces is growing rapidly. However, traditional contact sensing makes the spread of bacteria and viruses, and single sensing also limits the development. Hence, as an innovative product, a non-contact/contact dual-mode sensor has to come into being, which consists of stretchable bacterial cellulose (BC)-BC/graphene (Gr) helical fibers. The helical fiber with a sheath-core structure, and the degradable BC as the sheath and BC/Gr as the core, which exhibit a tensile strength of 113 MPa and elongation at a break of 477%. Under non-contact mode, the capacitance change (ΔC/ C0) arrives to ~0.6 (~60%) when the approaching distance is 0.5 cm, and the remote communication through capacitance changes when it is sewn on the lab-gown as a wearable wireless non-contact phone. Under contact mode, action guidance and detection are achieved successfully through interaction with virtual space. All in all, this work will lead to a new era of non-contact human-machine interfaces (HMI) and dual-mode sensors, providing a solid research foundation and leading thinking for wearable electronic products that require non-contact or multi-function Internet of Things (IoT) and virtual reality (VR) field.

1. Introduction

With the advent of artificial intelligence (AI) and the Internet of Things (IoT), the need for interaction between people and the environment for information exchange and experiencing the joy of the virtual world are further increased [1–4]. In particular, human-based control interfaces (such as Human Machine Interface, HMI) allow us to interact with the environment and even the virtual world in different ways, which has attracted widespread attention [5–9]. Furthermore, wearable HMI systems have become one of the most popular research areas because of their lightweight, portability, and low cost [10–13]. At present, all kinds of electrical and intelligent devices are filed in people’s life, from the inseparable smartphones in our lives to various operation buttons in aerospace, all of which need to be touched by human hands to complete the control [8,14–16]. However, traditional HMI systems usually need to be touched and controlled by human hands, which undoubtedly increases contact wear and unnecessary bacterial transmission [8]. Especially in the post-epidemic era, everyone is more reluctant to have direct contact with HMI in public places (hospitals, shopping malls) [5,8,17]. In addition, in biological and chemical laboratories, it is inevitable for researchers to answer or make emergency calls and control balances or other instruments during experimental operations. And the researcher’s gloves are contaminated by biological and chemical reagents and causing corrosion and damage to the instruments even causing the spread of biological viruses unquestionably [18]. In this case, the most effective way is to develop sensors with non-contact operation for HMI to prevent chemical contamination and bacterial virus transmission. Nevertheless, a single interaction function also limits the increasingly widespread usage needs of users. For example, in the field of wearable sports, sensors are often placed at various joints of the body, which in turn requires contact sensing to determine whether the movement is standard, to achieve more effective motion effects. Hence, the sensor not only have non-contact sensing capabilities but can also switch to contact sensing capabilities according to demand will be highly anticipated, which is gradually becoming a new trend in HMI.

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In the reported literatures, wearable HMI systems mainly include resistive [19,20], capacitive [7,9,21,22], and triboelectric [12,23,24] sensors according to the sensing principle, and they mainly includes pressure [11,19], humidity [8,25], temperature [26] and strain [27] sensors according to the quantitative principles. Among these, the capacitive sensor has attracted much attention because of its great independence, high sensitivity, repeatability and low power consumption [28,29]. Also, the human body is extremely easy to changing the electric field around the sensor and resulting in capacitance changes due to the inductive electric field [30,31]. Therefore, in addition to being designed as the traditional contact sensor, it is also easy to be designed as a non-contact capacitive sensor, thus avoiding unnecessary physical contact [7,30,31]. Although some progress has been made in capacitive sensors in recent years, they are mainly based on film electronic materials, and have achieved softness in the skin feeling [32]. Their impermeability makes it urgent for researchers to find a more comfortable capacitive sensor. Fiber, as the basic unit of clothing with excellent flexibility and comfort, is the best choice for wearable sensing devices [33]. At the same time, in some necessary occasions (such as pressure testing), the human body can also control the exertion of a certain pressure that has to be contacted. Therefore, we hope to prepare an intelligent dual-mode fiber-based sensor that can not only be used as a non-contact sensor but also as a necessary contact sensor through the selection of materials and the structure construction of fiber to ensure its mode switching and application in various variable scenarios.

Bacterial cellulose (BC), as a renewable bio-based material, is cultivated by bacteria (Gluconacetobacter xylinus) [34]. It not only has high strength, but also its insulation makes it suitable as the dielectric material for capacitive sensors [29,35]. In addition, graphene (Gr), as a typical two-dimensional (2D) material, has unique conductivity and lamellar structure stability [34,36]. It is complementary to one-dimensional BC nanofiber, which is very beneficial for forming a layered and porous internal structure in the fiber core [5,29]. Therefore, it is of great significance to construct the coaxial helical fiber using BC and Gr as raw materials. It not only has degradability and compatibility, but also the helical structure provides unique stretchability, which fully meets the daily needs of wearable devices [37–39]. Then assemble non-contact/contact dual-mode sensors, and use it as a new control system to conduct HMI in non-contact mode and contact mode, thereby making it an iterative product of traditional contact single function sensors.

In this work, we report a flexible and stretchable BC-BC/Gr helical fiber-based dual-mode sensor for approaching detection in non-contact mode and pressure detection in contact mode. The sensor is composed of composite BC-BC/Gr helical fibers with a sheath-core structure, and degradable BC as the sheath and the mixture of BC/Gr as the core. It is obtained by the coaxial spinning and coiling process. The flexibility is the unique properties of the fiber, while the extensibility is due to the unique helical structure. In non-contact mode, it can be used for non-contact HMI control, such as the non-contact operation screen obtained by cross-sewing the helical fiber on the lab-gown for emergency call response in the laboratory [40]. In contact mode, the sensors are placed on the knee joint and upper arm to obtain the pressure sensor and interact with the virtual space for daily home yoga action guidance and daily motion detection [41]. Based on this, we have successfully realized non-contact wireless phone calls and interaction between humans and virtual space, not only in the field of scientific research and human movement, but also in the field of virtual reality (VR) and medical and health fields, inspiring new and promising HMI applications.

2. Results and discussion

2.1. Preparation and construction of dual-mode sensing platform

Fig. 1a and Fig. S1 show the preparation process of BC-BC/Gr helical fiber with a sheath-core structure (degradable BC as the sheath and BC/Gr mixture as the core) and the schematic diagram of the dual-mode sensing platform. It’s well known that BC shows excellent prospects in the field of functional materials due to its unique renewability, high mechanical strength and insulation [35,42]. Therefore, BC-BC/Gr helical fibers with sheath-core structure are prepared by coaxially spinning and coiling process, which can be prepared continuously on a large scale and has the potential for industrial continuous batch production [10]. The spinning solution is extruded from the coaxial needle and then entered the coagulation bath for solidification. It is worth noting that after the dissolution process, the structure of Gr has not changed (Fig. S2). We crossed the two helical fibers vertically to form a dual-mode capacitive sensor at their intersection point [31,43]. The detection schematic diagram of the capacitive sensor for approaching signals in non-contact mode is shown in Fig. 1b, which can be perfectly
used for non-contact flexible keyboards even elevator buttons to avoid unnecessary physical wear and the spread of bacteria, viruses, biochemical reagent or other pollutants [40,44]. There are greatly considerations in public places as well as routine biochemical laboratories and medical places [5,44]. The pressure signal detection in contact mode is shown in Fig. 1c, which can be integrated with textiles for motion detection of body joints [6,45]. By combining with VR technology, action guidance and detection feedback can be achieved, making exercise simple and effective, which will prove immeasurable prospects in the fields of medical rehabilitation and sports fitness.

2.2. Morphology, structure and performance of BC-BC/Gr helical fiber

As shown in Fig. 2a, BC-BC/Gr fiber with a sheath-core structure shows a stable helical structure, which can be attributed to the excellent compatibility of homogeneous materials between BC sheath and BC/Gr core, the partial solubility of BC and the enhancement effect of Gr [29, 46]. When the spinning solution is extruded from the coaxial needle and then undergoes solvent exchange after entering the coagulation bath, the uneven grooved and folded structure is formed on the fiber surface due to the structural differences between BC and Gr (Fig. 2b). When used as a capacitive sensor, the existence of the grooved and folded structure is beneficial to the divergence of the electric field and the compression deformation ability of the fiber [6,7,9]. In addition, the cross-section of BC-BC/Gr composite fiber with BC as the sheath and BC/Gr as the core can be vaguely distinguishable (Fig. 2c). Although the sheath and core can be blurred apart, they are tightly fused (Fig. 2d), and due to the presence of BC in the sheath and core of the helical fiber, they are tightly bound together and own remarkable compatibility [29]. This is different from the poor compatibility caused by coating other materials as a

Fig. 2. (a, b) The surface SEM image of BC-BC/Gr helical fiber. (c) The cross-sectional SEM image of BC-BC/Gr helical fiber. (d) The boundary of the sheath-core structure. (e) The core of BC-BC/Gr helical fiber. (f) The sheath of BC-BC/Gr helical fiber. (g) EDS of the cross-sectional BC-BC/Gr helical fiber. (h) Weavability of BC-BC/Gr helical fiber. (i) Tensile stress-strain curve of BC-BC/Gr helical fiber. (j) FTIR spectra of BC, Gr and BC/Gr.
dielectric layer on the fiber surface, resulting in sheath-core delamination during the deformation process [7,47]. As shown in Fig. 2e, BC/Gr core exhibits a layered porous structure due to the structural heterogeneity of the undissolved BC nanofibers and the colloidal regenerated BC and Gr after dissolution [7,48]. BC sheath shows a subtle honeycomb structure, which is caused by the uneven double diffusion of the fiber in the coagulation bath (Fig. 2f). The existence of subtle honeycomb structure and the layered porous structure is beneficial for the compression deformation ability of the helical fiber electrodes as a capacitive sensor [6,7,9,28]. These structures are also confirmed by

Fig. 3. (a) Schematic diagram of the non-contact sensing principle. (b) The sensing capacities of the sensor at different distances. (c) The relationship between $\Delta C/C_0$ and the distance. (d) Capacitance changes of the longitudinal BC-BC/Gr helical fiber of the sensor in uniaxial tension. (e) The palm approach to the sensor at different frequencies. (f) Different fingers approach to the sensor successively. (g) Durability of the cycling test. (h) Position recognition in non-contact matrix. (i, j) Multi-point position recognition in non-contact matrix.
Energy Dispersive Spectrometer (EDS) results (Fig. 2g), in which the core is composed of C element (purple) with Gr as the main component (Fig. 2g), and the sheath is composed of O element (yellow) with BC as the component (Fig. 2g).

As a fiber-based wearable sensor for daily application, lightness and weavability are essential. Fig. 2h reveals that the BC-BC/Gr helical fiber can be prepared continuously, and woven or knotted. Meanwhile, placing BC-BC/Gr helical fiber on the small flower demonstrates its excellent lightness (Fig. S3). The helical fiber with a sheath-core structure also exhibits brightly tensile strength (113 MPa) and elongation at break (447%), due to the homogeneity between sheath and core materials, the excellent toughness of the sheath by BC and the reinforcement of core by Gr (Fig. 2i) [29]. The prominent weavability, lightness and mechanical properties establish a responsible foundation for its use as a wearable intelligent device [7,47]. The FTIR spectra of BC, Gr, BC/Gr are shown in Fig. 2j, where the peak at 1116 cm\(^{-1}\) is attributed to C–O stretching vibration, the peak at 1636 cm\(^{-1}\) is attributed to C–C bond stretching vibration, the peak at 2931 cm\(^{-1}\) peak is attributed to C–H stretching vibration of the aliphatic group, and the peak at 3443 cm\(^{-1}\) is attributed to –OH stretching vibration. No new peaks are found, indicating no obvious chemical interaction between BC and Gr [49,50].

2.3. Approaching sensing and application in the non-contact mode

Two separate helical fibers with sheath-core structure are cross-fixed, and the intersection point forms a capacitive sensor [7,31,43]. Fig. S4 shows that the capacitance decreases when the finger (conductor) approaches the sensor, and the capacitance increases when pressure is applied to the sensor, which can clearly distinguish between two signals, indicating the sensor’s dual-mode sensing ability and continuous signal switching ability without interference in non-contact and contact sensing processes. Fig. 3a and S5a demonstrate that when the finger approaches to the capacitive sensor at a certain frequency, the capacitance decreases due to the negative charges carried by the human skin interfering with its edge electric field, and the charge aggregation occurred between the two electrodes (Video S1) [31,51]. When the finger gradually approaches to the sensor with the scale, the capacitance change increases gradually and shows perfect repeatability (Fig. 3b).

The relationship between the capacitance change and the distance is shown in Fig. 3c. It can be seen that the distance is inversely proportional to the capacitance change [7,29,51]. As shown in Fig. 3b, when the finger approaches to the sensor along the scale from 30 cm directly above the sensor, the capacitance gradually decreases with the decrease of the approaching distance, that is, the capacitance change gradually increases. For sensors, response/leaving time also plays a significant role, hence the response speed of the approaching sensor is revealed in Fig. S5c, and both the approaching and leaving processes show a response/leaving time of 80 ms. We believe that it is related to the approaching speed and leaving speed of the fingers, also close to the reaction speed of the test instrument [29,44].

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As a stretchable capacitive sensor based on the helical fiber electrodes, stretching is inevitable during device or human movement [52, 53]. Therefore, further research is required to determine whether the stretchability of sensors can cope with tensile deformation in wearable electronic devices. Here, a self-made single-axis cyclic propulsor and a piece of sheet metal on the displacement platform were used to test the approaching cycling process. For the non-contact capacitive sensor, the single-axis stretching method is adopted. First, as the capacitive sensor composed of two intersecting BC-BC/Gr helical fibers, the longitudinal BC-BC/Gr helical fiber is gradually stretched from 0% to 300% (Fig. S6a). When ensuring the same approaching distance, the capacitive response remains almost unchanged with the increase of the strain (Fig. 3d). Next, based on the first step of stretching, the horizontal BC-BC/Gr helical fiber of the capacitive sensor is gradually stretched from 0% to 300% (Fig. S6b). Similarly, the capacitance response is almost the same when the approaching distance remains constant (Fig. S6c). This result is attributed to the stretching of the helical fiber-based capacitive sensors is not caused by the change in the internal structure of the fiber, but by the physical change caused by the unwinding process of the helical fibers [54]. All in all, the tensile deformation does not affect the sensing performance of the sensor in the non-contact mode. Meanwhile, the sensing abilities of the helical fibers after folding and bending were also characterized and stable sensing ability was proved (Fig. S7a, b) [24]. Hence, it is believed that the approaching response mainly depends on the initial capacitance of the sensor, the capacitance of the approaching object and the approaching distance [6,31].

As a non-contact sensor with practical application potential, it is essential to have the same sensitivity at different approaching frequencies. Fig. 3e shows that when the palm approaches to the sensor with three different frequencies at the same distances, the capacitance change rate presents almost the same results, ensuring the reliability and stability of our non-contact capacitive sensors in distance detection [5, 31]. In the process of testing, we found that the capacitance changes of the sensor were not completely consistent for the approaching of fingers and palms in different forms. Thus, further research was conducted on the capacitance changes of different fingers approaching to the sensor. The results show that as the number of fingers approaching to the sensor increases, the capacitance change increases, and shows good stability (Fig. 3f and S7c). This is attributed to the increase of effective overlap area between fingers and capacitive sensors, and the charge carried by different number of fingers is different, resulting in different capacitance changes in the sensor [30,31]. Also, the stable cycling process is presented by the self-made uniaxial cyclic propulsor instrument approaching to the capacitive sensor at a fixed frequency, which was conducted about 15000 cycles with each cycle lasting for 3 s, exhibiting a stable cycling process with a capacitance change of around −0.15 (Fig. 3g). Therefore, we speculate boldly that if we continue the cycling test, there may be still no change in the sensing performance, attributing to the approaching sensing formed in the non-contact mode without physical wear or mechanical damage [55]. To expand the practicality of the BC-BC/Gr helical fiber-based capacitive sensor in non-contact mode, the helical fiber electrodes are woven into a 4 × 4 matrix (named 1–4 on the X-axis and a–d on the Y-axis), and when a finger approaches to the top of matrix 3c, we find that the capacitance at the intersection of 3c changes the most (ΔC/C0 = −0.46) (Fig. 3h). Although the capacitance of other points in the matrix also shows varying degrees, the capacitance change is not significant compared to the 3c position, indicating that our non-contact capacitive sensor can be used for non-contact position recognition. Then by holding a metal rod above the four points of the matrix 1a-2b-3c-4d (Fig. 3i), we can observe a significant change in capacitance at 1a-2b-3c-4d, indicating its multi-point localization recognition ability (Fig. 3j).

During the experiment, we need to wear protective gloves. However, what’s troubling is that the protective gloves are usually contaminated by chemicals and biological bacteria in the process of the experiment, but researchers also have to touch computer keyboard or even make an emergency call. Repeated interruptions of the experiment and removal of gloves not only waste time and experimental regents, but also may delay the experimental process. So, it is common for buttons to be contaminated by the chemicals and biological bacteria on our gloves (Fig. 4a). Hence, we developed a non-contact smartphone keyboard that can be integrated into the lab-gown to respond or make emergency calls during the experiment. The non-contact keyboard can also be integrated into wearable calculators or other items that need non-contact operation (Fig. 4b) [23,56]. As shown in Fig. 4c, a non-contact wireless smartphone has been designed: (I) is a wearable keyboard composed of 12 groups of BC-BC/Gr helical fiber-based non-contact sensors, (II) is an integrated module controlled by bluetooth for processing and transmitting signals, and (III) is the display interface of the smartphone APP.
Fig. 4. (a, b) Experimental and application scenarios. (c) Schematic diagram of a non-contact wireless telephone. (d) Wireless phone workflow. (e) The finger close to “1”, “Del” and “Dial” three sensors, respectively, and the corresponding results displayed. (f) Volunteer used non-contact wireless smartphone to make phone calls during the experiment.
The physical picture is shown in Fig. S8, and the workflow of a wearable non-contact wireless smartphone is shown in Fig. 4d. First, the non-contact sensor is placed on the flat table, and a finger is approaching to the top of the individual sensor that has been numbered in advance. Fig. 4e presents that when the finger is close to the top of the position “1”, the smartphone shows the dial “1”, and the same finger close to “Del” and “Dial” indicates “delete” and “dialing” function, respectively. Fig. S9 shows the identification of each position, indicating that the non-contact sensor can perfectly meet the requirement of non-contact smartphone keyboard and emergency call answering and making operations in the laboratory. Video S2 shows the sensing process of finger approaching when a non-contact keyboard is on the desktop. Due to the

Fig. 5. (a) Contact sensing principle. (b) The relationship between $\Delta C/C_0$ and pressure. (c) Response/leaving time in contact mode. (d) $\Delta C/C_0$ with increasing pressure. (e) Sensing performance of fiber stretching on the lower side and fiber stretching on the upper side later. (f) The sensor is bent at different angles. (g) Capacitance change of leg raise at different speeds. (h) Capacitance change of squat when the sensor is placed at the knee. (i) Capacitance change of finger bend at different speeds. (j) Capacitance change of bicep strength. (k) The identification of weight position by $5 \times 5$ matrix.
unique flexibility, the non-contact sensor can be sewn onto the sleeve of the lab-gown of the volunteer. The numbers “3–6–9–9” are randomly approached with a finger, then the “del” is approached and the last number “9” is deleted, next the “dial” is approached, and finally, the call is successfully made (this phone number is arbitrarily dialed), and the video is recorded (Fig. 4f, Video S3, S4). This greatly reduces the pollution and corrosion of chemicals or experimental materials, as well as unnecessary harm to the human body, and reduces unnecessary contact and the spread of bacteria and viruses.

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2.4. Pressure sensing and application in the contact mode

Fig. 5a shows the schematic diagram of the sensor prepared with cross-placed helical fibers under finger pressure. The standard weight is applied successively to the intersection of the helical fibers from low to high. The brilliant reversibility, minimal hysteresis, and excellent cycling stability are demonstrated in Fig. 5b and S10. As shown in Fig. 5c, during the application of pressure and departure, the response/leaving time is 60 ms, which is significant for pressure sensors. Meanwhile, the sensing properties of the BC-BC/Gr helical fiber-based capacitive sensor were compared with other references, indicating its good dual-mode sensing ability (Table S1) [7,21,29,31,39,43,47,51,57–68]. Next, when 0.2 N (20 g), 0.5 N (50 g) and 0.7 N (50 g ÷ 50 g) are continuously applied to the sensor one by one, the capacitance change will increase with the increase of the applied force (Fig. 5d). According to the testing method of the non-contact mode, the helical fibers were stretched, respectively, and the capacitance change was tested under different tensile deformation at a certain pressure. It displays that the capacitance change can be negligible with the tensile deformation of the helical fiber (Fig. 5e). In practical application, bending is a deformation mode that cannot be ignored. We place one end of the cross-placed helical fiber flat on a table, and the other end is suspended, then use a tool to press the suspended end and make it continuously bend downwards at 0°, 30°, 60°, and 90°, respectively. The results are shown in Fig. 5f, which presents the pressure on the sensor increases with the increase of bending angle. On the other hand, the helical fiber is also subjected to a certain stretchability during bending, which makes the sensor exhibit an increase in capacitance change with the increase of bending angle [6]. This proves the double effects of pressure and tension during the bending process, but the impact caused by stretching is secondary and negligible. Cycling stability, as another criterion for sensors, is also significant. Hence, the tests were performed for about 5000 cycles (Fig. S11). The results show the basically stable capacitance changes, indicating that our pressure sensor has good cycling stability.

The sensing performance under bending and tensile deformation has inspired our potential to use pressure sensors for human motion detection. First, the sensor was placed on the knees of the volunteer to test the high leg lift at different speeds (Fig. 5g), and squat action (Fig. 5h). Although the capacitive sensor is located at the same position on the knees, different degrees of sensing ability are produced due to different actions, which has great identification potential for the accurate detection of different forms of movement [45,69]. Then, the cross placed helical fibers were placed on the volunteer’s finger and bent at different speeds (Fig 5i), presenting a stable response to finger bending detection, which would have great potential for finger detection in patients during medical rehabilitation [10]. Considering the muscle force detection in usual yoga/fitness exercises, we placed the sensor on the volunteer’s bicep (Fig. 5j). When the volunteer’s biceps arches, the sensor feel pressure, resulting in an increase in capacitance [6]. The detection of these human positions is based on the dual effects of pressure and tension on the sensor, which shows that our BC-BC/Gr helical fiber-based sensor has a great application prospects in the field of wearable electronic devices and human movement and rehabilitation. Integrating sensors into clothing to get smart clothing is a very influential research field in the future, which will receive more and more attention. Finally, we placed 20 g and 50 g of weights above the intersection of 2a-2b-3a-3b and 3d-4d-4e of the 5 × 5 matrix (named 1–5 in the X-axis and a–e in the Y-axis) (Fig. S12), and the mapping diagram is perfectly presented in Fig. 5k, proving the position recognition ability as a pressure sensor. If the number of fibers is continuously increased (i.e. increasing the number of crossing points) and the size of the sensor element is reduced, the resolution of the sensor can be further improved, which will further enhance its huge potential in the application of wearable electronic devices and smart devices.

To better demonstrate the practical versatility of the stretchable BC-BC/Gr helical fiber-based capacitive sensors, an intelligent yoga action guidance and feedback system was developed through the interaction between real and virtual spaces [3,41]. Fig. 6a–e show the bidirectional interaction workflow between real space and virtual space. Firstly, specific yoga actions are set for specific users in the virtual space, and then real users enter the room to exercise the yoga-guided actions. Then, BC-BC/Gr helical fiber-based capacitive sensor on the body collects and processes the signals generated during the exercise process, feeds them back to the processor, and marks and visualizes the corresponding positions in the virtual space to indicate the correct display of actions. Fig. 6d–f show the corresponding photos in both virtual and real spaces during the bidirectional interactive action guidance process. Firstly, volunteers enter the room and ready to start exercising according to the action guidance of the virtual space (Fig. 6d). According to the guidance of action 1 in virtual space, the user makes the corresponding action 1 in real space (Fig. 6d) and generates a signal (Fig. 6d). The signal is processed and entered into the training model, and then a knee in the virtual space is marked in green, indicating that the action is completed standardly (Fig. 6d). After action 1 is completed, the virtual space performs action 2 (Fig. 6e1), which is displayed in the virtual space. Then the user follows action 2 (Fig. 6e2), generates a signal (Fig. 6e3), and provides feedback to the training model to recognize the action. The two knees are marked in green to prove the standard completion of action 2 (Fig. 6e4). Finally, action 3 is shown in the virtual space (Fig. 6f1), and the user performs action 3 according to the guidance (Fig. 6f2). Four sensors located at the biceps and knees generate signals (Fig. 6f3), and the green lights at the corresponding position in the virtual space light up, indicating the correct and effective action 3 (Fig. 6d). The corresponding video can be found in Video S5. Of course, we believe that more BC-BC/Gr helical fiber-based sensors can also be embedded in sportswear to guide more complex and more yoga actions, which will become a useful reference for smart home fitness guidance.

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3. Conclusion

In summary, we have developed a dual-mode sensor, which can not only conduct approaching sensing in non-contact mode, but also conduct pressure sensing in contact mode. The sensor is made of BC-BC/Gr helical fiber with a shear-core structure, with degradeable BC as the shear and BC/Gr as the core, BC as a dielectric layer material, while Gr provides conductivity. The helical fiber exhibits a tensile strength of 113 MPa and elongation at a break of 477%, and its excellent tensile deformation is important in the field of wearable electronics. Meanwhile, BC-BC/Gr helical fiber-based sensor not only has excellent approaching sensing ability in non-contact mode. When the finger is 0.5 cm away from the sensor, the capacitance changes to −0.6 (−60%), can forming a non-contact smartphone keyboard. It also owns pressure sensing capability in contact mode, showing excellent application prospects in the field of information exchange between virtual space and real space. This is more powerful than sensor devices with only one sensing capability, especially in the post-epidemic era, where the non-contact sensing capability is even extremely significant. This design
provides a strong idea and lays a solid foundation for the dual-mode sensing and HMI/VR field.

4. Experimental section

4.1. Reagents and materials

The purified BC was prepared in our laboratory as described previously [70]. Graphene (Gr) with a thickness of less than 50 nm and the size range of 5–15 µm was prepared by the mechanical exfoliated method and was purchased from Shandong Leadernano Co. Ltd. N,N-dimethylacetamide (DMAc) were purchased from Sinopharm Chemical Reagent Co. Ltd. Acetone were purchased from Shanghai Titan Scientific Co. Ltd. Lithium chloride (LiCl) was purchased from Shanghai Aladdin Bio-Chem Technology Co. Ltd. All chemicals without any further purification.
4.2. Preparation of stretchable BC-BC/Gr helical fiber

The BC-BC/Gr helical fibers with shear-core structure were prepared by coaxial spinning and coiling process. First, BC/Gr with the ratio of 1:4 (w/w) were mixed in deionized water (5 mg/mL) homogeneously by the ultrasonic homogenizer (JY92-1IDN, Scientz, China), the mixture was called BC/Gr. The freeze-dried BC (4 wt%) were added in DMAc/LiCl (96 wt%, the content of LiCl was 7% by weight). The mixture was called BC/Gr. The freeze-dried BC (4 wt%) were added in DMAc/LiCl (94 wt%, the content of LiCl was 7 wt%) and the content of DMAc was 92–93 wt%) and BC/Gr composites (6 wt%) were added in DMAc/LiCl (94 wt%, the content of LiCl was 7–8 wt%) and the content of DMAc was 92–93 wt%) with mechanically stirring (600 rpm) (MC-OS20, ART Miccra, Germany) for 14 h at room temperature (~25 ºC), respectively. The dissolved solutions were left in the centrifuge for 15 min at 3000 rpm to remove the excess bubbles and achieved the uniform spinning solutions. Then the spinning solutions were filled into the syringe (2 mL) respectively, and coaxial spun by a dual channel syringe pump (Fusion 4000-X, Chemxyx, America). The injection speed was controlled at 4.9 m/min (core) and 1 m/min (sheath) by the coaxial needles (21 G (core)/16 G (sheath)). The as-prepared BC-BC/Gr helical fiber with shear-core structure were immersed in a coagulation bath (H2O/Acetone: 4:1 v/v). Then connected to the motor and coiled on a steel rod with a self-made equipment, and soaked in deionized water to remove the redundant solvents. After dried in a fume hood at room temperature (~25 ºC), the shear-core composite BC-BC/Gr helical fibers were obtained by removing the rod.

4.3. Fabrication of dual-mode sensor based on stretchable BC-BC/Gr helical fiber

The conductive wires were attached at the end of stretchable BC-BC/Gr shear-core composite helical fibers with silver paste for electrical connections. Then they were placed crosswise to obtain a capacitive sensor.

4.4. Characterization

The mechanical properties of BC-BC/Gr helical fibers were tested by an electronic universal material testing machine (Instron/5969) at a strain rate of 20 mm/min and the gauge length of 10 mm. All samples were tested at 25 ± 1 °C and 50 ± 2% humidity. Morphologies of the fibers were observed by field emission scanning electron microscope (FE-SEM, S-4800, Japan). The fibers were fractured in liquid nitrogen to exposure the cross-section and then sputter-coated with a thin gold layer before observation. Transmission electron microscope (TEM, JEM-2100, Japan) was used to characterize the morphologies of BC/Gr composite and the dissolved BC/Gr composite at 200 kV. The BC/Gr composite and dissolved BC/Gr composite suspension (0.03 mg/mL) were deposited onto the glow-discharged carbon-coated copper grid. The Fourier transform infrared spectroscopy (FTIR) was recorded on a FTIR spectrometer ( Nicolet 6700, Thermofisher) with the pressing potassium bromide troche method. The capacitance signals were obtained from a capacitance meter (IM3536, HIOKI, Japan) was used to characterize the morphologies of BC/Gr composite and the dissolved BC/Gr composite at 200 kV. The BC/Gr composite and dissolved BC/Gr composite suspension (0.03 mg/mL) were deposited onto the glow-discharged carbon-coated copper grid. The Fourier transform infrared spectroscopy (FTIR) was recorded on a FTIR spectrometer (Nicolet 6700, Thermofisher) with the pressing potassium bromide troche method. The capacitance signals were obtained from a capacitance meter (IM3536, HIOKI, Japan) at a voltage of 1 V and a frequency of 1 MHz [7]. During the procedure of the capacitance in response to pressure, the pressure was applied by weights and a custom-made force gauge. The capacitance was measured for 5 times and the average value is reported, and the sensing pixel with two crossed perpendicularly fibers was measured to characterize the basic sensing performance (Testing in a relatively stable static environment). In the approaching and pressure spatial detection using the 4 × 4 and 5 × 5 sensing arrays. The wireless smartphone keyboard system transmitted signals through the wireless Bluetooth module, and the alarm signal were output through the smartphone APP. The sensing application under pressure was reflected through the virtual space and real space interaction of the yoga action guidance and feedback system. The volunteer of human sensing experiment involved in this paper is Qianqian Liang, the first author of this paper.

CRediT authorship contribution statement


Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2023.108903.

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