

Three-dimensional flexible thermoelectric fabrics for smart wearables

Corresponding Author: Professor Zhi-Gang Chen

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors reported the production of highly elastic thermoelectric fabrics and employed them for sensing in the body with interesting applications for early detection risks and even for support of sign language recognition. This work is setting new standards beyond traditional thermoelectric generators and expand the range of applications of this technology.

The proposed 3D fabric structure facilitates a stable out-of-plane temperature difference, which significantly enhances both energy harvesting and signal transmission for sensing applications. Moreover, it ensures exceptional wearability, outstanding decoupling characteristics, and impressive sensing properties, including an ultra-high air permeability of 1300 mm s^{-1} , an accuracy of up to 0.02 K , and remarkable stability over 10,000 compression cycles.

The data is well-organized, and the manuscript is clearly articulated and concise. Therefore, I recommend it for publication in Nature Communications, pending the consideration of the following questions.

1. The manuscript covers a broad range of topics, from fabric preparation to temperature and strain sensing, including also device integration and testing of such devices. I recommend the addition of sections or subheadings to organize the text better.
2. Figure 3 explains the principle of decoupling using V-I curves, but some relationships between the voltage and current are a little confusing, and the authors should check the data and confirm the correlations.
3. The manuscript aims to highlight the sensing function of thermoelectric fabrics, but tests related to energy harvesting should be added for the completeness of the work to thermoelectric device.
4. The relevant part of Figure 5d is missing, the authors should make some changes. The author should carefully scrutinize the order of pictures.
5. The data related to the Seebeck coefficients are repeated in Figure 2b and Figure S8, just keep one.
6. Although the authors focus on three-dimensional thermoelectric fabrics, recent publications on elastic/stretchable thermoelectric materials need to be added and they shouldn't limit them to fabric-based materials.
7. The font size in many graph plots is too small. Besides, the color selection in Figure 1c is almost indistinguishable.

Reviewer #2

(Remarks to the Author)

This study presents an innovative three-dimensional (3D) flexible thermoelectric device with a unique inner rigid and outer flexible woven design. This advancement holds significant promise for wearable electronics by addressing critical challenges such as multi-signal decoupling, elasticity, and breathability. The integration of rigidity and flexibility, along with the incorporation of static air pockets to stabilize temperature differences, is particularly novel and demonstrates a comprehensive understanding of the practical requirements for wearable thermoelectric devices.

The research is thorough, and the results are clearly presented, making it a valuable contribution to the field. Subject to

minor revisions, this manuscript merits publication in Nature Communications.

Suggestions for revisions/improvement:

1. The multi-signal decoupling capability is a standout feature. A more detailed explanation of the underlying scientific principles or mechanisms enabling this decoupling would strengthen the manuscript and enhance reader comprehension.
2. While the superior performance of the TESF is demonstrated, discussing potential challenges in scaling up the production of these fabrics for commercial applications would add practical value.
3. Given the growing emphasis on sustainable technologies, a discussion of the environmental impact and sustainability of the materials and processes used in fabricating the TESF is highly recommended.
4. While the paper highlights applications in sign language learning and respiratory monitoring, a discussion of other potential applications, such as personal thermal management, energy harvesting, or soft robotics, would broaden the manuscript's scope and impact.

Some significant progress in TE materials are suggested to add as new references: Nat. Rev. Phys., 2023, 5, 8, 466–482.; Phys. Rev. Lett., 2012, 108, 26, 266806.; Adv. Energy Mater., 2020, 10, 41, 20202000757; Nano Energy, 2017, 41, 164–171.; Small Science, 2024, 10.1002/smssc.202400149.

Reviewer #3

(Remarks to the Author)

The authors reported a thermoelectric fabric sensor for synergistic sensing of temperature and pressures and reached a recording fast response in thermal stimulations and high robustness in load cyclizing. I am very curious for improvement of the thermal stimulations. What's the reason relative to the structure? Physic insight is necessary.

The authors also conducted multi-signal decoupling analysis, and claimed a full decoupling between the temperature and pressures. I did not considered it scientific rigorous since they only apply a small ΔT of 1K as fluctuation for the pressure measurement. It is suggested to add more violent temperature fluctuations as they discussed their decoupling performance and avoided the absolute claimed.

In the title, it claimed "Three-dimensional Flexible Thermoelectric Fabrics". In my opinion any fabricated could be considered as three-dimensional. The only difference between the authors used fabric and others, their fabric is thicker, which could not be a unique feature to support the big claimed "three-dimensional". The thicker elastic fabric space could be reasonable for better deformation and low thermal conductivity. However, how is it connected with better temperature and pressure sensing?

In the figure 5, for the position recognition, what's the new as compared with other work. Any quantification factor could used justify the progress by using the new fast response pressure sensor.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have addressed all my comments and I consider the paper is now ready for publication

Reviewer #2

(Remarks to the Author)

The authors have addressed all of my comments satisfactorily. The manuscript can now be accepted for publication as is.

Reviewer #3

(Remarks to the Author)

I have no more questions.

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Response to reviewers' comments

Reviewer #1

The authors reported the production of highly elastic thermoelectric fabrics and employed them for sensing in the body with interesting applications for early detection risks and even for support of sign language recognition. This work is setting new standards beyond traditional thermoelectric generators and expand the range of applications of this technology.

The proposed 3D fabric structure facilitates a stable out-of-plane temperature difference, which significantly enhances both energy harvesting and signal transmission for sensing applications. Moreover, it ensures exceptional wearability, outstanding decoupling characteristics, and impressive sensing properties, including an ultra-high air permeability of 1300 mm s^{-1} , an accuracy of up to 0.02 K, and remarkable stability over 10,000 compression cycles.

The data is well-organized, and the manuscript is clearly articulated and concise. Therefore, I recommend it for publication in Nature Communications, pending the consideration of the following questions.

Author reply: We sincerely appreciate the positive feedback and constructive suggestions from Reviewer 1, which significantly improve the quality of our manuscript.

Comment 1: The manuscript covers a broad range of topics, from fabric preparation to temperature and strain sensing, including also device integration and testing of such devices. I recommend the addition of sections or subheadings to organize the text better.

Author reply: We have reorganized the corresponding sections and incorporated subheadings for improved clarity. Additional information has been included in **Pages 6, 8, 11, 12, and 14** of the revised

manuscript.

Comment 2: Figure 3 explains the principle of decoupling using V-I curves, but some relationships between the voltage and current are a little confusing, and the authors should check the data and confirm the correlations.

Author reply: In response to the V - I curve in **Fig. 3** and its interpretation, we have reorganized the analysis of the voltage-current relationship and clarified the decoupling principle. In the revised manuscript, **Fig. 3e** shows that the V - I curves shift significantly to the right when the fabric is subjected to different ΔT s, indicating distinct thermoelectric properties. The V - I curves of the fabric under varying compressive strains at a constant ΔT exhibit corresponding slopes (Fig. 3f). The slope decreases with increasing pressure, corresponding to changes in resistance, while the voltage remains relatively unaffected by different pressure conditions. Additionally, compression tests on the fabric under a constant ΔT of 1 K were conducted (Fig. 3g). These tests reveal that applied pressure does not influence the thermoelectric voltage of the fabric, as its lateral shift remains consistent with the origin. The additional information has been incorporated on **Page 10** of the revised manuscript.

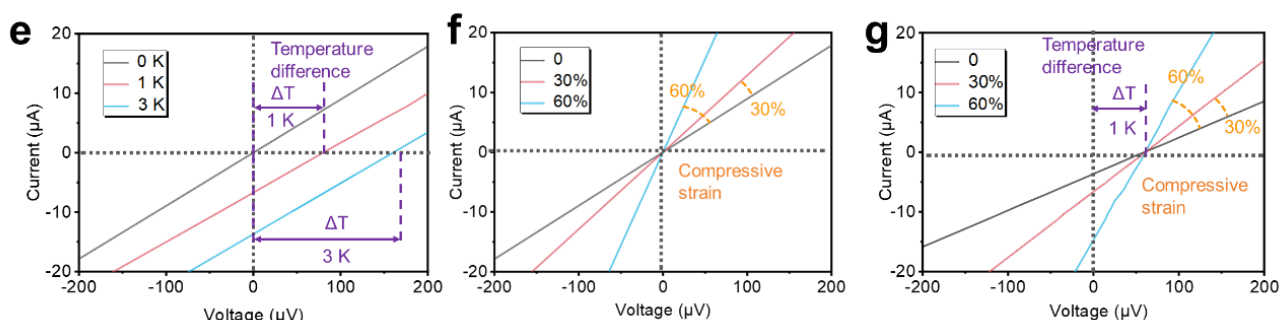


Fig. R1. (Figs. 3e-g in the revised manuscript). I - V curves of TESF under different conditions.

Comment 3: The manuscript aims to highlight the sensing function of thermoelectric fabrics, but tests related to energy harvesting should be added for the completeness of the work to thermoelectric device.

Author reply: In the revised manuscript, **Fig. R2a** illustrates the maximum output power of the device achieved at different ΔT s when the connected load resistance (R_{load}) is $110\ \Omega$, matching the internal resistance of the device. This is further confirmed by the maximum output power observed at varying load resistances, as shown in **Fig. R2b**. For energy harvesting tests, the device is worn on the user's wrist (**Fig. R2c**). The infrared diagram reveals a temperature difference of approximately 8 K between the top and bottom of the device. This significant temperature gradient arises from the low thermal conductivity of the 3D fabric, which effectively prevents the transfer of body heat to the top of the fabric. Consequently, the device can generate a consistent and stable voltage of 5.44 mV (**Fig. R2d**).

The additional information has been included on **Page 12** of the revised manuscript.

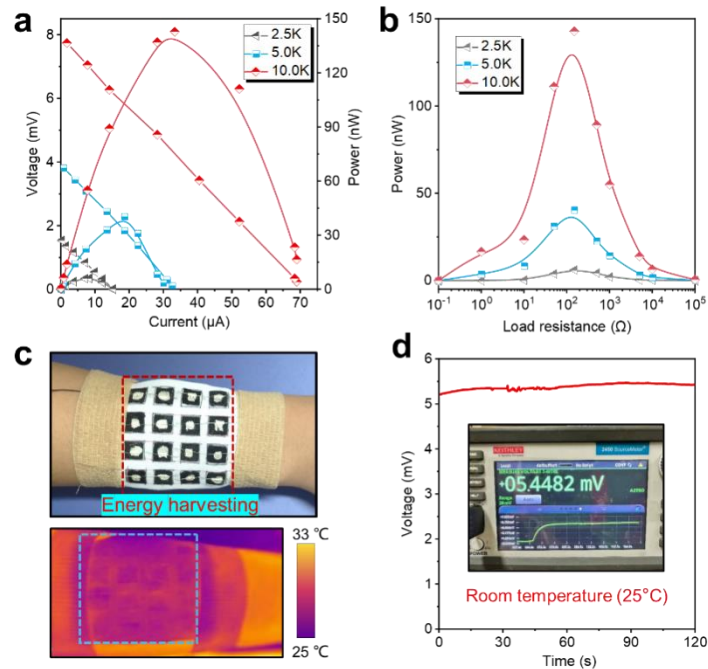


Fig. R2. (Supplementary Fig. 21 in the revised manuscript). Energy harvesting characteristics of TEF device. (a) The relationship between the output voltage and output power versus the current of

the device under different temperature differences. (b) The generated power of the device is a function of load resistance. (c) Physical drawing and infrared image of the device worn on the wrist. (d) At an ambient temperature of 20 °C, the device can generate 5.44 mV stably when worn on the wrist.

Comment 4: The relevant part of Figure 5d is missing, the authors should make some changes. The author should carefully scrutinize the order of pictures.

Author reply: We have supplemented **Fig. 5d** and meticulously verified the order of images in the manuscript to ensure consistency and clarity.

The additional information has been incorporated on **Page 14** of the revised manuscript.

Comment 5: The data related to the Seebeck coefficients are repeated in Figure 2b and Figure S8, just keep one.

Author reply: We have removed the duplicate Seebeck coefficients in **Supplementary Fig. 8**.

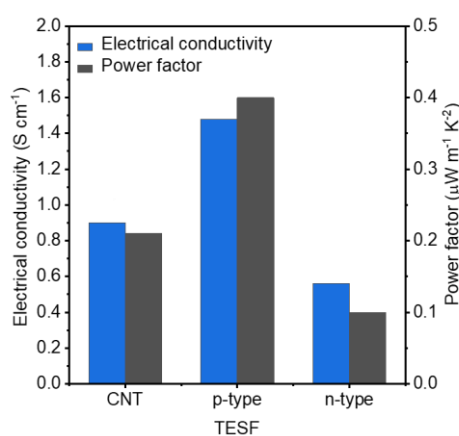


Fig. R3. (Supplementary Fig. 8 in the revised manuscript). Electrical conductivity and power factor

of the CNT TEF, p-type, and n-type TEF.

Comment 6: Although the authors focus on three-dimensional thermoelectric fabrics, recent publications on elastic/stretchable thermoelectric materials need to be added and they shouldn't limit them to fabric-based materials.

Author reply: Thank you for the valuable suggestion. Relevant publications on elastic/stretchable thermoelectric materials have been cited in the revised manuscript.

As highlighted on **Page 3**: Advanced strategies for achieving flexibility, and even elasticity, in TEDs include processing traditional thermoelectric materials into thin films or coating them onto flexible substrates ¹⁻⁴.

Comment 7: The font size in many graph plots is too small. Besides, the color selection in Figure 1c is almost indistinguishable.

Author reply: We have enhanced the font style in the figures throughout the manuscript, specifically in **Figs. 1b-f, Fig. 2h, Fig. 3, and Fig. 4**.

Additionally, the color scheme of **Fig. 1c** has been adjusted to better emphasize the noticeable differences.

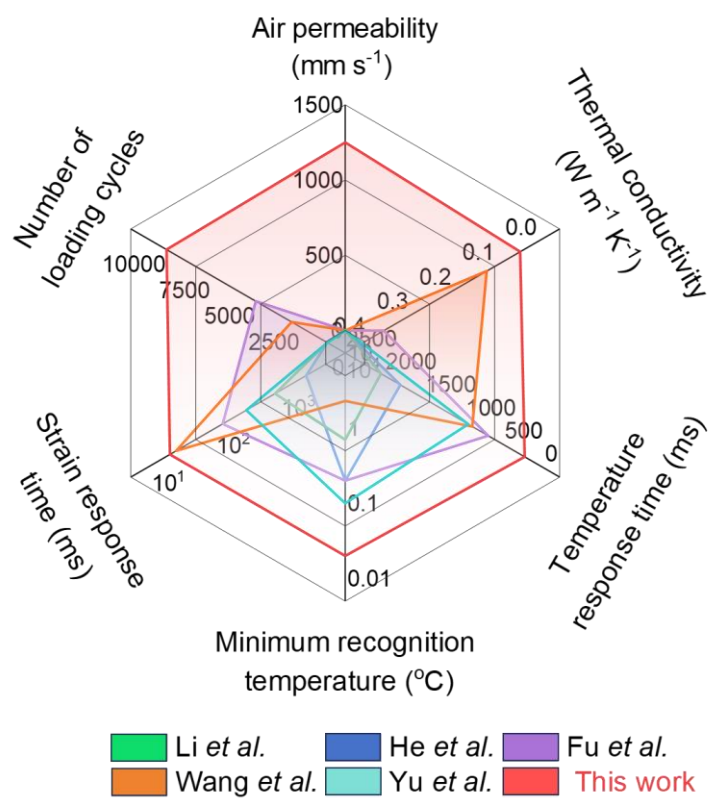


Fig. R4. (Fig. 1c in the revised manuscript). Comparison of performance metrics of this work with other reported dual-mode thermoelectric materials.

Reviewer #2

This study presents an innovative three-dimensional (3D) flexible thermoelectric device with a unique inner rigid and outer flexible woven design. This advancement holds significant promise for wearable electronics by addressing critical challenges such as multi-signal decoupling, elasticity, and breathability. The integration of rigidity and flexibility, along with the incorporation of static air pockets to stabilize temperature differences, is particularly novel and demonstrates a comprehensive understanding of the practical requirements for wearable thermoelectric devices.

The research is thorough, and the results are clearly presented, making it a valuable contribution to the field. Subject to minor revisions, this manuscript merits publication in Nature Communications.

Author reply: We sincerely thank Reviewer 2 for their valuable comments and constructive feedback, which have greatly contributed to improving the quality of our work.

Comment 1: The multi-signal decoupling capability is a standout feature. A more detailed explanation of the underlying scientific principles or mechanisms enabling this decoupling would strengthen the manuscript and enhance reader comprehension.

Author reply: The Seebeck coefficient of a thermoelectric material is defined as $S = \Delta V / \Delta T$. In thermoelectric materials with an elastic three-dimensional structure, compression deformation primarily influences the electrical resistance of the material, which directly affects its electrical conductivity while leaving the Seebeck coefficient largely unaffected^{5, 6}. Therefore, the Seebeck coefficient is influenced solely by the potential difference generated within the material and the temperature difference between its two ends. The potential difference is determined by the selected thermoelectric material system. In planar thermoelectric materials, higher thermal conductivity often leads to instability in the temperature difference between the two ends, thereby increasing signal

crosstalk within the material. In contrast, for our TESF, the three-dimensional structure effectively maintains a stable temperature difference, enabling a steady thermal voltage output and facilitating the observation of signal decoupling characteristics.

We further utilized a dynamic loading process to investigate the intrinsic signal changes in the TESF. When the TESF is not subjected to any temperature or pressure stimulation, its resistance corresponds to the slope of the V - I curve, denoted as $R_1 = dV/dI$ (**Fig. R5a**). Upon applying pressure, the TESF's resistance decreases, causing the V - I curve to rotate about the origin, noted as R_2 (**Fig. R5b**). At this stage, no voltage shift is observed in the V - I curve, indicating that the compression process does not influence the voltage signal. Subsequently, a constant temperature difference is applied to the TESF, resulting in a parallel shift of the V - I curve due to the material's Seebeck effect, with the offset value being $V = S \times \Delta T$ (**Fig. R5c**). The slope of the V - I curve remains unchanged (still R_2), confirming that the Seebeck effect generates a thermal voltage without altering the material's internal resistance. Finally, when the pressure is removed, the resistance of the TESF reverts from R_2 to R_1 , while the thermal voltage offset persists (**Fig. R5d**). This demonstrates that the piezoresistive effect only affects the internal resistance of the material and does not interfere with its Seebeck effect, further validating the decoupling property of the material.

The additional information has been incorporated on **Page 10** of the revised manuscript.

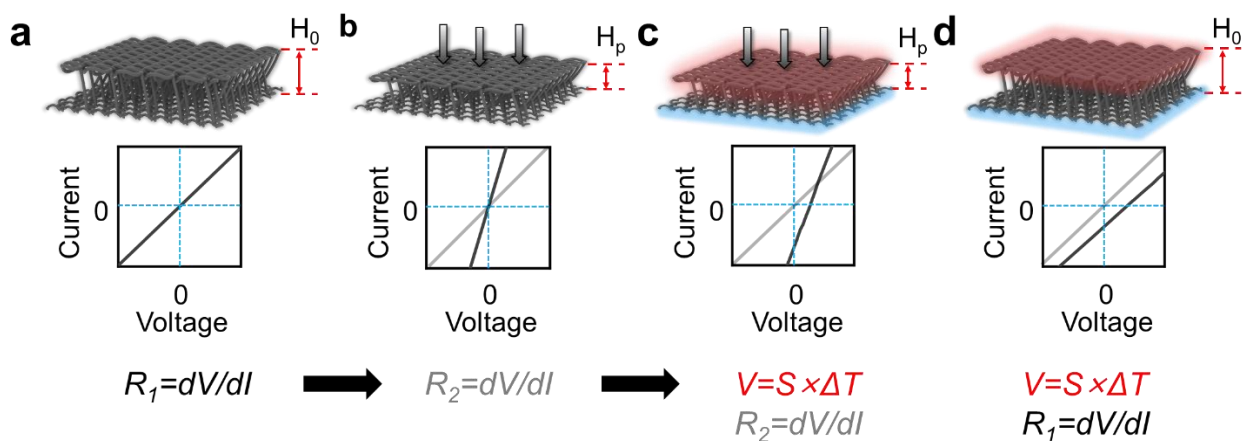


Fig. R5. (Figs. 3a-d in the revised manuscript). Decoupling mechanism of mechanical and thermal stimuli in TESF. *I-V* curves of TESF **(a)** without external stimuli, **(b)** under compressive strain alone, **(c)** under both compressive strain and ΔT , **(d)** under ΔT only.

Comment 2: While the superior performance of the TESF is demonstrated, discussing potential challenges in scaling up the production of these fabrics for commercial applications would add practical value.

Author reply: For the preparation of 3D spacer fabrics, we utilize an industrially established manufacturing process that enables large-scale automated production (**Fig. R6a**). For practical applications, these fabrics are often cut into sub-meter dimensions for further use and processing (**Fig. R6b**). However, the current fabrication of TESF is constrained by the size of the processing container, limiting the scalable preparation of TESF to sizes ranging from the centimeter scale to the meter scale (**Fig. R6c**).

We aim to incorporate a large-scale impregnation tank at the back end of the knitting process in our future work, which will enable the production of TESF on a larger scale and in bulk quantities (**Fig. R6d**).

The additional information has been added on **Page 7** of the revised manuscript.

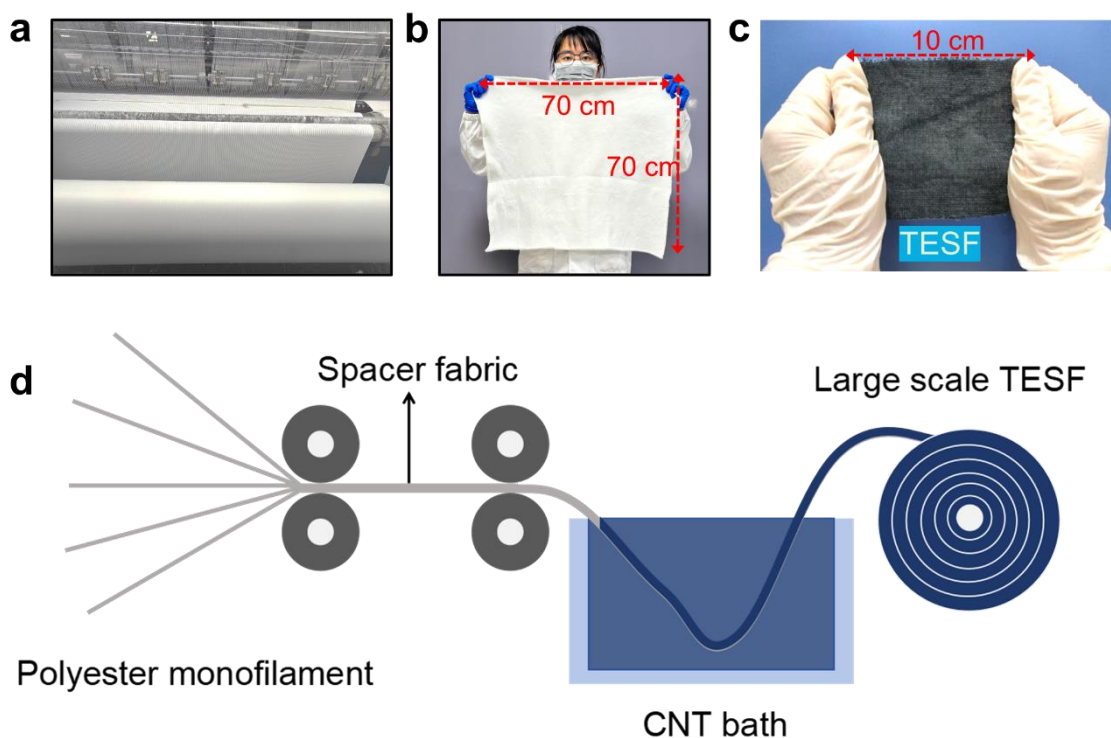


Fig. R6. (a) Physical diagram of mass production of spacer fabrics. (b) Spacer fabrics are cut to sub-meter sizes (70×70 cm). (c) Physical diagram of TESF (10×10 cm). (d) Schematic diagram for large-scale preparation of TESF in future work.

Comment 3: Given the growing emphasis on sustainable technologies, a discussion of the environmental impact and sustainability of the materials and processes used in fabricating the TESF is highly recommended.

Author reply: The primary materials utilized in the fabrication of TESF include PET (polyester) for the construction of spacer fabrics, and CNT along with PEDOT:PSS for the preparation of TESF. We have addressed each of these materials individually in the discussion.

Polyester: PET (including polyester monofilaments) is primarily produced through polymerization reactions using petroleum-based chemicals, making its production highly dependent on fossil

resources such as petroleum. The refining and chemical synthesis processes involved in its production consume significant energy and may impact the environment. However, PET materials offer exceptional durability and wrinkle resistance, ensuring a long service life ⁷. Additionally, PET has considerable recycling potential, with large-scale recycling already being implemented, particularly for PET bottles ^{8,9}. Converting waste PET products into new fiber materials through mechanical or chemical recycling is an effective strategy to minimize resource wastage and reduce the dependency on petroleum-based feedstocks for producing new PET. This approach not only conserves resources but also contributes to a more sustainable production cycle ^{10,11}.

CNT: The preparation of carbon nanotubes (CNTs) is commonly achieved through methods such as chemical vapor deposition (CVD), arc discharge, and laser ablation, which are energy-intensive and often dependent on fossil fuels, contributing to resource depletion. Recently, innovative approaches have been explored, including the production of CNTs from biomass sources like corn seeds and waste plastics, offering more sustainable alternatives ^{12, 13}. These approaches significantly reduce the environmental impact of CNT production. Moreover, recent studies have demonstrated that high-performance materials derived from carbon nanotubes can be effectively recycled and repurposed as structural reinforcement materials or electrical conductors, further enhancing their sustainability and practical value ¹⁴.

PEDOT:PSS: PEDOT:PSS is a relatively environmentally friendly conductive polymer, particularly advantageous due to its ability to significantly reduce organic solvent contamination when utilized in water-based solutions ^{15, 16}. However, the preparation of PEDOT:PSS involves the synthesis of conductive polymers (PEDOT) and polystyrene sulfonates (PSS), which still rely on non-renewable resources. Despite this, PEDOT:PSS has an almost negligible impact on the environment and human health. Recent reports on its application in food and medicine further highlight its high biocompatibility and sustainability ^{17, 18}.

The production process is divided into two stages: the preparation of 3D spacer fabrics and the subsequent fabrication of TEF. Each stage will be discussed separately.

Spacer fabrics preparation process: High-speed warp knitting machines are driven by electric systems, primarily utilizing frequency drives and intelligent control systems. With advancements in technology, modern high-speed warp knitting machines now incorporate energy-efficient motors and drive systems. Additionally, some equipment is equipped with intelligent control systems that can automatically adjust the operating mode based on production demands, thereby achieving significant energy savings^{19, 20}. The high-speed warp knitting machine does not directly produce exhaust or harmful gases during operation, nor does it generate carbon emissions, pollutant emissions, or wastewater. As a result, the knitting process has a minimal environmental impact.

TEF preparation process: TEF is prepared using water as the solvent, eliminating the risk of organic solvent contamination. The preparation process involves only solution impregnation without any chemical reactions or synthesis, making it highly environmentally friendly.

Additional information has been incorporated on **Page 6** of the revised manuscript and **Pages 2 and 3** of the Supporting Information.

Comment 4: While the paper highlights applications in sign language learning and respiratory monitoring, a discussion of other potential applications, such as personal thermal management, energy harvesting, or soft robotics, would broaden the manuscript's scope and impact.

Some significant progress in TE materials are suggested to add as new references: Nat. Rev. Phys., 2023, 5, 8, 466–482.; Phys. Rev. Lett., 2012, 108, 26, 266806.; Adv. Energy Mater., 2020, 10, 41, 20202000757; Nano Energy, 2017, 41, 164–171.; Small Science, 2024, 10.1002/ssm.202400149.

Author reply: Thank you for the valuable suggestion. The recommended works have been cited in the revised manuscript.

As shown in **Page 5**: “Among the various functional wearable electronics, wearable flexible thermoelectric devices (F-TEDs) stand out as excellent candidates for wearable energy harvesting and conversion systems²¹⁻²⁸.”

Reviewer #3

The authors reported a thermoelectric fabric sensor for synergistic sensing of temperature and pressures and reached a recording fast response in thermal stimulations and high robustness in load cyclizing.

Author reply: We sincerely thank Reviewer 3 for their valuable comments and suggestions on our work. We have carefully considered their feedback and incorporated the recommendations in the preparation of our revised manuscript.

I am very curious for improvement of the thermal stimulations. What's the reason relative to the structure? Physic insight is necessary.

Author reply: The detection of thermal stimuli in the manuscript is facilitated by a thermoelectric voltage generated based on the Seebeck effect, which is defined as: $V = S \times (T_1 - T_2)$, where S is the Seebeck coefficient, an inherent property of the material. To sustain the presence of thermal voltages, we focus on constructing a stable $T_1 - T_2$. This implies that reducing the thermal conductivity of the material enhances the accuracy and continuity of thermal stimulus perception and monitoring. Our prepared TESF comprises a top layer, a bottom layer, and an intermediate support spacer filament, forming a porous spatial structure. The spacer layer contains a significant amount of air, which has an extremely low thermal conductivity ($\sim 0.025 \text{ W m}^{-1} \text{ K}^{-1}$) compared to solid materials. As a result, the increased air content within the structure substantially reduces the overall thermal conductivity (**Fig. R7a**). Additionally, heat flow within the fabric is subjected to multiple scattering due to the fiber structure, further inhibiting rapid heat transfer (**Fig. R7b**)^{29, 30}. Therefore, spacer fabrics significantly enhance the diversity of heat flow paths, effectively lengthening the heat conduction paths and substantially reducing the thermal conductivity, thereby prolonging the duration of thermal stimulation.

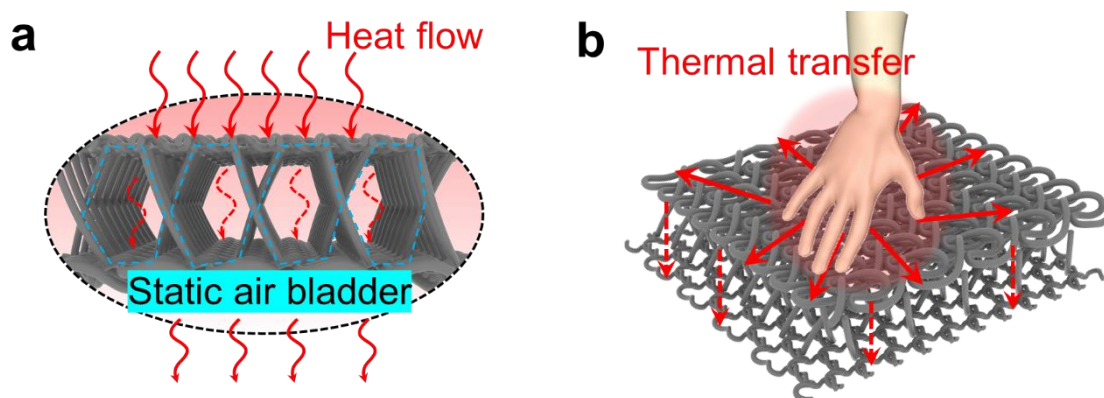


Fig. R7. (a) Schematic diagram of heat transfer through spacer fabrics. (b) Schematic of multiple heat scattering from fiber structures in spacer fabrics.

The authors also conducted multi-signal decoupling analysis, and claimed a full decoupling between the temperature and pressures. I did not consider it scientific rigorous since they only apply a small ΔT of 1K as fluctuation for the pressure measurement. It is suggested to add more violent temperature fluctuations as they discussed their decoupling performance and avoided the absolute claimed.

Author reply: To address practical application scenarios of wearable devices, we conducted additional tests under a temperature difference of 10 K, which further confirmed the decoupling characteristics of the device. The fabric was systematically analyzed using our temperature-variable compression test apparatus to study the decoupling behavior under different temperatures (**Fig. R8a**). The temperature difference was controlled in real-time using a pair of Peltier elements. We first assessed the internal resistance of the fabric under different deformations across a ΔT range of 0 to 10 K (**Fig. R8b**). As shown in **Table R1**, the temperature had a negligible effect on $\Delta R/R_0$, regardless of the applied compressive strain. This indicates that the internal resistance signal of the TESF remains unaffected by temperature crosstalk even at a temperature difference of 10 K. Additionally, we monitored the thermoelectric voltage output under varying compressive strains and observed that pressure had no

significant influence on the thermoelectric voltage (**Fig. R8c**). **Table R2** further illustrates that the compressive strain does not alter the output thermal voltage of the TESF, irrespective of the applied temperature difference. These findings clearly demonstrate that in this 3D material, the piezoresistive signals and thermoelectric voltage signals operate independently of each other.

Additional information has been incorporated on **Pages 10 and 11** of the revised manuscript.

Table R1. Detailed information of resistance response for the TESF to different compressive strains under different ΔT s.

ΔT (K) \ ϵ (%)	0	5	10
0	0	0	0
10	-0.03	-0.025	-0.022
20	-0.09	-0.08	-0.09
30	-0.15	-0.16	-0.15
40	-0.26	-0.27	-0.26
50	-0.4	-0.38	-0.4

Table R2. Detailed information of output thermal voltage for the TESF under different ΔT s and compressive strains.

ΔT (K) \ ϵ (%)	10	20	30	40	50
0	0	0	0	0	0
2	0.1086	0.11242	0.11023	0.10869	0.11023
4	0.2172	0.21943	0.21715	0.21961	0.21961
6	0.3258	0.32558	0.32841	0.325	0.32663

8	0.4344	0.43558	0.4376	0.43626	0.4344
10	0.533	0.54495	0.54389	0.53533	0.54432

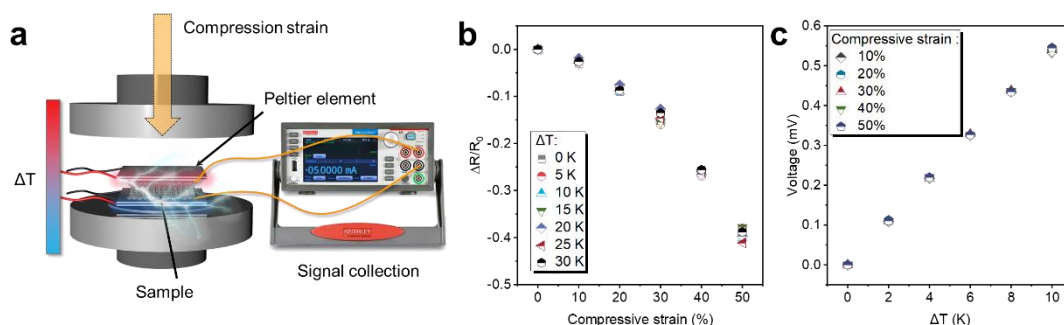


Fig. R8. (Supplementary Fig. 17 in the revised manuscript) (a) Schematic diagram of testing output thermal voltage of the TEF in the compressive strain state under different ΔT s. (b) Resistance response of the TEF to different compressive strains under different ΔT s. (c) Output thermal voltage of the TEF under different ΔT s and compressive strains.

In the title, it claimed “Three-dimensional Flexible Thermoelectric Fabrics”. In my opinion any fabricated could be considered as three-dimensional. The only difference between the authors used fabric and others, their fabric is thicker, which could not be a unique feature to support the big claimed “three-dimensional”. The thicker elastic fabric space could be reasonable for better deformation and low thermal conductivity. However, how is it connected with better temperature and pressure sensing?

Author reply: We appreciate that, from a macro perspective, all fabrics can be collectively referred to as 3D fabrics due to their inherent interwoven structure of fibers or yarns. Traditionally, however, knitted or woven fabrics with relatively small thickness are often referred to as two-dimensional fabrics for simplicity (Figs. R9a, b)^{31, 32}. In many cases, the term “three-dimensional” is used to emphasize the fabric’s thickness or its multi-layered spatial structure. Such structures can be achieved through

specialized processes, such as 3D weaving or laminated constructions, which result in enhanced thickness, internal porosity, and shape stability. An example of this is the spacer fabric utilized in our manuscript (**Fig. R9c**). Another reason for using the term “three-dimensional” is to highlight the unique temperature difference acquisition mechanism in our thermoelectric spacer fabric (TESF). In previously reported thermoelectric fabrics, temperature difference acquisition typically occurs in-plane (**Fig. R9d**). In contrast, the TEF described in this work leverages an out-of-plane temperature difference (**Fig. R9e**). To distinguish it from conventional thermoelectric fabrics and emphasize this novel mechanism, it is appropriate to name it a three-dimensional thermoelectric fabric. An additional explanation has been included in the revised manuscript for clarity.

Temperature sensing depends on the stability and accuracy of electrical signal output from thermoelectric materials under temperature differences. Two-dimensional planar fabrics typically construct temperature differences along planar surfaces. However, this configuration facilitates rapid heat conduction, leading to unstable temperature differences, which significantly impacts the precision and accuracy of temperature sensing (**Fig. R9d**). In contrast, the static air trapped within 3D spacer fabrics contributes to their inherently low thermal conductivity. This unique structure makes it easier to maintain a stable temperature difference between the top and bottom ends of the fabric, resulting in highly stable and accurate temperature sensing (**Fig. R9e**).

Compressive strain sensing depends on the resilience of the material. Conventional two-dimensional flat fabrics are typically only laterally malleable and lack vertical press-responsiveness due to their thinner structure and softer materials. In contrast, our TEF utilizes strong polyester monofilaments within the fabric, which bend under external pressure and recover to their original state once the force is removed. This unique feature provides TEF with excellent resilience and stability. Experimental results further confirm that our structure demonstrates ultra-fast resilience and exceptional recyclability, surpassing the performance of most thermoelectric materials reported to date.

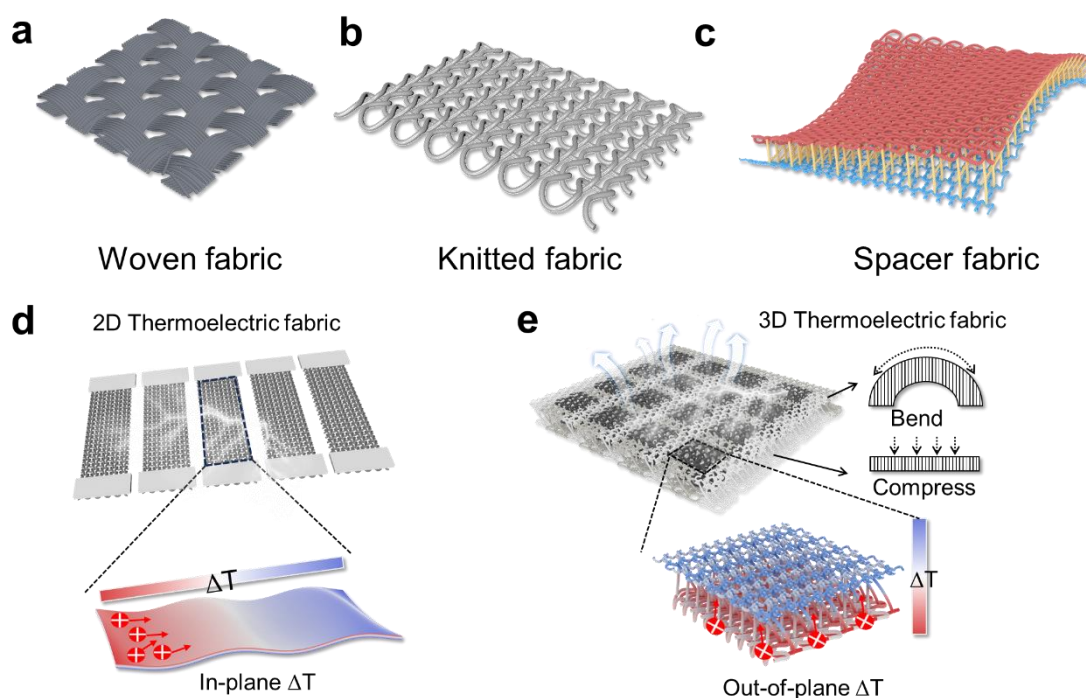


Fig. R9. Schematic graph of (a) woven fabric, (b) knitted fabric and (c) spacer fabric. Schematic diagram of (d) 2D thermoelectric fabric and (e) 3D thermoelectric fabric

In the figure 5, for the position recongnization, what's the new as compared with other work. Any quantification factor could use justify the progress by using the new fast response pressure sensor.

Author reply: For sensors intended for wearable devices to achieve long-term, real-time, and accurate monitoring, two critical characteristics are required: durability and stability^{33,34}. First, the sensor must exhibit excellent durability to withstand repeated deformation. Additionally, mechanical learning-assisted recognition often requires a substantial number of samples in the training set, imposing even higher demands on the sensor's durability. The TESF utilizes interlocking stitches to create a three-dimensional knitted structure, which provides effective support in all three directions while maintaining softness and stability. This design effectively prevents deformation of the sensor after repeated compression. Our TESF demonstrates significant advantages over recently reported

thermoelectric sensors, achieving durability for up to 10,000 compression cycles (**Table R3**). Moreover, both the resistance and the Seebeck coefficient of the TESF remain essentially unchanged after 10,000 cycles of compression (**Fig. R10a**).

The second critical factor is the response speed, as low hysteresis enables the real-time transmission of sensor signals. In wearable devices, such as those used for sports health monitoring, human behavior analysis, or medical applications, sensors must rapidly capture movement or pressure changes to provide instantaneous feedback³⁵⁻³⁷. The robust spacer filaments in the TESF ensure a quick rebound after compression. The response time and recovery time of the fabrics under large deformations are only 20 ms and 60 ms, respectively, which surpass the performance of thermoelectric sensors reported to date (**Table R3**).

Additional information has been highlighted on **Page 9** of the revised manuscript.

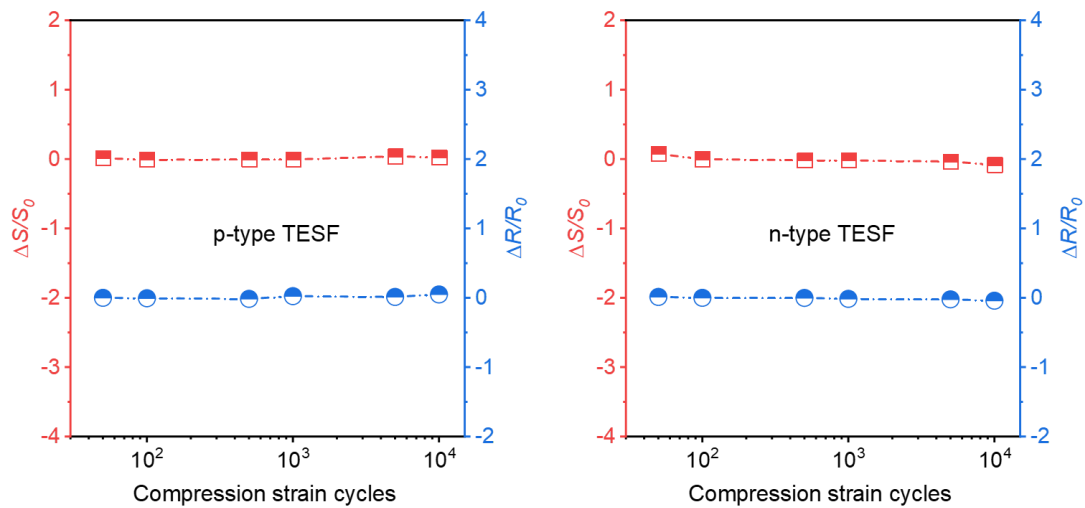


Fig. R10. (**Supplementary Fig. 14** in the revised manuscript) Changes of Seebeck coefficient ($\Delta S/S_0$) and resistance ($\Delta R/R_0$) of p-type TESF and n-type TESF during 10,000 compression cycles, where ΔS is the Seebeck coefficient change value, and S_0 is the initial Seebeck coefficient.

Table R2 (Supplementary Table 2). Comparison of strain sensing performance of the present study with reported devices.

	Strain response time (ms)	Max strain cycles	Ref.
He <i>et al.</i>	510	100	38
Zhang <i>et al.</i>	1610	1000	39
Tian <i>et al.</i>	200	6000	40
Zhao <i>et al.</i>	170	1000	41
Gao <i>et al.</i>	134	1000	42
Li <i>et al.</i>	80	100	43
Peng <i>et al.</i>	24.9	3200	44
3D TESF sensor	20	10000	This work

References

1. Zheng Z-H, *et al.* Harvesting waste heat with flexible Bi₂Te₃ thermoelectric thin film. *Nat Sustain* **6**, 180-191 (2023).
2. Wang L, *et al.* Solution-Printable Fullerene/TiS₂ Organic/Inorganic Hybrids for High-Performance Flexible *n*-Type Thermoelectrics. *Energy Environ Sci* **11**, 1307-1317 (2018).
3. Nan K, *et al.* Compliant and stretchable thermoelectric coils for energy harvesting in miniature flexible devices. *Sci Adv* **4**, eaau5849 (2018).
4. Hao Y, He X, Wang L, Qin X, Chen G, Yu J. Stretchable Thermoelectrics: Strategies, Performances, and Applications. *Adv Funct Mater* **32**, 2109790 (2022).
5. Khan ZU, *et al.* Thermoelectric Polymers and their Elastic Aerogels. *Adv Mater* **28**, 4556-4562 (2016).
6. Han S, *et al.* A Multiparameter Pressure – Temperature – Humidity Sensor Based on Mixed Ionic – Electronic Cellulose Aerogels. *Adv Sci* **6**, 1802128 (2019).
7. Memon H, Yasin S, Khoso NA, Memon S. STUDY OF WRINKLE RESISTANT, BREATHABLE, ANTI-UV NANOCOATED WOVEN POLYESTER FABRIC. *Surf Rev Lett* **23**, 1650003 (2015).
8. Chen R, Deng S, Cui T, Duan S, Jia Q, Zhang L. Progress in recycling and reutilization of waste polyethylene terephthalate. *Prog Rubber Plast Recycl Technol* **40**, 77-97 (2023).
9. Babaei M, Jalilian M, Shahbaz K. Chemical recycling of Polyethylene terephthalate: A mini-review. *J Environ Chem Eng* **12**, 112507 (2024).
10. Wang C-Y, Chu H-Y, Wang C-C. Converting waste PET plastics to high value-added MOFs-based functional materials: A state of the art review. *Coordin Chem Rev* **518**, 216106 (2024).

11. Wang K, *et al.* High value-added conversion and functional recycling of waste polyethylene terephthalate (PET) plastics: A comprehensive review. *J Environ Chem Eng* **12**, 113539 (2024).
12. Wyss KM, *et al.* Upcycling of Waste Plastic into Hybrid Carbon Nanomaterials. *Adv Mater* **35**, 2209621 (2023).
13. Duraia E-sM, Opoku M, Beall GW. Efficient eco-friendly synthesis of carbon nanotubes over graphite nanosheets from yellow corn: a one-step green approach. *Sci Rep* **14**, 16405 (2024).
14. Mikhalchan A, Ramos Lozano S, Fernández Gorgojo A, González C, Vilatela JJ. Network structure enabling re-use and near full property retention in CNT sheets recycled from thermoset composites. *Carbon* **220**, 118851 (2024).
15. Lu L, *et al.* Citric Acid and Polyvinyl Alcohol Induced PEDOT: PSS with Enhanced Electrical Conductivity and Stretchability for Eco-Friendly, Self-Healable, Wearable Organic Thermoelectrics. *Macromol Rapid Comm* **45**, 2400394 (2024).
16. Díez-Pascual AM. Environmentally Friendly Synthesis of Poly(3,4-Ethylenedioxythiophene): Poly(Styrene Sulfonate)/SnO₂ Nanocomposites. *Polymers* **13**, 2445 (2021).
17. Lv C, Zhou X, Chen C, Liu X, Qian J. Highly sensitive and flexible ammonia sensor based on PEDOT:PSS doped with Lewis acid for wireless food monitoring. *Chem Eng J* **493**, 152652 (2024).
18. Luo B, *et al.* Nonadjacent Wireless Electrotherapy for Tissue Repair by a 3D-Printed Bioresorbable Fully Soft Triboelectric Nanogenerator. *Nano Lett* **23**, 2927-2937 (2023).
19. Zheng B, Jiang G, Dong Z, Liu H. Design of warp knitting electronic shogging system based on mixed-velocity planning curve. *Text Res J* **91**, 1594-1608 (2021).
20. Zheng B, Jiang G, Zhang A, Zhang Y. Design of electronic shogging dynamic compensation

system for high-speed warp knitting machine. *J Text I* **113**, 412-421 (2022).

21. Jin Q, *et al.* Flexible layer-structured Bi₂Te₃ thermoelectric on a carbon nanotube scaffold. *Nat Mater* **18**, 62-68 (2019).
22. Ding Y, *et al.* High Performance n-Type Ag₂Se Film on Nylon Membrane for Flexible Thermoelectric Power Generator. *Nat Commun* **10**, 841 (2019).
23. Wang L, *et al.* Exceptional thermoelectric properties of flexible organic–inorganic hybrids with monodispersed and periodic nanophase. *Nat Commun* **9**, 3817 (2018).
24. Yang G, *et al.* The role of spin in thermoelectricity. *Nature Reviews Physics* **5**, 466-482 (2023).
25. Wang X, Du Y, Dou S, Zhang C. Room Temperature Giant and Linear Magnetoresistance in Topological Insulator Bi₂Te₃ Nanosheets. *Phys Rev Lett* **108**, 266806 (2012).
26. Yang G, *et al.* Ultra-High Thermoelectric Performance in Bulk BiSbTe/Amorphous Boron Composites with Nano-Defect Architectures. *Adv Energy Mater* **10**, 2000757 (2020).
27. Zhao L, *et al.* Significant enhancement of figure-of-merit in carbon-reinforced Cu₂Se nanocrystalline solids. *Nano Energy* **41**, 164-171 (2017).
28. Wang Y, *et al.* Advancements in Nanotechnology-Based PEDOT and Its Composites for Wearable Thermoelectric Applications. *Small Sci* **4**, 2400149 (2024).
29. Islam SR, Wang W, Junjie P, Jiang J, Shao H, Chen N. Study on thermal, mechanical, and wettability properties of three-dimensional weft-knitted spacer fabrics with various silica aerogels coating. *Text Res J* **93**, 3611-3629 (2023).
30. Sun Y, Lyu L, Yan B, Jiang G, Ma P. Preparation and characterization of 3D flexible high-distance spacer fabric/foam composite. *Compos Struct* **261**, 113549 (2021).
31. Bilisik K. Two-dimensional (2D) fabrics and three-dimensional (3D) preforms for ballistic and

stabbing protection: A review. *Text Res J* **87**, 2275-2304 (2016).

32. Ali M, *et al.* Development and Comfort Characterization of 2D-Woven Auxetic Fabric for Wearable and Medical Textile Applications. *Clothing Text Res J* **36**, 199-214 (2018).
33. He J, *et al.* A Universal high accuracy wearable pulse monitoring system *via* high sensitivity and large linearity graphene pressure sensor. *Nano Energy* **59**, 422-433 (2019).
34. Ouyang H, *et al.* Self-Powered Pulse Sensor for Antidiastole of Cardiovascular Disease. *Adv Mater* **29**, 1703456 (2017).
35. Lin Y, *et al.* Porous Enzymatic Membrane for Nanotextured Glucose Sweat Sensors with High Stability toward Reliable Noninvasive Health Monitoring. *Adv Funct Mater* **29**, 1902521 (2019).
36. Shi J, *et al.* Multiscale Hierarchical Design of a Flexible Piezoresistive Pressure Sensor with High Sensitivity and Wide Linearity Range. *Small* **14**, 1800819 (2018).
37. Teymourian H, *et al.* Wearable Electrochemical Sensors for the Monitoring and Screening of Drugs. *ACS Sens* **5**, 2679-2700 (2020).
38. He Y, Lin X, Feng Y, Luo B, Liu M. Carbon Nanotube Ink Dispersed by Chitin Nanocrystals for Thermoelectric Converter for Self-Powering Multifunctional Wearable Electronics. *Adv Sci* **9**, 2204675 (2022).
39. Zhang D, *et al.* Photo-thermoelectric effect induced electricity in stretchable graphene-polymer nanocomposites for ultrasensitive strain sensing. *Nano Res* **12**, 2982-2987 (2019).
40. Tian Y, *et al.* Ultra-stretchable, sensitive and breathable electronic skin based on TPU electrospinning fibrous membrane with microcrack structure for human motion monitoring and self-powered application. *Chem Eng J* **480**, 147899 (2024).

41. Zhao X, *et al.* Thermoelectric generator based on anisotropic wood aerogel for low-grade heat energy harvesting. *J Mater Sci Technol* **120**, 150-158 (2022).
42. Gao X-Z, *et al.* Self-Powered Resilient Porous Sensors with Thermoelectric Poly(3,4-ethylenedioxythiophene):Poly(styrenesulfonate) and Carbon Nanotubes for Sensitive Temperature and Pressure Dual-Mode Sensing. *ACS Appl Mater Interfaces* **14**, 43783-43791 (2022).
43. Li M, *et al.* Large-Area, Wearable, Self-Powered Pressure – Temperature Sensor Based on 3D Thermoelectric Spacer Fabric. *ACS Sens* **5**, 2545-2554 (2020).
44. Peng J, *et al.* MXene-based thermoelectric fabric integrated with temperature and strain sensing for health monitoring. *J Mater Sci Technol* **212**, 272-280 (2025).