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摩擦电纳米发电机自驱动传感体系研究进展

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摘　要

摩擦电纳米发电机(triboelectric nanogenerator, TENG)能够收集到周围环境以及人体的机械能，并通过摩擦起电和静电感应将其转化成电能，是解决当今化石能源危机，发展绿色能源的有效方式之一。纳米材料由于具有超高的比表面积、优异的稳定性、较低的成本和良好的导电性，是一种有效的新型导电填料，可以用来提高TENG的电输出性能。此外，基于摩擦电纳米发电机可以开发出自驱动多功能性传感器，以监控人类运动或外部环境。

关键词

摩擦电纳米发电机，纳米材料，风速测感，电子皮肤

Research Progress on Self-Driven Sensing System of Triboelectric Nanogenerators

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Abstract

Triboelectric nanogenerators (TENG) can collect the mechanical energy of the surrounding environment and human body, and convert it into electricity through friction and electrostatic induction, which is one of the effective ways to solve the fossil energy crisis and develop green energy. Nanomaterials are considered as a new and effective conductive filler to improve the electrical

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output performance of TENG because of their ultra-high specific surface area, excellent stability, low-cost, and high conductivity. In addition, based on triboelectric nanogenerators, self-driving multifunctional sensors can be developed to detect external stimuli of human motion or environmental conditions.

Keywords

Triboelectric Nanogenerator, Nanomaterials, Wind-Speed Sensing, Electronic-Skin

1. 引言

能源危机已引起各国的广泛关注，开发新型高效的绿色能源对社会发展具有重要意义。从环境中获取能源具有高度的可持续性和环境友好性，是一种很有前途的办法[1]-[6]。例如零排放的可再生能源：太阳能和风能[1] [7] [8] [9] [10]；地球上的蓝色能源：潮汐能、热能和渗透能[11] [12] [13] [14] [15]，都为实现可持续发展和绿色环保提供了新的思路。

物联行业和信息技术的飞速发展的关键驱动力是大数据和云计算及相关传感器技术。由于目前传感器网络包括数千甚至数百万具有不同功能的传感器节点[16] [17]，有必要开发能够收集环境机械能量用以驱动自身操作的自供电传感器技术，来实现传感器的无线性、可持续性和独立操作性。实现传感器的自供电，通常有两个路径：第一个路径是通过开发能够采集环境能量来驱动传统传感器的设备；另一个是研究一种新型传感器——自动供电传感器——其能够自主形成电信号，用于响应来自周围环境的冲击[18] [19] [20]。摩擦电纳米发电机(TENG)作为一种新的机械能收集技术，因其发出的特征电信号(幅度、频率、周期数等)是直接由输入的机械行为决定[21] [22] [23] [24]，所以可作为自供电的有源机械传感器。

TENG 性能的主要影响因素是器件结构、表面形貌、摩擦电材料和介电性能[25] [26] [27] [28] [29]。根据实际应用中的不同的器件结构，TENG 具有四种基本工作模式：垂直接触－分离、水平滑动、单电极和独立层模式[13] [22] [28] [30] [31] [32] [33]。通过在这四种基本模式的基础上进行交叉改进，研究人员已经设计了结构更加复杂和智能的 TENGs，能够满足在不同场景下，对不同类型的能量采集和自供电传感需求。由于摩擦电材料的表面形貌对有效接触面积有很大影响，而有效接触面积直接决定了接触带电过程中的表面总电荷，所以，材料的表面形貌影响 TENG 的输出性能[34]-[39]。目前，研究人员发现两种摩擦电材料之间的摩擦电极性差异越大(一种材料失去电子，另一种材料获得电子)，TENG 的输出性能就越好[40] [41]。如果摩擦电材料具有优异的介电性能，不仅可以提高表面电荷密度，还可以有效地避免静电击穿效应。因此，TENG 的材料，特别是摩擦电材料的选择，直接影响到 TENG 的输出性能。此外，所用材料的特殊物理和化学性质为 TENG 提供了很多理想的特性，如柔韧性、可伸缩性和生物相容性等[20] [23] [42] [43]。所以，根据实际情况，提高 TENG 器件机械和电学性能的关键是选择合适的结构、表面形貌、摩擦电材料。

本文主要目的是让读者了解什么是 TENG？TENG 的四种工作模式；不同材料通过不同工作模式产生电势差，在自驱动传感器中的应用。从 TENG 不同工作模式开始介绍到目前主要在收集风能；压力传感；轨迹监控等方面具体的应用前景。体现了 TENG 在机械能转化为电能的优势便捷。

2. 摩擦电纳米发电机简述

2.1. 摩擦电纳米发电机

在过去的几年里，出现了一种名为摩擦电纳米发电机(TENG)的新型能量收集技术。TENG 利用摩擦电效应和静电感应的耦合，具有新颖而独特的机理。与其他已开发的现有技术相比，它具有无与伦比的优势，比如高功率密度、轻重量、小体积、低成本、高灵活性甚至高透明性。自 2012 年王中林团队发布第一份报告以来，TENG 发展非常迅速，在全球范围内引起了广泛的研究兴趣[44] [45] [46]。研究人员通过构建先进的装置，极大地提高了 TENG 输出功率，并开发了该技术在能源和传感方面的相关应用。

2.2. 工作原理

摩擦电效应是一种电荷转移，任何两种材料在相互接触后，以相反的符号带电。再利用静电感应，将可提供移动电荷的导电电极制造在摩擦电荷的背面。在 TENG 中，背面电极上是感应电荷而不是摩擦电荷，而摩擦电荷实际上形成了输出电流。当携带相反摩擦电荷的两块材料进行相对运动时，两个电极之间产生的电位差会引起感应电荷的瞬态流动[28] [46] [47]。如果连接两个电极之间的负载能提供有效的输出功率，那么在这个过程中，机械能就能够转换成电能。由于相对运动的形式可以是多种多样的，所以 TENG 能够收集各种类型的机械能。

2.3. 工作模式

近些年来，通过改变电极配置和摩擦电层的移动方式来实现静电感应过程，已经建立了 TENG 的四种基本模式。

1) 垂直接触－分离模式：

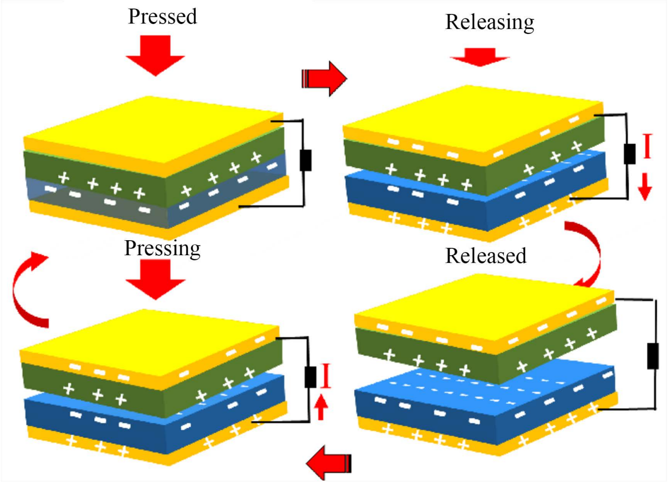

Figure 1. The working mechanism of vertical contact-separation TENG [28]
图 1. 垂直接触－分离 TENG 的工作机理[28]

垂直接触－分离模式是 TENG 的第一个基本模式(图 1)。在这种模式下，具有明显不同摩擦电极性的两层薄膜以堆叠配置相互面对，而电极附于介电膜的外表面上。如图 1 所示，在外部机械力的推动下，两摩擦电层之间可相互物理接触，进而形成带相反电荷的表面。随后，当释放时，两个表面从垂直至平面的方向上被一微小间隙所分隔，这会在二电极间形成一电位降，并驱动电子流通过连接的负载。如果间隙完全闭合，则摩擦电荷所形成的电位消失，而电子将返回以实现电气平衡。

2) 水平滑动模式：

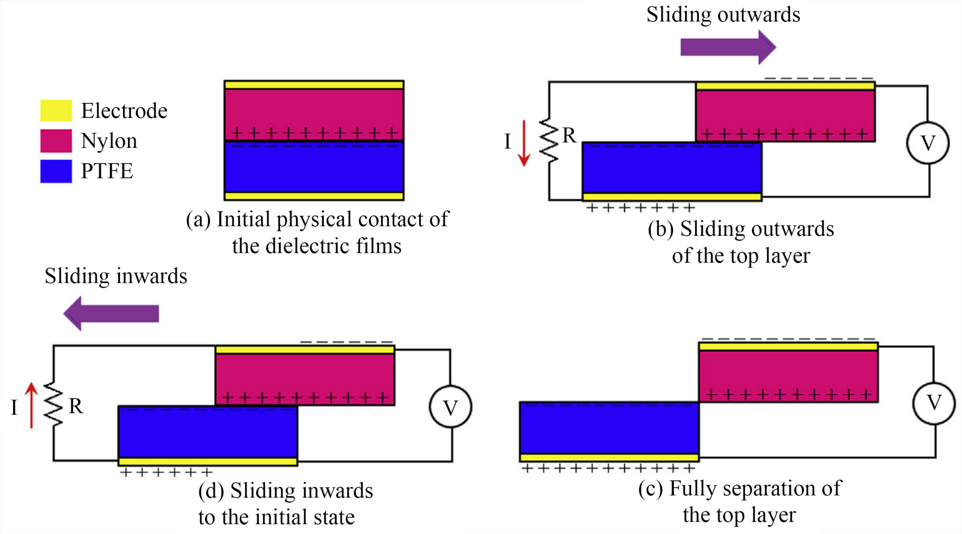

Figure 2. The working mechanism of horizontal sliding TENG [48]
图 2. 水平滑动 TENG 的工作机理[48]

基于水平滑动的 TENG 的器件结构与垂直接触-分离的相同(图 2)。电流是通过在两种材料表面间的周期性水平滑动形成的。从相同的接触状态出发，通过使接触层滑动而分离，从表面内方向上再进行分离。两种表面间的这种相对滑动，将在两种表面上形成相互摩擦电荷。感应电势将驱使在顶端与底部电极上的电子进行流动。

3) 单电级模式：

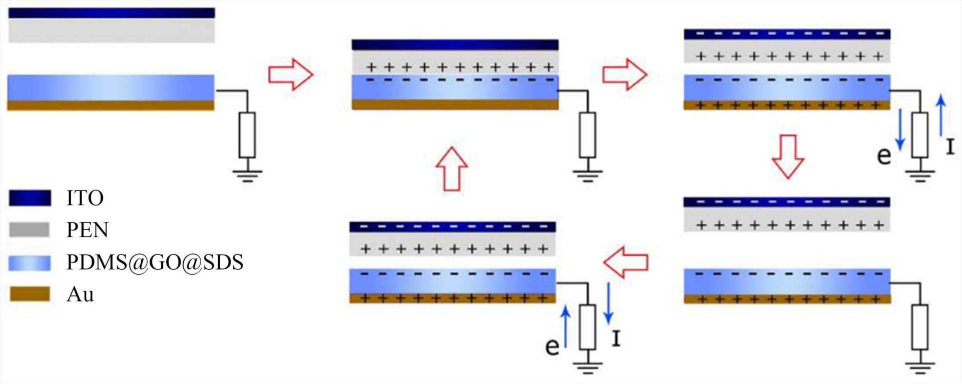

Figure 3. The working mechanism of single-electric TENG [49]
图 3. 单电级 TENG 的工作机理[49]

在自然界中，一些移动的物体，通常会因为和空气或其他物质(例如衣服和人体皮肤)接触，而导致带电。所以，这些运动的物质材料就能够直接作为 TENG 中的摩擦层，起到诱导发电的作用。但是，在这种情形下，如果必须连接电极，这在实际使用中是相当不便利的。在这方面，引入了单电极 TENG，其只有一个电极直接与移动的摩擦电层连接。另一个电极只是作为电子源的参考电极，可以是较大导体或者是地面(图 3)。如果 TENG 的尺寸有限，则移动的物体接近或离开 TENG 将会改变局部电场分布，从而导致底部的电极与地或参比电极之间发生电子交换以起到保持平衡电位的目的。

4) 独立层模式：

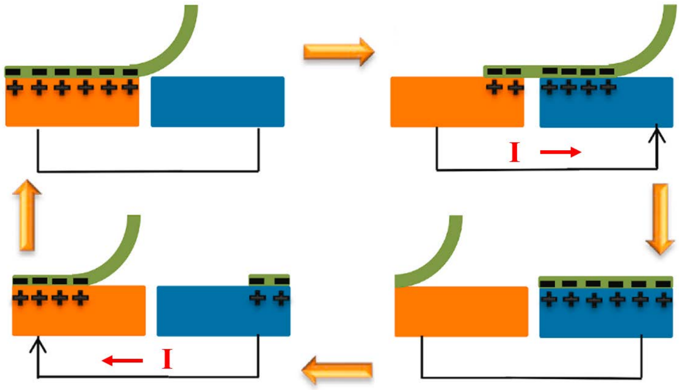

Figure 4. The working mechanism of individual layer TENG [9]
图 4. 独立层 TENG 的工作机理[9]

当从进行摩擦的自由移动的物体中获取能量时，两个固定电极在 TENG 中可以具有对称的配置。独立摩擦电层的运动使其交替接近两个电极中的任何一个，从而使感应电势差周期性地反转，以此来驱动外部负载(图 4)。

3. 应用领域

3.1. 生物能

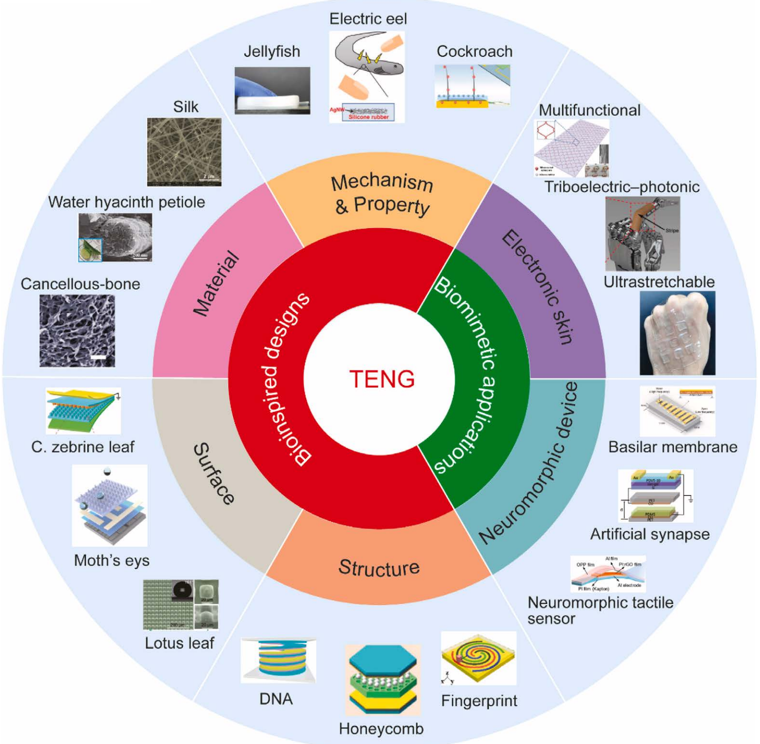

Figure 5. Bio-inspired TENG and biomimetic applications of TENG [32]
图 5. 受生物启发的 TENG 和 TENG 的仿生应用[32]

人体的肢体运动产生的能量可以视为一种机械能，也可以被 TENG 收集。因此，采集人体机械能为驱动电子皮肤提供了一种新的解决方案[18] [19] [23] [32] [50]-[64]。TENG 作为自供电传感器具有高灵敏度，可以快速响应，有效地将机械信号转换为电信号[51] [65] [66]。如图 5，基于 TENG 的电子皮肤已被用作可穿戴电源和自供电传感器，如运动、呼吸和触摸传感器，应用范围十分广泛。

3.2. 收集风能

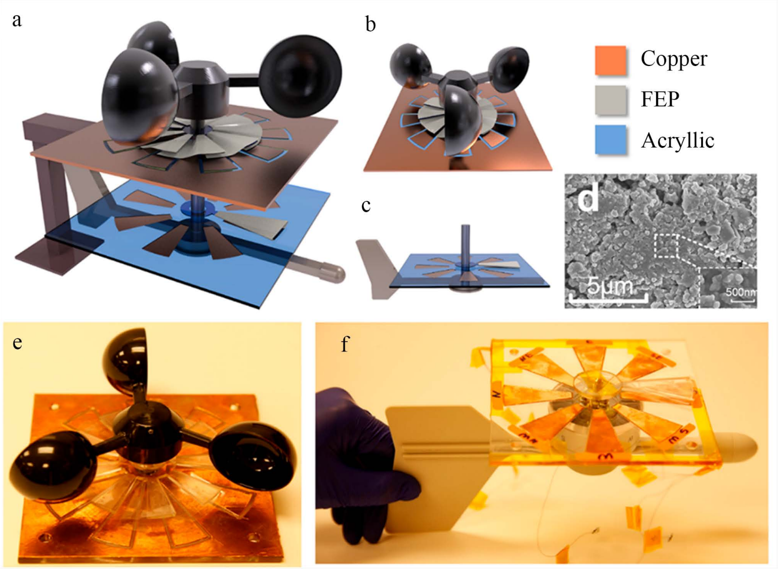

Figure 6. Triboelectric nanogenerator for collecting wind energy [67]
图 6. 收集风能的摩擦电纳米发电机[67]

风能作为一种清洁的、分布广泛的机械能源，越来越受到人们的重视，并可能在未来的电力供应中发挥重要作用。风力驱动的摩擦电纳米发电机被认为是 TENG 家族的一个重要的支流，它也可以作为自供电传感器，主动监测风速、湿度以及呼出的酒精浓度[6]-[12] [33] [68] [69] [70] [71]。

2018 年，Wang 等[67]提出了一种基于风速计摩擦电纳米发电机和风叶摩擦电纳米发电机(A-TENG)的自力式风力传感器系统，用于同时检测风速和风向(图 6 所示)。如图 6(a)~(c)所示，是由 FEP 作为摩擦材料组装成的 TENG 结构图与饼状转子和定子相连接的叶片。图 6(d)是摩擦材料 FEP 的扫描电镜图。图 6(e)和图 6(f)是 TENG 组装好的实物图。其采用柔性摩擦方式代替典型的刚性摩擦方式，大大提高了 TENG 的电输出性能。Wang 团队优化了尺寸、圆心角度和材料等参数，提高了分辨率、灵敏度和测量范围。优化后的 A-TENG 可以提供 88 V 的电压、6.3 μA 的电流，其对应的最大功率输出为 0.47 mW (风速为 6.0 m/s)，能够驱动电子设备进行数据传输和存储。TENG 信号的当前峰值可以用来分析风速，以减少能耗。A-TENG 对来风能够作出快速响应，并准确输出风向数据。其作为风速传感器系统，可以很好地探测到 2.7~8.0 m/s 的风速(与商用传感器一致)，并能够监测到 8 个风向。

3.3. 压力传感

TENG 的输出性能(开路电压、短路电流等)在很大程度上受外部机械刺激的幅度/频率影响，其中正常按压是最常见的类型之一。在这方面，基于 TENG 的主动传感器的最直接的应用是监测施加在 TENG 上的外部压力/触摸。基于这个原理，研究人员已经研制出几种具有灵敏度高、响应快和功耗低的传感器[21] [52] [72]。

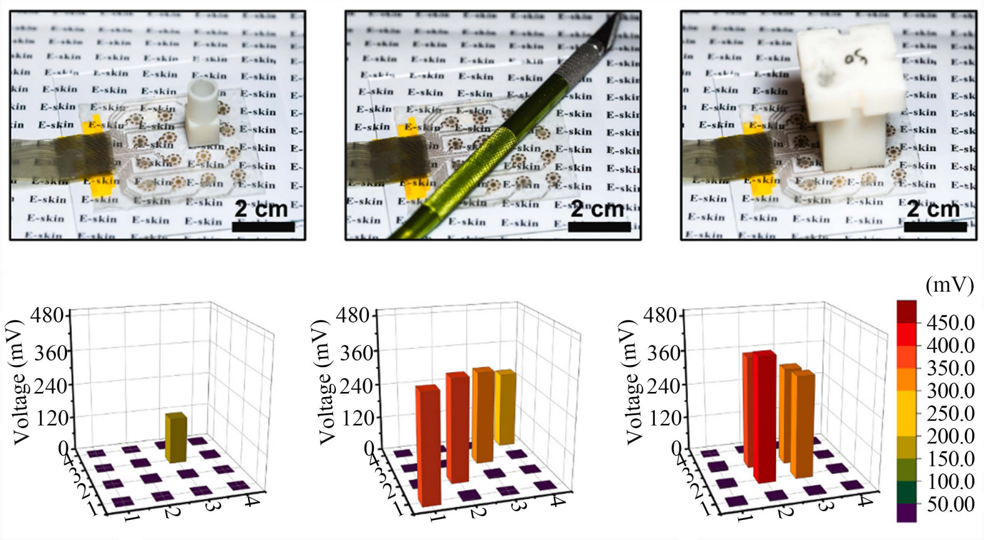

Figure 7. Pressure mapping of pressure sensor based on triboelectric nanogenerator [50]
图 7. 基于摩擦电纳米发电机的压力传感器的压力映射[50]

2021 年，He 等[50]根据蹦床的机械设计以及基于表皮电子学中的加工技术，研制了一款基于摩擦电效应的薄、软、可伸缩的电子皮肤自供电触摸感应器。在砂纸微结构修饰的辅助下，TENG 传感器的电学特性获得了极大的提高，可以在很宽的压力范围内进行分辨，灵敏度达到 0.367 mV·Pa^{-1}。该传感器具有良好的可伸缩性和传感稳定性，即使在高应变高达 35%的情况下也能准确地保持信号输出不变。如图 7 所示，用于压力映射的 4 × 4 触觉阵列，验证了自主供电的压力传感器的实用性。

3.4. 轨迹监控

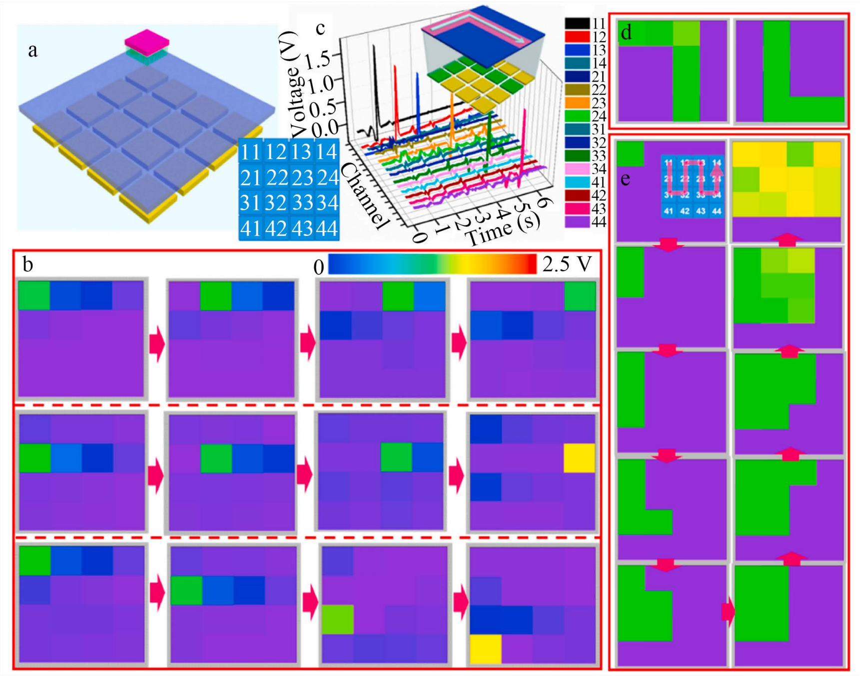

Figure 8. Trajectory tracking demonstration based on TENG matrix [65]
图 8. 基于 TENG 矩阵的轨迹跟踪演示[65]

目前，轨迹跟踪在自动控制、机器人和监视等各种应用中的需求越来越大。现有的跟踪传感器通常依靠光学、微波和声学。然而，所有的传感器在没有外部电源的情况下都不能工作。最近，研究人员致力于利用 TENG 进行一维的主动运动跟踪，可以在环境刺激触发时提取摩擦电纳米发电机的电信号[51] [65] [66]。

2020 年，Cui 等[65]报道了基于导电海绵电刷结构的 TENG 作为一种双模机械能量采集器和自供电传感器。基于导电海绵的触点分离和滑动模式的 TENG 拥有较高的电学特性、良好的机械反应灵敏度和环境适应性。另外，如图 8 所示，研究团队设计了采用导电海绵单元的弹道跟踪传感器矩阵。如图 8(a)是触觉轨迹映射阵列光学图像。图 8(b)和图 8(c)是实时信号映射的触摸轨迹传感器，可以反映触摸序列。图 8(d)和图 8(e)是基于 TENG 矩阵的轨迹跟踪演示。这优秀的实时监控能力和完善的轨迹记录，加上独特的自动供电系统，表明了 TENG 在自动供电轨迹跟踪方面有着极大的应用潜力。

4. 结论

摩擦电纳米发电机具有灵活的结构和吸引人的性能，它依赖于静电感应和摩擦电效应的耦合，将各种规模的机械能转化成电能。它可以作为这些小型电子设备供电的理想电源，也可以用作自供电的有源机械传感器。聚合物材料因其优异的柔韧性和易加工性，在摩擦电纳米发电机领域具有很高的应用前景。然而，由于其固有的导电和介电性能较差，限制了其在高功率密度器件中的进一步应用。因此通过对聚合物材料进行一系列的改性，例如对膜表面进行刻蚀和掺杂功能粒子，这样就可以应用于自供电传感设备。

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