Enhancing Piezoelectric Sensors in Sports Instrumentation: Addressing Durability with Nano-Coating Techniques

Syukran Hakim, Abdul Nasir, Ahmad Noor Syukri Zainal Abidin, Mohamad Rusydi Mohamad Yasin, and Waheb A. Jabbar

Abstract Piezoelectric sensors have significantly transformed the field of sports instrumentation by providing an unprecedented level of accuracy in the measurement and analysis of dynamic loads, motion, and vibrations. In the past, the utilization of flexible sensors in sports has been limited due to their inherent rigidity. However, significant progress in the field of material science has paved the way for a transformative era, enabling the development of flexible sensors with enhanced flexibility. This breakthrough has substantially broadened the range of applications for these sensors within the realm of sports. This review examines the impact of nano-coatings on improving the longevity of sensors, particularly in the challenging context of sports. The examination of specific instances, such as the composite of CNT/PVA/ZnO and the incorporation of ZnO nanostructures into sensors based on PVDF-TrFE, serves to underscore the collaborative relationship between novel material compositions and the effectiveness of sensors. Nevertheless, there are still existing gaps in our understanding, namely, about the enduring impacts of nano-coatings and their use in practical sporting settings. As the relationship between sports science and material engineering becomes more robust, there is a growing potential for customized sensor

S. Hakim · A. Nasir
Faculty of Electrical and Electronic Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

A. N. S. Z. Abidin (✉) · M. R. M. Yasin
Faculty of Manufacturing and Mechatronic Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
e-mail: ansyukri@miros.gov.my

A. N. S. Z. Abidin
Malaysian Institute of Road Safety Research (MIROS), Institut Penyelidikan Keselamatan Jalan Raya Malaysia (MIROS), Taman Kajang Sentral, Lot 125-135, Jalan TKS 1, 43000 Kajang, Selangor, Malaysia

W. A. Jabbar
School of Engineering and Built Environment, Birmingham City University, Birmingham, West Midlands, England, UK

systems that will enhance the integration of laboratory research with on-field applications. This paper offers a comprehensive analysis of the present status, obstacles, and prospective pathways of piezoelectric sensors that have been improved through the utilization of nano-coating techniques in the field of sports instrumentation.

Keywords Piezoelectric sensors · Nano-coating techniques · Sports instrumentation · Material durability · Flexible sensor design

1 Introduction to Piezoelectric Sensors Application in Sports

Piezoelectric sensors have become a crucial technology in the field of sports instrumentation due to their capability to accurately measure dynamic and static loads, motion, and vibrations (Chen et al. 2020; Kim et al. 2020; Babu et al. 2023; Sufian et al. 2021; Rosli et al. 2021a; Ma et al. 2019; Baharuddin et al. 2022; Patel et al. 2020; Abidin et al. 2022; Abdullah et al. 2022; Nasir et al. 2013; Su et al. 2020). These sensors, which possess the ability to transform mechanical energy into electrical signals, have been utilized in several domains, encompassing the monitoring of athletes' performance as well as the assurance of the structural soundness of sporting equipment (Su et al. 2020; Taborda and López 2020; Baharuddin et al. 2023; Atalla et al. 2022; Hasya et al. 2022; Ryu et al. 2021; Babu et al. 2022, 2021; Rosli et al. 2019; Liu et al. 2021; Zhao et al. 2022; Jamaludin et al. 2017; Ma et al. 2022). The CNT/PVA/ZnO composite has demonstrated promise in the monitoring of static and dynamic loads on concrete structures, suggesting its suitability for use in sports infrastructure (Chen et al. 2020). Furthermore, the emergence of wearable piezoelectric yarns has created opportunities for the analysis of gait data, hence offering valuable insights into the motions and biomechanics of athletes, as depicted in Fig. 1 (Ryu et al. 2021).

In the past, the utilization of piezoelectric sensors in the field of sports was constrained by their inflexibility and restricted flexibility (Ma et al. 2022; Rosli et al. 2021b; Jamaludin et al. 2018a, b; Zhang and Shi 2022; Nasir et al. 2015; Zhang et al. 2022; Elvirsson et al. 2022; Jamaludin and Yassin 2013; Chen et al. 2022; Md Kamil et al. 2022; Alsibai et al. 2018; Ramli et al. 2022; Homayounfar et al. 2022). Nevertheless, the field of material science and engineering has made significant progress in the development of sensors that possess flexibility and adaptability (Elvirsson et al. 2022; Jamaludin and Yassin 2013; Chen et al. 2022; Md Kamil et al. 2022; Alsibai et al. 2018; Ramli et al. 2022; Homayounfar et al. 2022; Binti Kamarudin et al. 2021; Ali et al. 2022; Liu et al. 2023; Farag et al. 2019; Atalla et al. 2020; Lee et al. 2021; Li et al. 2023; Nguyen et al. 2023; Wu et al. 2023; Saniman and Ihara 2016, 2014; Wang et al. 2023). The utilization of flexible sensors in sports has been enhanced by the transition from rigid sensors to more adaptable alternatives, such as binary spiky/spherical nanoparticle films (Kim et al. 2020) and cotton fabric (Ma et al. 2019).

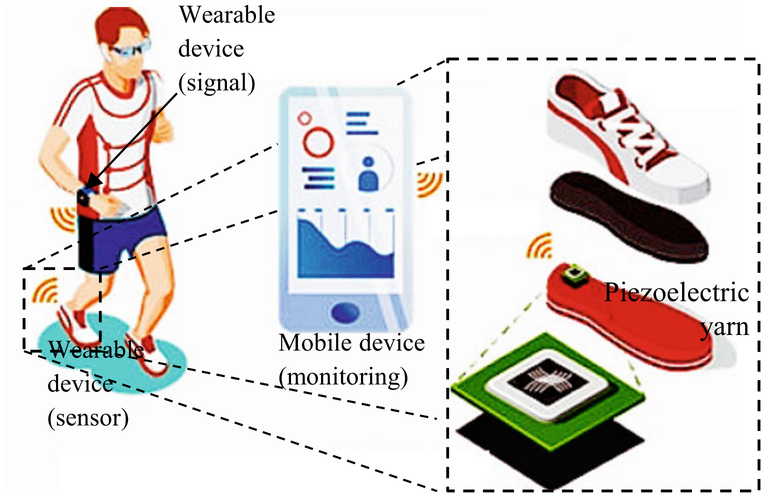

Fig. 1 Wearable piezoelectric yarn technology has made it possible to analyze gait data and gain insights into the biomechanics and motions of athletes (Ryu et al. 2021)

The aforementioned advancements have facilitated the ability to monitor players in real-time, hence improving training protocols, mitigating the risk of injuries, and conducting comprehensive performance analysis (Kim et al. 2020; Babu et al. 2023; Sufian et al. 2021; Rosli et al. 2021a; Ma et al. 2019).

The field of sports instrumentation has experienced notable progress in the sphere of piezoelectric sensor technologies. The developments in question are not solely confined to the design of the sensor, but also involve the selection of materials and the composition of their structures. An example of an improvement in the piezoelectric characteristics of PVDF-TrFE-based sensors is observed with the incorporation of ZnO nanostructures (Liu et al. 2023). In a similar vein, the employment of magnesium-doped zinc oxide nanorods has led to the creation of flexible piezoelectric pressure sensors with the ability to detect human mobility and vital signs in real-time (Li et al. 2023). Moreover, the advancement of triboelectric nanogenerators integrated into garments represents a shift toward the incorporation of these sensors directly into athletic apparel, hence facilitating uninterrupted data gathering, as illustrated in Fig. 2 (Wang et al. 2023).

Although piezoelectric sensors possess several advantages, their longevity, particularly in the challenging context of sports, continues to be a subject of concern (Liu et al. 2023; Farag et al. 2019; Atalla et al. 2020; Lee et al. 2021; Li et al. 2023; Nguyen et al. 2023; Wu et al. 2023; Saniman and Ihara 2016, 2014; Wang et al. 2023). The performance of these entities might deteriorate with time due to several factors, including repetitive mechanical stress, exposure to climatic conditions, and the effects of wear and tear. In order to tackle this issue, scholars have resorted to employing nano-coating methodologies. An example of the assessment of cementitious materials utilizing PZT sensors through the EMI approach revealed that

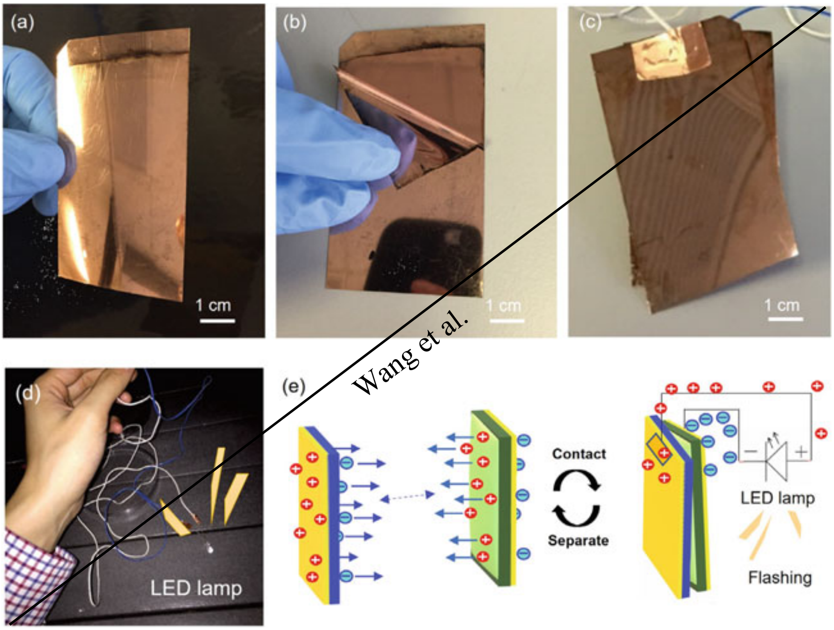

Fig. 2 **a**, **b**, and **c** Depict the two triboelectric layers that were initially bound together, respectively, before, during, and after separation. The two triboelectric layers—the PET and PE layers—had their exterior surfaces covered with a homogeneous, extremely sticky thin copper film that was created using a chemical procedure. **d** Picture displaying an LED bulb that is lit and powered by a sturdy, flexible TENG. **e** Diagram illustrating the workings of the flexible TENG, which has the ability to run an LED light (Saniman and Ihara 2016)

polymer-coated sensors, particularly those with polyester coatings, exhibit enhanced longevity compared to their uncoated counterparts (Su et al. 2020). In a similar vein, the application of nitride nano-coatings has been found to improve the thermal stability of sheathed platinum resistance sensors, thereby ensuring their compliance with international requirements (Zhao et al. 2022). The utilization of nano-coating techniques serves to augment the robustness of the sensors, hence broadening their scope of prospective applications within the realm of sports instrumentation (Zhao et al. 2022; Jamaludin et al. 2017, 2018a, b; Ma et al. 2022; Rosli et al. 2021b; Zhang and Shi 2022; Nasir et al. 2015; Zhang et al. 2022; Elvirsson et al. 2022).

The objective of this review article is to present a thorough overview of the use, evolution, and advancements of piezoelectric sensors in the field of sports. Special attention will be given to the issues associated with durability and the potential solutions provided by nano-coating techniques. The present study aims to provide a comprehensive overview of the fundamental principles behind piezoelectric sensors and their various applications.

2 Fundamentals of Piezoelectric Sensors and Their Applications

2.1 Basic Principles of Piezoelectricity

Piezoelectricity refers to the phenomena in which specific materials produce an electric charge when subjected to mechanical stress (Chen et al. 2020; Kim et al. 2020; Babu et al. 2023; Sufian et al. 2021; Rosli et al. 2021a; Ma et al. 2019; Baharuddin et al. 2022; Patel et al. 2020; Abidin et al. 2022; Abdullah et al. 2022; Nasir et al. 2013; Su et al. 2020). The distinctive characteristic of this property has been utilized in diverse applications, particularly within the field of sensors. The CNT/PVA/ZnO composite has been extensively studied due to its noteworthy piezoresistive and piezoelectric properties. The study revealed that the piezoresistive sensitivity of CNT/PVA films is subject to variation based on the degree of PVA doping. Moreover, the combination of carbon nanotubes (CNT), polyvinyl alcohol (PVA), and zinc oxide (ZnO) demonstrated considerable promise in the detection and measurement of both stationary and moving loads, particularly in relation to concrete structures, as depicted in Fig. 3 (Chen et al. 2020).

Moreover, there has been a significant interest in organic ferroelectric materials owing to their distinct characteristics and prospective utilization in piezoelectric sensors. One example of such a material is poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)), which has been extensively investigated for its method of nanostructure fabrication. The findings of the study indicate that the nanostructured organic ferroelectric film composed of P(VDF-TrFE) exhibits notable piezoelectric and ferroelectric properties. Furthermore, the efficacy of this substance was improved by a substantial increase of 24.3% (Zhang and Shi 2022).

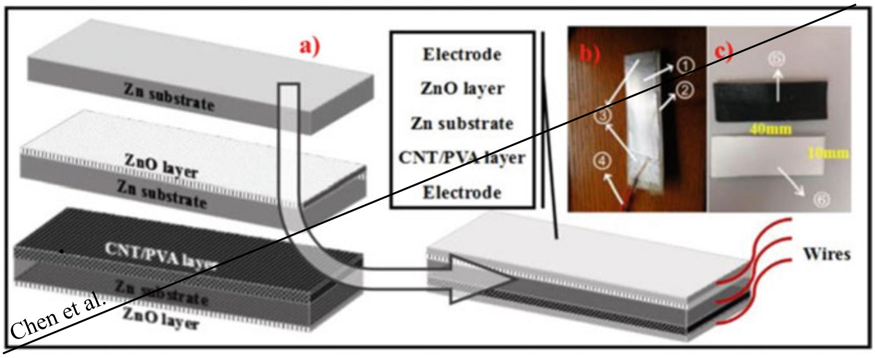

Fig. 3 The CNT/PVA/ZnO composite construction process is schematically diagrammed in (**a**), the CNT/PVA/ZnO configuration is shown in (**b**), and the CNT/PVA film and nano-ZnO array are shown in (**c**) from the front (① silver electrode, ② ③ adhesive tape, ④ wires, ⑤ CNT/PVA layer, and ⑥ nano-ZnO layer) (Chen et al. 2020)

2.2 Applications in Sports and Health Care

There has been a notable increase in the demand for motion monitoring systems within the domain of sports and health care. Flexible sensors have become increasingly popular due to their adaptability and comfort, making them a preferred option (Ma et al. 2019). One significant advancement in this field is the creation of a sensor that utilizes cotton cloth, as seen in Fig. 4 (Ma et al. 2019). The sensor exhibits not only a high level of sensitivity but also provides a wide range of sensing capabilities and a quick reaction time. The versatility of this technology is evident in its prospective applications, which encompass motion monitoring and the identification of vocal cord vibrations. This makes it a valuable instrument in the fields of sports and medical diagnostics (Ma et al. 2019). In addition, the utilization of gait analysis holds significant importance within the realm of sports, as it serves to optimize performance and mitigate the risk of injuries (Ma et al. 2019; Baharuddin et al. 2022, 2023; Patel et al. 2020; Abidin et al. 2022; Abdullah et al. 2022; Nasir et al. 2013; Su et al. 2020; Taborda and López 2020; Atalla et al. 2022; Hasya et al. 2022; Ryu et al. 2021). The subject has been significantly transformed with the advent of wearable piezoelectric yarn, commonly referred to as IEPY. IEPY is distinguished by its remarkable tensile strength and longevity, rendering it well-suited for the purpose of continuous gait data collection and processing. The prospective applications of this technology encompass various domains, including sports training, rehabilitation, and clinical diagnostics (Ryu et al. 2021).

Moreover, within the healthcare industry, it is of utmost importance to maintain a constant surveillance of human movement and critical indicators (Su et al. 2020; Taborda and López 2020; Baharuddin et al. 2023; Atalla et al. 2022; Hasya et al.

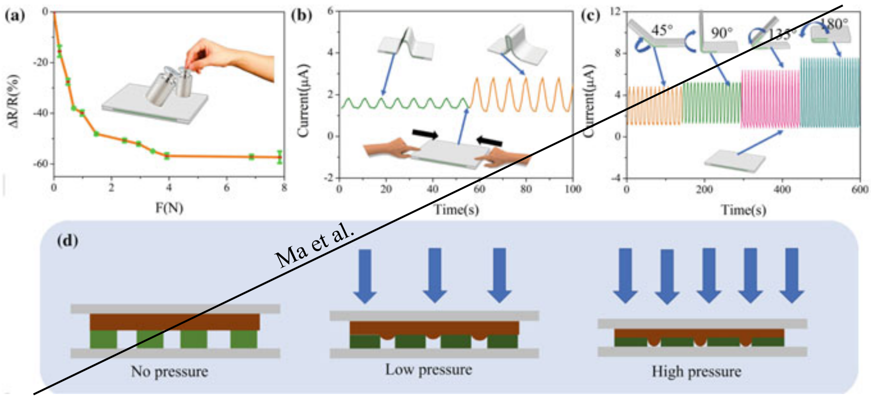

Fig. 4 Dynamic response tests include the following: **a** the sensor's relative resistance variation–pressure curve when applied at varying pressures; **b** a schematic diagram showing how the sensor's current changes as the angle of extrusion varies; **c** a schematic diagram showing how the sensor's current changes as the angle of folding varies; and **d** a schematic representation showing how the sensor deforms as pressure is applied (Ma et al. 2019)

2022; Ryu et al. 2021; Babu et al. 2022, 2021; Rosli et al. 2019; Liu et al. 2021; Zhao et al. 2022). The development of flexible piezoelectric pressure sensors, particularly those produced using Mg-doped ZnO nanorods, has facilitated the achievement of this outcome. The sensors demonstrate a remarkably high sensitivity of 3.1 V $N - 1$, which allows for the real-time monitoring of human mobility status and vital signs. These technological improvements show potential in the areas of remote patient monitoring, post-operative care, and sports performance analysis (Li et al. 2023).

3 Advancements in Sensor Design and Material Compositions

3.1 Innovative Sensor Designs

There has been a notable trend in sensor technology toward the development of designs that prioritize flexibility while maintaining high sensitivity. One significant progress in this field pertains to the creation of pressure sensors with binary spiky/spherical nanoparticle films, as depicted in Fig. 5. The sensors have exhibited notable sensitivity and a linear response within a broad spectrum of pressure levels. The architecture of these devices renders them highly suitable for use in healthcare monitoring and airflow detection, hence addressing the growing need for non-invasive and effective monitoring solutions (Kim et al. 2020).

The advent of wearable technology has significantly transformed the manner in which we observe and analyze biopotentials and bodily mobility. One notable advancement in this particular domain involves the innovation of electromechanical sensors that may be worn, which make use of the vapor deposition technique of PEDOT-Cl. The sensors possess the ability to detect a broad spectrum of pressures and have exhibited exceptional stability, maintaining 99.21% of their operational capacity following 70,000 cycles of bending. The aforementioned developments provide the ongoing monitoring of health and the study of sports performance, as seen in Fig. 6 (Homayounfar et al. 2022).

The incorporation of energy-harvesting devices into conventional garments has presented novel opportunities for the development of self-sustaining wearable electronics. Garment-integrated triboelectric nanogenerators are currently leading the way in this field of innovation (Wang et al. 2023). The devices, which have been created through the utilization of polymer-assisted metal deposition, possess qualities of both durability and flexibility. Additionally, they have the capability to be smoothly integrated into various types of apparel. The durability of their design enables them to endure regular usage and potential damage, such as exposure to water during wash testing, so presenting a bright prospect for the advancement of wearable technology (Wang et al. 2023).

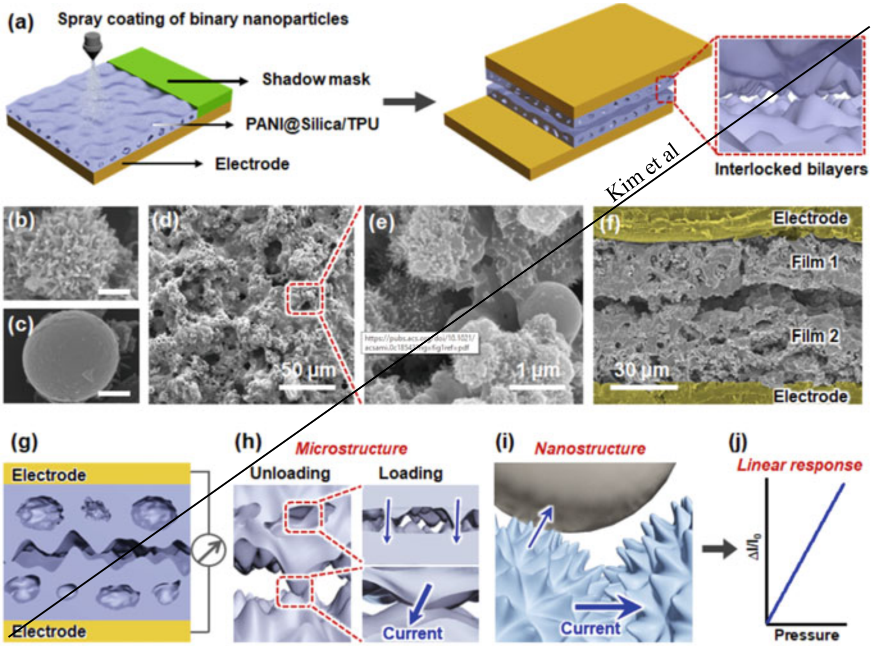

Fig. 5 The PANI@silica-based pressure sensor's, **a** diagram shows how the device is made. SEM pictures of the film surface, particles exposed on the film surface, a sea urchin-shaped PANI@silica particle, and a spherical PANI@silica particle (scale bar indicating 300 nm). The pressure sensor's cross-sectional SEM picture is shown in (**f**). **g** Interlocked porous bilayer film circuit diagram; **h** interlocked rough and porous microstructure current flow behavior under loading pressure; and **i** binary nanoparticle current flow. **j** Linear piezoresistive response induced by change in external pressure (Kim et al. 2020)

3.2 *Material Compositions and Their Impact*

The composition of materials significantly influences the functionality and efficiency of sensors (Homayounfar et al. 2022). The composite material consisting of CNT/PVA/ZnO demonstrates distinctive piezoresistive and piezoelectric properties. The sensitivity of the composite material, particularly in films composed of carbon nanotubes (CNT) and polyvinyl alcohol (PVA), has been found to exhibit variation depending on the level of PVA doping. Current research is investigating the possibilities of utilizing composites to monitor both static and dynamic stresses on structures, such as concrete. This exploration aims to provide real-time insights into the structural health of these materials (Chen et al. 2020).

The integration of nanostructures into sensor materials has the potential to greatly enhance their properties. For example, the incorporation of ZnO nanostructures into sensors based on PVDF-TrFE has led to a significant enhancement in their piezoelectric characteristics. In particular, it was observed that sensors containing 0.75 wt% ZnO NRs nanofiller demonstrated a piezoelectric response that was 2.4 times

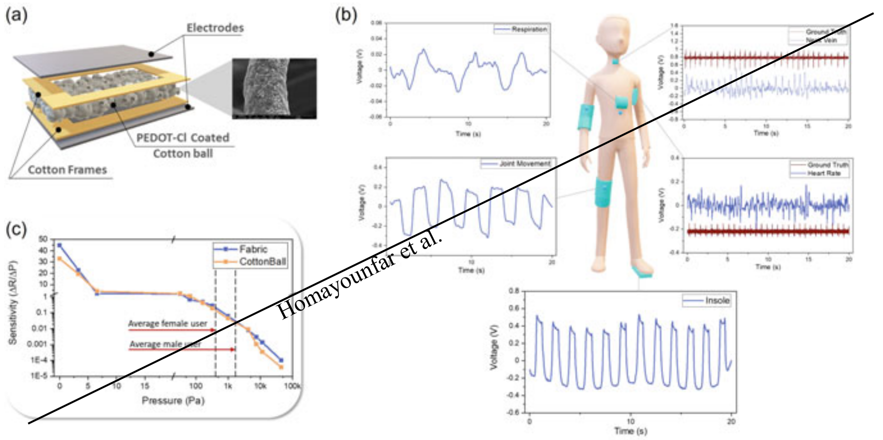

Fig. 6 **a** The sensor's schematic illustration, which includes a SEM image of the PEDOT-Cl coated layer; **b** signals obtained by the sensor that represent bodily movements and physiological processes; and **c** the sensor's sensitivity throughout a broad pressure range (Homayounfar et al. 2022)

higher than that of sensors made only of pure PVDF-TrFE. This finding highlights the significant influence of material composition on the performance of sensors (Liu et al. 2023).

The advancements in materials play a crucial role in enhancing the functionalities of piezoelectric sensors. An exemplary illustration can be observed in the utilization of magnesium-doped zinc oxide nanorods for the production of pliable piezoelectric pressure sensors. The sensors have successfully attained a remarkably high sensitivity of 3.1 V $N - 1$, hence facilitating their capability to continuously monitor the real-time motion status and vital signs of individuals. The progress made in the development of material compositions is establishing new standards in the field of health monitoring and diagnostics (Li et al. 2023).

4 Addressing Durability with Nano-Coating Techniques

4.1 Role of Nano-Coatings in Enhancing Durability

Nano-coatings have recently emerged as a crucial approach for augmenting the thermal stability of sensors. An exemplary illustration can be found in the sheathed platinum resistance sensor, which, upon application of a nitride nano-coating, satisfies global standards pertaining to platinum resistance. The aforementioned improvement guarantees the sensor's stability and accuracy, even when subjected to fluctuating thermal conditions. As a result, it becomes a dependable option for applications that require a high level of precision (Zhao et al. 2022).

In the realm of medicine, the paramount significance lies in the durability and user-friendliness of surgical instruments. The application of composite coatings on surgical needles has demonstrated a notable decrease in both the pressures required for insertion and retraction (Su et al. 2020; Taborda and López 2020; Baharuddin et al. 2023; Atalla et al. 2022; Hasya et al. 2022; Ryu et al. 2021; Babu et al. 2022, 2021; Rosli et al. 2019; Liu et al. 2021; Zhao et al. 2022; Jamaludin et al. 2017; Ma et al. 2022). Nano-coatings have been found to have a significant impact on the efficiency of surgical procedures, as well as the comfort and safety of patients. This highlights the potential of nano-coatings to bring about dramatic changes in medical applications (Patel et al. 2020). The adaptability of nano-coatings is demonstrated by the advancement of superhydrophobic, self-healing photothermal deicing, and photodetectors featuring a distinctive "papillary structure." The coatings, which are produced using a layer-by-layer assembly spray method utilizing nanomaterials of different dimensions (0D, 1D, and 2D), exhibit remarkable characteristics such as self-cleaning abilities, prolonged durability, and exceptional photothermal deicing capabilities. These advancements serve to emphasize the versatile possibilities of nano-coatings in many applications (Zhang et al. 2022).

4.2 Case Studies: Successful Implementations of Nano-Coatings

In the domain of construction and infrastructure, it is of utmost importance to ensure the quality of cementitious materials. PZT sensors, when coated with polymers and utilized in conjunction with the electromagnetic interference (EMI) approach, have demonstrated efficacy in detecting alterations in the mechanical characteristics of these materials. It is worth noting that polyester coatings have demonstrated superior durability compared to PDMS. This highlights the significance of carefully choosing the appropriate nano-coating for certain applications, as depicted in Fig. 7 (Su et al. 2020).

The investigation of incorporating graphene into low-emissive paint has been undertaken in order to improve its mechanical resilience. The study observed that graphene and graphene oxide (GO) of inferior quality exhibited enhanced mechanical durability and infrared (IR) emissivity. However, certain samples of greater quality have shown the potential to reduce emissivity. This particular case study highlights the intricate effects of nano-coatings and emphasizes the significance of material quality in attaining intended results (Elvirsson et al. 2022).

Bearings are of utmost importance in a wide range of mechanical systems, and it is crucial to monitor their bidirectional load in order to maintain optimal performance. A novel smart sensor coating has been created to effectively satisfy this requirement, wherein the performance of the coating is significantly controlled by the specific material properties and structural design. This particular case study serves as an

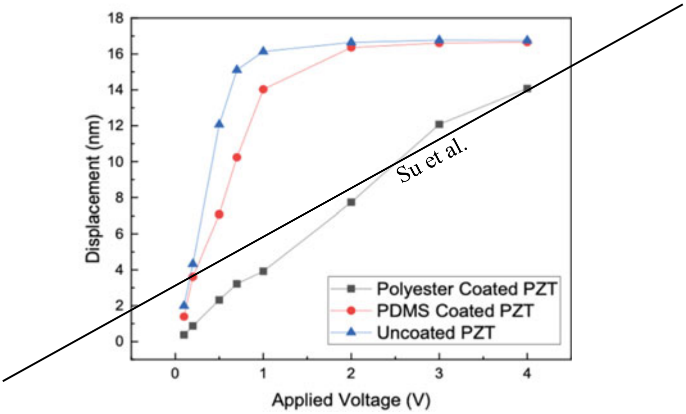

Fig. 7 Results of three different types coating of sensors' displacement measured by a laser Doppler vibrometer (LDV) at various applied voltages (Su et al. 2020)

illustration of how nano-coatings can be customized to fulfill precise monitoring needs within engineering applications (Nguyen et al. 2023).

5 Summary, Gaps, and Future Directions

The advancement of sensor technology, specifically in the domain of piezoelectric sensors, has had a significant impact. The incorporation of new materials and inventive designs has been a significant driving force behind advancements. The CNT/PVA/ZnO composite has demonstrated considerable potential in the monitoring of static and dynamic stresses on concrete structures, owing to its piezoresistive and piezoelectric properties. In a similar vein, the advancement of pressure sensors that possess flexibility and sensitivity, namely, those utilizing binary spiky/spherical nanoparticle films, has significantly broadened the scope of healthcare monitoring and airflow detection. The utilization of nano-coatings plays a crucial role in augmenting the longevity and efficacy of these sensors. Nano-coatings have demonstrated significant transformative effects, ranging from enhancing the thermal stability of sheathed platinum resistance sensors to enhancing the mechanical endurance of low-emissive paints by the use of graphene.

Although nano-coatings have demonstrated immediate advantages in terms of durability and performance, there is a lack of study about their long-term impacts. There are still unresolved inquiries pertaining to the probable deterioration of nano-coated sensors over time, the impact of environmental factors on their performance, and the overall duration of their functionality. The utilization of nano-coated sensors in sports applications holds significant promise, including a wide range of benefits such as the monitoring of athletes' performance and the assurance of equipment safety. Nevertheless, there exists a scarcity of scholarly investigations about the seamless integration of these sensors into sports gear, outfit, or equipment, as well as their performance under the demanding circumstances seen in professional sports.

The field of nanotechnology is constantly advancing and developing. Thus, it is imperative to investigate novel materials and inventive methodologies for the application of nano-coatings. In order to establish a connection between laboratory research and practical applications in the field of sports, it is imperative to adopt a collaborative approach. By facilitating collaboration between sports scientists, who possess comprehensive knowledge of the intricacies of athletic performance, and material engineers, who specialize in sensor technology, customized solutions can be devised. These collaborations have the potential to result in the development of sensors that not only assess performance but also contribute to the avoidance of injuries, optimization of equipment, and other related aspects.

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References

Abdullah NA, Abdullah FF, Sufian AH, Abidin AN, Jamaludin AS, Razali MN (2022) Effect of degradation by temperature onto nitrile rubber elastomer mechanical properties. Mater Today: Proc 48:1941–1946

Abidin AN, Azmi AH, Kassim KA, Jamaludin AS, Razali MN (2022) A review on automotive tires significant characteristic identification for general consumers. In: Proceedings of the 2nd energy security and chemical engineering congress, pp 375–385

Ali MA, Sivarao, Abdullah Z, Izamshah R, Kassim MS, Jamaludin AS (2022) Multi-response optimization of machining simulation approach using grey relational analysis. In: Lecture notes in mechanical engineering, pp 154–157

Alsibai MH, Hamran NNN, Nasir A, Abdullah AA (2018) A monitoring system for EPW safe use. J Telecommun Electron Comput Eng (JTEC) 10(1–2):131–135

Atalla Y, Hashim Y, Abd. Ghafar AN, Jabbar WA (2020) Temperature characteristics of FinFET based on channel fin width and working voltage. Int J Electr Comput Eng (IJECE) 10:5650

Atalla Y, Hashim Y, Abd. Ghafar AN (2022) The impact of channel fin width on electrical characteristics of Si-FinFET. Int J Electr Comput Eng (IJECE) 12:201

Babu D, Nasir A, Jamaludin AS, Rosle MH (2021) Holding, grasping and sensing of prosthetic robot arm like a real human hand, a journey beyond limits: an extensive review. In: Human-centered technology for a better tomorrow, pp 485–504

Babu D, Nasir A, Farag M, Sidik MH, Rejab SB (2022) Development of prosthetic robotic arm with patient monitoring system for disabled children; preliminary results. In: 2022 9th international conference on electrical and electronics engineering (ICEEE)

Babu D, Nasir A, Ravindran, Farag M, Jabbar WA (2023) 3D printed prosthetic robot arm with grasping detection system for children. Int J Adv Sci Eng Inf Technol 13:226

Baharuddin NJ, Abdul Manaf AR, Jamaludin AS (2022) Study on die shoulder patterning method (DSPM) to minimise springback of U-bending. Int J Autom Mech Eng 19:9509–9518

Baharuddin NJ, Manaf ARA, Jamaludin AS (2023) Study of springback behavior on U-bending part using die shoulder patterning method (DSPM). AIP Conf Proc 2544(1):040020

Binti Kamarudin SN, Lee H, Ishak I, Manaf AR, Jamaludin AS, Shaharudin MA, Zawawi MZ (2021) Rapid direct continuous method for hot embossing of glass microlens array combined with CO2 laser irradiation and external preheating/cooling. In: Lecture notes in mechanical engineering, pp 669–675

Chen S, Luo J, Wang X, Li Q, Zhou L, Liu C, Feng C (2020) Fabrication and piezoresistive/piezoelectric sensing characteristics of carbon nanotube/PVA/nano-zno flexible composite. Sci Rep 10

Chen F, Han L, Dong Y, Wang X (2022) Biomimetic self-adhesive structures for wearable sensors. Biosensors 12:431

Elvirsson J, Hallberg T, Karlsson LH (2022) Adding graphene to low-emissive paint. In: Target and background signatures VIII

Farag M, Azlan NZ, Alsibai MH, Ghafar AN (2019) Slippage detection for grasping force control of robotic hand using force sensing resistors. In: Proceedings of the 2019 5th international conference on computer and technology applications

Hasya N, Razali MNM, Jamaludin AS, Saffe SNBM, Hadi MA (2022) Micromilling performance analysis—Cold air assisted aluminium machining behaviour observation. In: Innovative manufacturing, mechatronics & materials forum 2022 (iM3F 2022), online conference, Pekan, Malaysia, pp 124–130

Homayounfar SZ, Kiaghadi A, Ganesan D, Andrew TL (2022) (Digital Presentation) harnessing wide-range, highly stable pressure sensitivity via PEDOT-Cl vapor printed textiles for health monitoring. In: ECS meeting abstracts. MA2022-02, pp 2286–2286

Jamaludin AS, Yassin A (2013) Analysis of laser sintered materials using finite element method. Sains Malaysiana 42(12):1727–1733

Jamaludin AS, Hosokawa A, Furumoto T, Koyano T, Hashimoto Y (2017) Evaluation of the minimum quantity lubrication in orthogonal cutting with the application of finite element method. Int J Mech Mechatron Eng IJMME-IJENS 17(01):104–109

Jamaludin AS, Akira H, Furumoto T, Koyano T, Hashimoto Y (2018a) High precision estimation on physical behavior for cutting with various tool rake angle by finite element method. In: Lecture notes in mechanical engineering, pp 715–723

Jamaludin AS, Hosokawa A, Furumoto T, Koyano T, Hashimoto Y (2018b) Study on the effectiveness of extreme cold mist MQL system on turning process of stainless steel AISI 316. IOP Conf Ser: Mater Sci Eng 319:012054

Kim Y-R, Kim MP, Park J, Lee Y, Ghosh SK, Kim J, Kang D, Ko H (2020) Binary spiky/spherical nanoparticle films with hierarchical micro/nanostructures for high-performance flexible pressure sensors. ACS Appl Mater Interfaces 12:58403–58411

Lee H, Binti Kamarudin SN, Ishak I, Manaf AR, Jamaludin AS, Shaharudin MA, Zawawi MZ (2021) Feasibility Study of wafer scale laser assisted thermal imprinting of glass nanostructures. In: Lecture notes in mechanical engineering, pp 917–923

Li M, Yao R, Liu Y (2023) A flexible and ultra-highly sensitive tactile sensor based on MG-doped zno nanorods for human vital signs and activity monitoring. Semicond Sci Technol 38:095012

Liu M, Liu Y, Zhou L (2021) Novel flexible PVDF-TrFE and PVDF-TrFE/zno pressure sensor: fabrication, characterization and investigation. Micromachines 12:602

Liu Y, Zeng X, Zhu L, Wang C, Geng K, Yao R (2023) Effect of nanostructure morphology and concentration on the piezoelectric performance of flexible pressure sensor based on PVDF-TRFE/nano-ZNO composite thin film. Curr Nanosci 19

Ma Z, Wang W, Yu D (2019) Assembled wearable mechanical sensor prepared based on cotton fabric. J Mater Sci 55:796–805

Ma H, Liu Z, Lou J, Ding Q, Jiang Y, Li X, Han W (2022) Bacterial cellulose/MWCNT coatings for highly sensitive and flexible paper-based humidity sensors. Cellulose 30:1193–1204

Md Kamil NH, Jamaludin AS, Mhd Razali MN, Abd. Ghaffar AN (2022) Temperature and heat flow analysis in a drying chamber through finite element method. In: Lecture notes in mechanical engineering, pp 309–316

Nasir A, Akagi T, Dohta S, Ono A, Masago Y (2013) Development of low-cost wearable servo valve using buckled tube driven by Servo Motor. Appl Mech Mater 393:532–537

Nasir A, Akagi T, Dohta S, Ono A (2015) Analysis of low-cost wearable servo valve using buckled tubes for optimal arrangement of tubes. In: 2015 IEEE international conference on advanced intelligent mechatronics (AIM)

Nguyen V-C, Le M-Q, Bernadet S, Hebrard Y, Mogniotte J-F, Capsal J-F, Cottinet P-J (2023) Design rules of bidirectional smart sensor coating for condition monitoring of bearings. Polymers 15:826

Patel KI, Zhu L, Reddy Gidde ST, Ren F, Hutapea P (2020) Influence of composite polymer coatings on the insertion force of needle-like structure in soft materials. Biomed Biotechnol 5

Ramli MR, Razak NA, Ismail I, Jamaludin AS, Manaf AR (2022) Effect of dimple size onto wear rate of mild steel AISI 1060 surface. In: Lecture notes in mechanical engineering, pp 99–102

Rosli AM, Jamaludin AS, Razali MN, Sani AS, Hamzah SB, Osman MS (2019) Modelling of fuzzy inference system for micro milling—A preliminary study through FEM. In: Lecture notes in mechanical engineering, pp 445–456

Rosli AM, Jamaludin AS, Razali MNM (2021a) Recent study on hard to machine material—Micromilling process. Evergreen 8:445–453

Rosli AM, Jamil N, Jamaludin AS, Razali MN, Yusoff AR (2021b) Tool wear observation during unconventional low speed machining using low cost micromilling. In: Lecture notes in mechanical engineering, pp 589–597

Ryu CH, Cho JY, Jeong SY, Eom W, Shin H, Hwang W, Jhun JP, Hong SD, Kim T, Jeong IW, Sung TH (2021) Wearable piezoelectric yarns with inner electrodes for energy harvesting and signal sensing. Adv Mater Technol 7

Saniman MN, Ihara I (2014) Application of air-coupled ultrasound to noncontact evaluation of paper surface roughness. J Phys: Conf Ser 520:012016

Saniman MN, Ihara I (2016) Feasibility Study on characterization of non-Gaussian rough surface by ultrasonic reflection method with the Kirchhoff theory. Mech Eng J 3

Su Y-F, Han G, Kong Z, Nantung T, Lu N (2020) Embeddable piezoelectric sensors for strength gain monitoring of cementitious materials: the influence of coating materials. Eng Sci

Sufian AH, Xun TZ, Abidin AN, Jamaludin AS, Razali MN (2021) Study on tire tread design effect onto tire-road contact behavior through FEM. In: Lecture notes in mechanical engineering, pp 893–902

Taborda JA, López EO (2020) Research perspectives on functional micro and nano scale coatings. Data Anal Med 1076–1109

Wang S-C, Zhang B, Kang L, Liang C, Chen D, Liu G, Guo X (2023) Flexible and robust triboelectric nanogenerators with chemically prepared metal electrodes and a plastic contact interface based on low-cost pressure-sensitive adhesive. Sensors 23:2021

Wu W, Wang Y, Sun J (2023) A bioinspired multilayer film with angle dependent and humidity responsive color-changing performances based on its crosslink networks. J Mater Sci 58:5808–5821

Zhang J, Shi F (2022) Preparation of organic ferroelectric material P (VDF-Trfe) nanostructure and its application in process simplification. Integr Ferroelectr 229:138–157

Zhang L, Zhang H, Yu X, Xu L, Wang D, Lu X, Zhang A (2022) Superhydrophobic MXene coating with biomimetic structure for self-healing photothermal deicing and photoelectric detector. ACS Appl Mater Interfaces 14:53298–53313

Zhao R, Luo W, Zhou A, Jiang Z (2022) Thermal stability evaluation of sheathed platinum resistance sensor based on nitride nano-coating. In: 2022 international conference on wireless communications, electrical engineering and automation (WCEEA)