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Advancements in carbon nanotube-based sensors for human motion detection

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ABSTRACT

Carbon nanotube (CNT)-based sensors are revolutionizing human motion detection through their unique combination of flexibility, sensitivity, and durability. This review examines the transformative impact of these sensors across healthcare, sports science, and wearable technology. Recent breakthroughs in hierarchical sensor architectures and hybrid materials have achieved unprecedented performance, with sensitivity exceeding conventional sensors by orders of magnitude and response times in milliseconds. These advances have enabled applications ranging from rehabilitation monitoring to high-precision athletic performance analysis. The integration of artificial intelligence with CNT sensors is opening new possibilities in personalized healthcare and human-machine interfaces. While challenges remain in manufacturing scalability and long-term stability, emerging developments in self-powered systems and biocompatible designs point toward widespread adoption in next-generation wearable devices. This review synthesizes current progress and identifies promising directions for future innovation in CNT-based motion sensing technology, highlighting its potential to transform how we monitor and understand human movement.

Keywords: Flexible electronics; Strain gauge; Wearable devices; Biomechanical monitoring; Smart materials.

1. INTRODUCTION

The ability to accurately detect and monitor human motion has become increasingly important across various fields, from healthcare and rehabilitation to sports science and human-computer interaction [1]. This growing demand has sparked intensive research into developing sophisticated sensing technologies that can effectively capture the complexity and subtlety of human movement. Among the various emerging technologies, carbon nanotube (CNT)-based sensors have garnered significant attention due to their exceptional mechanical, electrical, and structural properties that make them particularly well-suited for human motion detection applications [2, 3]. Traditional human motion detection systems have predominantly relied on optical, inertial, or mechanical sensors, each with their inherent limitations [4]. Optical systems, while providing high precision, often require complex setups with multiple cameras and are confined to controlled environments. Inertial sensors can suffer from drift and accuracy issues over extended periods [5]. Mechanical sensors, though reliable, can be bulky and restrict natural movement [6]. These limitations have driven the search for alternative sensing technologies that can offer improved performance while addressing the growing demand for wearable, unobtrusive motion detection solutions [7].

The emergence of CNT-based sensors represents a significant breakthrough in this quest. These sensors leverage the unique properties of CNT, which include exceptional mechanical strength, high electrical conductivity, and remarkable flexibility [8]. Their one-dimensional structure, with diameters in the nanometer range but lengths that can extend to micrometers or even millimeters, provides an ideal platform for detecting mechanical deformation and strain associated with human motion [9]. The ability of CNTs to maintain their electrical properties under significant mechanical stress makes them particularly valuable for developing sensors that can withstand the dynamic nature of human movement [10]. The significance of CNTs in sensing applications extends beyond their inherent properties. Their versatility in terms of fabrication and integration has enabled the development of various sensor architectures, from simple strain gauges to complex multi-functional sensing arrays. CNTs can be processed into different forms, including films, yarns, and composites, each offering

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unique advantages for specific applications [11]. Furthermore, their compatibility with flexible and stretchable substrates has opened new possibilities for creating conformable sensors that can seamlessly integrate with the human body. Recent advances in CNT synthesis and processing techniques have dramatically improved the quality and consistency of CNT-based sensors [12]. The ability to control CNT alignment, density, and surface functionalization has led to enhanced sensor performance in terms of sensitivity, response time, and reliability [13]. Additionally, developments in composite materials incorporating CNTs have addressed previous limitations related to mechanical durability and environmental stability, making these sensors more practical for real-world applications.

In the context of human motion detection, CNT-based sensors offer several distinct advantages. Their high strain sensitivity allows for the detection of subtle movements, while their mechanical flexibility enables comfortable, non-restrictive wear [14]. The ability to function under various environmental conditions and their potential for miniaturization make them suitable for long-term monitoring applications. Moreover, their electrical properties enable simple readout mechanisms and integration with existing electronic systems, facilitating real-time motion tracking and analysis [15]. The applications of CNT-based motion sensors span a broad spectrum of fields. In healthcare, these sensors are being used to monitor patient movement during rehabilitation, assess gait patterns, and track physical therapy progress. In sports science, they enable detailed analysis of athlete performance and movement optimization [16]. The gaming and virtual reality industries are exploring their potential for more intuitive human-computer interfaces, while the robotics field is investigating their use in developing more sophisticated motion control systems [17]. Despite these promising developments, several challenges remain in the widespread adoption of CNT-based motion sensors. These include issues related to manufacturing scalability, long-term stability, and cost-effectiveness [18]. Additionally, optimizing sensor design for specific applications while maintaining performance across various operating conditions continues to be an active area of research.

This review aims to provide a comprehensive analysis of the recent advancements in CNT-based sensors for human motion detection. We will examine the fundamental principles underlying their operation, explore various sensor architectures and fabrication methods, and discuss recent innovations that have enhanced their performance. Special attention will be given to applications in different fields and the challenges that need to be addressed for wider implementation. By synthesizing current knowledge and identifying emerging trends, this review seeks to provide researchers and practitioners with a thorough understanding of the state-of-the-art in CNT-based motion sensing technology and highlight promising directions for future development. The scope of this review encompasses both the technical aspects of CNT sensor development and their practical applications in human motion detection. We cover various types of CNT sensors, including single-wall and multi-wall configurations, different architectural designs, and various composite formulations. The review also address integration strategies with flexible substrates and electronic systems, as well as methods for improving sensor performance and reliability. The structure of this review is organized as follows: Section 2 establishes the fundamental principles of CNT-based motion sensors, examining their structural properties, working mechanisms, and key performance metrics that determine their effectiveness in motion detection applications. Section 3 provides a comprehensive analysis of sensor architectures and fabrication methodologies, comparing single-wall and multi-wall configurations while exploring various forms including films, yarns, and composites. Section 4 delves into recent technological advances, highlighting improvements in strain sensing capabilities, novel composite materials, and enhanced sensitivity and response time characteristics. Section 5 examines practical applications across three key domains: wearable motion monitoring, healthcare and rehabilitation, and sports performance analysis. Finally, Section 6 addresses current challenges in the field and discusses future perspectives, including emerging trends in self-powered systems and artificial intelligence integration. This organization provides readers with a systematic progression from fundamental concepts to practical applications and future directions in CNT-based motion sensing technology.

2. FUNDAMENTALS OF CNT-BASED MOTION SENSORS

2.1. Structure and properties of CNTs relevant to sensing

CNTs have emerged as a revolutionary class of nanomaterials, captivating researchers and engineers alike with their extraordinary structural attributes that render them exceptionally well-suited for an array of sensing applications. At their core, CNTs are composed of sp^2-hybridized carbon atoms ingeniously arranged in a cylindrical configuration, a structure that gives rise to their remarkable properties. This cylindrical arrangement can manifest in two primary forms (Figure 1): single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) [14]. SWCNTs, as their name suggests, consist of a solitary layer of carbon atoms rolled into a seamless cylinder. These structures typically exhibit diameters ranging from a mere 0.4 to 2 nanometers,

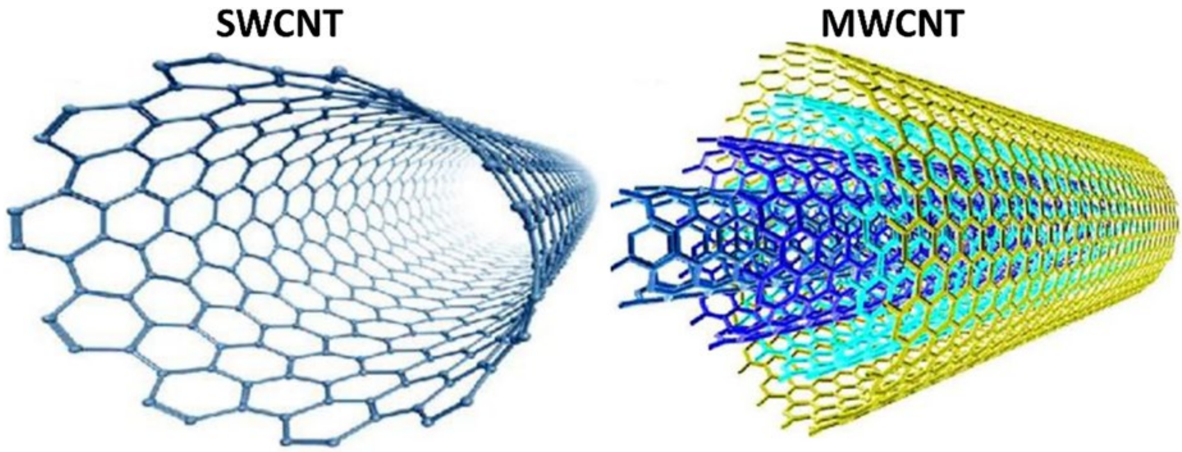

Figure 1: Structure of SWCNT and MWCNT.

placing them at the very forefront of nanoscale engineering. MWCNTs, on the other hand, present a more complex architecture, comprising multiple concentric tubes nested within one another, akin to a set of Russian dolls [19]. The diameters of MWCNTs can span a broader range, extending from a few nanometers to several tens of nanometers, depending on the number of constituent layers [20]. This tubular configuration, whether in single or multi-walled form, is not merely a structural curiosity but the fundamental basis for the CNTs' exceptional mechanical and electrical properties. These properties, in turn, form the cornerstone of their sensing capabilities, enabling the development of highly sensitive and responsive sensor systems [21]. The unique geometry of CNTs also facilitates their integration into various matrices and substrates, allowing for the creation of composite materials that can serve as the active elements in advanced sensing devices [22]. Furthermore, the high surface area-to-volume ratio inherent to these cylindrical structures provides an expansive interface for interaction with the surrounding environment, enhancing their sensitivity to physical and chemical stimuli [23]. This structural paradigm, combining nanoscale dimensions with macroscale applicability, positions CNTs at the forefront of materials science, particularly in the realm of sensor technology where the ability to detect minute changes in the environment is paramount.

The mechanical properties of CNTs play a pivotal role in their application to motion sensing technologies, offering a unique combination of strength, flexibility, and resilience that is unparalleled in the world of materials science [24]. CNTs boast an extraordinary tensile strength, with values reported to exceed 100 gigapascals, surpassing that of steel by orders of magnitude. This remarkable strength is complemented by an equally impressive Young's modulus, which can reach values of up to 1 terapascal, indicative of their exceptional stiffness along the axial direction [15]. However, what truly sets CNTs apart for motion sensing applications is their ability to maintain these superior mechanical properties while exhibiting remarkable flexibility and elasticity perpendicular to their axis. This seemingly paradoxical combination of strength and flexibility allows CNT-based sensors to endure repeated deformation cycles without succumbing to structural fatigue or degradation, a critical feature for devices intended for continuous motion monitoring [25]. The resilience of CNTs under dynamic loading conditions ensures the longevity and reliability of sensors, making them ideal for applications ranging from wearable technology to structural health monitoring of large-scale infrastructure. Moreover, the high aspect ratio of CNTs, where their length can exceed their diameter by a factor of thousands, enables them to form extensive, interconnected networks even when present at relatively low concentrations within a composite material [26]. This network formation is crucial for creating sensitive and responsive motion sensors, as it allows for the efficient transmission of mechanical deformations into detectable electrical signals [27]. The ability of CNTs to maintain their structural integrity and sensing capabilities under various environmental conditions, including temperature fluctuations and exposure to chemicals, further enhances their versatility in sensing applications. Additionally, the nanoscale dimensions of CNTs permit their integration into ultrathin and flexible sensor designs, opening up possibilities for non-invasive and imperceptible motion sensing in applications such as biomedical monitoring and smart textiles [28]. The combination of these mechanical attributes not only facilitates the development of highly sensitive motion sensors but also contributes to the creation of multifunctional materials that can simultaneously sense, actuate, and adapt to their environment.

From an electrical perspective, CNTs exhibit a fascinating array of properties that significantly enhance their sensing capabilities, particularly in the context of motion detection. The electronic behavior of CNTs is intricately linked to their structural characteristics, specifically their chirality (the angle at which the graphene sheet is rolled to form the tube) and diameter [29]. This structure-property relationship gives rise to a remarkable phenomenon: depending on these parameters, CNTs can exhibit either metallic or semiconducting behavior. Metallic CNTs display exceptional electrical conductivity, rivaling or even surpassing that of copper, with current densities reported to exceed 10^9 A/cm^2. Semiconducting CNTs, on the other hand, exhibit band gaps that are inversely proportional to their diameter, allowing for the fine-tuning of their electronic properties [30]. This electronic versatility is a key factor in the development of CNT-based sensors, as it allows for the creation of devices with varied sensing mechanisms and performance characteristics tailored to specific applications. For instance, semiconducting CNTs can be utilized in field-effect transistor (FET) configurations, where mechanical deformation can modulate the conductance, providing a direct electrical readout of motion or strain (Figure 2) [31]. Metallic CNTs, with their high conductivity, are particularly useful in creating conductive networks within composite materials, where changes in the inter-tube distances due to motion or deformation result in measurable changes in the overall electrical resistance of the network. The ability of CNTs to maintain their electrical conductivity under mechanical deformation is crucial for reliable signal transmission during motion detection [32]. This property stems from the robust sp^2 bonding network of the carbon atoms, which allows for the preservation of the electronic structure even under significant strain. Furthermore, the high carrier mobility in CNTs, which can exceed 100,000 cm^2/V·s at room temperature, enables rapid response times in sensing applications, allowing for the detection of high-frequency motions or vibrations [33]. The one-dimensional nature of electron transport in CNTs also contributes to their sensitivity to local electromagnetic environments, making them responsive to subtle changes in their surroundings [34]. This sensitivity can be harnessed for detecting not only mechanical motions but also variations in electric or magnetic fields associated with movement. The combination of these electrical properties with the mechanical robustness of CNTs opens up avenues for developing self-powered sensors, where the mechanical energy from motion can be converted into electrical signals, eliminating the need for external power sources in certain applications.

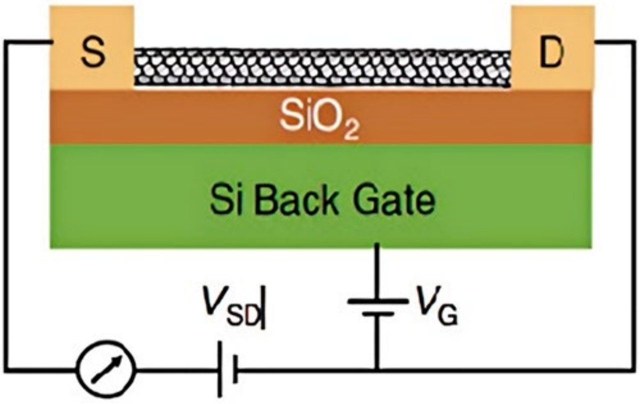

Figure 2: Illustration of CNT-based FETs for sensing.

Table 1: Comparison of CNTs with other emerging materials for motion sensing applications.

CHARACTERISTICS	CNTs	GRAPHENE	MXenes
Performance Metrics			
Gauge Factor	1–1000	100–500	50–200
Response Time	1–100 ms	5–200 ms	10–300 ms
Strain Range	Up to 500%	Up to 100%	Up to 60%
Fabrication & Scalability			
Cost	Moderate	High	Very High
Processing Complexity	Moderate	High	Very High
Stability	Excellent	Good	Moderate
Key Applications	Wearable electronics, sports monitoring, rehabilitation	Flexible electronics, pressure sensors	Biochemical sensing, electromagnetic shielding
Unique Advantages	Superior mechanical flexibility, excellent strain sensitivity, good stability	High conductivity, large surface area, good transparency	High hydrophilicity, excellent electromagnetic properties, tunable surface chemistry

While CNTs demonstrate exceptional properties for motion sensing, it is important to contextualize their performance against other emerging nanomaterials. Graphene, with its two-dimensional structure, offers extremely high electrical conductivity and theoretical surface area, but typically exhibits lower mechanical flexibility compared to CNTs. MXenes, as emerging 2D transition metal carbides, show promising chemical tunability and hydrophilicity, though their long-term stability remains a concern. Table 1 provides a comprehensive comparison of these materials in motion sensing applications.

2.2. Working principles and sensing mechanisms

The functioning of CNT-based motion sensors fundamentally depends on the modulation of their electrical characteristics when subjected to mechanical stress or strain. These sensors primarily operate through two distinct mechanisms: piezoresistive and capacitive effects, with piezoresistive sensing dominating the field due to its implementation simplicity and high sensitivity. In piezoresistive sensing, the electrical resistance of the CNT network undergoes measurable variations in direct correlation with applied mechanical deformation [35]. This relationship between mechanical input and electrical output enables precise motion detection and quantification. The sensing performance typically demonstrates gauge factors ranging from 1 to 100, depending on the specific CNT configuration and composite composition [36]. Recent studies have shown that aligned CNT networks can achieve even higher sensitivities, with gauge factors exceeding 200 under optimal conditions.

The piezoresistive response in CNT-based sensors manifests through a complex interplay of mechanisms operating at multiple structural scales. At the nanoscale level of individual CNTs, mechanical strain induces significant alterations in their electronic band structure, particularly affecting the bandgap and density of states. This phenomenon leads to variations in the intrinsic electrical resistance of individual nanotubes, with typical resistance changes ranging from 5% to 25% under normal operating strains [37]. However, the dominant contribution to the overall piezoresistive response occurs at the network level, where mechanical deformation substantially impacts the inter-tube junction resistance. When external strain is applied, the spatial distribution and contact geometry between adjacent CNTs undergo significant modifications, leading to changes in the number and quality of conductive pathways. This network-level response is particularly pronounced in polymer-CNT composites, where the polymer matrix's deformation can induce relative displacement between embedded CNTs [38]. Studies have shown that the contact resistance between CNTs can change by several orders of magnitude under strain, contributing to the high sensitivity of these sensors. The tunneling resistance at CNT junctions typically varies exponentially with inter-tube separation, with a characteristic tunneling distance of approximately 1−2 nm.

While piezoresistive sensing dominates the field, capacitive sensing mechanisms offer unique advantages in specific applications, particularly in pressure and normal force detection. In capacitive CNT-based sensors, the fundamental operating principle relies on measuring changes in capacitance between two conductive CNT layers separated by a compressible dielectric medium [39]. Mechanical deformation alters either the separation distance between the conductive layers or their effective overlap area, resulting in measurable capacitance variations. The relationship between applied pressure and capacitance change typically follows a non-linear behavior, with sensitivity varying from 0.1 to 1.0 kPa^{-1} [40]. Recent developments in capacitive CNT sensors have demonstrated enhanced performance through the optimization of dielectric materials and CNT layer morphology [41–43]. For instance, the incorporation of microstructured dielectric layers has shown to improve sensitivity by up to 300% compared to conventional flat configurations [44]. The capacitive sensing mechanism offers advantages such as lower power consumption and better stability under varying environmental conditions, making it particularly suitable for long-term monitoring applications.

2.3. Key performance metrics for motion sensors

The effectiveness of CNT-based motion sensors is evaluated through a comprehensive set of critical performance metrics, each playing a crucial role in determining the sensor's overall capability and applicability in various motion detection scenarios. These metrics not only define the sensor's basic functionality but also its suitability for specific applications, ranging from simple movement detection to complex motion analysis in fields such as biomechanics, robotics, and wearable technology.

Sensitivity stands out as a paramount metric, often quantified as the gauge factor in strain sensors. This metric represents the relative change in electrical response per unit strain and is fundamental in assessing a sensor's ability to detect subtle movements and differentiate between various motion intensities [45]. The sensitivity of CNT-based sensors exhibits a wide range, with gauge factors spanning from modest values of 2–5 to remarkably high values exceeding 1000. This extensive range is attributed to the diverse designs and compositions of CNT-based sensors [46]. For instance, sensors utilizing aligned CNT networks tend to show higher gauge factors compared to those with random CNT distributions. The incorporation of other nanomaterials, such as graphene or metal nanoparticles, can further enhance sensitivity [47]. It's worth noting that while high gauge factors are generally desirable, they must be balanced with other performance aspects to ensure overall sensor effectiveness.

Response time and recovery characteristics form another critical set of performance metrics that significantly impact a sensor's practical utility [48–52]. These parameters determine the sensor's ability to rapidly detect changes in motion and swiftly return to its baseline state, which is crucial for real-time motion tracking applications. CNT-based sensors typically demonstrate impressive response times in the millisecond range, with some advanced designs achieving response times as low as microseconds [53]. This rapid response enables the capture of fast, dynamic movements with high temporal resolution. The recovery behavior, including any hysteresis effects, is equally important. Hysteresis, which represents the lag between the sensor's response during loading and unloading cycles, can affect the accuracy of motion tracking, especially in applications involving repetitive movements [54]. Minimizing hysteresis often involves optimizing the CNT network structure and the polymer matrix in composite sensors. Some researchers have explored the use of self-healing materials or reversible cross-linking agents to enhance recovery characteristics and reduce hysteresis effects in CNT-based motion sensors.

Stretchability and working range are critical parameters, particularly for human motion detection applications. The sensor must maintain functionality across the full spectrum of human joint movements, which can involve strains exceeding 50% in extreme cases, such as finger bending or knee flexion. CNT-based sensors can be engineered to accommodate such large deformations while maintaining electrical connectivity, though this often involves a delicate balance between maximum strain range and sensitivity [55]. Strategies to enhance stretchability include the use of pre-strained substrates, serpentine structures, or 3D architectures that allow for greater deformation without compromising the CNT network. Some advanced designs have achieved stretchability exceeding 100% while maintaining good sensitivity, opening up possibilities for applications in soft robotics and highly conformable wearable devices [56]. However, it's important to note that there often exists a trade-off between maximum strain range and sensitivity, necessitating careful optimization based on the specific application requirements.

Durability and stability metrics address the sensor's ability to maintain consistent performance over extended periods and repeated use, which is crucial for long-term motion monitoring applications. These metrics encompass cycling stability, environmental stability, and drift characteristics. Cycling stability refers to the sensor's ability to maintain its performance over thousands or even millions of deformation cycles, which is particularly important for applications involving repetitive movements [57]. Environmental stability considers the sensor's resilience to various external factors such as temperature fluctuations, humidity changes, and exposure to chemicals or UV radiation. Drift characteristics, which describe the gradual change in sensor output over time under constant conditions, can affect long-term measurement accuracy [58]. CNT-based sensors must demonstrate reliable operation under these various conditions to be practical for extended use. Researchers have explored various approaches to enhance durability and stability, including encapsulation techniques, surface functionalization of CNTs, and the development of self-healing composites. Some advanced CNT-based sensors have shown remarkable stability, maintaining over 90% of their initial performance after tens of thousands of cycles, and exhibiting minimal drift over weeks of continuous operation [59].

Signal-to-noise ratio (SNR) and resolution capabilities are fundamental for accurate motion detection, especially in applications requiring fine motion control or detailed movement analysis. High SNR values ensure reliable detection of subtle movements against background noise, which is particularly important in environments with electromagnetic interference or mechanical vibrations [60]. Good resolution enables precise discrimination between different motion intensities, allowing for nuanced analysis of complex movements. These metrics are particularly critical in applications such as prosthetic control, sports performance analysis, or medical diagnostics where minute changes in movement patterns can be significant [61]. Advanced signal processing techniques, such as adaptive filtering or machine learning algorithms, are often employed to enhance SNR and improve resolution in CNT-based motion sensors [62]. Some state-of-the-art sensors have demonstrated the ability to detect strains as small as 0.1%, with SNR values exceeding 40 dB, enabling highly precise motion tracking and analysis.

The synergistic combination of these performance metrics determines the overall effectiveness of CNT-based motion sensors in practical applications. Understanding these fundamental aspects is essential for optimizing sensor design and selecting appropriate configurations for specific motion detection requirements. The continuous advancement in CNT synthesis, processing, and integration techniques has led to steady improvements in these performance metrics, expanding the potential applications of CNT-based motion sensors.

Recent developments in areas such as CNT purification, alignment techniques, and hybrid nanocomposites have pushed the boundaries of sensor performance, enabling new possibilities in fields ranging from healthcare monitoring to industrial automation. As research in this area progresses, we can anticipate further enhancements in sensor capabilities, potentially revolutionizing how we interact with and understand human and machine motion.

3. CNT SENSOR ARCHITECTURES AND FABRICATION

3.1. Single-wall vs multi-wall CNT sensors

The choice between single-wall and multi-wall carbon nanotubes significantly influences sensor performance and fabrication considerations in motion detection applications. Single-wall carbon nanotube sensors offer exceptional sensitivity due to their simpler structure and more predictable electronic properties. Their uniform molecular structure allows for more precise control over sensing mechanisms and enables better theoretical modeling of sensor behavior [63]. SWCNTs demonstrate superior electron mobility and can achieve higher gauge factors compared to their multi-walled counterparts, making them particularly suitable for applications requiring detection of subtle movements. For example, VU and KIM [64] developed a highly sensitive SWCNT-based strain sensor capable of detecting human motion with a gauge factor exceeding 280 (Figure 3), demonstrating the potential of SWCNTs for fine-grained motion sensing.

Multi-wall carbon nanotube sensors, while generally exhibiting lower sensitivity, offer several practical advantages. Their more robust structure provides enhanced mechanical stability and durability, making them better suited for applications involving repeated strain cycles or harsh environmental conditions. As demonstrated by SUZUKI *et al.* [65], MWCNT-based sensors can withstand strains up to 200% and exhibit excellent repetition durability over 180,000 cycles, highlighting their suitability for wearable applications. MWCNTs typically demonstrate better processability during sensor fabrication and can form more stable dispersions in various solvents and polymer matrices. The study by SUZUKI *et al.* [65] showcased the ability to create aligned MWCNT sheets through dry spinning, enabling the production of sensors with controlled resistance and high reproducibility. The lower cost and greater commercial availability of MWCNTs also make them more practical for large-scale sensor production. Furthermore, MWCNT-based sensors have demonstrated rapid response

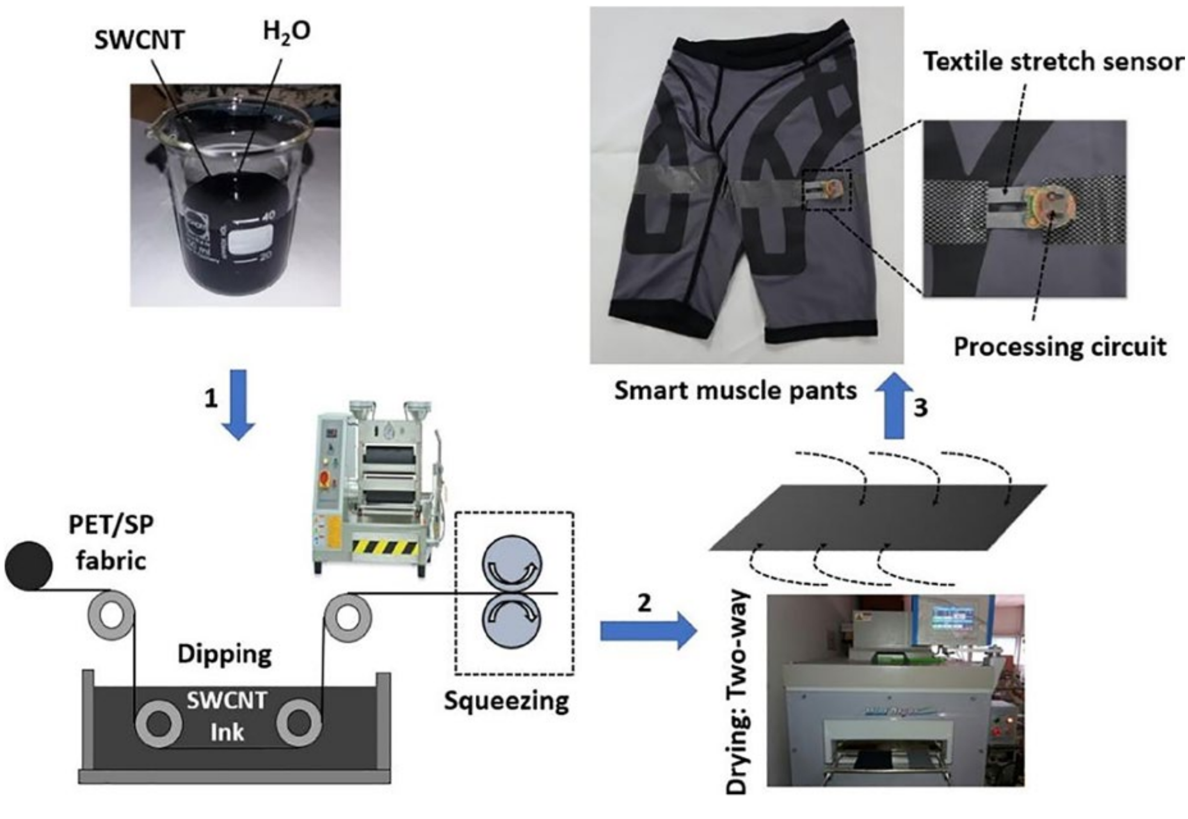

Figure 3: Fabrication of WCNT textile sensor [64].

times, with SUZUKI *et al.* [65] reporting a delay of less than 15 ms in their sensor, making them suitable for real-time motion detection applications such as human body motion sensing and data gloves for fine finger motion capture. The integration of these sensors into wearable systems illustrates the potential of MWCNT-based sensors in creating practical, textile-based wearable devices for various applications including sports performance analysis, healthcare monitoring, and virtual reality interfaces.

3.2. Common fabrication methods and architectures

The fabrication of CNT-based motion sensors encompasses various techniques, each offering distinct advantages for specific sensor architectures. Chemical vapor deposition (CVD) represents a widely adopted method for directly growing CNT arrays on substrates. This process enables precise control over nanotube orientation and density, crucial factors in sensor performance. The CVD method allows for the creation of aligned CNT forests that can be subsequently processed into various sensor architectures, offering excellent control over the final sensor structure. For instance, in the study by KIM *et al.* [66], zigzag-patterned CNT bundle arrays were synthesized on a silicon wafer using CVD and then transferred onto an Ecoflex substrate (Figure 4). This design allowed the sensors to achieve a GF of up to 64.08 and a strain range of 500%, showcasing the method's effectiveness in creating highly sensitive and stretchable sensors suitable for human motion detection.

Solution-based processing methods provide an alternative approach, offering greater flexibility in sensor design and easier integration with various substrates. These methods typically involve dispersing CNTs in appropriate solvents, often with the aid of surfactants or functionalization agents, followed by deposition through techniques such as spray coating, dip coating, or filtration. For example, MAITY *et al.* [67] utilized a spray layer-by-layer method to fabricate MWCNT-modified textiles, achieving a tunable resistance range from 100 mOhm to 2 kOhm. This approach allowed for the development of wearable sensors capable of monitoring both human body motion and environmental humidity, demonstrating the versatility of solution-based processing in creating multifunctional sensors. However, achieving uniform dispersion remains a significant challenge, as noted in the study, where the concentration and number of spray coatings significantly impacted the sensor's performance.

Screen printing and inkjet printing have emerged as promising techniques for fabricating CNT-based sensors, offering precise control over pattern geometry and material deposition. These methods require careful formulation of CNT inks with appropriate rheological properties and often involve the incorporation of polymeric binders or surfactants to ensure stable printing behavior. In the work by GO *et al.* [68],

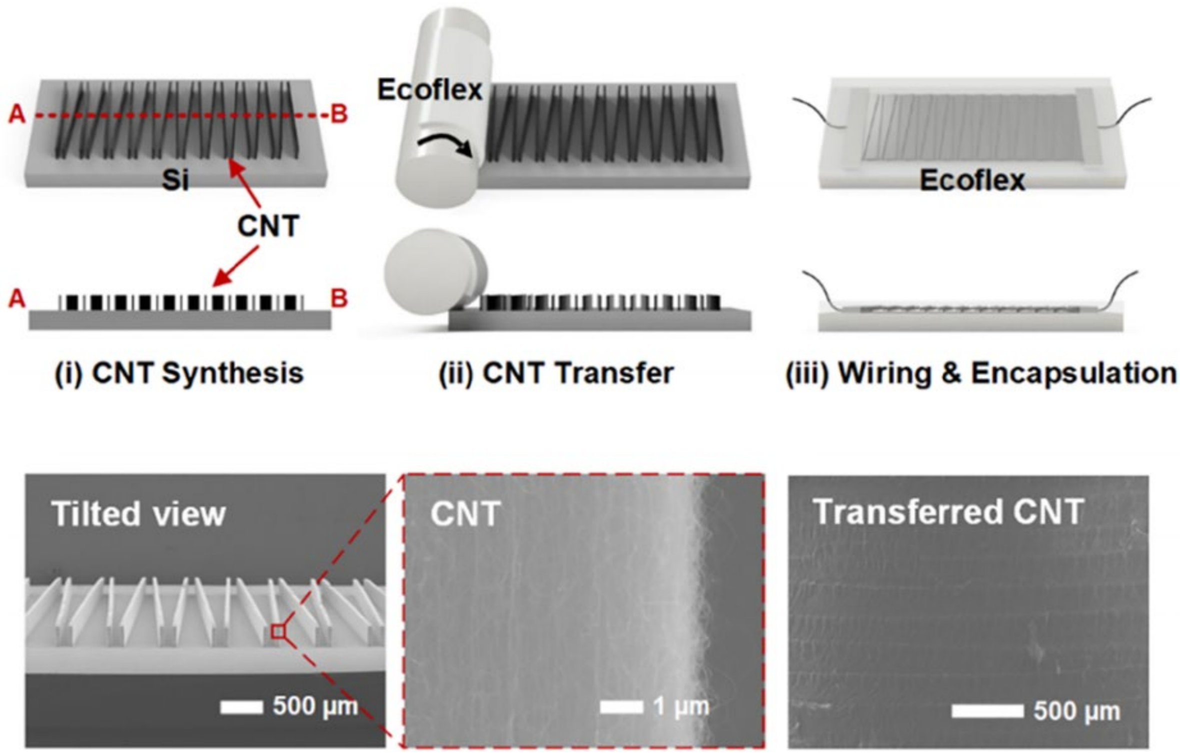

Figure 4: Patterned carbon nanotube bundles as stretchable strain sensors for human motion detection [66].

a high-resolution screen-printing technique was employed to create CB/CNT composite strain sensors with controllable sensitivity (Figure 5). The sensors exhibited gauge factors of 2.6 at 5% strain and 4.1 at 50% strain, with line resolutions ranging from 50 to 500 µm, highlighting the potential of screen printing in producing sensors with tailored electrical and mechanical properties. The ability to create complex sensor patterns through printing enables the development of sophisticated motion detection arrays and integrated sensor systems, as demonstrated by the stable performance observed over 300 bending tests.

3.3. Different forms (films, yarns, composites, etc.)

CNT-based motion sensors can be fabricated in various structural forms, each suited to specific applications and performance requirements. CNT films represent one of the most straightforward architectures, created through techniques such as vacuum filtration or direct growth. As demonstrated by YANG *et al.* [69], CNT films can be synthesized continuously through floating catalyst CVD achieving controlled sheet resistance and optical transparency by adjusting growth conditions. Their work showed that CNT films with 90% transmittance at 550 nm provided optimal coverage and conductivity for strain sensing applications. These films can be either free-standing or substrate-supported, with their thickness and density controlling key sensing parameters. For instance, QU *et al.* [70] developed a flexible conductive sponge by reducing Ag particles in CNT suspension

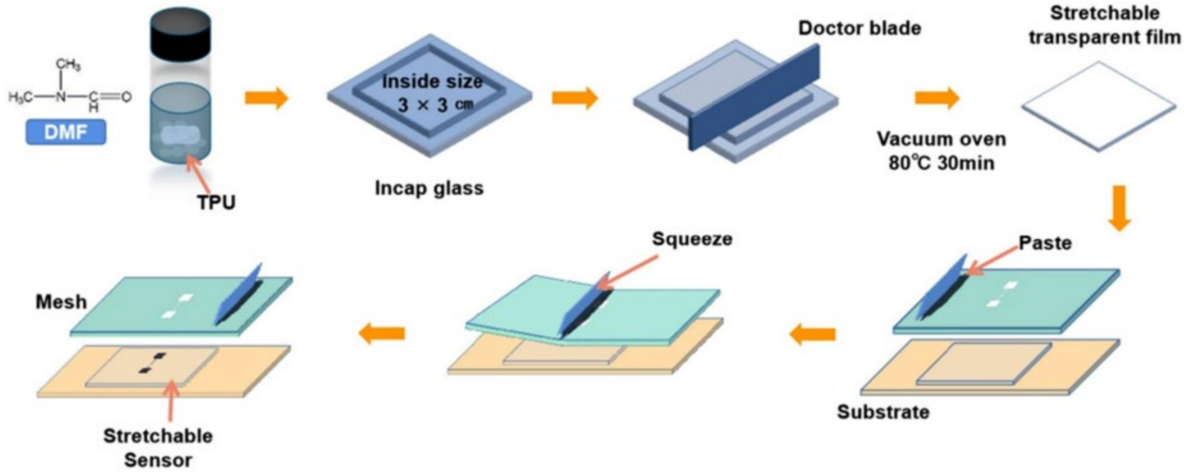

Figure 5: Fabrication of a fully printed strain sensor using a CB/CNT composite on a TPU substrate [68].

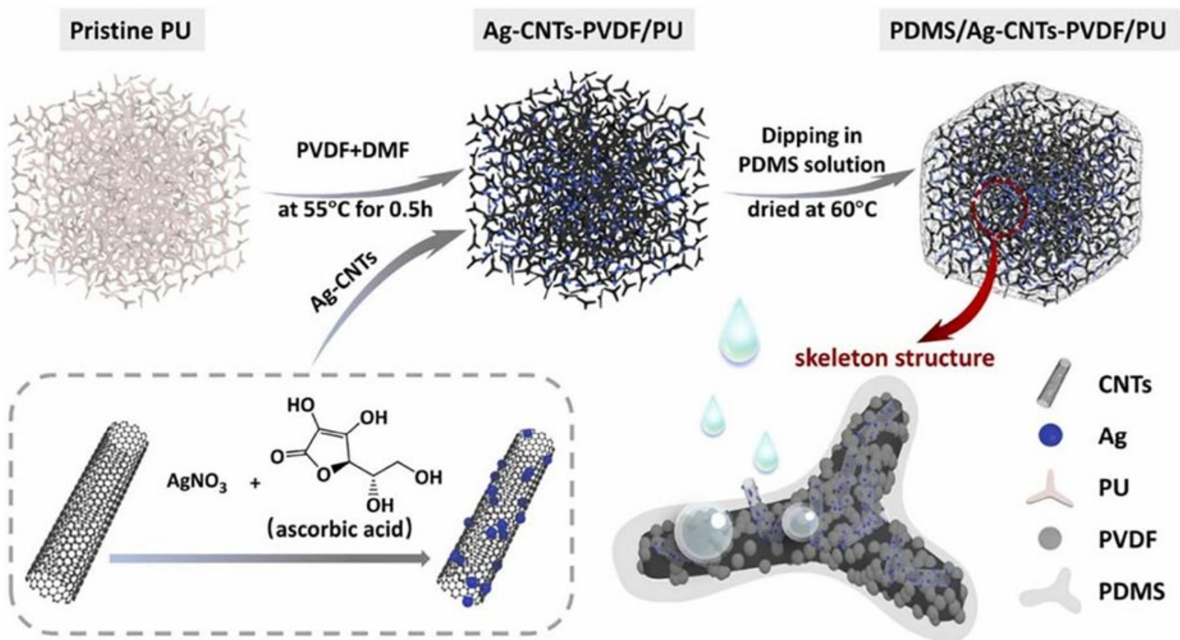

Figure 6: Scheme of the PDMS/Ag-CNTs-PVDF/PU sponge preparation process [70].

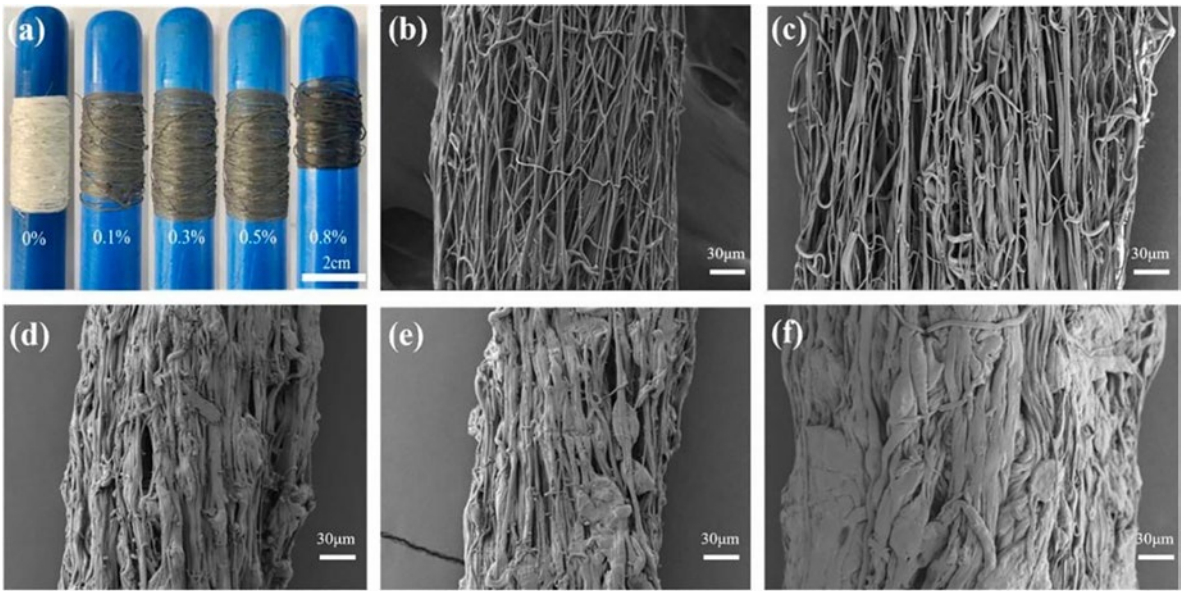

Figure 7: (a) CPY physical; (b) 0 wt% CNTs; (c) 0.1 wt% CNTs; (d) 0.3 wt% CNTs; (e) 0.5 wt% CNTs; (f) 0.8 wt% CNTs [71].

and combining with poly(vinylidene fluoride) solution (Figure 6), achieving superior conductive sensitivity up to 4.24 kPa^{-1} in the 0–20 kPa range. The film structure allows for excellent electrical connectivity and can be readily integrated into flexible sensor platforms, as evidenced by their demonstration of human motion detection capabilities.

CNT yarns and fibers offer unique advantages for wearable motion sensing applications. These structures can be produced through spinning processes, either from CNT arrays or solutions, resulting in highly aligned and mechanically robust sensing elements. YIN *et al.* [71] successfully demonstrated this approach by preparing PU/CNT composite nanofiber yarn using conjugate spinning technology, achieving high tensile strength (56.7 MPa) and elongation at break (504%). Figure 7 shows the photo of different CNT incorprated nanofiber with their SEM images. The fiber format enables seamless integration into textiles and allows for the creation of strain sensors that can detect movement in multiple directions. This was validated through their development of a susceptible wearable textile-type strain sensor that could monitor human body dynamics in real-time. The hierarchical structure of CNT yarns, with multiple levels of organization from individual nanotubes to twisted bundles, provides unique mechanical and electrical properties beneficial for motion sensing. CAI *et al.* [55] exemplified this by creating a transparent CNT-based capacitive strain sensor capable of detecting strains up to 300% with excellent durability over thousands of cycles. Their sensor exhibited deterministic and linear capacitive response throughout the strain range with a gauge factor close to the predicted value, demonstrating how the hierarchical organization of CNTs can be leveraged for superior sensing performance. The integration of such yarns into practical applications was demonstrated through their development of a data glove and respiration monitor, showing how CNT-based sensors can effectively capture complex human movements and physiological signals. These examples highlight how the careful control of CNT organization at multiple scales - from individual tubes to macroscopic assemblies - enables the development of high-performance motion sensors with tunable properties suited to specific applications.

4. RECENT ADVANCES IN CNT MOTION SENSOR DEVELOPMENT

4.1. Strain sensing capabilities and improvements

Recent developments in CNT-based motion sensors have led to significant advancements in strain sensing capabilities. The traditional limitations of strain range and sensitivity trade-offs have been addressed through innovative structural designs and material combinations. As demonstrated by YU *et al.* [72], super-aligned CNT films directly coated on PDMS substrates achieved an exceptionally wide sensing range of 400% strain while maintaining fast response times under 98ms. Their sensors exhibited remarkable durability, withstanding 5000 stretching-releasing cycles without performance degradation, highlighting the robustness of modern CNT-based sensing systems. Modern CNT strain sensors have achieved remarkable improvements in detecting both subtle movements and large deformations, with some devices capable of measuring strains from less than 0.1% to over 500% while maintaining high sensitivity throughout the operating range.

A notable advancement has been the development of hierarchical structures that enable multiscale strain sensing. These structures incorporate CNTs at different organizational levels, from nanoscale networks to microscale assemblies, allowing for more efficient strain transfer and improved signal generation. For instance, ZHAO *et al.* [73] demonstrated a hierarchical-structured CNT/PDMS composite film that achieved enhanced pressure sensitivity (0.1661 kPa^{-1}, 0.4574 kPa^{-1}, and 0.0989 kPa^{-1}) across different pressure ranges through controlled surface morphology (Figure 8). Similarly, AKHTAR and CHANG [74] developed a radially aligned CNT sensor that exhibited superior gauge factors and multidirectional sensing capabilities by leveraging hierarchical CNT arrangements. The implementation of pre-strain techniques during sensor fabrication has also proven effective in expanding the working range while maintaining high sensitivity at lower strain levels.

The optimization of CNT alignment and distribution within sensing elements has contributed significantly to enhanced strain detection capabilities. Controlled alignment techniques have enabled the creation of sensors with directional sensitivity, allowing for more precise motion tracking in specific directions. ZHU *et al.*'s [75] work with aligned few-walled CNTs (AFWCNTs) in polymer composites demonstrated how proper CNT orientation can achieve high precision and linearity in flexion sensing, with the devices showing stable performance even after 15,000 bending-unbending cycles. SEO *et al.* [76] further advanced this concept by developing a 3D network of single-walled CNTs embedded in PDMS, achieving a gauge factor of 35 at 1% strain through precise control of CNT alignment and distribution. Furthermore, the development of gradient structures, where CNT concentration varies systematically across the sensor, has led to improved strain distribution and more linear response characteristics.

These advancements in CNT-based strain sensors have been made possible through deeper understanding of the underlying sensing mechanisms. Rather than relying solely on traditional tunneling effects between randomly dispersed CNTs, modern sensors utilize controlled CNT arrangements to achieve specific sensing characteristics. For example, ZHU *et al.*'s [75] research revealed that the anisotropic conductivity of aligned CNTs and the distinct variation of "tube-to-tube" interfacial resistance are crucial for achieving high sensitivity

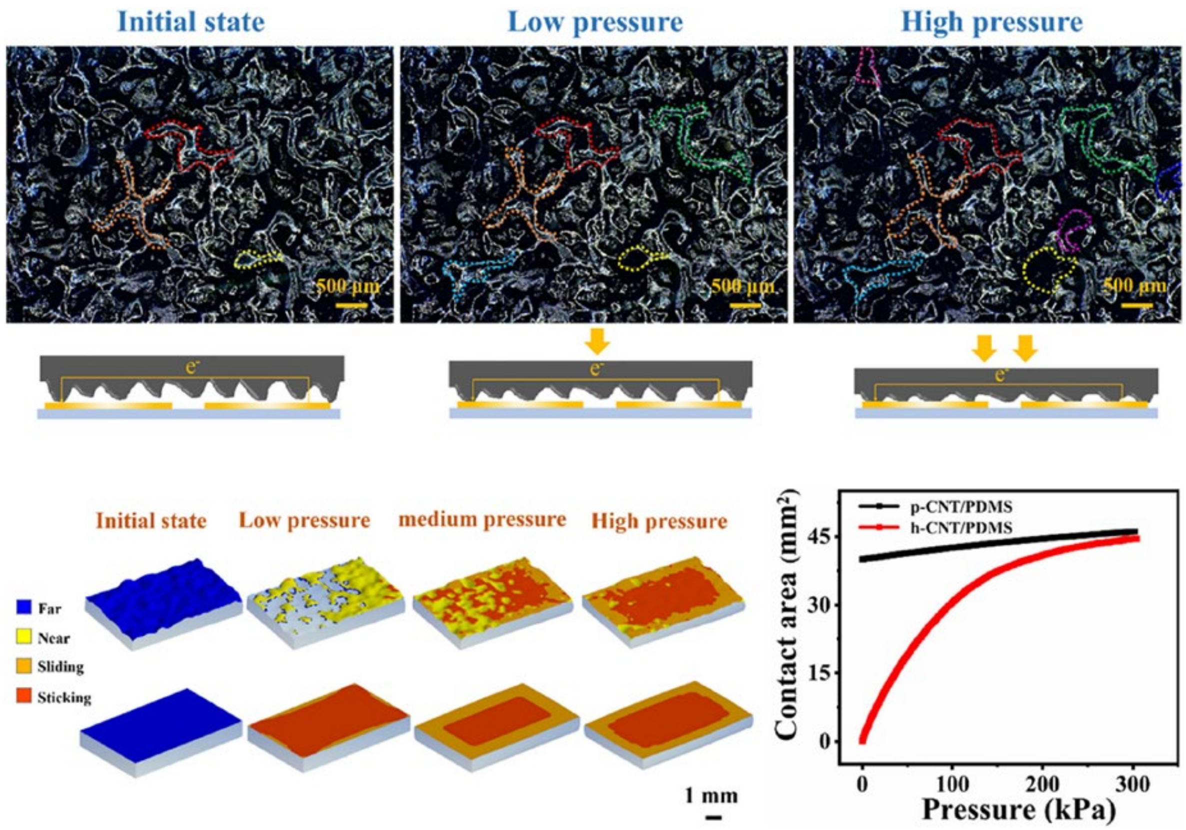

Figure 8: Optical images of the contact area between h-CNT/PDMS film and the test surface glass under different pressures with FEA modeling of the contact state of (Top) h-CNT/PDMS and (Bottom) p-CNT/PDMS films under different pressures [73].

and precision in motion detection. The integration of these principles with innovative structural designs has enabled the development of sensors that can effectively monitor complex human movements and joint articulations while maintaining stable performance over extended periods of use. This progress in CNT-based strain sensing technology has opened new possibilities for applications in wearable electronics, human-machine interfaces, and healthcare monitoring systems, where reliable and precise motion detection is essential.

4.2. Novel composite materials and structures

The field has witnessed remarkable innovation in the development of composite materials that combine CNTs with other functional materials to enhance sensing performance. The integration of CNTs with two-dimensional materials such as MXenes has emerged as a particularly promising approach. As demonstrated by LI *et al.* [77], decorating CNT surfaces with metallic Ag nanoparticles using pulsed laser ablation in liquid (PLAL) and combining them with delaminated MXene sheets achieved high sensitivity (12.7 kPa^{-1}) and excellent response characteristics. The uniform distribution of Ag nanoparticles (15–20 nm) on CNT surfaces helped reduce contact resistance between the materials. These hybrid structures leverage the complementary properties of different nanomaterials - the excellent conductivity of CNTs, the mechanical flexibility of MXenes, and the enhanced electron transport enabled by metal nanoparticles - to achieve superior sensing characteristics. The synergistic effects between CNTs and other conductive materials have led to enhanced sensitivity and more stable electrical properties under mechanical deformation, as evidenced by the ability to detect subtle human motions like breathing and pulse signals.

Recent advances in polymer science have enabled the development of new matrix materials specifically designed for CNT-based sensors. As shown in KIM *et al.*'s [78] work on 3D-printed multiaxial force sensors, the careful selection of thermoplastic TPU as a matrix material allowed direct fabrication of functional sensing structures without additional assembly steps. The TPU provided both mechanical flexibility and compatibility with the CNT sensing elements. Self-healing polymers incorporated with CNTs have shown promising results in creating sensors that can recover from mechanical damage, extending operational lifetime and reliability. The introduction of dynamic cross-linking in polymer matrices has improved the strain recovery characteristics and reduced hysteresis effects commonly observed in stretchable sensors. This was demonstrated in LI *et al.*'s [79] work where they engineered CNT/PDMS nanocomposites by introducing controlled porosity using citric acid monohydrate particles as templates, achieving enhanced sensitivity (GF = 15 at $\varepsilon > 15\%$) compared to non-porous structures.

Innovative structural designs have also emerged, including the development of micro-architected composites that optimize strain transfer and electrical connectivity. KIM *et al.* [78] demonstrated a 3D cubic cross structure that enabled simultaneous measurement of forces in three orthogonal axes through strategic placement of CNT/TPU sensing elements. Three-dimensional CNT networks embedded in carefully designed polymer architectures have demonstrated improved strain sensitivity while maintaining mechanical robustness, as shown by the porous CNT/PDMS sponges that exhibited both high sensitivity and good durability over 3000 cycles. The implementation of biomimetic structures, inspired by natural mechanical sensors, has led to new designs that effectively balance sensitivity and durability. For instance, the hierarchical porous structure created in CNT/PDMS composites mimics the mechanical sensing mechanisms found in natural systems, allowing efficient strain transfer and enhanced sensitivity. These advances in material design and fabrication techniques have enabled the development of sensors capable of detecting both large-scale motions like finger bending and subtle physiological signals like pulse and breathing patterns, demonstrating their versatility for various applications from human motion monitoring to soft robotics.

4.3. Advances in sensitivity and response time

Significant progress has been made in improving the sensitivity and temporal response of CNT-based motion sensors. Enhanced sensitivity has been achieved through the optimization of CNT network architecture and the introduction of novel signal amplification mechanisms. For instance, LI *et al.* [80] developed a highly sensitive and flexible piezoresistive sensor based on c-MWCNTs decorated TPU electrospun fibrous network, achieving a sensitivity up to 2 kPa^{-1} in the low pressure range (0–200 Pa) (Figure 9). This high sensitivity was attributed to the unique porous structures of the TPU nanofibers and the excellent conductivity path formed by the c-MWCNTs. The development of sensors with gauge factors exceeding 1000 has been realized through careful control of CNT junction properties and the implementation of crack-based sensing mechanisms. WANG *et al.* [81] demonstrated a strain sensor based on network cracks formed in multilayer CNT films/PDMS composites, achieving a maximum gauge factor of 87. This high sensitivity was enabled by the distinctive network cracks morphology, including gaps, islands, and bridges connecting separated islands.

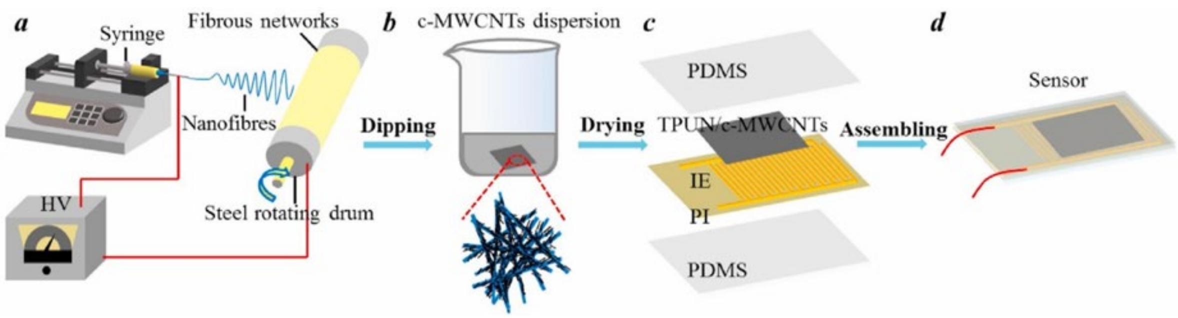

Figure 9: Schematic illustration of piezoresistive sensor based on c-MWCNTs decorated TPU electrospun fibrous network [80].

Response time improvements have been accomplished through advances in both materials design and signal processing techniques. The incorporation of highly conductive pathways within sensor structures has reduced electrical resistance and improved signal propagation speeds. For example, ZHANG *et al.* [82] reported a piezoresistive-capacitive dual-sensing breathable sensor with a spherical-shell network of MWCNTs, exhibiting a fast response time of 65 ms. This rapid response was attributed to the unique three-dimensional spherical-shell-structured conductive network of MWCNTs embedded in the porous PDMS structure. Advanced electrode designs and optimized contact interfaces have minimized parasitic capacitance effects, leading to faster response times in the millisecond range. LI *et al.*'s [80] sensor demonstrated a response time of less than 10 ms, which was achieved through the optimization of the conductive network formed by c-MWCNTs on the surface of TPU nanofibers.

The implementation of new sensing mechanisms, such as coupled piezoresistive-capacitive effects, has enabled simultaneous improvements in both sensitivity and response time. These hybrid sensing mechanisms provide complementary information about mechanical deformation, allowing for more accurate and rapid motion detection. ZHANG *et al.*'s [82] dual-mode sensor exemplifies this approach, offering both piezoresistive and capacitive strain-sensing capabilities. The piezoresistive mode showed a high sensitivity of −1.2/kPa, while the capacitive mode exhibited a sensitivity of 0.38/kPa, both over a wide pressure range of 1–520 kPa. This dual-sensing capability allowed for more accurate detection of both subtle and large strains, making it suitable for various human motion detection applications. Additionally, the development of multichannel sensing architectures has enhanced the ability to detect complex movements with improved temporal resolution. WANG *et al.*'s [81] network cracks-based sensor demonstrated excellent performance in detecting both subtle strains (e.g., pulse signals) and large strains (e.g., joint bending), showcasing its versatility in motion detection. The sensor's ability to distinguish various frequencies and pressures further improved its capability to capture complex movements accurately.

Recent advancements have also focused on improving the overall performance and practicality of CNT-based motion sensors. LI *et al.*'s [80] sensor exhibited excellent structural stability and durability for more than 1000 cycles, while Wang *et al.*'s sensor showed stable performance over 1500 cycles. These improvements in long-term stability are crucial for real-world applications of wearable motion sensors. Furthermore, researchers have made strides in enhancing the comfort and wearability of these sensors. ZHANG *et al.*'s [82] breathable sensor design, with a porosity of 53.9%, addressed the issue of skin affinity and comfort during prolonged wear. This approach allows for better heat and moisture dissipation, making the sensor more suitable for continuous monitoring of human physiological signals and movements.

5. APPLICATIONS IN HUMAN MOTION DETECTION

5.1. Wearable motion monitoring

The integration of CNT-based sensors into wearable devices has revolutionized the field of motion monitoring. These sensors can be seamlessly incorporated into clothing and accessories, providing continuous and unobtrusive tracking of body movements. As demonstrated by ZHONG *et al.* [83], multi-layer polyurethane-fiber-prepared CNT sensors can achieve sensitivity factors up to 127.74 with excellent durability over 6000 loading cycles, making them ideal for long-term wear. The flexibility and lightweight nature of CNT sensors make them particularly suitable for everyday wear, allowing for long-term motion monitoring without impeding natural movement or causing discomfort. This is evidenced by TAS *et al.*'s [84] development of directionally oriented CNT/PDMS films that can conform to body contours while maintaining high sensitivity, with gauge factors reaching 594 at 15% strain. Advanced wearable systems utilizing CNT sensors have been developed to monitor full-body kinematics. These systems typically employ networks of distributed sensors strategically placed at key anatomical locations. For instance, SUN *et al.* [85] demonstrated a flexible tactile electronic skin sensor array that could detect three-dimensional forces with a response time as low as 3.1 ms, enabling precise tracking of complex movements. The ability of CNT sensors to detect both large-scale movements and subtle positional changes enables comprehensive motion tracking, from major joint articulations to minor postural adjustments. This is particularly evident in their capacity to monitor various physiological signals - from detecting wrist pulses and finger bending to tracking throat muscle movements during speech, as shown in recent studies. The integration of these sensors into smart textiles has enabled the development of "electronic skin" that can map complex body movements with high spatial resolution. For example, researchers have successfully implemented 4 × 4 sensor arrays with double-sided rough porous structures that can simultaneously detect normal pressure up to 6 kPa and tangential forces up to 0.6 N, providing detailed mapping of movement patterns. Recent developments in wearable CNT sensor arrays have focused on improving motion detection accuracy while maintaining user comfort. Multi-layer sensor configurations have been implemented to capture movement in multiple dimensions simultaneously, as demonstrated by the development of sensors with specialized bump structures that can differentiate between normal and tangential forces. The development of breathable and washable sensor implementations has addressed practical concerns regarding long-term wearability and maintenance, making these systems more suitable for daily use. These advances are complemented by innovations in material design, such as the use of porous CNT/PDMS nanocomposites that combine high sensitivity with mechanical durability. The incorporation of specialized structures like scale-like features and aligned CNT arrangements has further enhanced sensor performance, enabling more precise motion tracking while maintaining the flexibility and comfort necessary for everyday wear. These improvements have led to systems capable of detecting both gross motor movements and subtle variations in pressure and force, making them valuable tools for applications ranging from athletic performance monitoring to medical rehabilitation.

5.2. Healthcare and rehabilitation

In the healthcare sector, CNT-based motion sensors have found significant applications in rehabilitation and patient monitoring. These sensors enable precise tracking of patient movement during physical therapy sessions, providing quantitative feedback about recovery progress. As demonstrated by DINH *et al.* [86], CNT yarns can be constructed into flexible thermal flow sensors capable of noninvasively monitoring respiratory patterns, which is crucial for evaluating breathing exercises during rehabilitation. Their work showed that CNT-based sensors could detect respiratory rates between 12–20 breaths per minute with a fast response time of 80 ms, allowing real-time tracking of breathing patterns. The ability to monitor range of motion, movement quality, and exercise repetition accuracy helps healthcare providers optimize rehabilitation protocols and adjust treatment plans based on objective data. This is evidenced by YAMAMOTO *et al.*'s [87] development of a printed multifunctional device incorporating CNT-based motion sensors that could distinguish between different physical activities like walking, running and lying down through distinct sensor output signatures. Rehabilitation applications have particularly benefited from the development of CNT sensors capable of detecting subtle changes in movement patterns. For instance, DU *et al.* [88] demonstrated CNT-PDMS composite sensors with gauge factors of 1.21 and linear piezoresistive ranges up to 40% strain, enabling detection of various human motions from finger bending to muscle contractions. These systems can identify compensatory movements or deviations from prescribed exercise forms, allowing therapists to provide timely corrections and prevent the development of improper movement habits. The continuous monitoring capabilities of these sensors also enable remote rehabilitation supervision, expanding access to therapy services and improving patient compliance with prescribed exercises. This is particularly valuable given that CNT-based sensors can be fabricated using low-cost printing methods on flexible substrates, as shown by DINH *et al.*'s [86] solvent-free fabrication approach using recyclable paper substrates. The integration of CNT sensors into prosthetic and orthotic devices has enhanced the functionality of assistive technologies. These sensors provide real-time feedback about limb position and movement, enabling more natural control of prosthetic devices and better adaptation to user intentions. DU *et al.*'s [88] work demonstrated that CNT-PDMS composites could effectively monitor joint angles during activities like finger bending (30°, 60°, and 90°) and muscle contractions, providing the precise positional feedback needed for prosthetic control. In orthotic applications, CNT sensors help monitor joint angles and movement patterns, facilitating better understanding of treatment effectiveness and allowing for dynamic adjustment of support levels. The ability to simultaneously monitor multiple health parameters alongside movement, as shown in YAMAMOTO's *et al.* [87] integrated device measuring acceleration, ECG, and temperature, provides a more comprehensive picture of patient status during rehabilitation activities. This multifunctional monitoring capability helps healthcare providers better understand the relationship between physical activity and physiological responses, enabling more targeted and effective therapeutic interventions.

5.3. Sports and performance analysis

The application of CNT-based motion sensors in sports science has provided new insights into athletic performance and training optimization. These sensors enable detailed analysis of movement mechanics across various sports disciplines, from golf swings to running gaits. As demonstrated in recent studies, CNT-based flexible strain sensors can effectively monitor complex basketball movements, including the critical phases of jump shots: catch, buildup, release, and return [89]. During basketball shooting analysis, these sensors placed on the wrist, elbow and shoulder can detect subtle technical details like wrist pressing mechanics, which has been shown to improve shooting accuracy from 60% to 80%. The high sensitivity and rapid response time of CNT sensors allow for capture of fast, dynamic movements that are crucial for understanding athletic technique and performance. This is particularly evident in soccer applications, where CNT sensors can differentiate between shooting and passing techniques by analyzing ankle motion patterns during instep kicks versus arch pushes, providing coaches with quantitative data to optimize player technique. Advanced motion analysis systems incorporating CNT sensors have been developed to provide real-time feedback during training sessions. These systems can track specific performance metrics such as joint angles, movement speed, and acceleration patterns, enabling athletes and coaches to identify areas for technique improvement. For example, graphene-coated fiber sensors have demonstrated the ability to monitor key joint movements with recognition rates above 90% for activities ranging from slow walking to fast running, while maintaining stable performance over 2000 cycles of motion [90]. The ability to monitor subtle changes in movement patterns helps prevent injury by detecting fatigue-related alterations in form before they lead to significant problems. Recent developments in carbon nanotube flexible strain sensors have achieved sensitivity coefficients approaching 1.0, allowing for precise detection of both large-scale movements like knee bending and subtle muscle contractions. The integration of CNT sensors into sports equipment has enabled more comprehensive analysis of equipment-athlete interaction. Sensors embedded in footwear can analyze running mechanics and impact forces, while instrumented sports implements provide data about swing mechanics and power transfer. Studies have shown that these sensors can maintain accuracy even under dynamic conditions, with error rates below 2% during stress-recovery cycles [91].

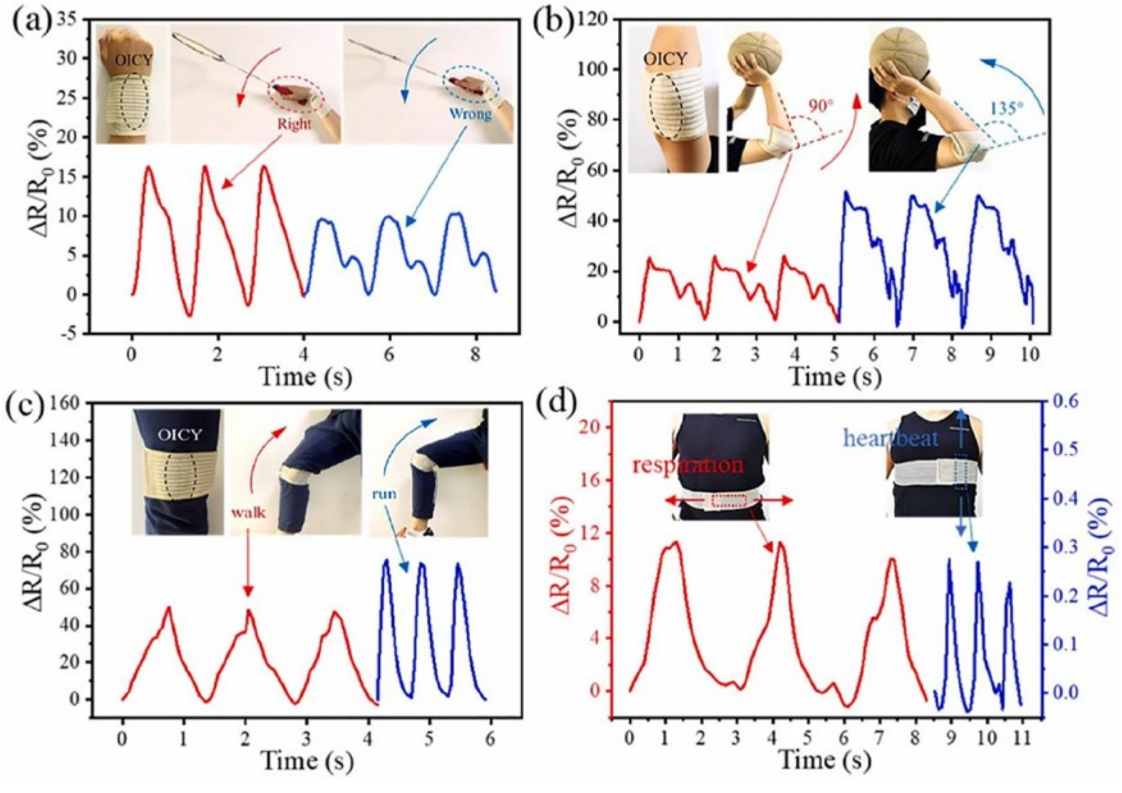

Figure 10: Application of the smart sports bandage in (a) badminton, (b) basketball, (c) walk and run, (d) monitoring respiration and heartbeat [92].

Moreover, the implementation of multidimensional sensing capabilities allows for simultaneous monitoring of different motion parameters - for instance, combining strain and acceleration measurements to provide a more complete picture of athletic performance (Figure 10) [92]. This comprehensive data collection approach has been particularly valuable in team sports, where sensors can track not only individual player mechanics but also movement patterns during specific game situations. The information helps in equipment optimization and technique refinement, leading to improved performance and reduced injury risk. Recent advances in sensor fabrication techniques, such as the development of graphene-coated composites and carbon nanotube/conductive polymer combinations, have further enhanced the durability and reliability of these systems, allowing for continuous monitoring throughout extended training sessions while maintaining high data accuracy and minimal hysteresis effects.

6. CHALLENGES AND FUTURE PERSPECTIVES

Despite significant advances in CNT-based motion sensors, several technical challenges persist. The inherent variability in CNT properties, including chirality and dimensionality, continues to affect sensor performance consistency. This variability impacts the reproducibility of sensor characteristics, making it difficult to achieve uniform performance across different production batches. Additionally, the long-term stability of CNT-based sensors remains a concern, particularly in environments with varying temperature and humidity conditions. Signal drift and hysteresis present ongoing challenges in sensor reliability [93]. While various strategies have been developed to minimize these effects, achieving completely stable and reproducible signals over extended periods of operation remains difficult. The integration of CNTs with flexible substrates also faces challenges related to mechanical fatigue and delamination, particularly under repeated strain cycles. These issues can lead to degradation in sensor performance and reduced operational lifetime. Another significant limitation lies in the current signal processing and data interpretation methods. The complex relationship between mechanical deformation and electrical response in CNT-based sensors often requires sophisticated algorithms for accurate motion interpretation [94]. The development of more efficient and reliable signal processing techniques remains crucial for improving the practical utility of these sensors.

The transition from laboratory-scale production to industrial manufacturing presents significant challenges for CNT-based motion sensors. Current fabrication methods often involve complex processes that are difficult to scale while maintaining consistent sensor performance. The dispersion of CNTs in polymer matrices, crucial for many sensor designs, becomes increasingly challenging at larger scales, where achieving uniform distribution and preventing agglomeration become more difficult [95]. Quality control and standardization represent major hurdles in large-scale production. The lack of standardized testing protocols and quality metrics makes it difficult to ensure consistent sensor performance across different manufacturing batches. Additionally, the cost of high-quality CNTs remains relatively high, impacting the economic viability of mass production. The need for specialized equipment and controlled manufacturing environments further adds to production costs.

The field of CNT-based motion sensors continues to evolve, with several promising research directions emerging. One significant trend is the development of self-powered sensors that can harvest energy from human motion, potentially eliminating the need for external power sources [96]. Research into hybrid materials that combine CNTs with other functional nanomaterials shows promise in achieving enhanced sensing capabilities while addressing current limitations. The integration of artificial intelligence and machine learning algorithms with CNT sensor systems represents another important research direction [97]. These approaches could improve signal processing efficiency and enable more sophisticated motion pattern recognition. Additionally, research into bio-compatible and biodegradable sensor designs is gaining momentum, particularly for healthcare applications where temporary monitoring is desired.

The integration of CNT-based sensors with artificial intelligence and Internet of Things (IoT) platforms represents a significant advancement in smart sensing systems. Recent implementations have demonstrated the powerful synergy between CNT sensors' high-fidelity data collection capabilities and AI's analytical prowess. IoT integration has further enhanced the utility of CNT sensors in healthcare monitoring. At the Tokyo Metropolitan Telemedicine Center, a network of CNT-based wearable sensors connected to cloud-based AI systems enables remote monitoring of elderly patients. The system employs edge computing to process sensor data locally before transmitting relevant information to healthcare providers. This smart system has demonstrated 93% accuracy in early detection of fall risks by analyzing gait patterns and movement anomalies, leading to a 40% reduction in fall-related incidents among monitored patients. Industrial applications have also benefited from AI-enhanced CNT sensor networks. Boeing's manufacturing facility implemented a smart quality control system using CNT strain sensors integrated with machine learning algorithms. The system monitors worker movements during critical assembly processes, providing real-time feedback to ensure compliance with standard operating procedures. This implementation reduced assembly errors by 35% and improved worker ergonomics by identifying potentially harmful movement patterns. These integrations face certain challenges, including the need for standardized data protocols and robust security measures for sensitive health data. Current research focuses on developing edge AI solutions that can process sensor data with minimal latency while maintaining privacy. Additionally, efforts are underway to create adaptive learning systems that can calibrate to individual user patterns and environmental variations, enhancing the accuracy and reliability of CNT-based smart sensing systems. The future of AI-integrated CNT sensors points toward increasingly autonomous and adaptive systems. Developments in neuromorphic computing architectures specifically designed for processing CNT sensor data show promise in creating more efficient and responsive smart systems. These advancements, combined with improvements in wireless power transmission and edge computing capabilities, suggest a trajectory toward truly intelligent sensing networks capable of complex decision-making and predictive analytics.

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