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Application of energy recovery mechanisms in wearable devices

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Abstract. Wearable devices have almost become a necessity in modern-day society due to their multifaceted functions, providing fitness tracking and health monitoring. Apart from this foundational role, daily wearable devices play a significant role in helping with health recovery, such as Mechanical Exoskeletons, in our high-demand society. However, one of the primary limitations of these devices is their dependency on finite battery life. This review paper aims to address this problem with the concept of energy recovery (ER) technology, which could be a potential solution for prolonging the operational time of wearables. These methodologies are primarily based on the theory of energy conservation and efficiency models, branching out into different aspects of thermodynamics, piezoelectricity, and the basic principles of human motion. Through the analysis of academic journals and primary studies, this review aims to provide a detailed explanation of how ER technology would work from various perspectives, identify constraints within the use of this technology, and suggest directions for future investigation. The objective is to promote the integration of energy recovery technologies into wearable devices, ultimately enhancing their efficiency for users.

Keywords: Energy Recovery, Wearable Devices, Piezoelectric, Thermoelectric, Kinetic Energy.

1. Introduction

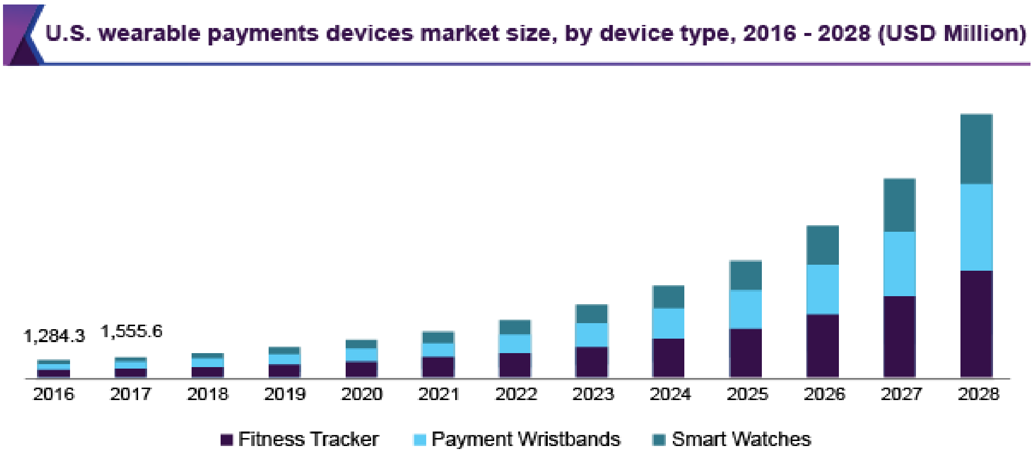
With the rapid development of technology, wearable devices, also known as wearable technology, refer to small electronic and mobile devices or computers with wireless communication capabilities that are incorporated into gadgets, accessories, or clothing. These devices can be worn on the human body, and in some cases, they can be invasive, such as microchips or smart tattoos [1]. The integration of wearable devices into our daily lives has brought about a range of capabilities, as illustrated in Figure 1. These devices serve not only fitness-related purposes, such as recording steps or providing training sessions, but also exhibit enormous potential in various fields, including healthcare, safety, and entertainment.

However, as the functionality of these devices continues to advance, along with the expansion of application scenarios and people's increasing reliance on them, a significant challenge arises — the growing demand for energy within these devices. Consequently, energy recovery technology has garnered considerable attention worldwide. This section will delve into the historical background, current market trends, and the pivotal role of energy recovery technology in addressing the challenges faced by wearable devices.

Figure 1. A broad view of different types of wearable devices that people are currently using.

The history of wearable devices can be traced back to the 1960s. Due to technological advancements, often referred to as the "Technological Revolution," and increased social stability, driven by rising prosperity, wearable devices have gradually entered the consumer market. This trend can be discerned from a financial perspective as well. Figure 2 demonstrates that the wearable market continues to grow, with a forecast of more than a 20% annual growth rate. The market is expected to exceed 40 billion EUR per year in the next 5 years and reach over 150 billion EUR by 2028, as stated by Aleksandr Ometov [1]. This growth underscores the rapid expansion of the wearable device market.

This field has evolved from basic health trackers to today's complex and multifunctional intelligent devices, including smartwatches for health monitoring, fitness tracking, rehabilitation training, health trackers, and medical exoskeletons. As the functions of these devices have increased, so too has the demand for energy. In the early stages, electronic watches could run for several months on a single button battery, while modern multifunctional smartwatches often require daily charging [2]. Therefore, one of the current significant challenges is how to ensure sufficient power to support advanced features while maintaining the device's small and lightweight design. [3]



Source: www.grandviewresearch.com

Figure 2. Market growth, payments, and market size of wearable devices in U.S. from 2016 to 2028.

One potential methodology to address this problem is the Energy Recovery Mechanism. Through energy recovery, these devices can operate for longer periods of time, ultimately enhancing the user experience. According to Aleksandr Ometov's research, achieving autonomy by harvesting energy from the environment is particularly appealing for wearable systems. The energy collected from the environment can take various forms, including motion, temperature gradients, light, electromagnetic radiation, and more. These methods encompass micro kinetic energy harvesting systems that utilize frequencies generated by human movement to harvest energy, the use of solar energy to power wearable devices, self-powered smart tissues, and wireless power transmission for implants [1]. These approaches have the potential to mitigate the energy challenges faced by wearable devices, considering the increased functionality, and align with objectives such as meeting user expectations for longer battery life and achieving environmental sustainability [4].

2. Applications

2.1. Different types of Energy Recovery Mechanisms and their working principles

This section aims to discuss recent advances in the state-of-the-art regarding different types of Energy Recovery Mechanisms. These mechanisms primarily include Piezoelectric, Thermoelectric, and Kinetic Energy theories. It will also present a practical application case, detailing how these methodologies could be implemented in wearable devices. Furthermore, this section will address the technical and practical limitations currently faced by these applications, which can be visualized in Figure 3.

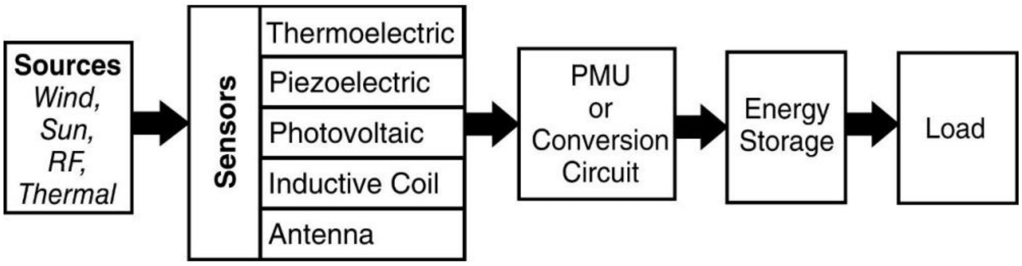


Figure 3. A block diagram of the most used Energy Recovery System.

The Piezoelectric Energy Recovery Mechanism is a technology that utilizes the Piezoelectric effect to convert mechanical energy, such as vibration and pressure, into electrical energy. This concept can be further elucidated using Figure 4, which demonstrates the Piezoelectric effect. The Piezoelectric effect is an electromechanical phenomenon first discovered by French physicists Pierre Curie and the Curie brothers in 1880. It generates voltage when specific materials are subjected to mechanical stress [2]. This occurs because mechanical stress induces the rearrangement of the electric dipole moment inside the material, resulting in an electric field and current. Materials such as quartz, lithium niobate, lithium tantalate, barium titanate, PZT, and potassium niobate are all considered Piezoelectric materials. These materials typically operate under two working modes in energy recovery applications: the 33 mode and the 31 mode. In the 33 mode, the applied pressure and the generated voltage are in the same direction, usually used for applications involving direct compression or stretching of materials. In the 31 mode, the force is applied along the x-axis, the width direction of the material, and is more commonly used in applications requiring lateral stress [3].

This technology is particularly relevant in wearable devices as it can recover energy from human motion, thereby providing power to the device and achieving energy recovery goals. In scenarios involving continuous active movement and ongoing physical activities such as breathing and heartbeat, this technology can serve as a stable energy source for energy recovery. In the case of discontinuous movement, a person weighing 68 kilograms can generate approximately 67 watts of electrical energy when walking at a speed of two steps per second [3]. This level of energy is sufficient to power some low-power wearable devices. Figure 5 illustrates a potential implementation on the lower part of the human body. While it is primarily effective in the upper limb area, especially at the wrist, it can have applications in various wearable device designs.

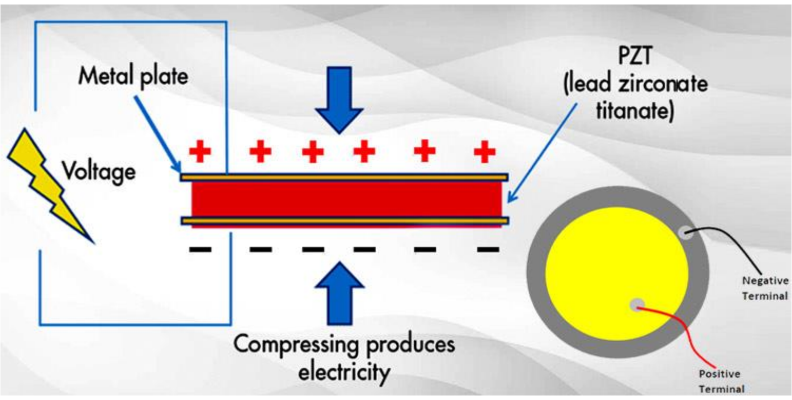


Figure 4. A diagram showing Piezoelectric's working principles, and how to convert mechanical energy into electrical energy.

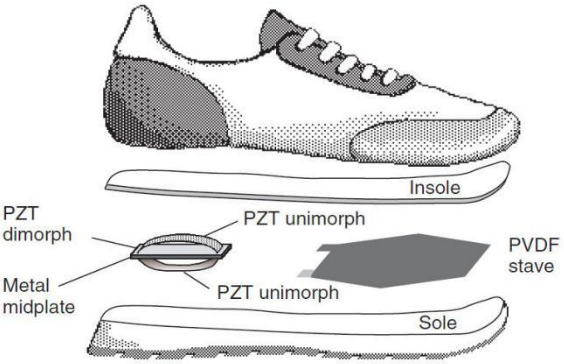


Figure 5. A real-life case where Piezoelectric Energy Recovery Mechanism would work.

Thermal Energy Harvesting typically refers to the process of extracting and storing thermal energy from the surrounding environment or a given system and converting it into electrical or mechanical energy [4]. This process is illustrated in Figure 6. Among the various methodologies available, the Seebeck effect is one of the most commonly used methods for heat recovery. This effect occurs when two different conductors or semiconductor materials are connected, and there is a temperature difference at the connection point. This temperature differential generates an electromotive force (voltage), resulting in a current that flows through an external circuit to power small electronic devices or to be stored in batteries. Consequently, thermal energy is effectively converted into electrical energy.

From another perspective, the human body has the potential to serve as an alternative source of energy, capable of converting various types of energy into electrical energy to drive small devices like wearable devices [5]. Specifically, the human body generates energy during various activities, including walking, running, breathing, and heartbeat. These energies typically exist in the form of mechanical energy, thermal energy, or biochemical energy. For instance, when you walk or run, the muscles in your lower body generate mechanical energy, and when you experience temperature changes, your body generates heat energy. These types of energy can be collected by transducers, devices designed to convert one form of energy into another [4].

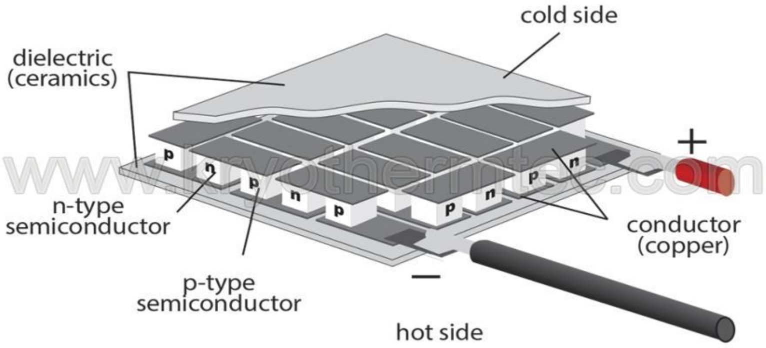


Figure 6. A simply diagram on how Thermalelectric Energy Harvesting works.

Kinetic Energy Recovery is an energy management strategy primarily used to convert kinetic energy from mechanical systems such as vehicles, industrial machinery, or wearable devices into usable electrical energy or other forms of energy. This is primarily achieved through processes like electromagnetic induction or other mechanical methods such as flywheel or spring systems. When a vehicle or human body decelerates or brakes, it often generates a significant amount of kinetic energy, which is typically dissipated in the form of thermal energy. However, this kinetic energy can be captured and converted into electrical energy or other available forms of energy. A notable example is the F-IVT (Flywheel Infinitely Variable Transmission). The linear F-IVT actuator, as shown in the architectural diagram in Figure 7, exemplifies energy recovery capability.

The F-IVT actuator employs a flywheel to store mechanical energy. When the system performs actions, such as walking or running, the flywheel rotates to store kinetic energy [6]. When energy is required, such as during uphill climbs or acceleration, the flywheel releases the stored kinetic energy and converts it into electrical or mechanical energy to assist the actuator. The F-IVT also features an Infinite Variable Transmission (IVT), capable of effectively converting the energy stored in the flywheel to meet different speed and torque requirements [7].

This technology, along with the kinetic energy recovery mechanism and simulation tools that accurately calculate the energy required for each step of the actuator, is primarily used for lower limb wearable robots and exoskeletons, such as walking aids or prosthetics, as depicted in Figure 8. It enables the completion of a full gait cycle without consuming additional energy, which can be particularly beneficial in fields like medical recovery and biomechanics, among others.

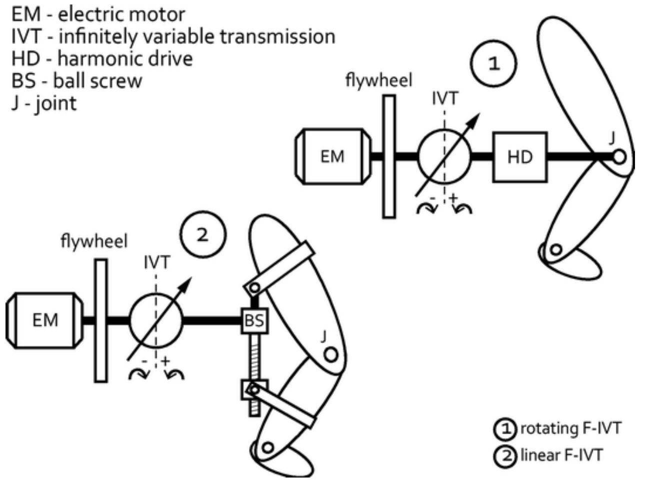


Figure 7. Image of the F-IVT architecture.

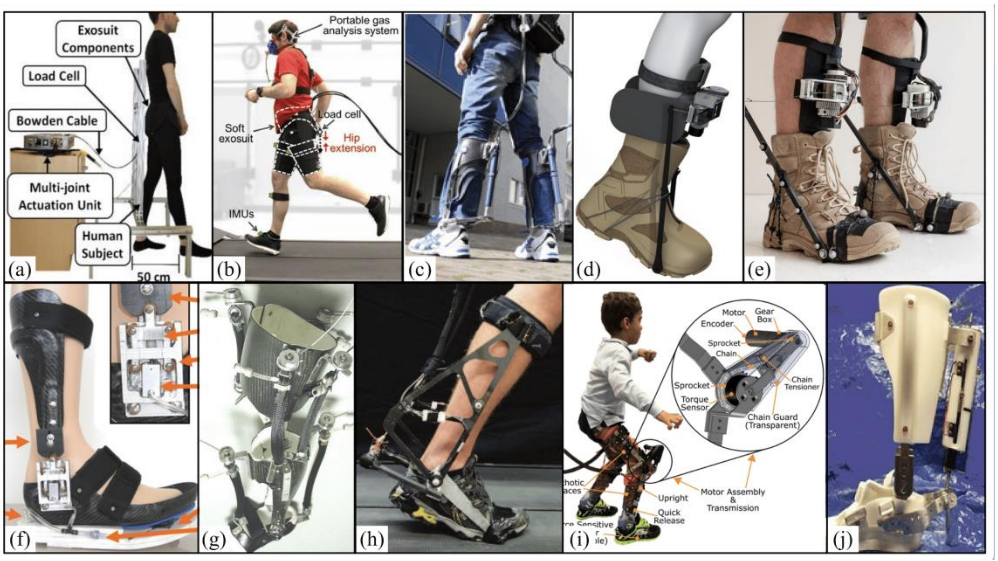


Figure 8. Exoskeletons such as walking aids or prosthetics.

2.2. *Case study on Piezoelectric Energy Recovery Mechanism*

To demonstrate the practical application of energy recovery in wearable devices, specifically in the context of Piezoelectric technology, this section will explore the application of this technology in wrist-worn devices through a detailed case study.

In wrist devices, the Piezoelectric Energy Recovery Mechanism demonstrates a high level of potential and practicality. This mechanism is primarily applied to health monitoring and physical rehabilitation devices, including smartwatches, heart rate monitors, and health trackers. Figure 9 illustrates the general process of how the Piezoelectric Energy Recovery Mechanism can be utilized in real-life situations. Materials with high voltage coefficients and mechanical strength, such as PZT or PVDF, are considered suitable Piezoelectric materials that can be embedded into wrist straps or watch bands. These materials undergo the Piezoelectric effect, where mechanical stress generated by the natural movement of the wrist is transformed into electrical energy, essentially acting as a Piezoelectric generator [3].

To be more specific, this mechanical stress causes the rearrangement of the electric dipole moment inside the piezoelectric material, resulting in the generation of electric fields and currents on both sides of the material. The generated electrical energy is then stored in a miniature battery or capacitor integrated into the device's circuits for later use.

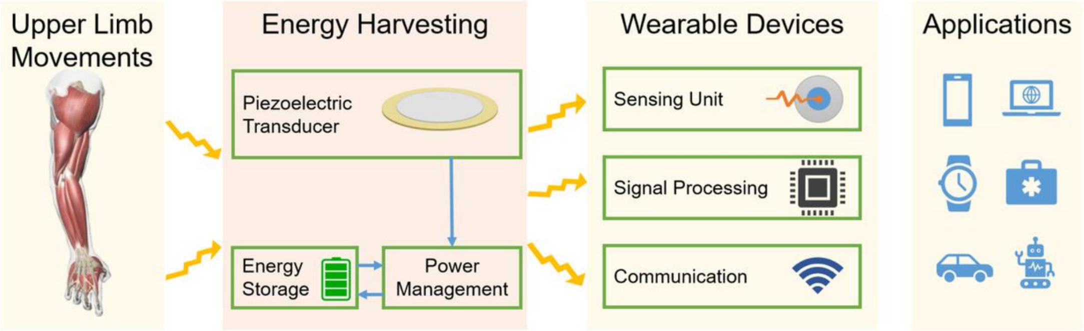


Figure 9. General process of the application of Piezoelectric Energy Recovery Mechanism.

The Piezoelectric generator applied on the wrist can achieve a power density of approximately 15.69 mW cm^{-3} [3]. This numerical value signifies that a high-power density typically implies that the system can generate more electricity within a smaller volume. This characteristic is particularly valuable for wearable devices, given their strict volume and weight limitations. High power density allows these devices to remain lightweight while ensuring a continuous power supply. To clarify, 15.69 mW cm^{-3} means that each cubic centimeter of piezoelectric material can generate 15.69 milliwatts (mW) of electrical power. Using this piezoelectric material theoretically only requires a volume of approximately 0.064 cubic centimeters. This can be confirmed through a simple calculation: (Required Material Volume (cm^3) = Required Electrical Power (mW) / Power Density (mW cm^{-3})) yields the value of 0.064 cubic centimeters of this piezoelectric material needed to generate enough electrical energy to support the normal operation of a wearable device [3]. This high power density implies that even in applications with low energy consumption, such as heart rate or sleep monitoring, this technology can provide sufficient electrical energy.

2.3. Challenges

While various types of energy recovery mechanisms, including a case study of Piezoelectric energy management strategies, provide substantial evidence supporting the concept of energy recovery, this technology also faces certain challenges. In the context of the previous case study, issues such as device durability, long-term comfort, and biocompatibility with the skin, including concerns about whether the materials used are toxic and might cause skin irritation or allergic reactions, can pose obstacles to achieving the optimal level of performance and outcomes [2].

In reality, the efficiency of energy conversion is often low. Piezoelectric, thermoelectric, and kinetic energy recovery mechanisms frequently encounter the challenge of low conversion efficiency, meaning that only a small fraction of the energy collected from these types of effects can be effectively converted into electrical energy. Furthermore, the high cost associated with materials and production processes may limit the widespread adoption of these technologies.

Nevertheless, the concept of energy recovery undoubtedly advances the current state of wearable devices, providing a viable and efficient solution for energy supply. Although there are technical and practical challenges, ongoing research is expected to address and resolve these issues over time.

3. Significance

3.1. Social and Environmental Impact

Promoting sustainable development through energy recovery is crucial, as this state-of-the-art technology holds significant potential in advancing sustainability. By harnessing energy from the environment or human activities, these technologies reduce our dependence on traditional batteries and power grids, consequently lowering carbon emissions and mitigating environmental pollution.

Furthermore, energy recovery technology finds applications in the medical and sports fields. For instance, blood glucose monitors can utilize it to assist users in checking their blood sugar levels, while fitness trackers have the potential to extend the lifespan of device batteries, improving the overall user experience.

From a practical standpoint, energy recovery technology enables wearable devices to offer more effective monitoring in emergency situations. For example, firefighters and police can employ these devices to continuously monitor their physiological status and the surrounding environment in real-time, enhancing safety [8].

3.2. Business potential

These future directions not only hold significance within the context of society and the environment but also possess substantial commercial value. With the rapid development of wearable devices and the Internet of Things (IoT), there is a high demand from individuals. This presents substantial business opportunities for enterprises, including investments and sponsorships. Given their wide-ranging application prospects and societal benefits, these technologies have attracted significant research and development investments from various sources, including governments, industries, and venture capital companies. This is expected to further expand the business channels for this technology.

Companies such as Apple, Samsung, and Huawei are pioneers in this field. According to the latest statistics from the International Data Corporation (IDC), the wearable device market has experienced significant growth. Global shipments are projected to reach 442.7 million units in 2023, representing a year-on-year increase of 6.3%. The expectation is that global shipments will further rise to 644.5 million units by 2027 [9]. These future directions not only excel in terms of technology but also carry substantial commercial value while delivering significant societal and environmental benefits.

3.3. Potential developments in research and application

One potential development is the enhancement of energy conversion efficiency in wearable devices. This entails not only optimizing current technologies but also exploring novel materials and methods for more efficient energy conversion. The objective is to maximize energy generation while minimizing waste, thus enhancing the sustainability and cost-effectiveness of these devices.

In addition, multifunctional integration will play a crucial role. With the continuous advancement of microelectronics technology, the next generations of wearable devices are expected to incorporate multiple energy recovery mechanisms [10]. This comprehensive approach may encompass piezoelectric, thermoelectric, and kinetic energy recovery systems.

Furthermore, looking at another perspective, future wearable devices are anticipated to be user-friendly, highly convenient, non-invasive, and potentially inconspicuous. Nevertheless, addressing the previously mentioned challenges and obstacles necessitates further research and studies [7].

3.4. Possible technological improvements or new application areas

In addition to wearable technology, energy recovery mechanisms may also revolutionize environmental monitoring systems. For example, air quality detectors or water quality monitoring equipment can be powered by energy recovered from environmental variables, reducing reliance on traditional power sources. Smart homes would also embrace this trend, where energy recovery technology can drive various sensors and devices, including lighting systems and security cameras.

4. Conclusion

In conclusion, integrating energy recovery mechanisms into wearable devices offers a promising solution to the pressing challenge of limited battery life. As wearable technology continues to evolve and play a vital role in modern society, the demand for power has grown substantially. Energy recovery technologies, encompassing methods like piezoelectric, thermoelectric, and kinetic energy, present an efficient means to prolong device operation and enhance user experiences. The practical application of these mechanisms, especially in wrist-worn devices, demonstrates their practicality and potential. Despite challenges related to durability and conversion efficiency, ongoing research is expected to address these obstacles. Energy recovery extends its significance beyond wearables, impacting environmental monitoring systems and smart homes. By harnessing energy from the environment and human activities, these technologies contribute to environmental sustainability and offer diverse applications in healthcare and sports. From a commercial perspective, the wearable technology market presents significant opportunities for businesses and investors, with prominent companies already investing heavily in the field. Looking forward, wearable devices are poised to benefit from improved energy conversion efficiency and multifunctional integration, ushering in a more sustainable and efficient era for these devices.

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