Wearable Sensors for Detecting and Measuring Kinetic Characteristics

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Abstract. Wearable devices play an important role in our daily life. We can use it in the sports area and the medical area. This review uses many articles to introduce how to use different sensors to analyze human kinetic characteristics. This review is divided into three parts. In the first sections, we will introduce the working principle and its calculation method of the different sensors such as IMUs sensors, pressure transducers, etc. The second part will show you some research about using wearable sensors to calculate the joint data and link the data with human movement. These researches can help us stay far away from joint diseases. In conclusion, we give some suggestions about the improvement of wearable devices.

1. Introduction
The first wireless smartwatch was released in 1994 and was developed in partnership with Microsoft. The watch is "linked" by reading light emitted from a computer via an optical sensor embedded in the watch to download information such as appointments and other reminders. The wireless download allowed this watch to ditch the keyboards and buttons of earlier smartwatches, increasing toughness and water resistance [1].

Recent developments in communication technology, microelectronics, MEMS sensor technology and data analysis techniques have also revolutionized the application of wearable technology for human activity detection and motion analysis. This analysis has allowed the athletes to take advantage of these small, inexpensive and accessible sensors for monitoring their techniques and activities. Wearable sensors are user-friendly with plug and play setup that is easy to use without any complicated arrangement. Moreover, wearables consisting of IMU sensors are proficiently used to classify activity and effort levels. These sensors are unobtrusive and improve reliable data acquisition in different environmental conditions and challenging terrain, unlike video setups that are very difficult to work under the water and on the mountain.
This paper presented a comprehensive reviewed application and recent development of wearable devices in recording and analyzing kinetic characteristics. Especially, this paper explored the application of wearable devices in the sport and medical field.

2. Principle of wearable sensors dealing with kinetic characteristics
The kinetic motion deals with plenty of physics. The main motion component is displacement, velocity, and acceleration. To measure and record data of motions, different kinds of wearable sensors have been invented and applied. The main kinds include accelerometers, gyroscopes, magnetometers, heart rate sensors, pressure sensors, etc. Accelerometer records the acceleration of movement. For example, users of the accelerometer can access their acceleration during or after the running. The gyroscopes were also a common wearable sensor. They differ from accelerometers by recording only angular acceleration. Multiple sensors are invented different recording movements of kinetic motion. However, an Inertial Measurement Unit (IMU) is introduced to combine these sensors. IMU is an electronic device that measures and reports a body's specific force, angular rate, and orientation. IMU is a combination of accelerometers, gyroscopes, and magnetometers. Therefore, this small unit can measure and report human movement. IMU is typically used to maneuver aircraft, including spacecraft, satellites, and landers. However, helping from the microcontroller, the IMU system can be applied on small chips. Therefore, the size of the IMU system is small. For example, the size of individual IMU sensor LIS3MDL is 64 mm³.

The small size enables the IMU system to be employed on the wearable device [2]. How does IMU work? An IMU provides 2 to 6 DOF (Degrees of Freedom), which refers to the number of different ways that an object can move throughout 3D space. The maximum possible is 6 DOF, which would include 3 degrees of translation (flat) movement across a straight plane/along each axis (front/back, right/left, up/down) and 3 degrees of rotational movement across the x, y, and z axes/ about each axis.

The raw data collected from an IMU gives some idea of the world around it, but that information can also be processed for additional insight. Sensor fusion is the (mathematical) art of combining the data from each sensor in an IMU to create a complete picture of the device's orientation and heading [3]. For instance, while looking at gyroscope information for rotational motion, the IMU incorporates an accelerometer's sense of gravity to create a reference frame. Besides, IMU can also additionally add information about the Earth's magnetic field to align the whole sensor to the Earth's frame [3].

![SIX DEGREES OF FREEDOM](image)

Figure 1. The overview of the proposed system.

3. Wearable sensors in sports and daily activities
For professional athletes, most injuries are caused by improper techniques and movements while training. Wearable sensors can detect and examine whether their motions are correct or not, reminding them of standardizing their skills. Moreover, athletes' motor habits can be reflected by how many times a motion is repeated in a match. Light and tiny wearable sensors can help test that. Similarly, in terms of normal people, incorrect walking gestures, running habits and sitting status may cause physical and body problems. Therefore, wearable sensors for detecting body movements play a more important role
in daily life. In this part, a summary of research works available in support of the use of wearable sensors for recording and analyzing people's kinetic characteristics has been presented.

3.1. Determining specific kinetic motion and movement

When a person is doing sport, his or her status is complicated. Take soccer as an example. It is rather difficult for sensors to distinguish similar gestures, such as ball kicking and collision with other players. To solve this specific problem, under the basis of using IMU sensors, novel arithmetic has been proposed to detect the motion of soccer kicks [4]. The differences between acceleration represent the change of direction and the differences of jerk collision.

Moreover, the angular difference between adjacent angular velocity vectors ($\omega$) is calculated to determine directional changes of rotational motions. The detailed formulas are shown below. These factors are used to distinguish ball-foot contact from sudden acceleration changes without contact.

\[
I(n) = j_{M,n} \cdot j_{A,n} \cdot sgn(s_n) \\
\quad j_{M,n} = \|j_n\|, \text{where } j_n = a_{n+1} - a_n \\
\quad j_{A,n} = 2(\alpha - a_{n+1} \cdot a_n) \\
\quad s_n = \sum_{\tau=n+1}^{\tau+1} (\beta - j_{\tau+1} \cdot j_{\tau})
\]

Merely referring to data from wearable sensors may be too abstract while analyzing human motions. As a complement, visual characteristics like images and videos allow coaches and athletes to study how a movement is performed more comprehensively. As the further research of the last reference, this article proposes a combination of wearable sensors with cameras [5]. Two cameras were set respectively from the side and top view. The former was used to observe in a wider view, and the latter was for recording the special information between legs and the ball. Collecting data samples from wearable sensors is synchronized with taking images by cameras. Therefore, when wearable devices collect data and decompose them into a series of sub-motions, corresponding images are generated and labeled simultaneously. The intuitive structure of this whole system can be seen in Figure 2. This combination has achieved high accuracy in detecting kicks. Among 80 tested samples, only 4 failed to detect the motion, which is quite encouraging.

![Figure 2. The overview of the proposed system.](image)

Strain sensors are catching more and more attention from scientists due to their high flexibility and advantage of testing mechanical deformation. They are suitable for specific conditions where traditional sensors cannot work well. A new type of flexible and low-cost fluidic strain sensor has been shown and discussed [6]. It is composed of a silicon tube that contains a mixture of water, sodium chloride 99.5% and glycerin 99%. The model of the sensor is displayed in Figure 3. In order to prevent electrolysis at electrodes, an AC source was used to replace the DC source. Howland current source and 4-point resistance measurement method were used to measure the resistance of their sensor. In application, this kind of sensor can detect the contraction or stretch of legs (Figure 4) and the motion state of fingers. The latter test has great potential in application to sign language translation.
Figure 3. (a) Model of fluidic strain sensor. (b) Geometry characteristics of the sensor at rest and being stretched.

Figure 4. The schematic diagram and application picture shows the sensor's attachment to the knees. Like the fluidic sensor mentioned before, a newly proposed conductive textile fabric sensor is also stretchable and flexible, aiming to monitor shoulder joint motion [7]. The sensor is a rectangle-shaped material made of knitted nylon 91% - elastane 9% coated with a conductive polymer. In order to improve the endurance ability, kinesiology tape was added to the sensor due to its elastic properties. The simplified manufacturing process of the sensor is shown in Figure 5. Using an experimental setup (mod. Instron 3365A, Instron, USA), the electrical data collected by the sensor was transformed into mechanical motion status. For the typical moving speeds of humans, the hysteresis error of the sensor was all below 3%, which are 2.59%, 1.81%, 2.41%, 1.42% and 0.42%. Results showed that the faster people raised their shoulders, the smaller error was, which displayed great potential in a future application. However, this article does not include much information about the characteristics of the tape, which is beneficial to muscle pain reduction and injury rehabilitation. Therefore, further work in combing the properties of kinesiology tapes with fabric sensors can be conducted to achieve the best effect of both joint motion sensing and muscle recovery.
With the rise of national fitness, more and more citizens have joined the group of running. Correspondingly, "how to run correctly" is an essential problem that people should pay attention to. Scientists have tried to use an IMU sensor to measure the movement of the ankle joint during running. Professor Byong Hun Kim and his team researched the relationship between running and ankle joints. Byong Hun Kim and his partner put equipment with IMUs sensors on the ankle to calculate the leg data, displayed in Figure 6. This research is very helpful in preventing the joint issue. Scientists can determine which running gesture will cause joint issues and which benefits the human body. It will help the public learn the right way to run to reduce the joint problem. Moreover, IMU sensors can be used in more athletic areas to help people correct their sports posture, letting them be far away from pain.

3.2. Determining full-body kinematics
Apart from partial body motion detection, joint or full-body kinematics detection is also necessary. As early as the year 2007, a scientist from Tokyo university had started research in this region. He proposed a unique system consisting of four wearable sensors: foot pressure sensing shoes, motion-sensing watch, sound sensing glasses, and pen-shaped ceiling sensor [8]. For the design of shoes, this article suggested that only several specific points of the insole needed to be implanted by pressure sensors, replacing measurement of the whole foot plane, which displayed the thought of simplification in design. All these sensors are connected by wireless communication. It utilized a behavior inference system to collect the data from sensors and transform them into postures and position information. Although the research was conducted at the early stage of wearable sensor development, it provided a good research orientation, combining different sensors to get a full image of the human's movements. It is worthy of reference.
Micro-inertial sensors also play an important role in human motion detection. However, this type of sensor is subjected to drift errors. Meanwhile, body segment motions are constrained because joints connect all segments, and uncertainties also exist in segment movements. Facing these challenges, Professor Zhang has presented a new model called Extended Dynamic Bayesian Network (shown in Figure 7) to comprehensively construct mutual relationships among different segments to demonstrate motion status [9]. It also proposes that separate models should be targeted at different body segments to get a full-body motion condition since one model does not fit all human body parts. This article is both helpful for specific movement and joint body kinematics detection.

![Extended Dynamic Bayesian Network](image)

Figure 7. The EDBN is used for upper limb motion detection. In this model, merely shoulder, upper arm, forearm and hand are taken into consideration, so there are four nodes at state space, and each node represents one segment.

4. **Wearable sensors detecting kinetics in the medical field**

Patients’ body status and moving postures need to be tracked to promote rehabilitation during the recovery process from muscle injuries and other specific diseases caused by muscles and joints. However, it is time-consuming and not convenient for citizens to have a muscle check in the hospital at set intervals. Wearable sensors for detecting kinetic characteristics provide users with a chance to know about their body status anywhere and anytime by simply putting it on the device. Meanwhile, doctors can also adjust the recovering plan timely based on the data collected from the patients. Therefore, wearable devices for detecting and monitoring muscle conditions and gestures also have great application potential in the medical field.

A new wireless data acquisition system has been proposed, consisting of three wearable sensors: force-sensitive resistor, flex sensor, and accelerometer [10]. The accelerometer was used for detecting vibrations of muscle. It can measure muscle displacement while contracting in 3 axes: longitudinal, lateral, and traverse to the muscle fiber. For FSR, a resistor-based component tracks the gait cycles by measuring the force applied by the foot per unit time. The flex sensor, combined with a static resistor, can measure the deflection extent of the sensor, thus obtaining the bending data of knees and ankles and the gait cycles. The authors chose Arduino UNO to analyze raw data, like reading in resistance variance and outputting voltage variance, then people's step numbers in a cycle were gained. The whole schematic of the system is demonstrated in Figure 8. It turned out that longer stride time and fewer steps meant worse muscle condition. The results are in Figure 9 and Figure 10, respectively. Through real-time surveillance of gait disturbance, users' muscle fatigue will be recognized, and detailed information will be recorded in daily life, which is helpful for doctors to make diagnoses.
Figure 8. Schematic representation of the proposed system.

Figure 9. Change of mean stride time from no fatigue to low fatigue.
Patients with Parkinson's find it hard to walk steadily and may fall easily. On the one hand, Chariklia Chatzaki and Vasileios Skaramagkas used different sensors to help Parkinson correct their walking gesture and help them have a regular life. Some researchers used back sensors (in Figure 11) to measure the change of the back flexion angles, neck flexion angles and neck flexion angles [11]. Scientists use data to analyze the posture of patients with Parkinson's during the process of walking. It contributes to their learning the issue of Parkinson's walking habit, and doctors can figure out the best treatment to overcome Parkinson's posture issue.

On the other hand, Se Hoon Kim and Seo Jung Yun use smart insoles to help Parkinson correct their gesture. Se Hoon Kim's team divided the foot into 12 areas (Figure 12) and measured the pressure about their walking through their feet (Figure 13). After that, they analyzed the sensors' data and found the relation between walking gestures and feet pressure. And then, they relate the foot length and feet pressure. At last, scientists give some suggestions about how to correct the gesture of parkinsonism. These suggestions are very helpful in future studies about helping people get away from the incorrect gesture when suffering from parkinsonism [12].

Figure 10. Decrease in total steps in 30 seconds with induced fatigue.

Figure 11. Application of back sensors.
Figure 12. Subareas divided on feet.

Figure 13. Five stages of the walking process.

Muscle contractile ability reflects muscle diseases and provides helpful information for medical evaluation. In pursuit of avoiding the negative effects of the traditional ultrasound probe, a novel wearable ultrasonic sensor was researched to measure muscle contractile properties [13]. The specialty is that the sensor's material, polyvinylidene fluoride, can attach to the skin surface without interfering with the tissue motion. The transmitter and receiver parts of the wearable ultrasonic sensor are placed on opposite sides of the muscle. After EMS electrically simulates the leg, the ultrasound time-of-flight method is used to test how the muscle thickness changes. The basic schematic of the experimental testing sets is in Figure 14. The data, including contraction duration, contraction speed, and sustain time, can be measured and recorded. This technology is both effective for stimulated and voluntary contractions, and it realizes continuous and non-invasive measurement.
Figure 14. A schematic of the measurement structure of GC muscle contractions, stimulated by EMS, using the developed WUSs.

Moreover, ACL (anterior cruciate ligament) is a serious injury, which is more common in professional athletes. The recovery process is long and uncertain to improve compliance with prescribed rehabilitation programs. Professor Ryan and his coworkers demonstrated the BioStampRC wearable sensor used to measure raw accelerometer data and surface electromyography (sEMG) data during ambulatory monitoring of patient’s daily activity [14]. People's gait cycle can be obtained from this information. Unlike previous research, this study allowed subjects to do free-living activities instead of being constrained to clinical or laboratory environments, which provides a possible solution for monitoring ACL reconstruction. Both patients' affected leg and contralateral leg have applied the sensor (demonstrated in Figure 15). It compared the sEMG amplitude of healthy leg and affected limb, and the experimental statistic well corresponded to the progress of patients' recovery, which means that this technique has achieved appreciable research progress [15].

Figure 15. (a) The model of BioStampRC. (b) Bilaterally attached to the anterior aspect of the thigh.
5. Conclusion
This review has introduced various researches in wearable sensors for recording and analyzing people's kinetic characteristics, including the working principle of different sensors, detecting joint and full-body kinematics, and potential application in the medical field. It finds out that with the development of the study in wearable sensors, the main orientation is changing to flexible materials that can directly attach to people's skin, such as fluidic strain sensors, conductive textile fabric sensors and ultrasonic sensors. These mentioned products are closer to practice while being put into use. Moreover, wearable sensors provide a new option in the medical field and have a bright future. The function of timely recording people's kinematic data in daily life can inform users of their health condition and allow doctors to monitor the process of patient's rehabilitation, thus facilitating the recovery from diseases (just like Parkinson mentioned in the article). However, up to today's work, there is still a lot to be improved. We need to ameliorate the stability, data collect accuracy and wireless signal transmission range in future work, probably by adjusting the algorithm and the structures of sensors. Meanwhile, to earn a good position on the market, products should be as user-friendly as possible.

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