

AI-Powered Wearable Mechatronics and IoT Systems for Enhanced Human Joint Health and Performance

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Abstract— The integration of AI-powered wearable mechatronics and IoT systems presents a groundbreaking advancement in the monitoring and analysis of human joint health. These innovative technologies enable continuous, real-time tracking of key joint parameters such as range of motion, joint torque, muscle activation, and load distribution. By leveraging sophisticated sensors, microcontrollers, and wireless communication, these wearable systems provide precise and actionable insights into joint mechanics. The incorporation of artificial intelligence and machine learning further enhances this capability, offering predictive analytics, personalized feedback, and early detection of potential joint disorders. This comprehensive approach not only optimizes rehabilitation and athletic performance but also supports preventive healthcare. This article explores the design, functionality, and applications of these cutting-edge systems, highlighting their transformative impact on joint health management and the future requirements for their development and implementation.

Keywords— Wearable Devices, AI-Powered Systems, Internet of Things (IoT), Joint Health Monitoring, Smart Wearables, Preventive Healthcare

I. INTRODUCTION

Our ability to move freely, perform daily activities, and achieve peak athletic performance hinges on the health of our joints. These complex structures, where bones, cartilage, ligaments, tendons, and muscles collaborate to enable movement, have traditionally been assessed through clinical examinations and imaging techniques. While valuable, these methods lack the continuous, real-time monitoring crucial for a dynamic and comprehensive analysis of joint function.

Recent advancements in wearable technologies, particularly those integrating mechatronics, artificial intelligence (AI), and the Internet of Things (IoT), have revolutionized the field of joint health monitoring. These wearable systems are designed to be worn comfortably on the body, continuously collecting data on joint parameters such as range of motion (ROM), joint torque, muscle activation, and load distribution. This real-time data collection is pivotal for applications in rehabilitation, sports performance optimization, and clinical diagnostics. However, current technologies still have limitations in achieving the required

accuracy, comfort, and seamless integration needed for everyday use.

Human joint health is fundamental to maintaining mobility, performing daily activities, and achieving peak athletic performance. Joints, as complex anatomical structures, facilitate movement through the coordinated function of bones, cartilage, ligaments, tendons, and muscles. The intricate dynamics of joint mechanics have traditionally been studied through clinical assessments and imaging techniques, providing essential insights into joint function and pathology. However, these methods often fall short in offering continuous, real-time monitoring, which is crucial for dynamic and comprehensive analysis.

Artificial intelligence, particularly machine learning (ML) algorithms, plays a transformative role in interpreting the vast amounts of data generated by these wearables. AI enhances the capability of these systems to provide predictive analytics, personalized feedback, and early detection of potential joint disorders. By recognizing patterns and anomalies in joint movement data, AI can offer valuable insights that were previously unattainable through traditional methods.

Mechatronics, the synergistic integration of mechanical, electronic, and computer systems, forms the backbone of these advanced wearables. Sensors like inertial measurement units (IMUs), force sensors, and electromyography (EMG) sensors embedded in the wearables capture high-resolution data on joint movements and forces. Microcontroller units process this data, which is then transmitted wirelessly via IoT technologies to external devices for further analysis.

This research article delves into the multifaceted approach of using AI-powered wearable mechatronics and IoT systems for enhanced joint health and performance. We explore the design and functionality of these systems, the key parameters they monitor, and the significant role of AI and ML in data analysis and interpretation. Furthermore, we discuss the current applications of these technologies in various fields and outline the future requirements for their continued development and implementation. Through this comprehensive examination, we aim to highlight the transformative potential of these advanced systems in revolutionizing joint health monitoring and management

while addressing the existing needs and limitations of current technologies.

II. HUMAN JOINT AND HEALTH CONDITIONS

The intricate joints of our body are the foundation of our movement and stability. They act like hinges, connecting bones to provide flexibility and support. But just like any complex machinery, joints are susceptible to wear and tear, injuries, and diseases. These workhorses are composed of bones, cartilage, ligaments, tendons, and synovial fluid. This combination allows for smooth movement, shock absorption, and proper alignment, all of which are essential for our daily activities, from walking and bending to even the most complex athletic maneuvers.

Types of Joints

Our bodies are marvels of movement thanks to joints, the connections between bones that grant us flexibility, stability, and diverse motion. There are three main joint types: the rock-solid, immovable fibrous joints like skull sutures; the slightly-movable cartilaginous joints in your spine; and the stars of the show, synovial joints, allowing free movement in knees, shoulders, and more. Each type plays a vital role in keeping us mobile and healthy.

Synovial joints (see Figure 1) reign supreme in the body, offering the most freedom of movement. These versatile joints come in six subtypes, each with its own special trick. Ball-and-socket joints, like the shoulder and hip, boast the widest range of motion, allowing us to swing our arms and rotate our hips. Hinge joints, found in the elbow, knee, and ankle, excel at movement in one plane, mimicking the action of a door hinge. Condyloid joints, present in the wrist and base of the fingers, grant us movement in two planes, perfect for side-to-side and up-and-down motions. Finally, gliding joints, like those between the carpal bones in the wrist and the vertebrae in the spine, allow for smooth sliding movements in one or two planes. This diverse cast of synovial joints working together keeps us mobile and capable of complex movements.

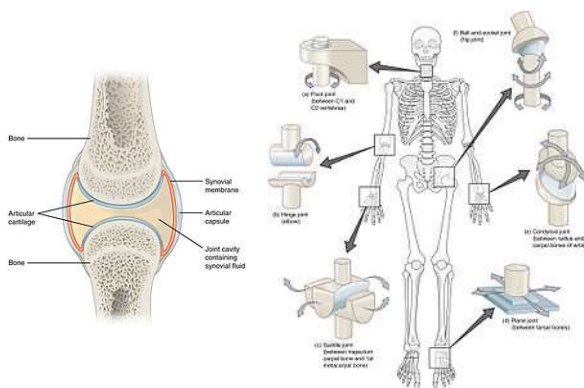


Figure 2 (a) Structure of synovial joint (b) Types of synovial joints. Clockwise from top-right: ball and socket joint, condyloid joint, plane joint, saddle joint, hinge joint and pivot joint. Source: https://www.physio-pedia.com/Synovial_Joints

Cartilaginous joints, (see Figure 2) the connectors for subtle movements, rely on cartilage for their structure. These slightly mobile joints, like the pubic symphysis and the discs between vertebrae, cushion the bones while allowing some flexibility. There are two main types: synchondroses and symphyses. Synchondroses, like the growth plates in children, use hyaline cartilage to connect bones. These can be temporary, fusing with age, or permanent, like the joint

between the first rib and sternum. Symphyses, on the other hand, employ stronger and more flexible fibrocartilage. They're found in areas needing both movement and stability, such as the pubic symphysis and the spine's intervertebral discs. Overall, cartilaginous joints play a vital role in supporting the body, absorbing shock, and distributing stress while allowing limited movement, essential for growth, development, and daily activities.

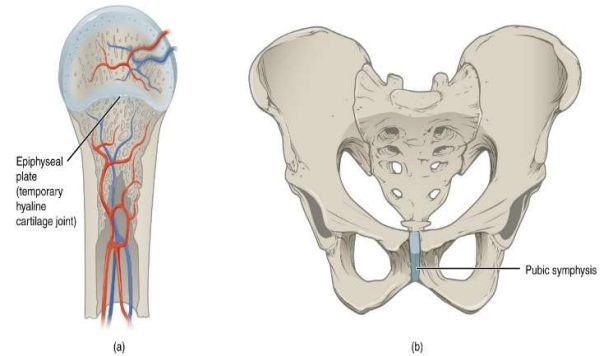


Figure 1 Cartilaginous joints (a) synchondroses eg. growth plate (b) symphyses eg. pubic symphysis Source:

<https://radiopaedia.org/articles/cartilaginous-joints>

Fibrous joints (see Figure 3), bound by fibrous connective tissue, provide stability and are found in the skull sutures. These immovable joints create strong connections between bones, offering essential support to the skeleton. There are three main types: **Sutures**: Immovable joints connecting the flat bones of the skull, allowing for growth in children but becoming fixed in adults. **Gomphoses**: Peg-in-socket joints that connect teeth to jawbones, allowing slight movement important for chewing. **Syndesmoses**: Joints where bones are connected by ligaments or an interosseous membrane, permitting limited movement. Examples include the joints between the tibia and fibula in the leg and between the carpal bones in the wrist. Fibrous joints ensure stability and support, protect the brain, and transmit forces during movement.

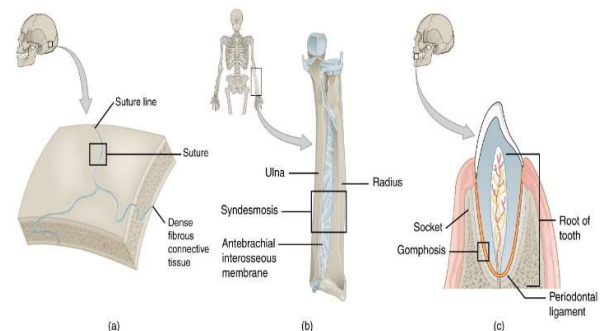


Figure 3 Fibrous Joints: Fibrous joints form strong connections between bones. (a) Sutures join most bones of the skull. (b) An interosseous membrane forms a syndesmosis between the radius and ulna bones of the forearm. (c) A gomphosis is a specialized fibrous j Source: <https://open.oregonstate.edu/andp/chapter9-2-fibrous-joints/>

III. JOINT HEALTH CONDITIONS

Monitoring human joints offers several important benefits for maintaining overall health and well-being. **Early detection of issues**: Monitoring can help identify abnormalities in movement patterns, swelling, or pain before they become major problems. This allows for early intervention and treatment, potentially preventing further

damage or progression of joint diseases like arthritis. **Improved recovery:** Monitoring joint movement after injuries or surgeries helps track progress and ensure proper healing. It can also help therapists tailor rehabilitation programs to optimize recovery. **Enhanced performance:** Athletes and people with physically demanding jobs can benefit by monitoring joint health to optimize training and prevent overuse injuries. **Pain management:** Monitoring can help identify the source and severity of pain, allowing for better pain management strategies. The criticality of monitoring a joint depends on several factors, including:

- **Weight-bearing:** Joints that bear significant weight, like the knees, hips, and ankles, are more susceptible to wear and tear and injuries. Monitoring these joints is crucial for preventing long-term problems.
- **Range of motion:** Joints with a wide range of motion, like the shoulders and spine, are more prone to instability and injuries. Monitoring these joints can help identify potential problems before they affect mobility.
- **Complexity:** Joints with complex structures and multiple ligaments, like the knee, are more prone to specific types of injuries. Monitoring these joints allows for early detection of ligament damage.

Following joints are important to monitor to avoid unhealthy conditions in future:

- **Knees:** They bear a significant amount of weight and are susceptible to injuries like torn ligaments and meniscus tears.
- **Hips:** Similar to knees, they bear weight and are prone to arthritis and bursitis.
- **Spine:** It provides flexibility and support, but misalignment or injury can lead to pain and mobility issues.
- **Shoulders:** These have a wide range of motion and are susceptible to rotator cuff injuries.
- **Ankles:** They support weight and allow for movement, but sprains and instability are common.

IV. HUMAN JOINT INJURIES

Our bodies rely on joints for movement and flexibility. But just like any complex machinery, joints are susceptible to injuries. These injuries can range from minor inconveniences to debilitating conditions, impacting our daily lives and overall well-being. This section delves into the world of human joint injuries, and explore the different types of injuries, from common sprains and strains to more serious conditions like dislocations and fractures. Also discussion on the causes of these injuries, including everyday activities, sports, and even age-related wear and tear. By understanding the different types of joint injuries, their causes, and potential treatments, we can take steps to prevent them and keep our joints healthy and mobile for years to come. Joint injuries can range from minor to severe and can affect any joint in the body which are outlined in Figure 4. Here are some of the most common types of joint injuries:

- **Sprains:** These occur when ligaments, the tough bands of tissue that connect bones at a joint, are stretched or torn. Sprains are often accompanied by pain, swelling, bruising, and limited mobility. The severity of a sprain depends on the degree of ligament damage.

- **Strains:** Similar to sprains, strains involve the stretching or tearing of muscles or tendons, the tissues that connect muscle to bone. Strains can cause pain, tenderness, muscle weakness, and difficulty moving the affected joint.
- **Dislocations:** These happen when the bones of a joint are forced out of their normal position. Dislocations are very painful and can cause swelling, bruising, and nerve damage. They require immediate medical attention to properly reset the joint.
- **Fractures:** These are broken bones, which can also affect the stability of a joint. Fractures near a joint can damage the cartilage or ligaments, leading to long-term complications.
- **Overuse Injuries:** These develop over time due to repetitive stress on a joint. Common overuse injuries include tendinitis (inflammation of a tendon) and bursitis (inflammation of a fluid-filled sac near a joint).
- **Meniscus Tears:** The meniscus is a crescent-shaped piece of cartilage that cushions the knee joint. Tearing the meniscus is a common sports injury that can cause pain, swelling, and clicking sounds in the knee.
- **Rotator Cuff Injuries:** The rotator cuff is a group of muscles and tendons that stabilize the shoulder joint. Rotator cuff injuries can cause pain, weakness, and difficulty moving the arm.



Figure 4 Human Joint Injuries (a) Sprain (b) Strain (c) Dislocation (d) Fractures (e) Overuse (f) Meniscus Tears (g) Rotator Cuff, this picture clarifies cause effect analysis of human joint injuries

This is not an exhaustive list, but it covers some of the most common types of joint injuries. If you experience any pain, swelling, or limited mobility in a joint, it's important to see a doctor to get a proper diagnosis and treatment plan.

V. IMPORTANCE OF MONITORING JOINT HEALTH

While modern medicine offers sophisticated tools for joint health assessment, traditional methods have played a vital role for centuries. Here's why monitoring joint health is important, and how some traditional practices can complement modern approaches:

Importance of Monitoring Joint Health:

- **Early Detection:** Monitoring helps identify issues like pain, stiffness, or swelling before they worsen. This allows for early intervention, potentially preventing long-term damage and improving treatment outcomes.
- **Improved Function:** By understanding your joint health, you can adjust activities to avoid further strain and maintain optimal function.

- **Pain Management:** Monitoring helps track pain patterns and identify triggers, allowing for better pain management strategies.

Traditional Methods and Wisdom:

- **Self-Observation:** Traditional methods emphasize self-awareness. Observing your joints for pain, swelling, stiffness, or changes in range of motion provides valuable insights.
- **Movement Patterns:** Traditional practices like yoga, tai chi, and specific movement exercises can help identify limitations or imbalances in movement that might indicate potential issues.
- **Dietary Practices:** Traditional food wisdom often emphasizes anti-inflammatory diets rich in fruits, vegetables, and healthy fats. These can support joint health by reducing inflammation.
- **Herbal Remedies:** Some cultures use herbal remedies like turmeric or ginger, known for their anti-inflammatory properties, to alleviate joint pain and discomfort. (**Disclaimer:** Always consult a healthcare professional before using herbal remedies.)
- **Heat and Cold Therapy:** Applying heat or cold packs to sore joints is a traditional practice used to manage pain and inflammation.

Limitations of Traditional Methods:

- **Diagnosis:** Traditional methods cannot diagnose the underlying cause of joint problems. They are best used alongside modern medicine.
 - **Specificity:** Many traditional practices are general and may not address specific joint conditions.
- Scientific Evidence:** The effectiveness of some traditional methods lacks strong scientific evidence.

VI. PROPOSED REAL-TIME MONITORING SYSTEM FOR KNEE JOINT

The integration of traditional and modern approaches to joint health can provide a comprehensive strategy for managing and preventing joint conditions. Traditional methods, such as recognizing early warning signs of joint discomfort, stiffness, or swelling, can prompt timely medical consultations, enabling early diagnosis and intervention. These early warning systems are invaluable in identifying issues before they escalate into severe conditions. Additionally, traditional practices such as heat/cold therapy and dietary adjustments can effectively complement contemporary medical treatments. Heat therapy can alleviate joint stiffness and improve flexibility, while cold therapy can reduce inflammation and pain. Nutritional strategies, including anti-inflammatory diets rich in omega-3 fatty acids and antioxidants, support joint health and overall well-being. By combining these traditional approaches with modern technologies like wearable mechatronics and AI-driven monitoring systems, individuals can achieve a holistic and proactive approach to joint health management, enhancing both preventive and therapeutic outcomes.

Real-time monitoring of the knee joint involves a sophisticated and multi-layered information processing system which is shown in Figure 5. Each layer plays a crucial role in ensuring accurate data collection, efficient processing, meaningful analysis, and actionable feedback. Here are the primary layers involved:

1. Sensor Data Acquisition Layer

- **Sensors Used:** Inertial Measurement Units (IMUs), force sensors, electromyography (EMG) sensors.
- **Data Collection:** This layer involves the continuous capture of raw data from various sensors placed on or around the knee joint.
- **Synchronization:** Ensures that data from different sensors are accurately synchronized for consistent analysis.

2. Data Preprocessing Layer

- **Noise Filtering:** Application of filters (e.g., low-pass, band-pass) to remove noise and irrelevant signals from the raw data.
- **Signal Conditioning:** Adjusting the signal to the appropriate range and format required for further processing.
- **Normalization:** Standardizing data to a common scale to facilitate comparison and analysis.

3. Feature Extraction Layer

- **Kinematic Parameters:** Extraction of joint angles, angular velocity, and acceleration from IMU data.
- **Kinetic Parameters:** Calculation of joint torque, forces, and load distribution from force sensor data.
- **Muscle Activation:** Analysis of EMG signals to determine the level and pattern of muscle activation.

4. Data Fusion Layer

- **Multi-Sensor Integration:** Combining data from different sensors to create a comprehensive and cohesive dataset.
- **Sensor Fusion Algorithms:** Utilizing algorithms (e.g., Kalman filter, complementary filter) to improve the accuracy and reliability of the extracted features.

5. Real-Time Analysis Layer

- **Pattern Recognition:** Using machine learning algorithms to identify patterns and anomalies in the joint movement data.
- **Predictive Analytics:** Applying predictive models to forecast potential issues or injuries based on current and historical data.
- **Biomechanical Modelling:** Creating real-time models of knee joint mechanics to simulate and understand joint behaviour under different conditions.

6. Feedback and Alert Layer

- **Real-Time Feedback:** Providing immediate feedback to the user through visual, auditory, or haptic alerts based on the analysis.
- **Performance Metrics:** Displaying key performance indicators (KPIs) such as joint angles, torque, and muscle activation levels on a user interface.
- **Customized Alerts:** Setting thresholds for specific parameters to alert users or clinicians when values exceed safe limits.

7. Data Storage and Transmission Layer

- **Local Storage:** Temporary storage of data on the wearable device for short-term use and immediate processing.
- **Cloud Storage:** Secure transmission of data to cloud servers for long-term storage, advanced analysis, and remote access.
- **Data Security:** Ensuring encryption and secure transmission protocols to protect user data privacy.

8. User Interface and Visualization Layer

- **Mobile Applications:** User-friendly apps on smartphones or tablets that visualize data and provide insights.
- **Dashboard Interfaces:** Comprehensive dashboards for clinicians to monitor patient progress and adjust treatment plans.
- **Interactive Features:** Tools that allow users to interact with the data, set goals, and track improvements over time.

9. AI and Machine Learning Layer

- **Model Training:** Continuous improvement of AI models using new data to enhance accuracy and predictive capabilities.
- **Personalization:** Adapting algorithms to individual user characteristics for personalized feedback and recommendations.
- **Adaptive Learning:** Implementing systems that learn and adapt based on user behavior and outcomes to optimize joint health management.

Each layer in the information processing pipeline plays an integral role in the real-time monitoring of the knee joint. From accurate data acquisition to sophisticated AI-driven analysis and user-friendly feedback mechanisms, these layers work together to provide comprehensive insights and support proactive joint health management. By continuously refining each layer, the effectiveness and efficiency of real-time knee joint monitoring systems can be significantly enhanced, offering substantial benefits for rehabilitation, sports performance, and overall joint health.

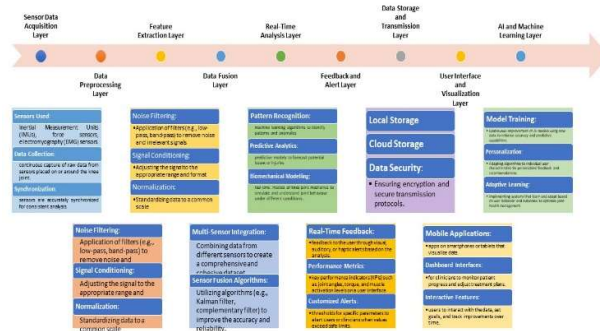


Figure 5 Real-Time IoT Based AI Monitoring System for Knee Joint Health Condition (Data Processing Layers)

The system integrates various sensors, processes data, and provides real-time feedback to users. The key components include an Arduino microcontroller, inertial measurement units (IMUs), force sensors, electromyography (EMG) sensors, and wireless communication modules shown in Figure 6. The Arduino-based real-time knee joint monitoring system offers an affordable and effective solution for continuous joint health assessment. By integrating various sensors, processing data locally, and transmitting it wirelessly, this system provides valuable insights into knee joint mechanics, aiding in rehabilitation, performance optimization, and early detection of potential issues. This setup demonstrates the potential for wearable technologies to revolutionize joint health monitoring and management.

This will offer real-time insights into knee health, these systems have the potential to revolutionize injury prevention, rehabilitation, and overall joint health management. Regular monitoring of joint health parameters

is crucial for early detection, intervention, and management of joint conditions. By tracking factors such as joint range of motion, muscle strength, and inflammation levels, healthcare providers can assess disease progression, evaluate treatment effectiveness, and tailor rehabilitation strategies. Furthermore, monitoring joint health in real time using advanced technologies allows for proactive interventions to prevent exacerbations and optimize joint function.

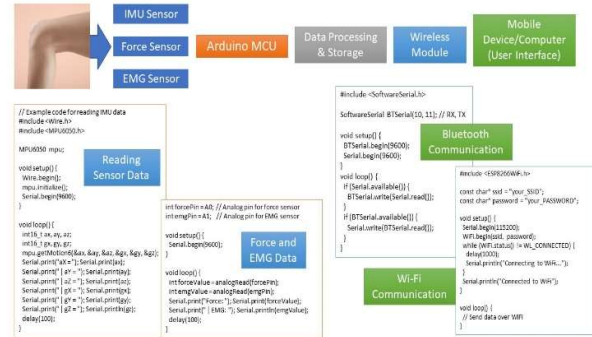


Figure 6 Arduino Board Based Real-Time IoT System for Knee Joint Monitoring

VII. CONCLUSION

The landscape of knee joint monitoring is undergoing a significant shift. Traditional methods, while valuable for general awareness, lack the depth and detail needed for proactive joint health management. This is where the exciting world of real-time monitoring with IoT-based wearables comes in.

The Need for IoT Wearables: Current trends highlight the growing need for wearable technology that seamlessly integrates with the Internet of Things (IoT). These wearables, equipped with advanced sensors, can collect real-time data on various aspects of knee function, providing a much more comprehensive picture of joint health than ever before.

Effective Measures of Real-Time Monitoring:

These IoT-based systems offer a multitude of effective measures. They can detect subtle changes in movement patterns or stress on the joint, allowing for early intervention and preventing future injuries. Additionally, athletes and those recovering from injuries can leverage this data to optimize training programs and track rehabilitation progress. Real-time monitoring can also empower individuals with knee pain to identify activities that exacerbate pain and develop personalized pain management strategies.

The Power of AI and Machine Learning:

Integrating AI and machine learning into these systems unlocks a whole new level of functionality. By analyzing the collected data, the software can provide insightful predictions about potential risks and recommend personalized actions. This empowers users to take a proactive approach to maintaining healthy knees.

Looking Ahead: The future of real-time knee joint monitoring is bright. Advancements in sensor technology will lead to smaller, more comfortable wearables with enhanced capabilities. AI-powered software will become even more sophisticated, offering personalized recommendations and predictions. Ultimately, these

advancements hold the potential to revolutionize injury prevention, rehabilitation, and overall joint health management, allowing us to keep our knees healthy and mobile for years to come.

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