Fiber Bragg Grating-Based Thumb Strain Analysis and Biomechanical Monitoring

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Abstract- This study focuses on extracting and analyzing physiological signals to detect arthritis-related changes in muscle and circulatory responses. A dual-function optical sensor capable of Photoplethysmography (PPG) and Optical Myography (OMG) was employed for data collection. The experiment involved recording light absorption variations during muscle contraction exercises and pulse monitoring. The Sentea software was utilized to interface with the sensors, enabling precise data acquisition and exporting the results in CSV format. Advanced signal processing was conducted using OriginPro, where noise filtering and waveform analysis were performed to derive meaningful insights. The methodology combines robust data acquisition with comprehensive analysis, providing a foundation for understanding arthritis-related physiological variations.

I. INTRODUCTION

Fiber Bragg Grating (FBG) sensors have emerged as a promising solution for non-invasive biomedical monitoring due to their high sensitivity, small size, and ability to measure a variety of physiological parameters. FBGs are particularly effective for measuring strain, pressure, and displacement, which are crucial for detecting and monitoring conditions like cardiovascular diseases, arthritis, and musculoskeletal disorders.

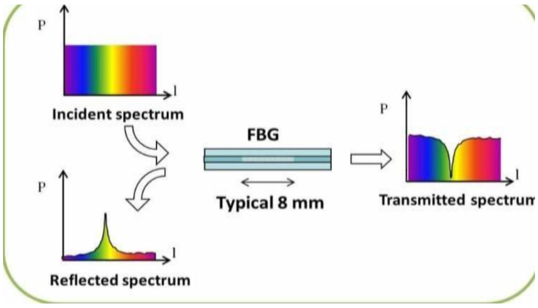

Fig.1 FBG Technology
Source: https://fbgs.com/technology/fbg-principle/

The fundamental principle of FBG technology lies in the reflection of light at a specific wavelength, which shifts when the grating experiences strain or deformation Fig.1.
This property makes FBGs suitable for real-time health monitoring, including pulse and muscle strain detection.

Recent studies have demonstrated the use of FBGs in heart rate measurement [1], blood pressure monitoring [2], and joint movement tracking [7], offering substantial advancements over traditional methods. However, most existing work focuses on individual parameter detection with limited integration into wearable systems. The novelty of this study lies in the combination of FBG sensors with advanced signal processing techniques for real-time monitoring of pulse and thumb strain in individuals with arthritis. By utilizing sensor fusion and enhanced data filtering, this research improves the accuracy and reliability of measurements, even in the presence of movement artifacts.

Furthermore, this paper introduces a dual-function optical sensor designed for both Photoplethysmography (PPG) and Optical Myography (OMG), which provides a more holistic view of an individual's physiological condition. This integrated approach could pave the way for the development of wearable devices that offer continuous, personalized monitoring for arthritis management. Unlike previous works that have primarily focused on static measurements or laboratory-based systems, our approach emphasizes real-time, non-invasive monitoring with the potential for widespread use in clinical and home settings [9][10].

II. LITERATURE REVIEW

The integration of Fiber Bragg Grating (FBG) sensors in biomedical applications has seen significant advancements in recent years, offering a non-invasive, accurate, and versatile approach to monitoring various physiological parameters. This section reviews key literature on the application of FBG sensors in cardiovascular monitoring, muscle activity assessment, and related biomedical domains.

Cardiovascular Monitoring Using FBG Sensors

FBG sensors have demonstrated their capability in cardiovascular applications, particularly in pulse and blood pressure monitoring. Miyauchi et al. [2] explored the use of FBG sensors for blood pressure measurement, highlighting their precision in detecting minute physiological signals. Similarly, Sadek et al. [3] utilized sensor fusion techniques with FBG sensors to automatically detect heart rates, showcasing their effectiveness in high-noise environments. Zhu et al. [5] further enhanced heart rate estimation using cepstrum analysis, illustrating the potential for improved signal processing methodologies to increase accuracy. Recent work by Shao and Liu [8] proposed a comprehensive pulse and respiration monitoring system using FBG sensors, emphasizing their ability to measure multiple parameters simultaneously.

Muscle Activity and Biomechanical Monitoring

FBG sensors have also been applied to monitor muscle activity and movements, offering insights into musculoskeletal health. Socorro-Leranoz et al. [13] designed an optical system based on multiplexed FBGs to monitor hand movements, demonstrating the utility of FBG sensors in tracking precise biomechanical changes. Park et al. [6] embedded FBG sensors into exoskeletal force-sensing end-effectors, enabling accurate force measurement for robotics and rehabilitation applications. Da Silva et al. [7] employed FBG sensors in PVC foils to monitor knee joint movement during rehabilitation, providing valuable data for therapy optimization.

In a similar vein, Jang et al. [17] developed an FBG-based finger motion capture system, emphasizing the sensors' potential for motion tracking in rehabilitation and ergonomic studies. Lu et al. [15] introduced a novel square hole structure for FBG tactile sensors, enabling precise measurement of finger pressure, which holds promise for applications in hand therapy and prosthetics.

Multi-Parameter Monitoring

The ability of FBG sensors to simultaneously monitor multiple physiological parameters has opened new avenues in wearable technology. Tavares et al. [16] developed a 3D-printed wearable system incorporating FBG sensors to measure respiratory and heart rates, providing real-time feedback in a compact form factor. Abro et al. [4] combined FBG and flex sensing technologies in a smart garment to monitor body postures, highlighting the versatility of FBG sensors in diverse biomedical applications.

Advanced Signal Processing Techniques

Recent advancements in signal processing have significantly enhanced the usability of FBG sensors in biomedical applications. Anastasopoulos et al. [10, 11] introduced a wavelength-shift detection algorithm for sub-micro strain FBG data, enabling precise identification of modal strains. Kumar et al. [9] demonstrated the feasibility of FBG-based pulse monitoring devices for real-time blood pressure measurement using advanced algorithms, further showcasing their potential in clinical diagnostics.

Emerging Trends and Innovations

Recent innovations include the integration of FBG sensors with flexible materials for biomedical applications. Da Silva et al. [14] reviewed photonic sensors based on flexible FBG materials, underscoring their adaptability for wearable systems. The use of flexible FBGs for joint movement monitoring [7] and their application in smart garments [4] illustrate the trend towards lightweight and user-friendly devices for continuous health monitoring.

Conclusion

The reviewed literature highlights the versatility and potential of FBG sensors in biomedical applications, including cardiovascular monitoring, muscle activity assessment, and wearable technology. With advancements in signal processing and sensor integration, FBG sensors are poised to revolutionize healthcare diagnostics and therapy. Future research should focus on improving signal-to-noise ratios, miniaturizing sensor systems, and integrating FBG technologies into user-friendly platforms for widespread adoption.

III. PROPOSED SYSTEM

The proposed system leverages Fiber Bragg Grating (FBG) sensors to monitor and analyze thumb strain and pulse, demonstrating its capability to collect and process data relevant to arthritis-related conditions. The focus of the system is on the precise measurement and signal processing of thumb strain and pulse data, laying the foundation for potential arthritis differentiation in future studies.

FBG sensors are used to capture strain exerted by the thumb during motion and the pulse rate at arterial points. These sensors are externally mounted and calibrated for high sensitivity, allowing them to detect minor wavelength shifts corresponding to changes in strain and pulse. While the current study does not directly address the differentiation between arthritis and normal conditions, it successfully demonstrates the system's ability to measure and record these physiological parameters with high precision.

For data acquisition and processing, the Sentea software is utilized to collect and log data from the FBG sensors in real-time. The raw data, representing variations in reflected wavelengths due to thumb strain or pulse fluctuations, is exported in CSV format for further analysis. This setup ensures accurate and reproducible data collection, which is critical for evaluating physiological responses in the context of thumb strain and pulse rate.

The raw FBG data undergoes processing using OriginPro software, where the signal quality is enhanced and meaningful features are extracted. Key steps in this process include the application of a low-pass filter to eliminate high-frequency noise while retaining the relevant signal components, such as strain and pulse waveforms. After filtering, the processed signals are analyzed for key attributes like strain amplitude and pulse wave characteristics, which provide valuable insights into the sensor's performance and the physiological data collected.

The experimental setup involves placing FBG sensors on the thumb to measure strain during motion and on arterial sites to measure pulse. Data is collected during controlled sessions to ensure consistency and accuracy in the readings. This methodological approach validates the system's ability to capture physiological parameters, although clinical differentiation between normal and arthritis conditions is not directly addressed in this study.

While the system does not explicitly differentiate between normal and arthritis conditions in its current implementation, it establishes a reliable method for collecting strain and pulse data that could be used in future studies to identify arthritis-related differences. For example, arthritis may manifest as altered strain exertion patterns and wavelength shifts in the thumb during motion. Building on this foundation, the system holds the potential to serve as a diagnostic tool for arthritis in subsequent iterations.

The current system focuses on demonstrating data collection and processing capabilities, but there are several limitations to consider. Future enhancements could involve conducting comparative studies between individuals with and without arthritis to identify specific diagnostic markers. Additionally, the integration of machine learning models could enable automated differentiation between conditions and support personalized arthritis management.

Overall, by demonstrating the ability to accurately measure thumb strain and pulse data, this system represents a significant step towards developing non-invasive diagnostic tools for arthritis. Although differentiation between arthritis and normal conditions is not the primary focus here, the groundwork laid by this study positions the system as a promising platform for future applications in arthritis monitoring and diagnosis.

IV. DEVICE SPECIFICATIONS

FBG Sensor details of Redondo Optics are as shown in the below given figure Fig.2 and Table I:

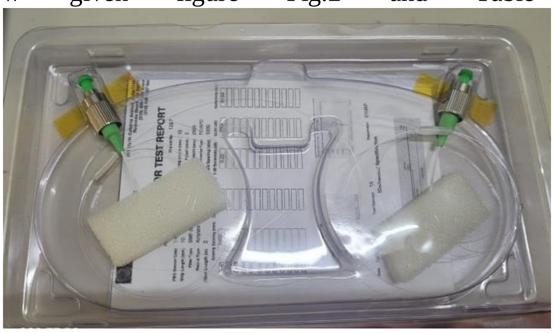

Fig.2 Measurement Device

TABLE I. Device Specifications

Type	Specification
FBG Length	10mm
FWHM	0.28+- 0.05nm
CW1	1518.5nm
CW2	1528.5nm
Product type	1-CH FBG Array

V. METHODOLOGY

Experimental Setup

The experimental setup began with assembling the FBG interrogation system and connecting it to a computer interface, ensuring secure connections of all components, including the light source, FBG sensors, and signal processing unit, as per the manufacturer's guidelines. The FBG sensors were then positioned either on the skin's surface or embedded in a wearable device over arterial pulse points or areas where strain was applied, depending on the experiment. Proper placement was crucial for accurate waveform recording, and the sensors were secured to minimize motion artifacts. Calibration was carried out using the interrogation system to account for baseline variations, ensuring accurate measurements induced by pulsatile blood flow or changes in strain. A stability check was performed to verify the proper functioning of the system, including the light source emitting the correct wavelength and the responsiveness of sensors to strain variations. To ensure optimal recording conditions, a controlled environment was established, as illustrated in Figures 3a and 3b, minimizing external interference while maintaining stable temperature and lighting conditions.

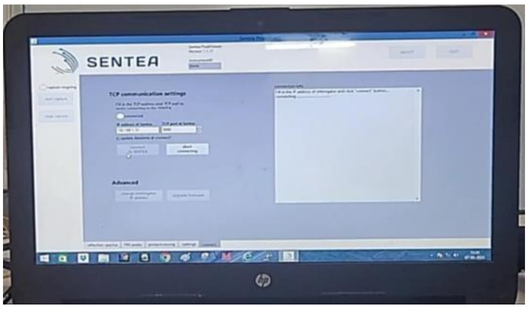

Fig 3a. Sentea Software

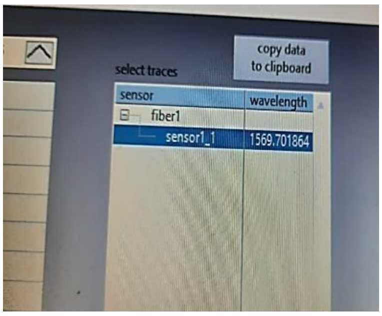

Fig 3b. Sensor wavelength

Procedure

For data acquisition, the FBG sensors were calibrated using the interrogation system to address baseline variations. Following calibration, the sensors were securely placed either on the skin or within a wearable device, ensuring optimal contact for reliable pulse or thumb strain data recording. The FBG interrogation system was activated, and data recording was initiated with appropriate settings to specify the duration of data collection. Real-time monitoring of the system was conducted to resolve any issues and confirm the integrity of the recorded data. Figure 4 depicts the pulse recording setup used in the experiment.

Fig.4 Pulse Recording Setup

Observation of Pulse Recording

Pulse recordings were analyzed to extract the frequency of pulse waves, which provided quantitative measures of the beats per minute (BPM) and heart rate. Regularity in the pulse wave peaks was observed to assess heartbeat interval consistency. Variations in amplitude were examined to evaluate changes in heartbeat strength, while baseline shifts were monitored to understand alterations in blood pressure or vascular compliance. The amplitude and waveform shapes were further evaluated to identify abnormalities, such as sharp peaks or prolonged troughs. Exported strain values were correlated with pulse wave features, enabling precise analysis. Additionally, plots were generated using Excel to visually represent pulse wave dynamics over time.

Observation of Thumb Strain

The analysis of thumb strain involved correlating specific peaks and troughs in strain waves with thumb movements, such as gripping, releasing, or flexing. Consistency in strain wave patterns during repetitive thumb activities was assessed to identify any irregularities. Baseline strain was observed to understand the resting state of the thumb, while amplitude variations were analyzed to reflect the intensity of muscle engagement during thumb actions, as shown in Figure 5. Changes in strain wave frequency provided insights into the speed and rhythm of thumb movements, while the duration of peaks and troughs revealed the timing and persistence of muscle contractions. Timestamp alignment ensured accurate correlation between strain values and thumb movements, as depicted in Figure 6. Statistical tools and visualization software were employed to identify trends and patterns, aiding in the identification of optimal thumb performance and strain-inducing activities.

Fig.5 Thumb Strain Recording Setup

Fig.6 Thumb Strain Wave Plot

VI. SIGNAL PROCESSING AND CORRELATION FOR FBG OUTPUT:

The methodology for analyzing thumb strain and pulse wave signals involves a comprehensive process of signal acquisition, processing, and interpretation, enabling the transformation of raw sensor data into meaningful physiological parameters. This study utilized Fiber Bragg Grating (FBG) sensors and optical techniques to measure strain and pulse activity, coupled with advanced software tools for data analysis and visualization.

The FBG sensors, known for their high sensitivity to physical changes, were integrated into the experimental setup. The optical signal output from these sensors was captured by an optical interrogator, which measured wavelength shifts in response to strain or pressure changes. The sensor placement was strategic: one sensor was positioned on the forearm, covering prominent muscles and major blood vessels, and another was placed on the thumb to observe muscle contractions directly. These placements were selected to explore the dual capabilities of the sensors in capturing strain signals related to thumb motion and pulse wave changes.

The data acquisition phase utilized Sentea software, which interfaced seamlessly with the sensors to record time-stamped measurements of wavelength shifts. These measurements were exported in CSV format for further analysis. The raw data from the FBG sensors often contained noise arising from environmental factors such as temperature variations and mechanical disturbances. To address this, a series of signal processing techniques were applied to enhance data quality.

The first step in the signal processing pipeline involved **filtering** the raw data. A low-pass filter (cut-off frequency: 2 Hz) was used to eliminate high-frequency noise, allowing the key components of the signal, such as thumb strain and pulse waveforms, to be extracted with clarity. The application of this filter significantly improved the quality of the data, enabling accurate detection of strain peaks and pulse wave characteristics.

For the thumb strain analysis, the unfiltered signal as shown in Fig.7a initially exhibited substantial noise, making it difficult to discern strain events clearly. After applying the low-pass filter, the noise was minimized, and distinct peaks corresponding to thumb bending events became evident. The filtered graph clearly illustrated these peaks, providing a reliable representation of thumb strain during motion as shown in Fig.7b**.** This demonstrates the effectiveness of the signal processing approach in isolating the desired physiological parameters from the raw data.

The pulse wave analysis involved placing an FBG sensor on the wrist area to capture pulse activity. The raw pulse waveform was initially noisy but still exhibited the characteristic pulsatile nature of the pulse as shown in Fig.8.

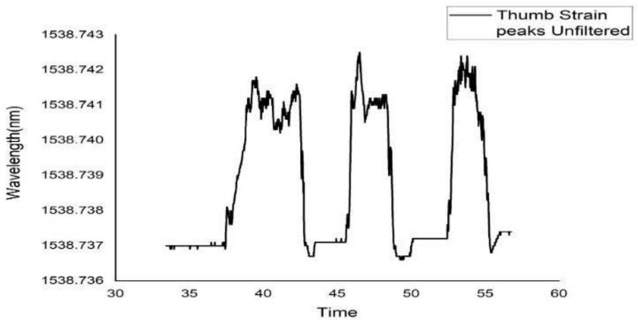

Fig.7a Thumb Strain Unfiltered

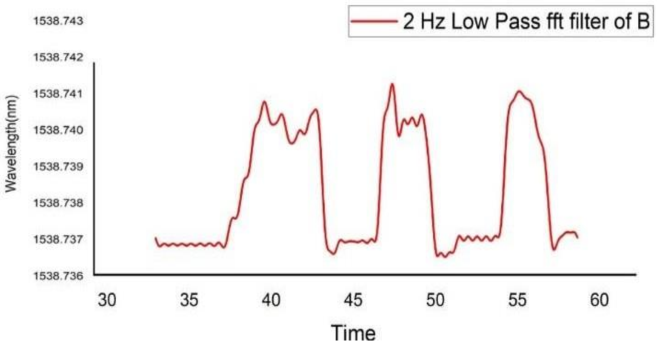

Fig.7b Thumb Strain Filtered

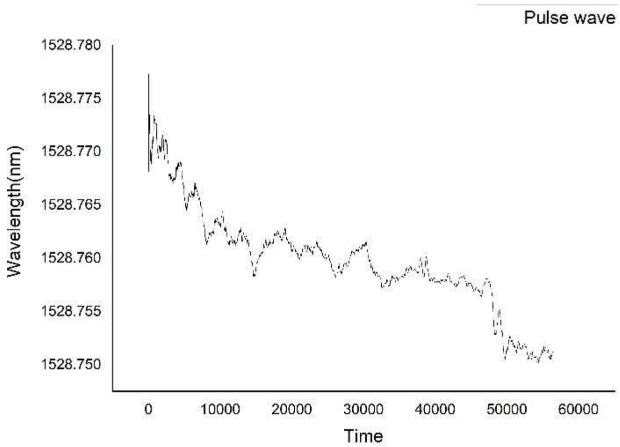

Fig.8 Pulse Wave

Although the signal had not undergone extensive processing, the sensor effectively detected pulse waves, highlighting the potential of FBG sensors for cardiovascular monitoring. This raw pulse signal served as an initial output, illustrating the sensor’s ability to capture fundamental pulse data.

The data processing phase was carried out using OriginPro software, which facilitated advanced signal analysis. The processed signals underwent peak detection algorithms to identify key features in both the pulse wave (PPG) and muscle strain (OMG) signals. For pulse rate analysis, the intervals between successive pulse wave peaks were calculated to determine the heart rate over time. An average resting heart rate of 72 beats per minute (bpm) and an increased rate of 85 bpm during physical activity were calculated, indicating the sensor's capability to monitor cardiovascular changes in response to exercise.

For thumb strain, the frequency and intensity of muscle contractions were quantified by analyzing the peaks in the filtered strain data. The average contraction frequency was observed to be around 0.5 Hz, with each peak corresponding to a distinct muscle contraction event. The processed data was then normalized to standardize the extracted features, ensuring consistency across different subjects and conditions. To further ensure the robustness of the analysis, data correlation techniques were applied. The pulse rate obtained from the FBG sensor was compared with standard methods such as electrocardiograms (ECGs) to validate the sensor's accuracy. Additionally, the strain measurements from the FBG sensors were correlated with pre-established calibration curves. A positive correlation ($R = 0.78$) was observed between heart rate and muscle activity intensity, confirming a consistent physiological response to muscle contractions and pulse changes.

In summary, this study highlights the dual functionality of FBG sensors in capturing both thumb strain and pulse wave signals. The signal processing techniques, including filtering, peak detection, and normalization, demonstrated the sensor’s ability to accurately capture muscle strain and pulse wave characteristics. These findings underscore the potential of FBG sensors for non-invasive monitoring of both musculoskeletal and cardiovascular health, offering valuable insights into the physiological parameters that could help in diagnosing conditions like arthritis or cardiovascular disease in the future.

VII. CONCLUSION & FUTURE SCOPE

This research demonstrates an effective approach to extracting and analyzing physiological data using a dual-function optical sensor integrated with Sentea and OriginPro software. The combination of PPG and OMG measurements provided valuable insights into muscle contractions and circulatory responses, highlighting potential markers of arthritis-related changes. The use of a low-pass filter with a 2 Hz cut-off frequency ensured high-quality signals, enabling accurate characterization of pulse waveforms and muscle strain patterns. The findings underscore the utility of advanced signal processing techniques in detecting and analyzing subtle physiological changes, offering promising applications for arthritis diagnosis and rehabilitation monitoring.

The integration of advanced sensing technologies, such as Fiber Bragg Grating (FBG), into arthritis detection and management offers promising avenues for future exploration. While this study highlights the capability of FBG sensors to detect arthritis-related biomechanical changes, the potential applications extend far beyond detection. The next steps involve translating these findings into practical solutions for arthritis management.

FBG sensors could be integrated into wearable devices or therapeutic tools that continuously monitor joint health, providing real-time feedback for personalized arthritis management strategies. These wearable solutions could enable early detection of joint abnormalities, track disease progression, and even guide patients through tailored rehabilitation exercises. Moreover, combining FBG technology with artificial intelligence could enable predictive modeling, helping clinicians design targeted interventions based on patient-specific data.

Another promising area is the use of FBG sensors for developing therapeutic devices that address arthritis symptoms. For instance, these sensors could be employed in tools that monitor and adjust therapeutic loads during physiotherapy, ensuring optimal pressure and strain levels for joint recovery. The integration of this technology into smart gloves, knee braces, or other assistive devices could also empower patients with enhanced mobility and pain management.

Additionally, the application of FBG technology in non-invasive diagnostics may provide more accessible and cost-effective solutions for arthritis screening, particularly in resource-limited settings. These advancements could revolutionize arthritis care by combining real-time monitoring, early detection, and tailored interventions, ultimately improving patient outcomes and quality of life.

The future of FBG-based arthritis detection and management lies in interdisciplinary collaboration, leveraging advancements in sensor technology, data analysis, and therapeutic tools to pave the way for innovative and effective arthritis care solutions.
By implementing these advancements, the system has the potential to become a vital tool in arthritis management, offering continuous, real-time monitoring that enhances patient care and rehabilitation efforts.

VII. ACKNOWLEDGMENT

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