

WEARABLE SENSORS FOR STRESS MONITORING IN MENISCUS INJURY REHABILITATION

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ABSTRACT

Monitoring vital signs is essential in identifying physiological stress, particularly in rehabilitating meniscus injuries. Stress can compromise the effectiveness of physiotherapy, affecting recovery. This paper reviews monitoring technologies, such as those that consider heart rate and sweating sensors, and their application in remote patient monitoring. It highlights the importance of collecting real-time data to personalize treatments and optimize recovery and explores the challenges and benefits of this approach. Integrating these technologies can significantly improve therapeutic results, prevent stress, and improve patients' quality of life.

KEYWORDS

Meniscus injuries; Stress; Wearable sensors; Remote monitoring; Physiotherapy; Personalized medicine.

1. INTRODUCTION

The menisci are two structures of fibrous cartilage in the knee that absorb shocks and contribute to its stability (Makris et al., 2011). There is a lateral meniscus on the outside and a medial meniscus on the inside. The femur is rounded, and the tibia is flatter, creating little congruence between them. The menisci increase congruence and provide a larger area for load transmission in the knee (Fox et al., 2012).

Sensors detect and respond to physical or chemical stimuli, converting them into electrical signals that can be measured and analyzed (Heikenfeld et al., 2018). In the context of stress monitoring, wearable sensors have been developed to continuously capture physiological signals, allowing for tracking in various areas of health, such as post-traumatic stress disorder (PTSD) (Zamkah et al., 2020). These devices offer continuous and real-time stress data collection, which can be used in clinical diagnostics or personal monitoring.

Meniscus injuries represent a significant challenge for patients undergoing rehabilitation, especially due to the associated biomechanical and psychological consequences (Rao et al., 2015). Several studies have shown that the knee's stability during the landing of a jump can be a crucial factor in predicting and monitoring these injuries, which underlines the importance of using sensors to analyze the body's movement and response. However, in addition to physical factors, some patients suffer a traumatic injury, such as a meniscus tear, and may develop symptoms of post-traumatic stress, impacting their recovery supported by physiotherapy (Thomson et al., 2002). The response to post-traumatic stress can be monitored through various vital signs, such as heart rate variation, electrodermal activity, and cortisol levels (Vavrinsky et al.,

2021). Sensors can help analyze knee stability, providing a comprehensive approach to optimizing rehabilitation (Porciuncula et al., 2018).

As during meniscus rehabilitation, the emotional state of patients may fluctuate, it is worthwhile to facilitate monitoring tools for the rehabilitation team to prevent physiological stress and avoid its negative impact. Instead of only focusing on physical symptoms, the proposed holistic approach seeks to rehabilitate individuals by considering their physical, mental, and psychological dimensions.

In this paper, we explore the monitoring of vital signs and biomechanics in the identification of post-traumatic stress in patients with knee injuries, discussing the sensors used and the types of data collected. In addition, we propose a new test that combines the assessment of stability during the landing of a jump with the analysis of the physiological stress response to control recovery and prepare a personalized approach for each patient more precisely.

The remainder of this manuscript is organized as follows. In section 2, the methodological part of the paper is addressed. Next, the set of sensors considered in the study is described, and methodologies used to identify physiological indicators associated with PTSD are addressed, followed by a study of the implementation techniques identified in the literature. Section 3 proposes a novel approach for stress identification in the injured person and discusses its advantages and limitations. The conclusions are drawn in section 4, where suggestions for further research are also discussed.

2. METHODOLOGY

This paper is based on the analysis of studies published in 2019 and 2025, selected from recognized scientific databases such as PubMed and Web of Science. The research was conducted using keywords related to physiological monitoring, physiotherapy, meniscus, and PTSD, ensuring the relevance of the included studies. For the selection of articles, those that directly address the use of sensors in the assessment of vital signs and in the rehabilitation of patients with meniscus injuries have been considered, as well as their application in identifying physiological responses to stress. Studies that do not present empirical data, reviews without critical analysis of the methods used, and works that do not address the relationship between stress and recovery have been excluded.

In this way, we can analyze the diagnosis of injuries with sensors and how much stress they cause after they occur. This type of injury is common, especially among athletes, and can result in pain, swelling, and joint dysfunction (Buckwalter, 2003). Traditionally, the diagnosis is based on the patient's clinical history and detailed physical examinations that assess the integrity of the meniscus through specific knee movements. However, the accuracy of these tests can vary depending on the doctor's experience and the specific characteristics of each patient.

Sections 2.1 and 2.2, respectively entitled "Sensors" and "Implemented techniques", present a description of the main types of sensors analyzed in this work and the methodologies used to identify physiological indicators associated with PTSD. Figure 1 summarizes the relationship between the sensors mentioned, the techniques used, and the main results obtained from the analysis of the data collected.

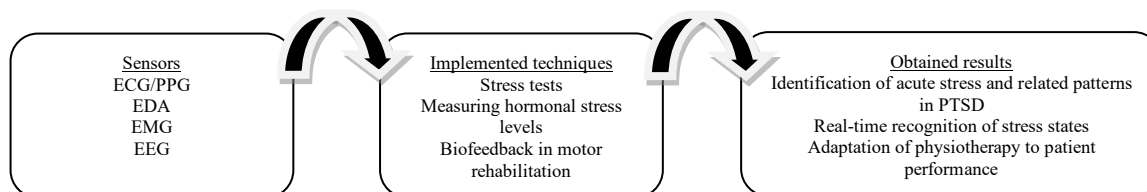


Figure 1. Link between sensors, implemented techniques, and results obtained.

2.1 SENSORS

With technological advancements, sensors are emerging as a promising tool in diagnosing these injuries, offering more objective and quantitative assessments. On the one hand, one of the most common is the heart rate variability (HRV) sensor, which measures the variation in the intervals between heartbeats (Kranjec et

al., 2014). It can be based on the electrocardiogram (ECG), which uses electrodes on the skin to record the heart's electrical activity, or on photoplethysmography (PPG), which uses light to measure variations in blood flow (Affanni, 2020; Iqbal et al., 2022). HRV is an essential indicator because post-traumatic stress can cause autonomic dysfunction, altering the response of the nervous system (Kranjec et al., 2014).

On the other hand, electromyography (EMG) sensors measure muscle electrical activity, which can be very useful in detecting responses associated with conditions like PTSD (Morales-Sánchez et al., 2022). This examination captures muscle contractions and the pattern of muscle activity in real-time, which can reflect tensions in the body, such as those caused by stress.

The electroencephalogram (EEG) can also be used to identify brain wave patterns related to PTSD (Roohi-Azizi et al., 2017). Small electrodes on the head capture the brain's electrical activity, allowing the detection of hyperactivity in the amygdala, a region associated with fear, and dysfunction in the prefrontal cortex, which regulates emotions (Al-Ezzi et al., 2020; Roohi-Azizi et al., 2017).

Another important sensor is the Electrodermal Activity/Galvanic Skin Response (EDA/GSR), which measures the activity of the sympathetic nervous system (SNS) through the galvanic skin response (Affanni, 2020). Small electrodes detect variations in the skin's electrical conductance associated with involuntary sweating, reflecting increased anxiety and stress (Giannakakis et al., 2022). In addition, motion sensors, such as Inertial Measurement Units (IMUs), help identify symptoms like kinesiophobia, a condition where the individual feels excessive, irrational, and debilitating fear in performing movements (in this case, of the injured knee), common in patients with PTSD (Feldhege et al., 2015).

Elevated or dysregulated cortisol levels are often associated with stress, making it a relevant biomarker for diagnosis and monitoring (Dhama et al., 2019). Hence, sensors that measure cortisol levels, the stress hormone, can be applied through devices that analyze sweat, saliva, or blood in real-time (Wang et al., 2022).

The main advantages of using tiny sensors include early diagnosis, continuous monitoring, and greater accessibility compared to applied imaging equipment. However, challenges such as standardizing the protocols, interpreting the collected data, and patient adherence to these devices must be considered.

In Table 1, we can analyze the monitoring and treatment of post-traumatic stress, where studies are investigated that describe the use of physiological sensors to monitor the autonomic response to stress as a way to assess the psychological recovery of patients undergoing physiotherapy.

Table 1. Summary of the sensors considered in the literature

Name	Reference	Purpose
ECG	(Affanni, 2020), (Al-Ezzi et al., 2020)	Electrical activity of the heart
PPG	(Iqbal et al., 2022)	It uses light to measure variations in blood flow
EMG	(Morales-Sánchez et al., 2022)	Electrical activity of the muscles
EEG	(Roohi-Azizi et al., 2017)	Regulates emotions
EDA	(Affanni, 2020)	The activity of the SNP through the galvanic skin response
Motion sensor	(Feldhege et al., 2015)	Identification of stress-related symptoms
Cortisol level sensing	(Wang et al., 2022)	They analyze sweat, saliva, or blood in real-time.

2.2 IMPLEMENTED TECHNIQUES

Based on the analysis, one of the analyzed studies used wearable sensors to monitor the physiological response to stress in a group of 35 healthy volunteers, who used devices equipped with PPG sensors to record variations in heart rate, providing relevant data for identifying patterns associated with PTSD in a recovery context (Iqbal et al., 2022). The participants were subjected to different stimuli to induce states of stress and relaxation. Among the identified protocols were the Stroop Test, used to assess the impact of cognitive effort on physiological response, the Trier Social Stress Test, which simulates social situations to trigger stress reactions, and the Hyperventilation Test, which induces respiratory changes to evaluate the response of the autonomic nervous system (Iqbal et al., 2022). The periods of exposure to stress were interspersed with moments of rest to allow for the comparison between distinct physiological states. The collected data included continuous HRV and skin conductance measurements, two indicators widely used to assess the autonomic stress response (Kranjec et al., 2014). The subsequent analysis of the signals allows for identifying

activation patterns in the sympathetic and parasympathetic systems, providing insights into how the body reacts to this type of stimuli.

Another study aimed to evaluate the accuracy of a wearable sensor system developed to measure physical activity and knee angle in patients with neuromuscular disorders and gait alterations (Feldhege et al., 2015). To this end, a device composed of accelerometers and flexion sensors was created, capable of recording the movement of the knee joint during different motor activities. The system was validated by comparing sensor data with reference measurements made by a digital goniometer and a laboratory motion capture system (Feldhege et al., 2015). The participants performed a series of controlled movements, including knee flexion and extension, walking at different speeds, and specific activities. This approach highlights the importance of wearable sensors in objective rehabilitation monitoring and facilitates continuous patient progress tracking. The integration of these devices with other vital sign monitoring tools can contribute to a broader analysis of the relationship between physiological stress and recovery, especially in patients with PTSD associated with meniscus injuries (Feldhege et al., 2015), (Kuczyński et al., 2025).

A paper that used electromyographic biofeedback (EMG-BF) to improve muscle activation in 10 football players who had undergone a meniscectomy has also been analyzed (Morales-Sánchez et al., 2022). During 6 to 10 sessions, sensors were used to measure the electrical activity of the quadriceps muscles. These data were used to help the participants improve muscle control and facilitate the recovery of motor function, promoting adequate muscle activation.

Although the study focused on recovery, it was possible to conclude that monitoring muscle activity and using biofeedback can directly impact the stress response during the recovery process (Morales-Sánchez et al., 2022). The approach could be applied to patients with PTSD, as emotional and psychological factors play a fundamental role in physical recovery (McNally et al., 2003).

We have paid attention to a study that monitors certain physiological signals, namely EDA and HRV, obtained through an ECG (Affanni, 2020). The methodology involves placing EDA sensors on the surface of the hands, which are responsible for capturing the galvanic skin response. In contrast, in (Affanni, 2020), an ECG sensor was positioned on the chest region to record cardiac activity. Measurements were taken under different experimental conditions to validate the system's effectiveness, comparing the sensors' responses to stimuli that induce stress (Affanni, 2020). The parameters analyzed included skin conductance and variations in the R-R intervals of the ECG, as both indicators are recognized by the autonomic nervous system (Affanni, 2020). This approach allowed for the real-time assessment of stress impact. It paved the way for future applications in clinical contexts, such as monitoring patients in motor recovery, where stress can directly influence rehabilitation.

In turn, we have found that using EEG to investigate the correlations between patterns of brain activity and the severity of PTSD symptoms may be of potential interest, as described by the authors from (Roohi-Azizi et al., 2017). The sample consisted of individuals diagnosed with this disorder, subjected to resting EEG sessions and during exposure to trauma-related stimuli (Meyer et al., 2018). For data collection, electrodes were positioned according to the international 10-20 system, recording neuronal activity in different brain regions (Roohi-Azizi et al., 2017). The methodology included the analysis of the spectrum of EEG signals, focusing on the alpha, beta, delta, and theta frequency bands, where associations between these and PTSD symptoms were sought (Roohi-Azizi et al., 2017). The relevance of this approach for the recovery of patients with meniscal injuries and PTSD lies in the possibility of controlling the impact of stress, contributing to the personalization of rehabilitation strategies.

Table 2 summarizes all the methods that can be used in tests using the sensors mentioned in Table 1.

Table 2. Summary of all the methods mentioned

Name	Reference	Method
PPG sensors	(Iqbal et al., 2022)	Different stimuli to induce states of stress and relaxation
Wearable sensor system	(Feldhege et al., 2015)	Measure physical activity and knee angle in patients with neuromuscular disorders and gait alterations.
EMG-BF	(Morales-Sánchez et al., 2022)	Measure the electrical activity of the quadriceps muscles
EDA and HRV through an ECG	(Affanni, 2020)	EDA sensors on the surface of the hands, while an ECG sensor was positioned on the chest
EEG	(Meyer et al., 2018)	Resting EEG sessions and during exposure to trauma-related stimuli

3 SOLUTION PROPOSAL

This study have revealed key findings on techniques that strongly support the proposed solution. The use of PPG and ECG sensors allowed for the real-time identification of stress states through changes in HRV, especially when patients were exposed to cognitive and social stressors (Giannakakis et al., 2022). This finding emphasizes the feasibility of integrating HRV-based metrics into rehabilitation sessions to adjust therapy intensity dynamically. Additionally, the application of EDA sensors revealed patterns of electrodermal activity consistent with sympathetic nervous system activation, which was shown to correspond to patient-reported anxiety during physiotherapy exercises (Fernandez Rojas et al., 2023). This insight helps clinicians identify stress peaks that may compromise performance or recovery.

EMG biofeedback methods demonstrated that targeted muscle activation can be improved with real-time monitoring, reducing involuntary tension and stress linked to poor motor control (Morales-Sánchez et al., 2022). These findings highlight the benefit of integrating EMG sensors into early rehabilitation stages, especially after procedures such as meniscectomy. Furthermore, EEG analysis revealed correlations between specific brain wave patterns (notably in the alpha and beta bands) and PTSD symptoms, reinforcing the importance of including neurophysiological stress markers in recovery programs for individuals with post-traumatic profiles (Micoulaud-Franchi et al., 2021). Collectively, these discoveries provide a robust foundation for developing a comprehensive, sensor-based monitoring system that detects physiological stress and contributes to the personalization of rehabilitation strategies. Combining these validated techniques makes it possible to reformulate rehabilitation plans in real-time, focusing on improving motor confidence and emotional regulation during recovery from meniscal injuries.

The present solution proposes the implementation of vital signs monitoring system based on the use of state-of-the-art wireless electrodes capable of accurately measuring heart rate fluctuations during the execution of specific exercises (Virginia Anikwe et al., 2022). Simultaneously, applying highly sensitive sensory devices on the patient's hands is employed, designed to detect changes in sweating, a physiological biomarker widely associated with activating the sympathetic nervous system and, consequently, stress (Zamkah et al., 2020). These two methods enable an exact monitoring of the patient's physiological response during exertion, especially in meniscal injury rehabilitation. The collected data would be transmitted directly to healthcare professionals responsible for therapeutic monitoring so that no time is lost in receiving the information. In this way, doctors and physiotherapists will be able to access an objective and continuous analysis of certain patient parameters, allowing for more informed clinical decision-making tailored to each case's individual needs. Based on the information received, it becomes possible to adjust the intensity and nature of therapeutic exercises, reducing the risk of overload and optimizing the recovery process. Table 3 compares the pros and cons of the solution we would like to implement in the diagnostics.

In addition to the limitations already mentioned, the proposed solution faces several technical and practical challenges worth highlighting. Firstly, sensors such as ECG and EDA are highly sensitive to movement artifacts, which can compromise data quality during intense physical exercise, requiring additional care in fixation and calibration. Inter-individual variability in the physiological stress response also requires an initial calibration period to establish personalized reference values, which can delay immediate practical application.

Another relevant obstacle is the complexity inherent in integrating multimodal data. Time synchronization between different sensors and the joint interpretation of physiological signals requires advanced data fusion systems, which are demanding to implement and maintain. In addition, the continuous collection of vital signs raises critical privacy and security issues, requiring strict compliance with the General Data Protection Regulation (GDPR) and the existence of robust technological infrastructures.

Table 3. Advantages and disadvantages of the proposed solution

Advantages	Disadvantages
Real-time monitoring	High cost
Personalization of treatment	Dependence on the internet connection
Reduction of injury risk	Noise and possible interferences
Remote monitoring	Synchronization between sensors
Integration with emerging technologies	Acceptance by the patient
	Need for technical training of healthcare professionals

When monitoring cardiac electrical activity using ECG, the electrodes are generally placed in the chest area, which allows direct capture of the electrical signals generated by the heart, particularly the QRS complex. In this way, a more accurate and stable reading of HRV is obtained.

To detect EDA or GSR, electrodes are usually placed on the palms of the hands or the tips of the fingers. These regions have a high density of sweat glands, which makes them ideal for detecting small variations in the electrical conductance of the skin caused by changes in sweating. During times of stress or emotional strain, the sympathetic nervous system is activated, increasing sweat secretion and, consequently, skin conductance. These devices work integrated into a WBAN (Wireless Body Area Network), allowing the real-time collection of the patient's responses without the wires or movement restrictions. The data is then sent to a sensor integrated into a watch, enabling both the patient and healthcare professionals to easily access the results and make informed decisions for the rehabilitation process. Figures 2 and 3.a) summarize the location of the ECG and EDA/GSR electrodes, respectively, and Figure 3.b) shows a smartwatch that is used to receive the data collected from the aforementioned electrodes via WBAN.

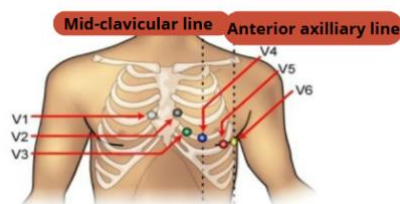


Figure 2. When monitoring cardiac electrical activity with an ECG, electrodes are usually placed on the chest area to directly capture the heart's electrical signals, especially the QRS complex.



Figure 3.a) To detect electrodermal activity, electrodes are usually placed on the palms of the hands or the tips of the fingers, where there is a higher concentration of sweat glands. b) Example of a smartwatch that will be used to receive the data collected.

It should also be noted that, although this solution can identify physiological reactions associated with stress, it is not always possible to distinguish between emotional and physical stress, leading to incorrect interpretation without proper contextualization. Finally, the high cost of acquisition (before price reduction due to future mass-production) and the need for frequent maintenance and technological updates may represent additional barriers to its large-scale application.

4 CONCLUSION

The relationship between stress and physiotherapy is undeniably complex, as both factors directly influence the effectiveness and progress of injury recovery, including meniscal injuries. Stress, especially physical and emotional, can negatively affect the patient's performance during rehabilitation, potentially increasing the risk of complications. This factor can interfere with performing exercises correctly, hindering muscle regeneration. Therefore, precise and real-time monitoring of vital signs, such as HRV and sweating, becomes essential to understand these variables during treatment.

The proposed approach represents a significant advancement in physiotherapy in the future. Combining these two methods makes obtaining a detailed and dynamic view of the patient's physiological response to stress possible. Technology offers the opportunity to carry out quick interventions tailored to each person's reality, according to their level of effort and stress tolerance. These systems can identify recovery patterns and predict possible complications, allowing physiotherapists to anticipate and further personalize treatment according to the patient's needs.

As a prospect for future work, it is planned to progressively implement the solution developed in hospitals and clinics specialized in physical rehabilitation to validate its applicability in real clinical scenarios. This phase will allow the system to be tested in a supervised environment, assessing its ability to monitor physiological indicators associated with stress during physiotherapy sessions accurately. In addition, the impact of therapeutic personalization based on biometric data will be analyzed, as well as the acceptance and usability of the system by health professionals and patients.

In the medium and long term, this approach aims to support the integration of continuous monitoring technologies into existing clinical protocols, contributing to the evolution of more effective, personalized, and patient-centered rehabilitation models.

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