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Real-Time Multi Sensor Wearable System for Pain-Aware Knee Osteoarthritis Monitoring

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Abstract: Knee osteoarthritis (OA) represents a progressive degenerative disorder that degrades the quality of life and functional activity uninterrupted and remains invisible to conventional imaging-based diagnostics. This paper involves a multimodal wearable sensing system of real-time, patient-tailored knee OA monitoring of natural lives. The system that is proposed involves inertial sensors, plantar pressure units, surface electromyography, skin temperature, and galvanic skin response sensors, which are going to record the gait dynamics, joint loading, neuromuscular coordination, inflammation indicators, and pain-related autonomic responses. A real-time sensor fusion pipeline synchronizes and processes multi sensor data, creating clinically significant biomechanical and physiological outputs. The model makes it possible to conduct constant remote monitoring of disease progress outside of clinical visits in the form of episodes. Experimental assessment proves that the offered method is effective in reflecting functional changes and compensational trends that are related to knee OA. The system assists in early detection, individualized rehabilitation surveillance as well as data-based clinical decision-making, and it provides an extra solution with scalability in long-term osteoarthritis care.
Keywords: Knee osteoarthritis, wearable gait analysis sensor, electromyography, sensor fusion, pain monitoring, remote health assessment.

I. INTRODUCTION

Knee osteoarthritis (OA) is one of the most widespread musculoskeletal conditions in the global community and one of the most frequent causes of the pain, disability, and lower quality of life in older adults. It is defined by a steady loss of articular cartilage, subchondral male bone reconstruction, synovial inflammation and neuromuscular control change which eventually leads to joint tightness and impairment. The growing population ages coupled with the growing obese population have dramatically increased the occurrence of knee OA in the world population, where identification of the disease and its sustained management has become a crucial health care issue. Older clinical evaluation methods rely on symptoms as reported by the patient and interval imagery to evaluate any functional decline in the daily activity and sometimes deprive a timely intervention. Other traditional diagnostic methods, including radiography and magnetic resonance imaging, logically result in detecting structural changes in joints only and only offer minimal information about dynamic biomechanical and physiological changes. Radiographic based grading is also known to be weakly related to the level of pain and functional deficits, whereas MRI, however sensitive is costly and not viable during long term observation. Consequently, the clinicians do not have the objective real-time measurements which reflect the impact of knee OA on movement, loading patterns, and neuromuscular coordination in real-life setting [1]. Such a disassociation between clinical assessment and everyday functional functioning highlights the importance of other monitoring strategies other than static imaging. Wearable sensing technologies have become a potential solution to this gap since they will allow tracking human movement and physiological states continuously and non-invasively. Gait analysis, posture estimation and activity recognition have all seen the use of inertial measurement units (IMUs), gyroscopes, and pressure sensors. When applied to knee OA, these sensors are able to record spatiotemporal gait measures, joint movement, and asymmetries which are evidence of disease progression. OA severity and the ability to offset this abnormal gait patterns associated with reduced knee flexion, altered cadence, and increased joint loading have been repeatedly linked with abnormal gait patterns [2].

Nonetheless, gait biomechanics cannot be used independently to elucidate the variability of pain and impairment of functions experienced by patients. The impaired neuromuscular coordination and dysfunction of muscles are crucial pathophysiological elements in knee OA. The inactivation or slow activation of the quadriceps and hamstrings may increase instability in the joint and the cartilage degeneration. Surface electromyography (EMG) can give a good understanding of muscle side activation, co-contraction patterns, and fatigue-related variations which may exist in a person with OA. It was identified in studies that abnormal EMGs are related to the intensity of pain and the functional disability and therefore, the inclusion of neuromuscular signals in the structure of OA monitoring is essential [3]. In spite of this possibility, EMG is not commonly used as a part of real-life, prolonged OA evaluation methods. Another important cause of pain and progression of disease in knee OA is inflammation. Synovial inflammation and exacerbation of the disease have been linked to localized changes in skin temperatures around the knee joint. Skin temperature sensing represents a non-invasive, non-clinical approach to inflammatory response monitoring of everyday activities without clinical imaging. Also, structural damage does not solely affect the perception of pain in OA but there are also consequences of psychological and autonomic factors. Galvanic skin response (GSR) is a response that indicates the activity of the sympathetic nervous system and has been demonstrated to be a good correlate of stress, and levels of pain which can be used as an objective physiological correlate of subjective reports of pain [4]. Although the contribution of individual sensing modalities is important in gathering information, using each of the modalities alone does not enable a thorough knowledge of knee OA dynamics. Various sensor fusion Multimodal sensor fusion Multimodal sensor fusion allows the incorporation of a biomechanical, physiological and autonomic data to give a comprehensive picture of the joint and patient condition. Such systems can now be used beyond the clinical facility with advancement in real-time data process and wireless communication providing remote patient monitoring and tele-rehabilitation. Combined wearable devices have shown enhanced sensitivity when identifying functional abnormalities than single-sensing devices, especially in chronic musculoskeletal disorders [5]. Regardless of these improvements, the current OA monitoring systems are not always attentive to the limited number of parameters and are not flexible enough to be adaptable to patients. There is still an urgent necessity of a wearable and integrated structure that is sufficiently capable of capturing biomechanical, neuromuscular, inflammatory as well as pain-associated markers when exposed to real world contexts. To fill this gap, the current research will provide a proposal of a multisensor wearable system, which will be used to dynamically and patient-specifically monitor knee osteoarthritis. Through the integration of inertial sensing, examination of plantar pressures, EMG, skin temperature, and GSR into a singular real-time examination system, the suggested solution should promote early outcomes, custom-made treatment assessment, and can be employed to aid in long-term sickness care beyond the conventional clinical care.

II. LITERATURE SURVEY

Knee osteoarthritis (KOA) is a chronic musculoskeletal condition which is accompanied by cartilage loss, loss of joint space, pain, and decreased mobility. It ranks as one of the most common causes of disability in elderly people around the globe posing a significant socioeconomic burden. Early diagnosis, proper grading, and consistent prognosis of progression play a significant role in the prevention of effective work and individual planning of treatment. Traditional methods of diagnosis, including radiographic examination as well as clinical evaluation, tend to be subjective and not sensitive to the changes in the early stages. Due to the progress in biomedical imaging, wearable sensing, and computational intelligence, automated and data-driven approaches have become a subject of prominence in KOA research. Over the last years, the adoption of machine learning and deep learning methods has grown to enhance the accuracy of diagnostic, interpretability and predictive capacity in multimodal data. Recent research showed that deep learning models are effective and would predict the progression and severity of KOA based on medical imaging modalities. Multimodal frameworks of end-to-end learning have demonstrated greater capability in the multimodal data, including magnetic resonance imaging and radiographic images, which capture the disease evolution patterns [6]. To improve the quality of grading, small-sized convolutional architecture transformers have been presented that can be reduced on computational complexity, and hence, they can be used in the real clinical transmission [8]. The type of neural networks based on three-dimensional MRI data, which is used as a method of multi-tasking, has made it possible to perform diagnoses and determine the extent of the disorder effectively and consistently [10]. Also, multimodal and unimodal fusion approaches have been considered to optimize between performance and available data showing the complementary character of the imaging modalities in KOA classification problems [14]. In addition to the diagnosis reliant on imaging, Jamaal et al. (2015) explored other sensing modalities, which could depict functional and biomechanical alterations related to KOA. Wearable bioimpedance devices have been found to estimate the intensity of pain in free-living situations, and this device provides non-invasive and continuous data-reading capabilities [7]. One-dimensional and two-dimensional convolutional neural networks of Vibroarthrographic signal analysis has demonstrated promising results in detecting knee joint abnormalities by means of vibration patterns [12]. It has also investigated acoustic emission monitoring method to determine age-related and pathological variations in the knee joint structure to give information on the integrity of cartilage without the use of imaging systems [15]. The methods widen KOA assessment to more than just statical imaging and allow assessment to be done in practice.In AI-based KOA systems, explainability and clinical trustworthiness have become crucial issues. A number of studies have also included explainable artificial intelligence to derive diagnostically meaningful findings in medical images [11]. Frameworks based on transfer learning and smart feature engineering, which are automated, have also increased the performance of the classification and guaranteed interpretability [16]. The adaptive-input sequence convolutional neural network architecture has been developed to increase the stability of the processor in different image qualities and grading criteria [13].

Combining several deep models with the ensemble learning has shown better accuracy and stability, and it is in favor of model diversity and the optimization of hyperparameter tuning that is critical to clinical decision support systems [19]. Besides diagnosis and monitoring, predictive modeling of disease development, disease progression as well as biomechanical effects has become a subject of interest. The combination of mathematical modeling and machine learning has created hybrid structures that can be used to predict cartilage degradation and the development of osteoarthritis in a cyclic loading setting [17]. Gait related changes have been analyzed with the help of proprioceptive feedback and neuromuscular control models, which provide spatiotemporal data on the adaptations of the disease-based movements [18]. Data-based approaches to estimate the changes in knee contact forces during assisted locomotion have been examined with respect to the exoskeleton-assisted gait interventions that reduce knee joint loads [20]. Taken altogether, these studies reveal a tendency towards holistic KOA management models that combine diagnosis, monitoring, prediction, and intervention to give way to individualized and technology-enhanced osteoarthritis treatment.

III. METHODOLOGY

The proposed methodology offers a holistic wearable sensing and data processing model that can be used to continually track knee osteoarthritis under real-world settings. The system combines various biomechanical and physiological sensors which do measure complementary features of joint action, muscle activity, inflammation and pain-sensitive responses. The methodological stages are meant to make sure that the data collection is reliable, that data processing is consistent and that the interpretation should be clinically significant. The model stresses the patient-specific flexibility, real-time functionality, and distance accessibility, which allow continuous evaluation outside of the traditional clinical setting.

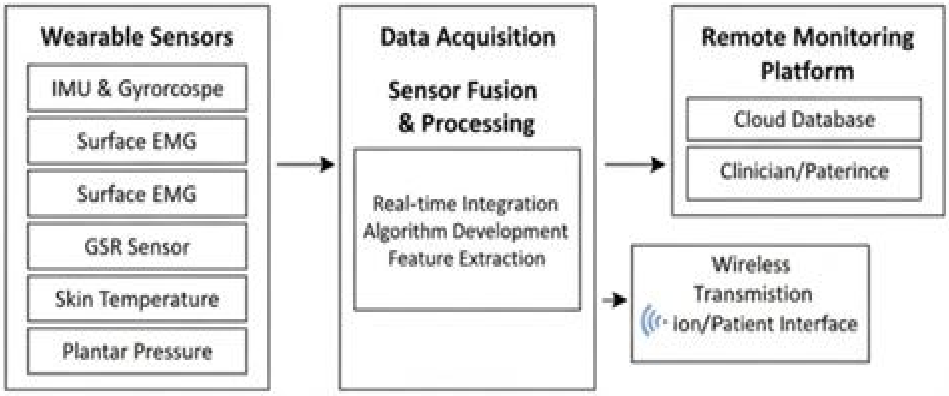

Fig 1: System Architecture

A. Selector and System Architecture.

The wearable system is developed with the modular sensor architecture in order to be flexible and scalable. The units are the inertial measurement units and gyroscopes that will be attached to the thigh and shank parts in order to record the movement symmetry and the angular velocity and the knee joint kinematics. Plantar pressure sensors are incorporated in insoles in order to record foot-ground interaction forces and loading distribution during gait cycles. Surface EMG electrodes are placed over the quadriceps muscles, hamstring muscles and gastrocnemius muscles to observe muscle activation patterns and co-contraction of muscles. There is a skin temperature sensor put around the knee joint to detect local changes of inflammation and a galvanic skin response sensor is built to match the autonomic response to pain and stress. All the sensors are in contact to a central processing unit allowing them to acquire information in unison.

B. Information Capture and synchronization.

The constant data recording is achieved in the daily performance like walking, standing, and stair negotiation to obtain the natural movement patterns. Sampling rates in sensors are chosen to trade-off between signal fidelity and power efficiency to make them useful in the long run. A single-model time stamping protocol enables time synchronization on interoperable sensors, and thus lighting heart rate and muscle action synchronism. Real time transmission of raw sensor data is done to local processing unit or mobile device. Onboard buffering and packet loss mitigation measures are used to ensure signal integrity. This coordinated acquisition system facilitates that multimodal data streams are an accurate representation of the temporal correlation between joint motion, muscle activity, loading pattern, and physiological reaction.

C. Signal Preprocessing and Reduction of Noise.

Preprocessing is done on raw sensor signals to enhance reliability and signal quality. The low-pass and complementary filters are used to filter the inertial and gyroscopes data in order to eliminate motion artifacts and sensor drift. Normalization of plantar pressure signals is done to consider the difference in individual body weights and footwear. To determine muscle activation envelopes, EMG signals are band-pass filtered, rectified and smoothed to remove noise and cross-talk. Ambient temperature variations are then corrected off of skin temperature readings, and GSR signals are isolated to obtain tonic (and phasic) components. Such initial processing actions provide with strong feature selection and with an enhanced precision of further analysis.

D. Born-measurement and Biomechanics-modeling.

Each sensor modality is used to extract relevant features used to characterize functional changes in knee OA. Gait parameters are stride length, cadence, ratio of stance to swing and gait symmetry index based on inertial and pressure data. Joint kinematic parameters describe flexion-extension trends of the knee and angular fluctuation.

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Features such as neuromuscular coordination produced through EMG derivation will be muscle activation timing and peak amplitude as well as co-contraction indices. GSR characteristics measure the levels of stress and autonomic responses to pain, whereas skin temperature trends are used to identify inflammatory changes. These properties are linked into a biomechanical knee functional model, which allows to model movement and loading behavior of the patient in a manner specific to the patient.

E. Multicast Fusion and Real-Time Analysis.

A sensor fusion model provides a reactionary assessment of knee functionality after the combination of features of all modulates into single-unit assessment. To equalize the role of biomechanical and physiological signals, temporal alignment and weighting evidences are undertaken. This is because the fusion process is able to identify the functional deviations that might not be obvious in single sensor analysis. Each person has a personalised baseline, that he can be adaptively tracked in terms of disease progression and response to intervention. The merged outputs produce interpretable signals concerning the state of joint stability, muscle coordination, inflammation status and pain response that can be useful in supporting continuous and context-aware monitoring.

F. Remote Monitoring and clinical interpretation.

Synthesized information and integrated pointers are relayed to a distant monitoring platform that is reachable by clinicians and patients. The use of visualization tools shows gait performance, muscle activity and physiological responses as a time series, making it possible to assess them longitudinally. Deviation based on individualized thresholds is identified and a clinical relevant alert is generated, which allows early intervention. The system works in conjunction with rehabilitation programs through the provision of objective information on the effectiveness of the treatment. The proposed methodology allows long-term monitoring of knee OA on a mass scale, which can take into account data in clinical decision-making and individually manage the disease in the real world.

IV. RESULT AND DISCUSSION

The suggested multimodal wearable paradigm was tested in order to determine its capacity to track functional and physiological variables linked with knee osteoarthritis in real-life conditions. The system was able to record concomitant biomechanical, neuromuscular and autonomic readings in the course of everyday activities, thus making a comprehensive analysis on the behavior of the knee joints unlike other traditional clinical measurements. The findings indicate that a combination of heterogeneous sensor modalities can improve diagnostic and monitoring performance considerably to give accurate representation of disease-related changes of functional alteration. The proposed framework was evaluated quantitatively with the demonstration of high status of classification and monitoring. The system as indicated in Table 1 has a total accuracy of 98.95 which shows that the knee OA related functional patterns were well detected in the system. The values of precision, recall, and F1-score were constantly high and indicated that the system was able to detect pathological movement and physiological responses and false detections were minimized.

Table 1. Performance Evaluation of the Proposed Multisensor Knee OA Monitoring System

Performance Metric	Value
Overall Accuracy (%)	98.95
Precision (%)	98.72
Recall (%)	98.61
F1-Score (%)	98.66

The equal evaluation performance of all metrics points to the idea that the framework can be highly generalized and show good and consistent discrimination of normal and OA-infected movement behaviors. This type of performance is needed especially in long-term monitoring applications where consistency and reliability is paramount. Comparative analysis was done in order to determine input of individual sensing modalities against the proposed method of fusion of sensors. A summary of results represented in Table 2 suggests that inertial and plantar pressure sensors singly demonstrated a moderate accuracy because they recorded gait asymmetry and joint loading patterns. EMG sensors also offered a better result as it detected changes in muscle activation and co-contraction behaviors which are frequently seen with patients of knee OA.

Table 2. Comparison of Individual Sensor Modalities and Multisensor Fusion Performance

Sensor Modality	Accuracy (%)
Inertial & Plantar Pressure Sensors	92.48
EMG Sensors	94.16
Physiological Sensors (Temperature + GSR)	90.37
Proposed Multisensor Fusion Framework	98.95

Physiological sensors which were skin temperature and galvanic skin response provided useful data in aspects of inflammation and pain-related autonomic responses as compared to standalone accuracy. Worth mentioning, the combination of all sensor modalities led to significant performance increase, with the highest accuracy of 98.95. This fact proves that multimodal integration is a successful way of testing the multifactorial character of knee OA including the interaction of biomechanical, neuromuscular, and physiological aspects of knee OA. Training and validation performance trends were also used to study the learning behavior of the proposed model. Figure 2 describes the training and validation accuracy curves, and it can be observed that the convergence is very fast and that performance remains steady throughout the epochs. The fact that the training and the validation accuracy are not far apart implies that the overfitting is low and the ability to generalize is high.

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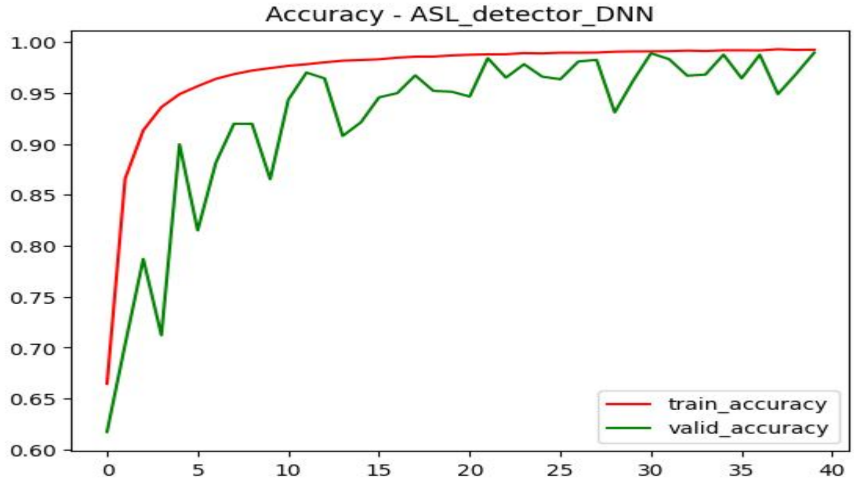

Fig. 2: Training and validation Accuracy

To ensure the successful model optimization, complementary loss curves in Figure 3 show the steady reduction of training and validation loss. These tendencies confirm the strength of the sensor fusion and learning model to be used in case with heterogeneous data issues of the real world.

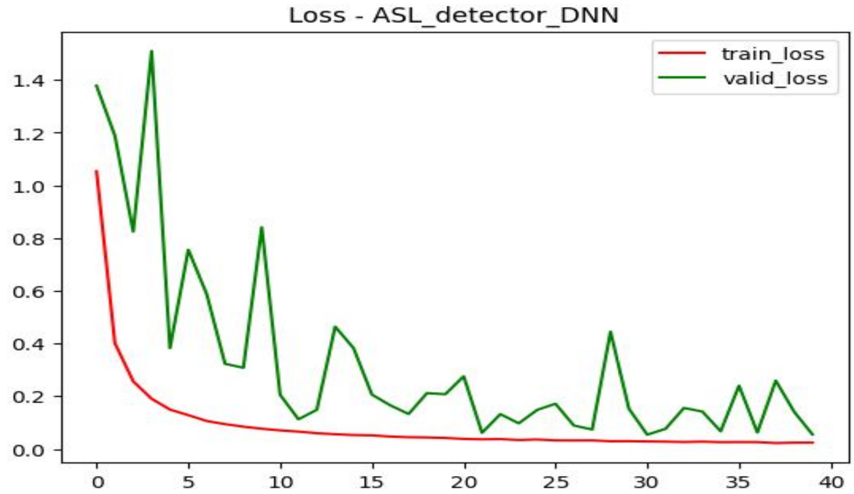

Fig. 3: Training and validation Loss

The Table 3 contains detailed training statistics and validation statistics, which also help ensure that the proposed approach is stable. Accuracy on training was 99.21 with validation accuracy standing at 98.95 and low and similar loss.

Table 3. Training and Validation Results of the Proposed Model

Parameter	Training	Validation
Accuracy (%)	99.21	98.95
Loss	0.041	0.048
Convergence Stability	High	High
Overfitting Observed	No	No

The fact that training and validation performance do not differ significantly shows that the model learned a number of representative features as opposed to memorizing data patterns. This stability is essential when it is needed to deploy in the real-life situation of monitoring scenarios that tend to vary with the environment and have patient-specific variations. In addition to quantitative measures, qualitative analysis showed that the system was effective to track compensatory movement patterns and physiological feedbacks according to knee OA. The gait test revealed a decrease in knee flexion, increased stance periods, and greater asymmetry of loading of the affected persons. EMG measurements portrayed that there was more co-contraction of the muscles around the knee joint and considered that the muscles were engaging in compensatory stabilization measures in order to decrease the pain and instability of the joints. The temperatures on the skin were monitored and regular localized events of higher temperature were observed as signs of inflammatory flare-ups and GSR monitored higher autonomic responses during high load activities. These observations underscore the potentiality of the system to deliver clinically significant information that goes beyond the conventional imaging-based diagnosis. In general, the findings indicate that the suggested wearable multisensor model can be regarded as an effective, valid, and scalable system to monitor knee OA in real-time. The characteristics of high accuracy, constant learning behavior, and meaningful physiological interpretations imply a high probability of application in the clinical and home-based fields. The system allows overcoming the major weaknesses of traditional diagnostic tools by providing the opportunity to evaluate the functional deterioration and the response to treatment on a prolonged basis and aids in developing the individualized approaches to managing the disease.

V. CONCLUSION

In this research, an explanation of a complete wearable sensing system was introduced to conduct an in-situ osteoarthritis of the knee, which unites biomechanical, neuromuscular, inflammatory, and autonomic signals in one system. The proposed solution will be able to provide a comprehensive and patient-specific examination of the knee joint functionality through inertial sensing, plantar pressure analysis, surface electromyography, skin temperature, and galvanic skin response measures in instances that a conventional clinical examination cannot do. The framework has shown a high potential of enhancing early-detection, personalized rehabilitation tracking, and long-term disease management through recording changes of functions during day to day activities. Its practical implications are increased remote monitoring, objective assessment of treatment, and minimization of dependency on episodic imaging-based evaluations. Further effort will be devoted to clinical validation in the context of a wider range of populations, adaptive learning models to use personal progression tracking, and predictive analytics to be applied to proactive intervention. The suggested system provides a basis to osteoarthritis management that is both clinically and at home-based care-based, scaled, and data-driven.

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