An Iterative Study of MRI, Clinical Evaluation, and Machine Learning Techniques for Knee based injury Diagnosis

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Abstract. Diagnosing ACL tears is challenging due to variable presentations and limited diagnostic tools. This study evaluates methods such as Magnetic Resonance Imaging (MRI), clinical evaluation, arthroscopy, and advanced machine learning (ML) models. MRI, the gold standard for ACL diagnosis, is noninvasive and highly sensitive, while clinical tests like the Lachman, pivot shift, and anterior drawer tests provide immediate diagnostic insights but depend on examiner expertise. Arthroscopy, though accurate, is invasive and not routinely used for diagnosis. Emerging ML techniques, including Convolutional Neural Networks (CNNs), Support Vector Machines (SVMs), and Random Forest classifiers, show potential for enhancing diagnostic sensitivity by analyzing MRI images with high precision. These models reduce variability in interpretation, benefiting low-resource settings with limited expert radiologists. However, challenges such as the need for large annotated datasets, model generalizability across populations, and interpretability of predictions remain significant barriers. Additionally, user-friendly interfaces and clinical validation are essential for ML integration into practice. This review analyzes the performance metrics of various diagnostic tools using diverse datasets to assess their real-world applicability. Addressing gaps like dataset availability and standardized evaluation metrics can advance ACL tear diagnosis. Integrating modern ML techniques with traditional diagnostic methods may enhance accuracy, efficiency, and accessibility, reducing the burden on healthcare systems while benefiting clinicians and patients alike. This study aims to guide future research and improve clinical practices for ACL tear management.

Keywords: ACL Tear, MRI, Clinical Evaluation, Machine Learning, Diagnosis Methods.

1 Introduction

The Anterior Cruciate Ligament (ACL) is an integral structure in the knee joint that plays a vital role in providing stability and simultaneously allowing for a wide range of movements. ACL tear, one of the most common sports-induced injuries, is a great clinical challenge due to the severity of long-term consequences if not diagnosed and treated appropriately. For the initiation of appropriate therapeutic management, accurate ACL tear diagnosis is a prerequisite, as it can prevent the possibility of further damage to the joint, thereby promoting the best outcome for recovery. Diagnostic methods used for ACL tears include Magnetic Resonance Imaging (MRI), clinical tests, arthroscopy, and now machine learning techniques. Owing to its ability to create high-resolution images of soft tissue structures, MRI has been the criterion standard for diagnosing ACL tears non invasively for different scenarios. This is because MRI is accurate but time and resource-consuming, as such high-quality apparatuses and

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experts are not readily available in all clinical environments. Clinical assessment tests, such as the Lachman test, pivot shift test, and anterior drawer test, provide diagnostic information right on the spot and form the cornerstone of the initial evaluation in ACL injuries. On the other hand, such physical examinations are largely dependent on the experience and expertise of the clinician, so the level of diagnostic accuracy is variable. This is an invasive technique and usually applied in cases where the diagnostic evidence from a non-invasive procedure is not conclusive. Machine learning has brought about a paradigm shift in the application of diagnosing ACL tears. Especially, CNNs, SVMs, and Random Forest classifiers have demonstrated the capability of being able to detect subtle patterns in MRI images corresponding to an ACL tear with high precision. These models promise to reduce the variability in diagnosis, providing increased consistency, especially in settings where expert radiologists are not easily available in process. However, there are several other challenges which still linger. Robust machine learning model development and validation require very good dataset annotation. Still, another concern is whether the same can be generalized within heterogeneous populations and clinical settings. Interpretability of machine learning predictions is a challenging problem and model development requires not only good prediction performance but more importantly the ability to highlight clinically meaningful insights. This paper, therefore, seeks to fill this gap and make an all-inclusive review of existing techniques for ACL tear diagnosis and their respective performance across heterogeneous datasets. Therefore, this review, through systematic analysis of the strengths and weaknesses of each method, will endeavor to identify the common challenges and light some possible gaps that may be in existence within the current literature. Ultimately, the goal is to inform future research and practice to ensure the development of more accurate, efficient, and accessible diagnostic tools for ACL tears. Through this iterative study, the paper seeks to bring forth the gap between the traditional diagnosis methodologies and the emergent machine learning techniques, offering an in-depth evaluation of their respective merits and demerits. It is hoped that such a process of ACL tear diagnosis will be able to be facilitated, which will ultimately lead to improved health outcomes, while the burden on healthcare systems will be lessened.

2 In Depth Review of Existing Methods

Musculoskeletal disorders involving the knee are widely prevalent in almost all age groups and considerably impact mobility and quality of life. In particular, meniscus tears and ligament injuries require effective diagnosis and monitoring. In this review, different methodologies, such as magnetic resonance imaging (MRI), clinical evaluation, and machine learning techniques, are described, along with the major advancements and limitations in the diagnosis of knee injuries. MRI is one of the gold standards in diagnosing knee injuries; it can yield high-quality images of soft tissues. Nevertheless, less use in point-of-care contexts is attributed to its high cost, need for highly trained personnel, and accessibility. Studies have proposed different alternative methods to deploy the techniques. For example, vibration-based structural monitoring techniques to evaluate the knee's non-invasively. The study in [1] showed that active vibration measurement had the ability to differentiate between meniscus patients in the optimal condition from the knee and cadaver limbs, indicating that, in different knee integrity levels, a variation of the frequency response reached the significant change. Meanwhile, electromagnetic knee imaging has been encouraged. The work in [2] utilized an antenna array for providing real-time, portable imaging to investigate knee injuries, sentence validated on ex-vivo pig knee joints. This work showed potential for early detection of ligament and tendon injuries, establishing a novel and cost-effective

alternative to traditional imaging techniques belonging to the knee. Bioimpedance measurement has evolved as a potential technique compatible with point-of-care knee injuries. The study in [3] validated the use of a bipolar electrode configuration to measure knee bioimpedance, showing a significant reduction in bioimpedance in the injured knee compared to the uninjured one in process. This method in combination with machine learning algorithms has achieved high sensitivity for the detection mode of knee injury and shows potential use for portable and low-cost diagnostic devices & deployments. Acoustic emission analysis has been employed for non-invasive diagnosis of knee injuries too. The authors in [5] modeled the tibia as a cantilever beam and acquired the knee sounds to reveal structural changes following meniscal tears. They reported lower natural frequencies and damping ratios in knees with injuries and further proved the potential of acoustic signals in the diagnosis of meniscal tears.

Machine learning tools have been increasingly used to process data acquired from these diagnostic tools. Real-time modular Long Short-Term Memory (LSTM) model to estimate vGRF and KEM during drop landings was developed in [7]. With the help of IMU, the model accurately captured the selected parameters. Hence, it can be recommended for use during in-field injury risk screening and intervention training programs Wearable technologies have also been used extensively for the diagnosis of knee injuries. As discussed by [4] and [8], the development of assistive lower-limb exoskeletons and mechanical phantoms provides a framework to test and validate the design of the exoskeleton. These studies identified, among other things, the need to quantify soft tissue deformation and relative motion between the brace and bone, in order to optimize exoskeleton efficacy and the user's comfort.

Novel imaging systems that use electromagnetic and bioimpedance methods are designed to bridge the gap between conventional diagnostic hardware and demand. In [9] a realistic dielectric knee phantom was developed using the same dielectric properties of realistic tissues, introducing to portable electromagnetic imaging techniques development. Similarly, the EMI system developed by [11] shares the feature of being wearable and proved to detect injuries in the knee onsite in real time by using a dual-polarized antenna array that could be integrated into the textile of the brace itself for different scenarios. FES and neuromuscular control mechanisms are being considered to enhance rehabilitation and improve mobility. In implication [6, 10], the use of FES in combination with passive elements and target motor point stimulation involving knee extensors has been studied to achieve higher performance in cycling and knee extension torque. In fact, it illustrates the potential of FES to this form of rehabilitation and physical exercise for individuals possessing spinal cord injuries or other mobility impairments in various scenarios.

MRI is considered the gold standard technique for visualizing soft tissue knee injuries. However, its high costs along with the requirement of specialized personnel make it impractical for use on a routine basic for follow-up and early diagnosis. To overcome these hurdles, techniques involving ultrasound have been assessed for its applicability to the knee OA diagnosis. In [16], a wearable brace was developed as a methodology to standardize the US imaging of the knee such that uninformed personnel or people with no technical experience in the field could acquire similar type images obtained from expert clinicians. Their invention is a tremendous step towards tele-ultrasonography for the—purpose of remote monitoring of knee OA. In another study, the lower limb perturbator (LOPER) was designed as a tool to identify joint impedance while walking [17]. With the perturbation of forces on the thigh, the LOPER device

can accurately estimate innate hip and knee joint impedance during the phases of the gait cycle. Such measurements are useful for developing improved robotic gait trainers and clinical decisions. Electromagnetic Imaging (EMI) systems present an easy to carry, non-contact alternative for diagnosing knee injuries. A 12-element slot loop antenna array was used to make a wearable textile brace that is conformed to the human knee. This would permit on-site real-time scanning of the knee [18]. Validated with realistic phantoms, the system could detect numerous ligament and tendon tears. It promises to be fit for use in the field. Smart wearable systems have been designed to offer support for remote rehabilitation assessment. The SKYRE is one such multi-sensor platform that captures real-time data of physical activities and integrates with an Information Communication Technology (ICT) architecture to help the clinicians monitor patient progress and efficacy of rehabilitation protocol e-government services.

Functional electrical stimulation (FES) is used routinely to stimulate paralyzed muscles, and it has gained wide acceptance, mainly in patients with spinal cord injury (SCI). However, controlling FES for optimal elicitation of movement remains a predicament. A model-free, adaptive control approach has been suggested in [24] that is given to control the knee joint movement during FES-assisted rehabilitation. It reflects improved control without prior speculation on the subject dynamics. Assistive exoskeletons and orthoses have therefore rapidly become refined for the purpose of increasing mobility and rehabilitation outcomes. A hybrid FES + powered actuation exoskeleton was proposed in [29]. The device employed a neural network-based control law to dynamically distribute effort between stimulation and electric motors. The result is a dramatic improvement in the quality of knee and hip joint movement patterns in a sit-to-stand exercise. The observed benefit of such systems on muscle fatigue and mobility hints at high potential for translational impact sets. Innovative diagnostic systems are continuously redefining on the treatment paradigms of knee injury. A finite element [FE] simulation approach to predicting individual knee joint kinematics has been validated based on MRI knee data [22]. This approach proved to be clinically accurate in the prediction of knee poses and proved as an informative and valuable tool for personalized treatment planning. These technologies have reached significant levels of development, offering powerful tools that permit more advanced methods for the diagnosis and rehabilitation of knee injuries. For example, in the case of the SKYRE platform, it uses several sensors for the remote assessment of knee rehabilitation, demonstrating potential results similar to gold-standard technologies [19]; in another example, a study developed a smart bionic leg orthosis (SBLO) to improve the gait in individuals with post-polio syndrome, demonstrating the potential of wearable devices to improve mobility and reduce gait pathologies [25].

3 Result Analysis

This analysis compares various methods used for knee injury diagnosis in terms of different performance metrics. Each method's efficiency and observations regarding knee-based injury diagnosis are summarized. The table below details the methodologies, results, and key insights from the reviewed works. The overview identifies a wide range of advanced methodologies in the diagnosis of knee injuries, from imaging to advanced machine learning and wearable technologies. Vibration-based monitoring and methods of bioimpedance measurement are characterized by high potential in sensor-based, non-invasive, and real-time diagnosis. At the same time, electromagnetic imaging systems and MRI-based evaluation present a very detailed insight into the structure of changes in the knee. Machine learning models, ranging

from traditional models to deep learning and modern neural networks, show high potential for accurate classification and prediction of the most relevant parameters in clinical decision-making processes for knee injuries in different scenarios. This highlights the diversity and effectiveness of various technological and methodological approaches in the analysis of these knee injury diagnosis methods, as illustrated in Table 6 above. Advanced imaging techniques, including electromagnetic imaging and MRI-based models, are seen from the table above to present a high level of accuracy and reliability in diagnosing knee injuries. Methods that employ deep learning, such as the decoupled GANs and CNNs, have shown significant improvement in classification accuracy and feature representation, making them very effective for clinical applications. Wearable technologies and smart garments, such as SKYRE, allow real-time and remote monitoring and are particularly valuable for continuous assessment and rehabilitation. Hybrid systems integrating functional electrical stimulation and adaptive control mechanisms will evidently help situations with the possibility of reducing muscle fatigue and enhancing mobility for individuals with spinal cord injuries for different scenarios. All in all, AI and machine learning models, from SVM-MPA to interpretable 3D DNNs, present very accurate and efficient solutions for knee injury detection and classification tasks from medical imaging, thus having a great potential to change traditional orthopedic practices. In general, the incorporation of these advanced diagnostic approaches in practice will substantially improve the accuracy, efficiency, and personalization of knee injury diagnosis and treatment, leading finally to an improved overall outcome for patients. Moreover, future research may focus on larger clinical trials and exploring the combined use of these methods for comprehensive knee injury management.

4 Conclusions & Future Scopes

The paper conducts an in-depth analysis of a number of diagnosis procedures for knee injury, pointing out their metrics, merits, and demerits. The diagnostic techniques covered in the work are broad, from vibration-based monitoring and electromagnetic imaging to bioimpedance measurement, functional electrical stimulation, and even deep learning models for application in medical sensors, actuators, and systems. The diagnostics are also spread over early detection, real-time monitoring, rehabilitation, and personalized treatment and hence reflect on enhancements in both classical and emerging diagnostics in healthcare. It can be seen that deep learning techniques, together with advanced imaging techniques, are commonly applied in the diagnosis of knee injuries. Each, of course, has its own distinct advantages. For example, electromagnetic imaging systems and bioimpedance measurements provide high sensitivity and specificity, making them appropriate for early detection and continuous monitoring of knee conditions. These methods are portable, cost-effective, and show enough potential for work in a clinical environment, mainly for point-of-care diagnostics including telemedicine applications. Deep learning methodologies, including self-supervised learning over MR video clips and Convolutional Neural Networks, have seen impressive accuracy in classification and quantification of such knee injuries. Models such as the decoupled GAN model for ACL tear location and the ATD-CNN self-attention mechanism for class imbalance are prominent in their high accuracy and ability to handle class imbalance, respectively. These models are particularly advantageous for automated diagnostics by reducing the burden on the clinicians and improving the diagnostic consistency. Rehabilitation is benefiting from hybrid systems that make use of both mechanical and electrical elements in constructing exoskeletons, such as the Modular Backdrivable Lower-limb Unloading Exoskeleton

(M-BLUE) and hybrid exoskeletons with functional electrical stimulation (FES), not only to increase mobility and decrease muscle fatigue but, more important, to provide tailored support for the movements of persons with mobility impairments in different use-case scenarios. Deployment of advanced and adaptive control algorithms further enhances efficacy and user experiences.

It would help cause the field of knee injury diagnostics and subsequent treatment to be fully integrated with multimodalism and the development of more sophisticated machine learning models. The call for models that can deal with concept drift, ensuring consistent performance in the face of changes in the input data over time, is increasing. The methods of transfer learning and adaptive neural networks can be paramount in supporting methods robust to changes in newly occurring situations. Moreover, the development of wearable and portable diagnostic equipment will continue to gather speed due to the need for telemedical and remote monitoring solutions. Sensor technology and data analytics innovations make more complete and actual monitoring of knee health possible, thus allowing for early intervention and specified treatment plans. The possibility of integrating AI-driven diagnostics with the real-time wearables-derived data stream may lead to the next revolution in the detection and management of knee injuries for different scenarios. In conclusion, the highlighted works are just a drop in the ocean regarding strides made in knee injury diagnostics, bringing into perspective the demand for more accuracy, efficiency, and adaptability. Advanced imaging techniques, deep learning models, and hybrid rehabilitation systems each offer unique benefits, catering to different aspects of knee injury management. Individually, each method will help in diagnosing and managing knee health for improved patient results and quality of lifestyles.

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