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Artificial Intelligence in Three-Level Prevention of Patellar Dislocation: Review and Summary of Existing Literature

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Abstract. Patellar dislocation is a common sports injury, which can cause pain, swelling, ligament damage and a recurrence risk. Current prevention measures mainly focus on the secondary and tertiary levels, while the primary prevention methods are limited. This article reviews the representative studies related to this topic: In terms of primary prevention, machine learning and deep learning can predict patellar instability based on magnetic resonance imaging (MRI) images and automatically measure anatomical risk factors such as patellar height; in terms of secondary prevention, machine learning models can use lipid metabolism indicators to assist in the diagnosis of recurrent dislocation and predict the clinical outcomes after medial patellofemoral ligament (MPFL) reconstruction surgery; in terms of tertiary prevention, artificial intelligence (AI) assessment and correction systems can improve functional scores and training compliance in knee joint postoperative rehabilitation, but the rehabilitation guidance generated by AI is still not accurate enough in details such as weight-bearing, brace use, and range of motion. Overall, AI has significant potential in imaging risk prediction and rehabilitation monitoring, but it is still weak in providing qualitative guidance. Moreover, existing studies have several limitations, including small sample sizes, limited geographical representation, and an imbalance in research focus, with primary prevention receiving more attention than secondary and tertiary prevention.

Keywords: Patellar Dislocation, Artificial Intelligence, Risk Prediction, Diagnosis, Rehabilitation

1. Introduction

Patellar dislocation is a type of sports injury that occurs in the knee joint. Typical symptoms include intense pain and hemarthrosis (internal bleeding, which causes swelling and more pain) and can cause temporary immobility in the region. Ligaments such as the medial patellofemoral ligament (MPFL) can be severely damaged. This type of injury can be caused by twisting motion, sudden lateral cuts, and relatively rarely, direct contact that shifts the patella out of the joint. Around 93% of traumatic patellar dislocations occur without contact [1]. With an annual incidence rate of 5.8-77.8 per 100,000 people, patellar dislocation is incredibly prevalent, especially in subjects under 20 years old [2]. If not treated properly, problems such as patellofemoral instability (PFI), recurrent dislocation, persistent knee pain, and patellofemoral osteoarthritis will arise. Specifically, the

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recurrence rate of dislocation normally ranges from 17%-36% due to differences in patient age and anatomical risks [3].

Undoubtedly, patellar dislocation significantly disrupts the daily life of potentially hundreds of thousands of people, and large-scale prevention can reduce the time and financial investment of many families in treating the disease, also stopping any mental trauma caused by the negative experiences in the incident injury and the treatment process. Prevention has three main levels, which include primary (prevention's literal meaning), secondary (treatment), and tertiary (rehabilitation) [4]. Prevention of Patellar dislocation is, however, currently limited mainly to secondary and tertiary prevention. Most existing literature mainly covers post-injury measures, but there is a current deficit in methods present to allow large-scale primary prevention to happen, apart from check-ups at hospitals. Patients normally have to realize the presence of risk factors after an initial injury has happened. However, artificial intelligence (AI) provides an opportunity to end this deficit.

AI is an emerging field with incredible potential. With the ability to self-learn and access vast databases, AI can find entries much more quickly than a human and provide real-time data analysis, offering possibilities in the sports rehabilitation field. It could engage in risk prediction, diagnosis & treatment support, and rehabilitation guidance & monitoring. AI's advantages include real-time monitoring and the ability to notice minor yet risky movement patterns that are hardly noticed by the human eye. However, the real feasibility of this application still needs to be assessed and reviewed, and there are currently very limited literature collectively organizing the different possibilities of AI usage on prevention of patellar dislocation. This paper aims to review existing literature on different AI applications to tackle patellar dislocation and address current limitations in the field, providing advice for future first-hand research.

2. Primary prevention

Primary prevention addresses the literal meaning of prevention: It aims to save a potential patient from his or her first diagnosis of the disease, in this case an initial patellar dislocation, which is usually associated with a healthy lifestyle, including regular exercise and a balanced diet; this is also applicable to patellar dislocation prevention, as maintaining enough rest and nutrients can greatly prevent accidents originating from fatigue.

A more promising primary prevention approach is risk factor identification, which traditionally can be done from birth (genetic disorders) or through regular check-ups at hospitals. By identifying risks early, people could address these weaknesses through various methods (using supplements, wearing protective wear in sports etc.) and avoid the initial dislocation. Some factors that have a significant correlation to risk of patellar dislocation include trochlear dysplasia, patella alta, and demographic factors (e.g. age, gender).

One prominent factor that is highly related to patellar instability (which induces dislocations easily) is trochlear dysplasia. As patellar dislocation is basically caused by abnormally large lateral translations of the patella, while trochlear dysplasia is "characterized by a shallow or flattened femoral trochlear groove" which allows larger horizontal movements of the patella. Nearly 96% of patients with objective patellar stability have this condition [5]. Another considered factor in risk identification is Patella alta, a patella that has an abnormally high place in relation to the tibia. This high place prevents it from being stabilized by the trochlear groove, which is made of bone, and the patella's stability would purely rely on soft tissues. Patella alta is present in 60.0% of patients with recurrent patellar dislocation [6]. As for demographic factors, patellar dislocation is more common in females (65%) and those aged under 18 years (females 31.4%, males 15.8%). This condition is the most prevalent in younger females [7].

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All of these parameters could be assessed through technology such as magnetic resonance imaging (MRI) and then be analyzed by human or simple algorithms, but this would be rather time-consuming, and there is a potential risk of incorrect judgement. With AI and by using machine learning or even advanced deep learning, prediction models can be built to identify patellar instability prior to an injury.

A clinical observational study investigated statistical shape analysis and machine learning based prediction of PFI. Their experiment utilized data from a total of 51 MRI scans (in 49 patients), with 20 being from people with PFI and 31 from patients not diagnosed with PFI that were age-matched and sex-matched. The MRI images were loaded into an open-source software and then manually delineated by experienced radiologists, producing 3D surface models. The models were evaluated through principal component analysis (PCA), and the variations found in the shape of the trochlear floor and intercondylar width significantly correlated with the PFI/Non-PFI distinction (as Multivariate analysis indicates). The discriminative shape features collected from this statistical shape analysis (SSA) were used by a machine learning-based prediction. Several different machine learning classifiers, such as linear discriminant analysis (LDA) and support vector machine (SVM) with a linear kernel (novel to this study), were used, achieving significant accuracies of 0.893±0.018 (LDA) and 0.909±0.015 (SVM with a linear kernel). Three other classifiers were used, with relatively lower accuracies (SVM with rbf kernel 0.845±0.022, k-nearest neighborhood 0.778±0.019, random forest 0.823±0.023). Sensitivity and specificity were also measured for each classifier, with SVM with a linear kernel having the highest values in both parameters (0.884±0.030 and 0.931±0.012, respectively). This study demonstrated the capabilities of machine learning models in predicting PFI and analyzing surface models of anatomical tissue, which are highly relevant to patellar dislocation prediction [8].

Another diagnostic study developed an automatic measurement model for patellar height, which was based upon deep learning and knee radiographs. From a selected total of 1218 left knee radiographs and 1320 right knee radiographs, 200 of each side were selected as the testing set, while the remaining 1018 left knees were used for training (n=916) and validation (the remaining 102), summing up to a total of 1418 knee radiographs used. All of these radiographs were annotated in pixel-level point form by three radiologists independently, and the inter-observer and intra-observer reliability were both assessed (both >99.0%). The training sets were augmented through horizontal flip, random rotation and random scaling, later unified to the same resolution. The deep learning–based system consisted of a landmark detection network (involving heat map production) and mathematical formulas in order to determine several patellar height parameters. The parameters included Insall-Salvati index (ISI), Caton-Deschamps index (CDI), Modified Caton-Deschamps index (MCDI), and Keerati index (KI). High measurement performance and measurement generalizability were achieved in the ISI, CDI, and the KI: Intra-class correlation coefficient (ICC, the greater the value the more reliable and replicable of the data) = 0.91–0.95, correlation coefficient (r) = 0.84–0.91, mean absolute difference (MAD, a measure of data dispersion) = 0.02– 0.05, and root mean square (RMS, quadratic mean) = 0.02–0.07. The model was weaker in measuring the MCDI, though (ICC = 0.65, r = 0.50, MAD = 0.14, RMS = 0.18). There was no significant performance difference between measurements in the left knee and the right knee by the deep learning model. This study has proven the potential of AI in assisting the measurement of anatomical data from clinical imaging, which may help in identifying risks associated with patellar dislocation, such as patella alta [9].

DOI: 10.54254/2753-8818/2027.39309

3. Secondary prevention

Secondary prevention is conducted when primary prevention is unsuccessful, and an initial occurrence or early symptoms are present. It attempts to identify the problem at its earliest stage so effective measures can be implemented in time in order to mitigate secondary effects and restore function [10]. In the context of patellar dislocation, this is the immediate and early interventions after an initial dislocation to prevent recurrent patellar dislocation and/or permanent MPFL tears. This often means quick diagnosis and personalized treatment methods to immediately tackle the condition, sometimes involving surgery.

Conservative treatment methods relative to secondary prevention are the early measures taken to reduce pain and edema, and to regain basic movement capability. Cold packs and immobilization are implemented right after the injury; aspiration of the knee effusion is also done if necessary. Knee flexion is also controlled, starting from 30 degrees and increasing to 90 degrees after a few weeks [11]. Braces are commonly used in the early stages after injury to support the knee and basic movement function, and a reduction in weight bearing is also suggested [12]. Normally, the partial weight-bearing process may last for 2-3 weeks, by then a basic level of mobility can be gained. However, conservative treatment can almost never solve patellar instability completely- relocations are common, and the timeline of recovery can vary greatly between individuals due to anatomical or personal differences.

One very common surgical measure is MPFL reconstruction. The MPFL is an incredibly important ligament responsible for stabilizing the knee joint and is often teared when patellar dislocation occurs. The MPFL in individuals with PFI is usually longer and thinner, which reduces its ability to resist forces, thereby increasing the risk of initial and recurrent dislocation [13]. MPFL reconstruction therefore aims to recreate the stability by implanting a graft in place of the original ligament through drilling holes in the femur and patella and fixing the graft in place. Autografts are usually preferred because of their high biocompatibility and availability, and there is also a range of drilling and fixation techniques such as the double-tunnel technique which aims to recreate the fan-shaped anatomy of the MPFL [14]. The biggest problem associated with pure human-based MPFL reconstruction is incorrect positioning of the holes for MPFL fixation. For example, when the femoral fixation point is too anterior, it may produce severe patellar chondropathy and patellofemoral osteoarthritis [15].

Clearly, a balance of the two types of treatments is required to halt the progression of patellar dislocation, but both treatment categories are flawed if only humans intervene. However, if AI can be involved in supporting treatments (whether conservative or surgical) or providing accurate diagnoses, secondary prevention could be addressed in a much larger scale, saving financial costs and reducing potential harm for many patients.

A case-control study investigated how machine-learning models can predict clinical outcomes after MPFL reconstruction. Using a total of 218 patients who underwent MPFL reconstruction from January 2018 to December 2022, 42 predictive models were constructed to measure 7 different post-MPFL reconstruction clinical outcomes, including failure to achieve minimum clinically important difference of clinical scores (4 different metrics), return to pre-injury sports, pivoting sports, and recurrent instability. 6 machine-learning algorithms were used, such as random forest, logistic regression, support vector machine etc. Model performance was tested using measurements including area under receiver operation characteristic curve (AUC), accuracy, specificity, and sensitivity. The performance in predicting failure to achieve the minimum clinically important difference for the 4 different scores was averagely good, with AUC and accuracies being 0.969 and

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97.0% (the Kujala score), and 0.760 and 76.8% (the Tegner score); prediction of the other two scores both had an AUC of over 0.850 and an accuracy of over 85.0% (Lysholm score, International Knee Documentation Committee score). Shapley additive explanation (SHAP) summary plot was also used to identify predictive factors regarding the clinical outcomes, allowing the model to determine significant predictive factors for return to pre-injury/pivoting sports and recurrent instability. For example, factors that predicted the return to pre-injury sports outcome were low preoperative Tegner score, shorter time to surgery, and absence of severe trochlear dysplasia. Thus, this study provided valuable data regarding AI's potential in assisting treatment outcome related stages in patellar dislocation [16].

However, even after a surgery, recurrent patellar dislocation can happen, and some people may have higher risks of recurrence than others which can be diagnosed with the help of AI. An observational study investigated how parameters related to lipid metabolism can be used in diagnosing recurrent patellar dislocation using interpretable machine learning, as obesity is also a crucial factor influencing the risk of patellar dislocation. A total of 260 patients with recurrent patellar dislocation were in the study group, and 547 healthy individuals were included in the control group. Each patient had 14 data features collected, which can be categorized into two groups (demographic characteristics and blood lipid metabolic factors). Demographic factors included gender, age, height, weight and Body Mass Index (BMI), while blood lipid metabolic factors included total cholesterol (TC), triglycerides (TG), high-density lipoprotein (HDL) and several more. All of these factors were thought to be associated with recurrent patellar dislocation. Pearson correlation coefficients were calculated, and PCA was done on lipid biomarkers and anthropometric variables. A two-layer ensemble machine learning model was used, with the first layer including ten machine learning models as base classifiers (random forest, adaptive boosting etc.) and the second layer being one meta classifier (Logistic Regression). Stratified five-fold cross-validation was done on the training set for all models. 70% of the data was used for training and the remaining 30% was used for testing, evaluating the model on various aspects including sensitivity, specificity, receiver operation characteristic curve and the corresponding AUC, and 3 other performance parameters. The ensemble model the team developed eventually reached an AUC of 0.82, which is the same as the AUC of the base model CatBoost used (the individual base model that had the highest AUC). The ensemble model also had a sensitivity of 0.82. This study showed the capability of machine learning models in using blood lipid metabolic parameters to assist in the diagnosis of recurrent patellar dislocation [17].

4. Tertiary prevention

Tertiary prevention focuses on minimizing long term effects of diseases with persistent influence, and in the case of patellar dislocation would be return-to-work rehabilitation. Physiological practices often address the necessity of both kinesiotherapy for full range of motion (ROM) and quadriceps muscle strengthening for restoration of the dynamic component of the patellar soft-tissue stabilizers [11].

Currently, rehabilitation is considered as stage-based, with different time periods after surgical intervention corresponding to different goals of functional recovery. Most mobility is gained within 12 weeks, with different goals in the first six weeks (Early phase) and weeks 6-12 (Intermediate phase). In the early phase, goals like full passive knee extension, passive knee flexion of 125°, adequate quadriceps control and full weight bearing (with normal gait mechanics) should be achieved. Corresponding exercises include mini-squats, straight leg raises, quadriceps sets and gluteal sets. In the Intermediate phase, a full range of motion, painless training, good muscle control

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in squats or lunges, and knee-flexed single leg balance are aimed for, with exercises such as step-ups, wall slides, single leg balance, and hip/core training. In this stage, psychological issues such as avoidance behavior should also be addressed, and the patient should be informed about how to return to activity. A late phase extending to 6 months after surgery aims for further strengthening of the body and capability of difficult moves such as proper landing mechanics after jumping [18].

The problem for current rehabilitation exercises is that different individuals may have different capabilities and recovery speeds. It is hard for human coaches to observe these differences and personalize the most suitable recovery pace and exercises for their patients. But with AI, this may be achieved through consistent monitoring and personalized advice based on the access of vast data sets.

An interventional study evaluated the efficacy of an AI-based assessment and correction system in post-anterior cruciate ligament (ACL) reconstruction surgery rehabilitation. The relevance of this study to patellar dislocation is still high; both procedures aim to restore joint stability and involve tunnel creation and graft placement. They also have similar average return-to-sport timelines, approximately 6–9 months. A total of 79 participants were involved, all between ages 18-50 and experienced ACL reconstruction surgery. They were divided into 2 groups: a control group (n=40) who received conventional rehabilitation exercises, and a trial group (n=39) who received rehabilitation guided and supported by an AI-based assessment and correction system. In the trial group, AI was used to monitor patient performance using non-wearable 3D motion capture technology, identify key functional deficits, and also display model videos for rehabilitation protocols. Comparing patient data with standard references, the system was able to produce reports which included evaluations on metrics like movement scores, key joint ranges of motion, deviation angles and more. Results indicated that the trial group achieved statistically significant ($p < 0.05$) higher Lysholm scores, International Knee Documentation Committee (IKDC) scores, and Berg Balance Scale (BBS) scores in all time points recorded (1, 2, 3, and 4 months after surgery) compared to the control group. The trial groups also had more significant improvements in knee joint ROM and functional exercise adherence scores, all statistically significant ($p < 0.05$). This study suggested the possibilities of AI in the monitoring of post-surgical rehabilitation, and this success in ACL reconstruction surgery recovery could possibly be generalized to other knee-joint stability-related protocols, such as MPFL reconstruction [19].

A structured review aimed to compare the post-operative rehabilitation recommendations (weight-bearing, brace use, ROM, return to sport (RTS) standards) for MPFL reconstruction, tibial tubercle osteotomy (TTO), trochlear osteoplasty, and combined surgeries, and to evaluate the consistency between the AI-generated recommendations and the published plans. It included 63 post-operative rehabilitation plans for patellar instability (35 isolated MPFL reconstruction, 9 isolated TTO, 4 isolated trochlear osteoplasty, 15 combined surgeries), and additional exploratory AI comparisons were made using ChatGPT, Gemini, and Open Evidence. The results showed that the isolated MPFL reconstruction plan was the most consistent, with 66% allowing immediate weight-bearing tolerance ($p<0.001$), 63% of the locking braces being used for no more than 6 weeks ($p<0.001$), and 51% achieving full ROM within 6-12 weeks ($p=0.002$); the isolated TTO was more conservative, with 56% delayed/non-weight-bearing and 67% of the braces being used for more than 6 weeks, but without a significant advantage ($p>0.05$); the trochlear osteoplasty plan was too few and heterogeneous; the combined surgery plans were mostly protective but with large variations. RTS was mainly based on time, function, and strength criteria (76%–89%), psychological preparation (43%), and doctor approval (22%); the median RTS time was 6 months, and there were no significant differences among the surgical procedures ($p=0.361$). AI solutions can replicate the

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general principles of rehabilitation after MPFL reconstruction to support accelerated recovery, but they lack the specificity required to distinguish between different surgical procedures. AI-generated guidance has a degree of accuracy, but lacks important detail on full ROM time range, bracing time, and weight bearing for non-MPFL reconstruction surgical procedures. This provides negative evidence on the application of AI in proposing rehabilitation designs, suggesting more development on the technology. AI usage is beneficial, but complete reliance would not be suggested currently [20].

5. Limitations in current research

Several limitations have been identified. The most common issue seen is a relatively weak sample; a limited number of cases are often included for model training or participation in the protocol, and these cases are also mostly limited to the researcher's geographical location (i.e., lack of geographical generalizability). In addition, current studies rarely parallel AI-based results with conventional procedures, causing a lack of direct comparison and identification of comparative advantages and weaknesses. In terms of all research present as a whole, screening-based studies were much more common compared to evaluating language-based data, and research on primary prevention and AI was much more prominent than secondary and tertiary prevention. A shift in research focus is needed, and future researchers should address this imbalance.

6. Conclusion

In conclusion, a review of exemplar literature on how AI can be integrated within the three levels of prevention in patellar dislocation and associated conditions & procedures was done. Through analysis of six studies and their experimental data, existing research has proved AI's capability in risk and outcome prediction based on imaging data and rehabilitation monitoring with sensors, but AI is currently still relatively weak in providing qualitative guidance because of a lack of crucial details in generated content. An existing imbalance in the number of entries associated with primary prevention and secondary/tertiary prevention was also identified. In the future, researchers should first aim to address the deficit in the number of studies within the realms of AI and secondary and tertiary prevention of patellar dislocation, preferably through more interventional investigations to provide comparisons between control groups and trial groups which current studies lack; researchers from different world regions can also collaborate to ensure the geographical diversity of the investigated samples.Overall, AI has considerable potential in the prevention and management of patellar dislocation and other sports injuries. With further research and validation, supported by adequate funding and appropriate regulatory frameworks, AI may help individuals better understand their risk of patellar dislocation and facilitate earlier preventive interventions. Even when an injury occurs, AI-assisted diagnosis, treatment planning, and rehabilitation may help reduce healthcare costs, improve treatment efficiency, and provide more timely guidance.

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