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A knowledge-based intelligent framework for anterior cruciate ligament rehabilitation monitoring

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ABSTRACT

This study presents an integration of knowledge-based system and intelligent methods to develop a recovery monitoring framework for post anterior cruciate ligament (ACL) injured/reconstructed subjects. The case based reasoning methodology has been combined with fuzzy clustering and intelligent classification techniques in order to develop a knowledge base and a learning model for identifying the recovery stage of ACL-reconstructed subjects and objectively monitoring the progress during the convalescence regimen. The system records kinematics and neuromuscular signals from lower limbs of healthy and ACL-reconstructed subjects using self adjusted non-invasive body-mounted wireless sensors. These bio-signals are synchronized and integrated, and a combined feature set is generated by performing data transformation using wavelet decomposition and feature reduction techniques. The knowledge base stores the subjects' profiles, their recovery sessions' data and problem/solution pairs for different activities monitored during the course of rehabilitation. Fuzzy clustering technique has been employed to form the initial groups of subjects at similar stage of recovery. In order to classify the recovery stage of subjects (i.e. retrieval of similar cases), adaptive neuro-fuzzy inference system (*ANFIS*), fuzzy unordered rule induction algorithm (*FURIA*) and support vector machine (*SVM*) have been applied and compared. The system has been successfully tested on a group of healthy and post-operated athletes for analyzing their performance in two activities (ambulation at various speeds and one leg balance testing) selected from the rehabilitation protocol. The case adaptation and retention is a semi-automatic process requiring input from the physiotherapists and physiatrists. This intelligent framework can be utilized by physiatrists, physiotherapists, sports trainers and clinicians for multiple purposes including maintaining athletes' profile, monitoring progress of recovery, classifying recovery status, adapting recovery protocols and predicting/comparing athletes' sports performance. Further, the knowledge base can easily be extended and enhanced for monitoring different types of sports activities.

1. Introduction

The monitoring of recovery progress after anterior cruciate ligament (ACL) injury/reconstruction is crucial for athletes for not only restoring their knee joint stability for dynamic activities and successful returning to sports but also minimizing the risks of re-injury, cartilage degeneration and early onset of osteoarthritis [1–6]. ACL injury causes deterioration in the sports performance or premature end to the career for athletes as ACL is one of the critical ligament for knee joint stability, maintaining normal gait patterns, preventing anterior tibial translation, and controlling knee axial rotation and varus movements [7]. It can be completely or partially ruptured as a result of deceleration due to sudden changes of direction, twisting and/or pivoting during sports, like soccer and basketball. The tearing or rupture of ACL affects gait patterns and variability, and causes changes in kinematics, kinetics and neuromuscular activities of athlete. The absence of ACL results in the loss of mechanical control of the knee, loss of proprioception due to unavailability of mechanoreceptors present in the ligament and neurophysiologic dysfunction, hindering the athletes to participate in sports activities. Efficient and effective rehabilitation programs are essential for athletes following ACL reconstruction as well as for those having ACL deficiency. The rehabilitation programs are designed to rebuild muscle strength, re-establish joint and neuromuscular

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control and to enable the athletes to return to pre-injury activity level. The goal based criteria (e.g. muscle strength, functional and static knee stability, range of motion) are suggested to safe return to sports rather than relying on some specific time period for rehabilitation [7–9]. The conventional methods for post-ACL reconstruction recovery assessment test the static and dynamic knee stability of subjects. However, the dynamic knee stability analysis usually lacks quantifiable constructs, and some subjective or partially objective evaluations and knee rating scores are performed in order to evaluate the recovery progress of ACL reconstructed (ACL-R) subjects [10–15]. Moreover, physiological variations in subjects and coopers/non-coopers phenomenon indicate that the rehabilitation process may differ for an individual or a group of subjects [16]. Thus, in order to provide an effective cure and timely intervention during recovery process, a comprehensive rehabilitation monitoring system is essential for ACL reconstructed (ACL-R) subjects.

Intelligent techniques have been found effective for different medical applications including medical diagnosis, pathology classification, rehabilitation of lower limb movements after neurological disorders and implantation of artificial limbs [17–22]. These techniques assist clinicians in decision making process about subjects' health condition. Although, there has been number of studies using intelligent mechanisms for assessment and classification of gait patterns for subjects having lower limb impairments due to stroke or cerebral palsy but few efforts have been made for gait and recovery analysis after ACL injury/reconstruction. Mostly the assessment of injured/reconstructed subjects is still based on the comparison of mean and peak values or some other statistics of kinematics, kinetics and neuromuscular parameters with controlled subjects [6,23–27]. Moreover, in most of the previous studies individual parameters are observed and few efforts have been made for developing an intelligent assistive tool for monitoring recovery of athletes after anterior cruciate ligament (ACL) injury and reconstruction [28,29]. In order to differentiate between ACL intact (ACL-I) and ACL deficient/injured, an intelligent classification system has been developed using adaptive neuro-fuzzy inference (ANFIS) system based on arthrometric data [30]. This system recognizes the normal and ACL injured subjects with high values of sensitivity and specificity but it does not consider the knee dynamics changes in ACL-R subjects. A classification model to test the gait normality of ACL-R subjects has been proposed in [28] based on principal component analysis and regression modeling techniques. This system used 3-D rotational kinematics and the classification results indicated the presence of abnormal gait patterns in frontal and transversal planes for ACL-R subjects still 1 year after surgery with an accuracy of 93.75%. Recently, an intelligent recovery classification model has been presented for ACL-R subjects to monitor their rehabilitation progress during different ambulation and balance testing activities [19]. This system integrates the kinematics and neuromuscular signals and the accuracy of the classification results is approximately 95% for different activities monitored. Although these studies used computational intelligent techniques for differentiating the normal and impaired human motion but post-surgical monitoring and prognosis of rehabilitation and sports performance of ACL-R subjects are fairly complex processes because of the involvement of multiple varying factors for each subject. The restoration of normal gait patterns does not ensure the complete recovery and return to high level sporting activities. In addition, keeping a record of pre- and post-surgery treatments and their effectiveness, adjustments in individual's rehabilitation protocol and all the different experiences during convalescence is a complicated phenomenon for physiatrists and physiotherapists. These experiences can be used to learn and adapt the rehabilitation procedure for ACL-R subjects having similar parameters or patterns. In order to build such an exhaustive system, a knowledge base of athletes' profiles can be developed to store the pre-injury, pre-surgery and post-surgery (during rehabilitation period) information about athletes' knee dynamics and other relevant parameters. Based on this information and past experiences, a learning model can be developed for improving the recovery after ACL injury/reconstruction. An effective method to build this learning system is to use case based reasoning (CBR) paradigm which maintains a case repository of past experiences (old problem-solution pairs) and solves the new problems by using or adapting the existing solutions [31].

CBR has been used as a decision supporting technique in variety of healthcare applications [32]. Based on CBR approach, a gait disorder analysis system has been proposed in [33] to help general practitioners. This system records lateral and forward movements of center of mass by using an accelerometer and retrieve similar cases based on the experts' knowledge. In order to provide diagnosis and prognosis for stroke patients, CBR based system has been successfully developed using data collected through robotic tool [34]. The system retrieves a potential solution for stroke diagnosis by finding similar cases from the repository of stroke patients with explicit diagnosis and prognosis. Recently, different intelligent techniques have been combined with CBR approach to build hybrid/soft CBR systems for complex medical domains. A hybrid system combining Self Organizing Maps (SOM) and CBR has been developed in [35] for evaluating postural control of subjects based on trunk sway with a prediction accuracy of more than 90%. For diagnosis and treatment of stress, a reliable hybrid CBR system (88% accuracy) has been designed by using finger temperature [36]. The hybrid models based on integration of CBR and fuzzy decision tree provide accurate forecasting in the domains of breast cancer (98.4% accuracy) and liver disorders (81.6% accuracy) [37]. Another application of combining CBR and cluster analysis is the development of a health monitoring system for elderly subjects based on pulse rate and blood oxygen saturation data [38]. This system classifies the pulse rate and blood oxygen saturation with an accuracy of 93%.

This research aims at developing an intelligent framework using knowledge-based system and artificial intelligence (AI) techniques for monitoring and classification of recovery status of athletes, and evaluating their sports performance after ACL reconstruction. A knowledge base has been designed to store the subjects' profiles and problem/solution pairs by integrating adaptive learning techniques and reasoning model to build an extensible recovery progress monitoring system which provides efficient and effective solution based on the existing cases. Non-invasive body-mounted motion and electromyography (EMG) wireless sensors have been used to collect the kinematics and neuromuscular data from ACL reconstructed and healthy subjects during various ambulation and balance testing activities. Different statistical and time/frequency features have been extracted from kinematics and EMG data, and a feature reduction method has been applied to reduce the large number of features and generate a set of appropriate integrated kinematics and neuromuscular patterns. In order to facilitate the efficient selection and retrieval of cases and flexible knowledge base design, the fuzzy clustering technique has been used to form the groups of subjects based on their current recovery stage after ACL reconstruction. Different intelligent classification techniques (adaptive neuro-fuzzy inference system, fuzzy unordered rule induction algorithm and support vector machine) have been explored and compared for finding the similar case from the knowledge base. Once relevant cases are selected, adaptation is performed by adjusting the recovery protocols for individuals based on the previous known solutions and the performance evaluation can be done. This framework will facilitate the clinicians, physiotherapists, physiatrists and sports trainers in determining the recovery stage of ACL-R subjects based on the data collected during different rehabilitation activities and identifying the subjects lacking