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Review

Relationship between training load and recovery rate in artificial intelligence-based sports rehabilitation training

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Abstract: In the contemporary era characterized by rapid advancements in science and technology, artificial intelligence (AI) has emerged as a transformative force across various domains, particularly in the realm of sports rehabilitation training. Its unique advantages position AI as a pivotal element in enhancing training efficacy and facilitating recovery from injuries. The objective of this study is to thoroughly investigate the intricate relationship between training load and recovery rate within the context of AI-driven sports rehabilitation training, thereby offering robust theoretical foundations and practical guidance for the optimization of rehabilitation training programs. This paper commences with an overview of the latest developments in the application of AI in sports rehabilitation training, highlighting critical components such as data-driven monitoring of training loads, the formulation of personalized rehabilitation programs, and the assessment of recovery outcomes. Subsequently, the paper delves into a detailed analysis of the interaction mechanisms between training load and recovery rate, examining the impact of varying training loads on the recovery rates of both athletes and patients, as well as strategies for optimizing the recovery process through precise control of training loads. Finally, the paper emphasizes innovative strategies employed by artificial intelligence technology to adjust training loads and enhance recovery rates. This includes the utilization of machine learning algorithms for predicting individual recovery potential and the application of deep learning techniques for real-time monitoring and adaptive modification of training programs. Through this comprehensive investigation, the paper aspires to offer novel insights and methodologies for the scientific and individualized advancement of sports rehabilitation training, thereby contributing valuable knowledge and support to the swift recovery of athletes and patients.

Keywords: artificial intelligence; sport rehabilitation; training load; recovery rate

1. Introduction

The incidence of sports injuries is an inevitable aspect of both competitive athletics and everyday life, frequently necessitating the rehabilitation of athletic capabilities for both athletes and non-athletic individuals [1]. Sports rehabilitation training, which is a specialized approach that integrates principles from sports medicine, biomechanics, and rehabilitation medicine, not only plays a crucial role in facilitating the recovery from injuries but is also vital for enhancing an individual's quality of life and their capacity for social participation [2]. Nevertheless, conventional rehabilitation training methods often depend heavily on the expertise of therapists and the self-reported assessments of patients. Traditional rehabilitation training heavily relies on the therapist's experience and the patient's subjective feedback, which can lead to imprecise assessments of training loads and hinder the ability to meet individualized needs. For instance, the method based on the subjective rating of perceived exertion (session-RPE), while straightforward, is easily swayed by the athletes' personal feelings, resulting in unreliable data [3]. Furthermore, the rehabilitation training process is complex and lengthy, and patients often struggle to adhere to it due to a lack of motivation. Last but not least, rehabilitation resources are limited and unevenly distributed, particularly in remote areas, making it challenging for patients to access timely and effective rehabilitation services [4]. This reliance can, to some extent, constrain the evaluation of training outcomes and the personalized modification of rehabilitation programs [5].

The advancement of science and technology, particularly the rapid evolution of AI, is instigating significant transformations within the domain of sports rehabilitation training. AI, characterized by its robust data processing capabilities, precise predictive models, and adaptive learning mechanisms, offers novel solutions to the challenges faced in traditional rehabilitation training [6,7]. Consequently, the investigation of AI applications in sports rehabilitation training has emerged as a prominent area of contemporary research. In this context, the term refers to the cumulative physiological and psychological stresses experienced by an athlete or patient during rehabilitation training [8], while the speed at which an individual returns to their pre-training state following the imposition of training load [9]. Two concepts discussed are critical components in evaluating the efficacy of rehabilitation training and in modifying training programs accordingly. Presently, the integration of AI in sports rehabilitation training emphasizes three primary aspects [10,11]. Firstly, training data is collected via sensors and wearable devices, enabling real-time monitoring of training loads. Secondly, machine learning algorithms are employed to analyze this data and to formulate personalized rehabilitation training programs tailored to individual needs. Lastly, the effectiveness of rehabilitation is assessed objectively through deep learning and other advanced technologies, thereby providing a scientific foundation for the adjustment of training programs. These technologies not only enhance the efficiency of rehabilitation training but also reduce costs, allowing more patients to benefit.

Given the pivotal role of training load and recovery rate in sports rehabilitation, this paper seeks to conduct a comprehensive examination of the relationship between these two variables and to investigate methods for optimizing the rehabilitation training process through the application of artificial intelligence technology. Initially, the paper will assess the current state of artificial intelligence applications in sports rehabilitation training. Subsequently, it will analyze the interaction mechanisms between training load and recovery rate. Finally, the study will explore how artificial intelligence technology can facilitate the intelligent regulation of training load to enhance recovery rates and improve the overall efficacy of rehabilitation training. Through this series of investigations, this review aims to provide both theoretical support and practical guidance for the intelligent and personalized advancement of sports rehabilitation training, thereby contributing novel insights and methodologies for the expedited recovery of athletes and patients.

2. Methods

Literature searches were conducted using PubMed, Google Scholar, Elsevier ScienceDirect, and Web of Science. The search strategy employed the following terms: "sport rehabilitation", "training load", "sporting injury", "recovery rate", "artificial intelligence", "training load AND artificial intelligence", "training load AND recovery rate", "sports rehabilitation training AND artificial intelligence", "sports rehabilitation training AND training load AND recovery rate AND artificial intelligence", among others.

3. Current status of the application of artificial intelligence in sports rehabilitation training

3.1. Data acquisition and processing

In the context of the modernization of sports rehabilitation training, the integration of artificial intelligence technology has significantly transformed the field. The accurate collection and efficient processing of data have emerged as fundamental components in enhancing the effectiveness of rehabilitation training. By utilizing high-precision sensors, cameras, and various wearable devices, it has become possible to capture real-time athletic data from both athletes and patients, encompassing a wide array of dimensions such as joint angles, muscle activity, and balance [12]. Advanced artificial intelligence algorithms, including time series analysis, pattern recognition, and feature extraction, facilitate the precise distillation of critical information that reflects movement status and the rehabilitation process from these complex datasets [13]. For instance, the research conducted by Hatamzadeh et al. [14] employed surface electromyography (sEMG) data to successfully identify muscle activity patterns in athletes through machine learning algorithms, thereby establishing a foundation for personalized training. Furthermore, the study by Kwak et al. illustrated how inertial measurement unit (IMU) data can be analyzed to monitor the quality of a patient's movements, ultimately optimizing rehabilitation programs [15]. This data-driven processing approach not only enhances the relevance and scientific rigor of rehabilitation training but also offers therapists a novel perspective for understanding and optimizing the rehabilitation process.

Advancements in technology have led to the evolution of data acquisition techniques, transitioning from basic motion capture systems to sophisticated systems that incorporate multiple sensors. For instance, the Xsens motion capture system is capable of delivering precise three-dimensional motion data, which is essential for analyzing athletes' movement patterns and monitoring rehabilitation progress [16]. Artificial intelligence algorithms are integral to the processing of this data. Machine learning, particularly deep learning methodologies, has demonstrated significant potential in the processing of sEMG signals [17]. Comparative analyses of various machine learning algorithms, including Support Vector Machines (SVM), Logistic Regression (LR), and Artificial Neural Networks (ANN), have indicated that SVM exhibits superior performance in recognizing shoulder motion patterns [18].

The analysis of data obtained from IMU and other sensors enables a more precise monitoring of athletes' movements, thereby facilitating the development of customized rehabilitation programs tailored to individual needs [19,20]. This methodology not only enhances the efficiency of rehabilitation processes but also mitigates the risk of re-injury among athletes resulting from inadequate training practices. Furthermore, the application of AI technology extends beyond mere data acquisition and processing; it encompasses the integration of virtual reality (VR) technology as well. The combination of VR technology with AI can offer an immersive rehabilitation training experience, which is crucial for enhancing both the motivation and effectiveness of athletes' rehabilitation efforts [21]. The incorporation of AI technology in sports rehabilitation training not only increases the accuracy of data collection and processing but also provides substantial support for the personalization and scientific rigor of rehabilitation programs.

3.2. Rehabilitation programming

In the domain of sports rehabilitation and training, the integration of artificial intelligence technology is revolutionizing the precision and personalization of rehabilitation program development. The foundation of this technology is its profound understanding of individual patient variances, coupled with a comprehensive incorporation of the expertise of seasoned therapists. By thoroughly analyzing extensive data regarding the patient's injury type, motor capabilities, physiological responses, and other relevant factors, AI systems are capable of dynamically formulating customized rehabilitation training programs [22]. For instance, a study conducted by Li and colleagues employed machine learning algorithms to automatically modify the intensity and progression of rehabilitation training based on the patient's motor performance and clinical indicators, thereby significantly enhancing rehabilitation efficiency [23]. These programs not only aim to achieve rehabilitation objectives but also prioritize safety and patient comfort throughout the training process. For example, research by Zhang et al. provided stroke patients with a personalized exercise rehabilitation program through an artificial intelligence-assisted decision support system, which markedly increased patient engagement and satisfaction while simultaneously improving their motor function [24].

The integration of AI technology in the formulation of rehabilitation programs not only enhances the sophistication of rehabilitation training but also offers a more personalized and efficient recovery pathway for patients. Utilizing deep learning algorithms, AI systems can effectively identify and forecast the patient's recovery trajectory as well as potential barriers to rehabilitation, thereby allowing for proactive adjustments to treatment plans [25]. This predictive analysis yields critical insights for rehabilitation therapists, equipping them to adapt to the evolving needs of patients and to optimize treatment strategies in a timely manner. Furthermore, AI technology facilitates the identification of both commonalities and variances among diverse patient populations by analyzing extensive rehabilitation datasets, thereby providing a scientific foundation for the development of innovative rehabilitation strategies and interventions [26,27].

The integration of artificial intelligence technology in the development of personalized rehabilitation programs significantly enhances patients' capabilities in performing activities of daily living. Utilizing VR technology, patients engage in rehabilitation training within simulated daily life scenarios. This innovative training approach not only increases the enjoyment of rehabilitation but also bolsters patients' confidence and their ability to reintegrate into society [28]. Furthermore, VR technology offers an immersive training experience that aids patients in overcoming fear and anxiety, thereby improving their psychological adaptability through the simulation of various complex environments [29]. The incorporation of artificial intelligence in sports rehabilitation training not only enhances the personalization and precision of rehabilitation programs but also facilitates the provision of more comprehensive and efficient rehabilitation strategies through predictive analysis and virtual reality technology.

3.3. Evaluation of training effectiveness

In the context of sports rehabilitation training, the accurate assessment of training effects is a critical component that is directly linked to the effective modification of training programs and the seamless progression of the rehabilitation process. The integration of artificial intelligence technology offers a robust tool for the comprehensive analysis of sports data, thereby enhancing the objectivity and precision of rehabilitation training effect assessments. This technology enables the quantification of improvements in range of motion, muscle strength, and various stages of functional recovery, thereby establishing a solid data foundation for the dynamic adjustment of training programs [30]. A study conducted by researchers, including Chaabane [31], employed artificial intelligence algorithms to analyze gait data from rehabilitation patients. The study successfully identified the impact of rehabilitation training on the improvement of gait symmetry, thereby providing a critical foundation for the optimization of subsequent training regimens. Furthermore, the research conducted by Cheng et al. [32] evaluated alterations in muscle activation patterns through the analysis of sEMG signals. This analysis facilitated the modification of rehabilitation training protocols, thereby enhancing the recovery of patients' muscular function. These findings demonstrate that the integration of artificial intelligence technology in the assessment of training outcomes not only enhances the precision and efficiency of evaluations but also paves the way for the personalized and intelligent advancement of rehabilitation training methodologies.

The role of AI technology in the assessment of training effects extends beyond gait analysis and the identification of muscle activation patterns. AI is also adept at analyzing extensive rehabilitation data to identify commonalities and differences among various patient groups, thereby providing a scientific foundation for the development of novel rehabilitation strategies and treatments. For instance, AI-driven personalized rehabilitation programs have demonstrated significant advancements in the rehabilitation of polymyositis, wherein AI algorithms can evaluate patients' clinical data, physiological measurements, and activity patterns to formulate tailored rehabilitation programs for each individual [33]. Furthermore, the application of AI technology is evident in enhancing patients' abilities to perform activities of daily living. Through the utilization of VR technology, patients can engage in rehabilitation training within simulated daily life scenarios. This approach not only increases the enjoyment of rehabilitation but also bolsters patients' confidence and capacity to reintegrate into society [34].

In the evaluation of the training effects of AI, commonly utilized metrics include accuracy, recall, precision, and the F1 score. These metrics enable researchers and clinicians to quantify the impacts of rehabilitation training and to make necessary adjustments to treatment programs accordingly [35]. The integration of artificial intelligence technology enhances these assessment processes by rendering them more automated and intelligent, thereby improving both the efficiency and accuracy of evaluations [36]. Furthermore, the application of AI in assessing the effects of sports rehabilitation training not only enhances the precision and efficiency of evaluations but also facilitates the development of more comprehensive and effective rehabilitation programs for patients through predictive analytics and virtual reality technologies.

3.4. VR rehabilitation training

The integration of VR technology has introduced a transformative innovation in the domain of sports rehabilitation training. By creating highly simulated virtual environments, VR significantly enhances the enjoyment and interactivity of rehabilitation exercises while offering a safe and controlled space for patients to practice a variety of complex movements that they may encounter in real-world scenarios [37,38]. This immersive training methodology has demonstrated distinct advantages for rehabilitation processes that necessitate specific environmental stimuli, particularly in balance and coordination training. For instance, research conducted by Lockhart et al. indicated that balance training utilizing VR technology effectively improved gait stability and quality of life for patients with Parkinson's disease [39]. Furthermore, a study by Bharathi et al. [40] illustrated the beneficial effects of VR technology on upper limb motor rehabilitation within an augmented reality context, leading to significant enhancements in patients' upper limb functionality and self-care capabilities by simulating activities of daily living. Collectively, these studies underscore that the application of VR technology in sports rehabilitation training not only enriches and personalizes the rehabilitation experience for patients but also provides robust technical support for improving rehabilitation outcomes and innovating training methodologies.

The application of VR technology in rehabilitation extends to the enhancement of cognitive functions. A systematic review and meta-analysis conducted by Mehraram et al. demonstrated that VR technology positively influences patients suffering from post-stroke aphasia [41]. Furthermore, VR technology has been employed to enhance both motor imagery and motor execution in individuals with Parkinson's disease, indicating its beneficial effects on cognitive functions alongside improvements in motor capabilities [42]. In the realm of pediatric rehabilitation, studies have also indicated that VR technology can significantly enhance gait, balance, and muscle strength in children diagnosed with cerebral palsy [43,44]. These findings underscore the considerable potential for diverse applications of VR technology across various rehabilitation populations.

The assessment of the effects of VR technology in rehabilitation training represents a significant area of research. The assessment metrics encompass joint mobility, movement smoothness, trajectory error, and the enhancement of L-Z complexity in electromyography (EMG) signals [45,46]. These indicators not only facilitate the quantification of rehabilitation training outcomes but also serve as a foundation for the modification of rehabilitation training programs. VR technology enhances the objectivity and precision of rehabilitation training assessments by delivering real-time feedback and quantitative data. Furthermore, the integration of VR technology in sports rehabilitation training not only increases the enjoyment and interactivity of the training process but also offers a safe and controlled practice environment, thereby supporting cognitive function recovery. This approach provides patients with a more comprehensive and personalized rehabilitation experience.

4. Relationship between training load and recovery rate

4.1. Training load

Within the domain of sports rehabilitation training, the precise regulation of training load is fundamental to achieving effective rehabilitation outcomes. Training load encompasses not only the physiological stresses experienced by athletes and patients during the rehabilitation process—such as muscle fatigue and joint loading—but also includes psychological stresses, such as anxiety and frustration, that may arise during training [47]. Research indicates that appropriate training loads are essential for eliciting adaptive physiological and psychological responses, thereby facilitating the rehabilitation process [48]. For instance, Hoppeler et al. demonstrated that by meticulously controlling training load, improvements in muscle strength and endurance can be effectively achieved, thereby expediting the rehabilitation process [49]. However, it is crucial that load regulation is conducted with care; insufficient load may fail to provoke adequate physiological and psychological adaptations, while excessive load may result in overtraining syndrome. As noted by Lombardi et al., overtraining can lead to endocrine disruption, diminished immune function, and other complications, which can adversely affect recovery rates [50]. Consequently, the determination of training loads in rehabilitation should be tailored to individual differences, the nature of the injury, and the stage of rehabilitation to ensure that rehabilitation objectives are met without imposing unnecessary physical and psychological burdens.

The regulation of training load constitutes a complex and dynamic process that necessitates ongoing monitoring and evaluation of an athlete’s physiological and psychological conditions. Heart rate variability (HRV), recognized as a non-invasive monitoring tool, has been extensively utilized to assess exercise load and recovery status [51]. Variations in HRV can indicate an individual’s adaptation to and recovery from training loads, thereby offering a scientific foundation for the adjustment of training regimens [52]. Furthermore, the regulation of training load must also consider the selection of training methods and modalities, specifically addressing the questions of to train and to train. The stepwise load reduction training (SLRT) method has emerged as a novel approach, demonstrating efficacy in enhancing muscular strength, endurance, and cross-sectional area in novice individuals by reducing the load while increasing the number of repetitions during training [53]. This method integrates the benefits of both continuous and interval training, effectively enhancing the body's aerobic and anaerobic work capacity, and presents a promising strategy for rehabilitation training.

In the context of rehabilitation training, it is essential to consider both the long-term readiness (Preparation) and the current readiness (Readiness) of the individual when determining training loads. This necessitates the customization of training programs to accommodate the unique characteristics, training history, and current health status of each athlete [54,55]. By developing a sport-specific functional system, athletes can attain enhanced levels of readiness and competitiveness while incurring minimal adaptation costs. In summary, the precise regulation of training load represents a critical component of sports rehabilitation training, which must comprehensively account for the individual's physiological and psychological conditions, as well as the selection of appropriate training methodologies, to optimize rehabilitation outcomes.

4.2. Rate of recovery

The recovery rate serves as a critical metric for evaluating the efficacy of sports rehabilitation training, reflecting the speed at which athletes and patients revert to their pre-training condition following training sessions. This recovery process is influenced by a multitude of factors, including the intensity and frequency of the training load, as well as the physiological and psychological characteristics of the individual, alongside their nutritional and sleep status [56]. For instance, Alzakerin et al. observed that high-intensity training loads, if not adequately managed for recovery, may result in diminished athletic performance and an elevated risk of injury [57]. Furthermore, individual variances, such as age, gender, and genetic predispositions, significantly affect the recovery rate. The importance of nutrition and sleep, regarded as the two foundational pillars of recovery, should not be overlooked. Lynch et al. demonstrated in their research that sufficient sleep and appropriate nutritional supplementation can markedly enhance the recovery rate and reduce the recovery duration for athletes [58]. In practical applications, as evidenced by the study conducted by Soler-López et al., the recovery status can be more accurately evaluated through the monitoring of biochemical markers and the subjective experiences of athletes, thereby providing a scientific framework for the adjustment of training programs and the optimization of recovery strategies [59]. Consequently, the assessment and management of the recovery rate constitute an essential component of rehabilitation training, which is vital for ensuring training effectiveness and mitigating the risks associated with overtraining.

The investigation of recovery rates encompasses mechanisms operating at both the molecular and cellular levels. At the molecular level, researchers are examining the dynamics of protein synthesis and catabolism in muscle tissue following exercise, as well as the implications of these alterations for recovery rates [60,61]. For instance, a study examining the factors that influence recovery rates after fatigue induced by intermittent tonic contraction in atrophied flounder muscle revealed that the inhibition or facilitation of sarcoplasmic reticulum Ca^{2+} release significantly impacts recovery rates [62]. This finding indicates that the regulation of intracellular calcium ions within muscle cells may be a critical component of the recovery process. At the cellular level, researchers have concentrated on how cells detect and respond to mechanical forces, and how these responses influence cell growth, differentiation, and gene expression—factors that are essential in determining recovery rates.

Furthermore, the investigation of recovery rates encompasses various facets of biomechanics, including the mechanical behavior of biomolecules, the interactions between cells and the extracellular matrix, as well as the mechanical properties of tissues and organs [63,64]. Such studies enhance our comprehension of the mechanical mechanisms underlying the recovery process and establish a theoretical foundation for the advancement of novel rehabilitation techniques and strategies. For instance, by examining the biomechanical responses of muscles following mechanical stimulation, we can develop more effective rehabilitation training programs aimed at facilitating the rapid recovery of muscle function.

4.3. Relationship analysis

An extensive analysis of the relationship between training load and recovery rate has revealed a complex interaction between these two variables. Within a specific physiological range, a positive correlation exists; that is, a moderate increase in training load can stimulate adaptive changes within the organism, thereby enhancing the recovery rate [65]. This phenomenon has been corroborated by researchers such as Andrade, who demonstrated that moderate training loads facilitate muscle protein synthesis and cellular repair, which subsequently accelerates the recovery process [66]. However, this relationship is not limitless; when training load surpasses an individual's tolerance threshold, recovery rates may not only fail to improve but may also decline. As noted by Sansone et al., overtraining can result in hormonal imbalances, suppression of immune function, and the accumulation of muscle microdamage. The interplay of these physiological responses can ultimately hinder the recovery process and may even lead to excessive fatigue and injury [67]. Consequently, understanding the dynamic equilibrium between training load and recovery rate is essential for the development of a scientifically grounded rehabilitation training program. In practical applications, as suggested by Daly and other researchers, the monitoring of objective indicators such as heart rate variability, blood biochemical markers, and levels of muscle fatigue can assist therapists and coaches in accurately identifying the critical threshold of training load, thereby ensuring the safety and efficacy of rehabilitation training [68].

Numerous scholars, both domestically and internationally, have employed sports biomechanical models to quantify challenging-to-measure human parameters, such as muscle force. This research has facilitated an exploration of the impact of various movements on human muscle joints and rehabilitation mechanisms. The findings from these studies contribute to a comprehensive understanding of the effects of training loads and assist in the optimization of rehabilitation training programs [69]. Furthermore, individualized rehabilitation training programs demonstrate greater efficacy compared to generic rehabilitation programs, as they are specifically tailored to the unique circumstances and types of injuries of individual patients. This targeted approach is particularly beneficial when integrated with evidence-based care, leading to improved postoperative rehabilitation outcomes for elderly patients suffering from intertrochanteric femoral fractures.

5. Artificial intelligence-based load adjustment strategy for rehabilitation training

5.1. Personalized training load recommendation

In the context of the modernization of sports rehabilitation training, the incorporation of artificial intelligence technology has significantly transformed the precise regulation of training loads. The strategy of personalized training load recommendations, which is grounded in sophisticated AI algorithms such as deep learning, seeks to customize the optimal training load for each individual. This is achieved through comprehensive analysis and in-depth mining of athletic data and physiological indicators pertaining to athletes and patients [70]. A notable example of this approach is the machine learning-based model developed by Nguyen et al., which evaluates an individual's biomechanical parameters and physiological responses to deliver accurate, personalized load recommendations for rehabilitation training [71]. Furthermore, Wang and colleagues employed artificial intelligence technology to analyze electromyography data from a substantial cohort of athletes, successfully predicting the onset of muscle fatigue and subsequently adjusting training loads to mitigate the risk of sports injuries [72]. These instances exemplify the advancements and practical applications of personalized training load recommendations, which not only enhance the efficacy of rehabilitation training but also significantly diminish risks associated with the training process, thereby establishing a robust foundation for the personalized and intelligent evolution of sports rehabilitation training.

The advancement of personalized training load recommendation strategies has significantly benefited from the integration of artificial intelligence in the monitoring of training loads in sports. By employing sophisticated AI technologies, a scientific, precise, and sustainable methodology for monitoring and adjusting athletes' training loads can be established. Artificial intelligence systems are capable of processing and analyzing a wide array of data, including physiological, biochemical, psychological, and nutritional information collected from athletes during training sessions. This capability enables coaches to gain a comprehensive understanding of the training loads and recovery levels experienced by athletes [73]. Through the insights derived from AI data analysis, coaches can develop customized training plans that align with the individual abilities and needs of athletes, thereby enhancing training outcomes and competitive performance.

Sarirete posited that digital intelligent training methods are gaining prominence globally. Through a systematic literature analysis, he detailed the advancements in the application of machine learning algorithms within the realm of sports training, highlighting their distinctive features. Furthermore, he proposed a model framework for the application of machine learning in sports training, aiming to facilitate communication between the sports training community and the information science community. This initiative seeks to support the development of personalized training solutions driven by research in artificial intelligence technology [74].

5.2. Dynamic adjustment of training load

The strategy of dynamically adjusting training loads is predicated on the utilization of wearable devices and sensor technology to facilitate real-time monitoring of the physiological and psychological states of athletes and patients. This includes the assessment of critical indicators such as heart rate, blood pressure, and skin conductance. A significant advantage of this approach lies in its capacity to adapt training loads flexibly according to an individual's real-time recovery status, thereby minimizing the risk of injury while optimizing training effectiveness [75]. Fradkin et al. demonstrated a successful reduction in injury risk among their athletes and enhanced training efficiency through the implementation of a dynamic monitoring system. Similarly, Gallant et al. developed a model for dynamic training load adjustment that is based on heart rate and blood lactate thresholds, which automatically modulates training intensity in response to athletes' real-time physiological data, effectively preventing overtraining and enhancing athletic performance [76]. Furthermore, Belbasis et al. significantly improved the safety and efficacy of rehabilitation training by employing smart clothing to monitor muscle activity, enabling timely detection of muscle fatigue and subsequent adjustments to the training regimen [77]. Collectively, these studies indicate that the strategy of dynamically adjusting training loads not only enhances the individualization of rehabilitation training but also provides a robust framework for ensuring the long-term health of athletes and patients.

The strategy of dynamically adjusting training loads necessitates a comprehensive analysis and application of training data. Heart rate variability (HRV), recognized as a significant physiological indicator, serves to reflect the training status and recovery of athletes [78]. Yiiong and his colleagues demonstrated through a series of experiments that utilizing HRV as an indicator in athletes' endurance training can effectively enhance their cardiorespiratory adaptive capacity [79]. Specifically, when an athlete's HRV value is low, adjustments to the athlete's training regimen can be made by reducing training intensity; conversely, when the HRV value is high, improvements in endurance can be achieved by increasing training volume. Furthermore, the glucose content in saliva correlates with blood glucose levels, and saliva testing for glucose offers the advantage of convenient and flexible sampling. Takahiro Arakawa and his team at Tokyo Medical and Dental University proposed a glucose sensor that employs a cellulose acetate membrane as an interfering membrane, facilitating wireless real-time monitoring of glucose levels in saliva [80]. The advancement of these non-invasive monitoring techniques provides substantial data support and enhances the potential for the dynamic adjustment of training loads.

5.3. Optimization of training programs

The implementation of an optimized training program is designed to facilitate continuous and comprehensive enhancement of rehabilitation training by leveraging the extensive expertise of professionals alongside the advanced computational capabilities of artificial intelligence. This methodology not only markedly enhances training outcomes but also provides robust technical support for the standardization and customization of rehabilitation training. For instance, Russo et al. developed an AI-driven optimization system that autonomously modifies the training regimen based on the athlete's rehabilitation progress and feedback, thereby expediting the rehabilitation process and increasing training satisfaction [81]. Conversely, Yang and colleagues employed machine learning algorithms to analyze a substantial dataset of rehabilitation training, identifying a more effective muscle activation pattern. The revised training program, informed by these findings, demonstrated significant improvements in muscle strength and endurance [82]. These examples underscore the transformative impact of artificial intelligence technology in the optimization of rehabilitation training programs, shifting reliance from the subjective assessments of individual experts to the objective insights derived from big data analysis and algorithmic models. This transition facilitates the development of scientifically grounded and precise training regimens, heralding a revolutionary advancement in the domain of sports rehabilitation.

The integration of AI technology in the optimization of training programs encompasses a quantitative analysis of athletes' training loads. For instance, the utilization of Global Positioning System (GPS) technology in assessing the training load of soccer players establishes a scientific foundation for the monitoring and adjustment of these loads [83]. By quantifying training loads, coaches can effectively understand and identify the distribution characteristics and adaptive mechanisms associated with these loads. This understanding enables the scientific organization of training loads in accordance with game characteristics, cyclical patterns, and other relevant factors, thereby enhancing athletic performance during competitions. Furthermore, the application of AI technology in monitoring training loads is also evident in the assessment of athletes' heart rate variability (HRV). As a critical indicator of an athlete's training status, HRV monitoring can significantly enhance cardiorespiratory adaptability [84]. These findings underscore the pivotal role of AI technology in the optimization of training programs, facilitating scientific management and personalized adjustments of training loads through precise data analysis and predictive modeling.

6. Discussion and outlook

The integration of artificial intelligence technology in sports rehabilitation training demonstrates substantial advantages in optimizing training programs and evaluating training outcomes in real time. Through precise data analysis and predictive modeling, AI offers athletes and patients scientifically grounded training recommendations, highlighting a nonlinear threshold effect between training load and recovery rate. This observation underscores the necessity for coaches and rehabilitation specialists to closely monitor the physiological feedback of individuals during training sessions to mitigate the risks of overtraining and insufficient recovery. Furthermore, this study elucidates the pivotal role of individual differences in rehabilitation training, as significant variations exist in the responses and recovery rates to training loads among individuals of differing ages, genders, physical fitness levels, and injury histories. Consequently, it is imperative that the AI system incorporates these factors when recommending appropriate training loads.

The evolution of rehabilitation training systems is increasingly focusing on the integration of multidisciplinary technologies, which amalgamate insights from biomechanics, psychology, and nutrition to deliver comprehensive rehabilitation services for both athletes and patients. The utilization of deep learning and big data analytics is anticipated to enhance the precision of training load recommendations and the reliability of predictive models. Furthermore, advancements in smart wearable devices are expected to facilitate more efficient data collection for rehabilitation training, enabling real-time monitoring and precise adjustments of training loads. Interdisciplinary research will play a crucial role in addressing complex challenges in rehabilitation training, such as optimizing rehabilitation programs through the application of neuroplasticity principles. Additionally, the establishment of a long-term tracking mechanism to assess the enduring effects of rehabilitation training will aid in validating the long-term benefits of AI-assisted rehabilitation interventions. Through persistent research and practical application, there is a strong rationale to believe that AI-driven sports rehabilitation training will evolve to become more efficient, personalized, and intelligent, thereby providing substantial support for athletes and patients in their recovery journeys.

It is important to highlight that there are still several challenges associated with the use of AI technology. AI systems depend on vast amounts of personal health data, including biomechanical data, physiological indicators, and rehabilitation progress. The collection, storage, and utilization of this data raise significant privacy concerns, particularly when it is shared and used across different organizations. As the volume of data increases, so does the risk of data breaches and misuse. Ensuring data security and compliance is a crucial prerequisite for the effective application of AI in sports rehabilitation. Additionally, rehabilitation professionals must receive adequate training to effectively utilize AI tools. Unfortunately, many professionals currently lack the necessary skills and knowledge, which hinders the widespread adoption of AI technologies. While the short-term effects of AI in sports rehabilitation have been preliminarily validated, its long-term effects require further investigation. Establishing a long-term tracking mechanism to evaluate the enduring benefits of rehabilitation interventions is a vital direction for future research.

7. Conclusion

This review uniquely integrates artificial intelligence with training load-recovery dynamics. By exploring how AI can be utilized to optimize the relationship between training load and recovery rate, it offers a fresh perspective on the practical application of AI techniques to enhance rehabilitation outcomes. By systematically reviewing existing research findings, we have gained insights into how AI can enhance the precision of training load recommendations in a data-driven manner and how dynamic adjustments can maximize recovery outcomes. Future research endeavors will aim to further develop the theoretical framework of this domain and investigate the broader applications of AI technology in sports rehabilitation training. We anticipate that through interdisciplinary collaboration and innovation, more accurate and personalized rehabilitation training programs can be established, thereby offering robust scientific support for the expedited recovery of athletes and patients, and ultimately fostering the ongoing advancement of the sports rehabilitation field.

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