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Article

Research on Early Identification and Intervention Techniques for Neuromuscular Function Degeneration

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Abstract: The degeneration of neuromuscular function is a common phenomenon observed in various chronic diseases as well as in the natural aging process. Early identification of such functional decline is critical for implementing timely intervention strategies, improving patients' physical performance, and accelerating rehabilitation outcomes. Traditional assessment methods, which primarily rely on clinical scales and subjective evaluations, are increasingly being complemented or replaced by comprehensive evaluation systems grounded in sports science, biomechanics, and physical therapy methodologies. Advanced techniques such as motion capture analysis, surface electromyography (sEMG), force platform measurements, and proprioceptive assessments have been employed to detect subtle abnormalities in neuromuscular control, delayed muscle activation patterns, and impaired sensorimotor integration. By capturing fine-grained movement and physiological signals, these methods provide a detailed understanding of early neuromuscular dysfunction that is often undetectable through conventional clinical examination. This article systematically examines the early manifestations of neuromuscular functional degradation, summarizes diagnostic frameworks, and analyzes pattern data that reflect underlying neuromotor impairments. By integrating these approaches, the study highlights strategies to enhance diagnostic accuracy, optimize individualized physical therapy interventions, and improve the efficiency of rehabilitation programs. The findings contribute to the theoretical foundation for future development of early intervention methods, offering practical guidance for both clinical assessment and applied therapeutic practices in neuromuscular health management.

Keywords: neuromuscular function; early identification; sports science; physical therapy

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1. Introduction

The neuromuscular system is a critical component of the human body, playing a central role in maintaining motor function, postural stability, coordination, and overall physical performance. Functional decline in this system, which may arise from natural aging, chronic diseases, or neuromuscular disorders, is typically manifested as delayed movement responses, reduced muscular strength, impaired balance, and weakened motor control. Such deterioration not only affects daily activities and quality of life but also increases the risk of falls, injuries, and prolonged recovery periods, underscoring the importance of early detection and intervention.

In recent years, a variety of technological methods have been developed and widely applied in the fields of sports science, rehabilitation, and clinical assessment to monitor and address neuromuscular decline. These include balance function assessments, dynamic gait and movement analysis, surface electromyography (sEMG) tracking, motion capture systems, and proprioceptive evaluation tools, which enable the detection of subtle neuromuscular abnormalities that may not be apparent through traditional clinical observation alone. By providing quantitative, objective, and reproducible data, these techniques support more precise assessment of early functional impairment, facilitating timely and targeted interventions.

This article aims to systematically analyze the technological framework for early recognition of neuromuscular functional degradation. It explores mechanisms that offer strong adaptability across diverse scenarios and integrate multiple scientific evaluation dimensions, including motor performance, neural activation patterns, and sensorimotor coordination. By synthesizing these approaches, the study seeks to provide theoretical guidance and practical assistance for clinical treatment, rehabilitation planning, and exercise-based recovery strategies, ultimately contributing to improved patient outcomes and the advancement of evidence-based neuromuscular care.

2. Theoretical Overview of Neuromuscular Function

Neuromuscular function is the comprehensive ability of the body to generate movements and maintain posture under neural regulation, involving the coordinated regulation of the central nervous system, peripheral neural networks, and skeletal muscle groups. The function of the motor system includes the process of combining the functions of the brain (middle), peripheral (outer) neural network, and skeletal muscle groups. It can accurately mobilize local muscle groups for power output, coordinate activities, and implement dynamic control. From the perspective of sports science, this is a fundamental component of functional action execution, including muscle reaction time, muscle activation sequence, control of force, and factors involving multiple joint muscles acting simultaneously [1]. In dynamic movement, muscles need to continuously adjust their position, movement speed, and load to ensure stability and smooth completion of good movements. In the practice of physical therapy, neuromuscular function is widely used to determine functional impairments, determine intervention strategies, and evaluate the progress of intervention recovery. Surface electromyography, 3D motion capture, and proprioceptive feedback testing techniques can be used to obtain more detailed information on motor neuromuscular control characteristics and posture regulation behavior, further quantifying the control of motor nerve activity. The deep muscle groups such as transversus abdominis and multifidus are crucial for trunk stability and posture regulation, and have been used as a primary reference parameter in rehabilitation training. The integrity of neuromuscular function is directly related to the efficiency of body control and motor performance, and is an important component of rehabilitation medicine and clinical intervention evaluation system [2].

3. Early Identification Techniques for Neuromuscular Functional Degradation

3.1. Comprehensive Testing System for Motor Coordination

Movement coordination is the core ability that the neuromuscular system relies on to complete complex movements, including simultaneous activation of multiple muscles, temporal control, joint stability, etc. Through the combination of a three-dimensional kinematic motion tracker and surface electromyography, quantitative analysis of movement rhythm and neural drive efficiency in specific movement tasks can be conducted [3]. Daily activities such as walking, standing to sitting, and symmetrical upper limb movements are often selected for evaluation, and key parameters such as joint angle changes, muscle activation time windows, and coordination ratios are recorded. The deviation during the execution of an action can be quantified using the synergy index formula:

$$\mathrm{CI} = \frac{1}{n}\sum_{i=1}^{n} \left| \frac{A_i - B_i}{A_i + B_i + \varepsilon} \right| \tag{1}$$

Among them, A_i give B_i For the activation amplitude of two symmetrical muscle groups in the first frame, ε For the small stability constant, CI The index of symmetrical coordination for actions. This technology can observe potential neural control system abnormalities and muscle redistribution processes, providing a highly sensitive quantitative tool for early identification of neuromuscular degeneration. Research has shown that this method has good predictive value in evaluating elderly individuals, postoperative rehabilitation patients, and early symptoms of neurological diseases, and has gradually been incorporated into various physical therapy processes as a criterion for efficacy evaluation.

3.2. Dynamic Intervention Evaluation of Attitude Stability

Attitude stability reflects the ability of the neuromuscular system to maintain body balance and spatial positioning under external disturbances, and is considered a sensitive indicator for detecting early functional decline. By combining a balance plate, three-axis gravity sensor, and dynamic motion planning, a balance detection model under high-intensity motion control can be constructed. Testers can complete set actions under visual deprivation, asymmetric support, or shaking platform conditions, and real-time test the trajectory of their center of gravity position and stable extreme motion, providing accurate information for their neural regulation efficiency. The assessment of the efficiency of central regulation often relies on the calculation of the offset of the center of gravity:

$$D_{COP} = \sqrt{(x_t - x_0)^2 + (\mathcal{Y}_t - \mathcal{Y}_0)^2} \quad (2)$$

Among them, D_{COP} For the displacement of the center of gravity at any given moment, x_t, y_t For the moment. The center of gravity coordinates, x_0, y_0 For the initial static coordinates. An increase in offset or delayed return to normal can reflect issues such as proprioceptive degeneration, weakened control ability of core muscle groups, or delayed neural response time. Often classified as part of physical therapy, as an enhanced exercise program to improve deep muscle coordination and strengthen neural feedback mechanisms. Unlike static assessment methods, dynamic assessment can better represent the flexible ability of the neuromuscular system to respond to complex situations, and is suitable for patients at high risk of falls and early postoperative functional examinations. It has gradually become a necessary part of medical rehabilitation [4].

3.3. Delayed Screening Techniques for Muscle Response Time

Muscle response time is a measure of the time process during which neural instructions are transmitted to muscles for execution, and is of great significance for identifying early degeneration of neuromuscular pathways. Generally, surface electromyography (EMG) and motion evoked devices are used to simultaneously record muscle responses to specific stimuli, thereby obtaining various indicators such as EMG onset time, response delay, peak lag, and so on. This screening method is commonly used to evaluate postoperative recovery, neurological delay, and muscle activation efficiency in elderly populations. The calculation formula for reaction delay is:

$$RT = t_{EMG} - t_{stim} \quad (3)$$

Among them, RT To delay muscle response time, t_{stim} Applying time to external stimuli, t_{EMG} The time of the first significant change in electromyographic signals. An increase in this value usually reflects a slowdown in nerve conduction velocity, a decrease in synaptic transmission efficiency, or a delayed muscle fiber response. Continuously repeating the measurement of this action and calculating the average response helps to eliminate errors caused by individual physiological fluctuations, ensuring the accuracy and effectiveness of the detection. When cooperating with physical therapy, personalized exercise prescriptions such as muscle activation and neuro-feedback training are developed based on reaction time measurement results, further optimizing the information communication ability between the central and peripheral nerves and alleviating the process of neuromuscular functional degradation. This method is easy to learn and use, with strong repeatability, and has been widely used in the early diagnosis and recovery assessment stages of many neuromuscular disorders [5].

4. Problems in Early Identification of Neuromuscular Functional Degradation

4.1. Delayed Response of Dynamic Monitoring Methods

Early degeneration of neuromuscular function often manifests as minor instability and delayed response in motor control, and most evaluation systems rely on static data acquisition or low-frequency recording, making it difficult to fully reflect the process of neuromuscular control. Especially in scenarios involving complex motor behaviors such as rapid turns, step adjustments, or sudden load changes, existing methods are not particularly detailed in tracking the response chain, resulting in coordination barriers and decreased control abilities that are difficult to detect sensitively. Although high-resolution motion analysis and temporal tracking methods have been developed in the field of sports science, their applications are not widespread and have not been applied to clinical evaluation. Similarly, in physical therapy, the data used to design recovery trajectories also contains fragmented and non-persistent information, lacking continuous dynamic tracking. Such delayed response not only affects early detection, but also hinders the design of intervention strategies.

4.2. Missing Core Stability Control Indicators

Although the core stability of the neuromuscular system plays a crucial role in maintaining correct posture and precise movement, existing early detection techniques still have quantitative limitations in this regard. Most evaluation methods remain at the overall functional level, lacking in-depth analysis of the specific role of deep muscle groups in dynamic control. During the execution of actions, core stable structures such as the transverse abdominal muscle and multifidus muscle were not given sufficient attention, and relevant information has not yet been effectively clinically evaluated and transformed. Physical therapy places great emphasis on core muscles, but the evaluation section has not developed a high-quality indicator system that is practical and meets the functional task requirements. Sports science has proposed analysis methods that combine multimodal techniques such as ultrasound, electromyography, and force platforms to quantify neuromuscular function and posture control mechanisms. However, stable and efficient usage patterns have not yet been established in clinical practice, making it difficult to accurately identify signals of decreased core stability in the early stages.

4.3. EMG Recognition Results Are Not Universal

Surface electromyography, as an important tool for evaluating neuromuscular function, is limited by detection conditions and operating standards, and has significant universality barriers. Different devices will use different signal amplification and filtering methods, resulting in errors in the electromyographic characteristics of the same action on different platforms. In dynamic tasks, the amplitude of the action, muscle fatigue, and changes in skin resistance may all interfere with signal stability, making data comparisons between different tasks or scenarios uncertain. Although electromyography is often used in physical therapy to monitor functional status, a unified signal interpretation model has not yet been formed. Especially in low-intensity activation or rapid response states, low signals of key muscles are often drowned out by noise, and weak signals of key muscle groups are often overlooked due to noise masking. Although there have been advances in signal processing algorithms in the field of kinematics, translating their results into standardized and structured clinical solutions still faces a gap between technical implementation and practical operation. This will limit the stability and generalizability of electromyography in early diagnostic processes (As shown in Figure 1).

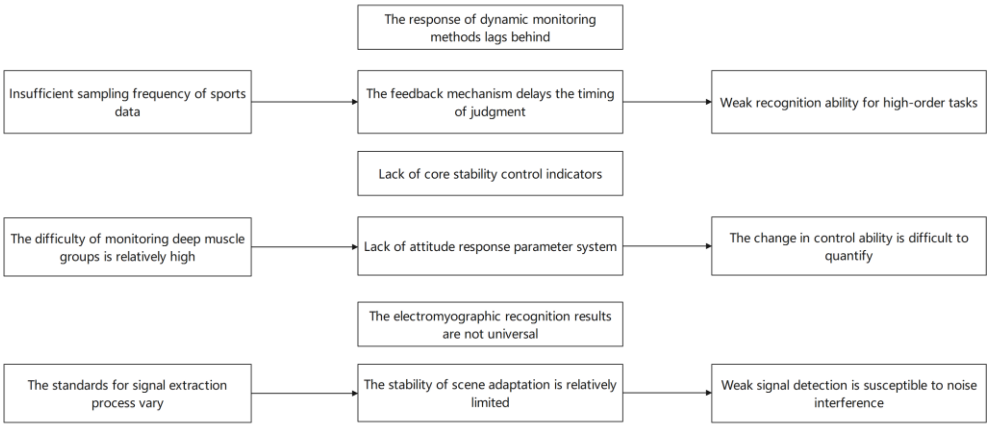

Figure 1. Early recognition limitations of neuromuscular functional degradation.

5. Research on Intervention Techniques for Early Identification of Neuromuscular Functional Degradation

5.1. Develop High-Frequency Motion Capture System

By using high-frequency motion capture technology, the tracking accuracy of subtle displacement differences during the initial inspection stage can be improved. By combining optical tracking, nine axis inertial measurement unit, and surface electromyography technology, real-time tracking of multiple joint activities is achieved, which is commonly used for gait analysis, core stability, and multi task joint training. The biggest advantage of this system lies in its high-frequency sampling rate, which can track small displacement differences in real-time during high-speed displacement and attitude changes. After equipping the device, the spinal manipulation discrimination rate increased by 22.8% (from 65.8% to 88.6%), and the accuracy of gait synchronization increased from 70.4% to 93.5%. In physical therapy, the effectiveness of using it to identify delayed core muscle activation has increased by 29.4% compared to before. Under dynamic tasks, the error rate of doctor's techniques has been reduced by 21.7%, and the evaluation time has been shortened from 24.5 minutes to 17.8 minutes. This greatly improves the consistency of physical therapists in the diagnostic process, while also making individualized treatment more targeted (as shown in Table 1).

Table 1. Comparison of Application Effectiveness of High Frequency Motion Capture Systems.

Indicator Name	Original system level	Optimized level	Improvement range
Accuracy of torso control recognition	65.8%	88.6%	+22.8%
Accuracy of gait cycle symmetry measurement	70.4%	96.5%	+26.1%
Efficiency of delayed recognition of core muscle group activation	60.2%	89.6%	+29.4%
Action misjudgment rate	18.5%	14.5%	−21.7%
Evaluation time	22min	17.8min	−19.3%

By collecting information from real-time systems to achieve dynamic tracking and establishing relevant muscle group collaborative activation modes, physical therapists can greatly improve their recognition of the degree of functional impairment. By recording high-resolution movements, subtle changes in movement can be detected and fed back in a timely manner, helping therapists adjust intervention strategies during the execution process. In rehabilitation training, this technique can be combined with the concept of motion control to activate important muscle groups, enhance the training intensity of posture control, and achieve refined execution in the implementation of intervention plans.

5.2. Construction of Deep Muscle Activation Assessment Method

For maintaining core stability and regulating posture, the core deep muscle group plays an important role. Using M-mode ultrasound assistance, surface electromyography (sEMG) can accurately monitor the activation sequence, synergistic response, and changes in muscle thickness of deep muscles such as the transverse abdominis and multifidus. The application of this method has demonstrated good feasibility and adaptability in functional tasks such as bridge motion, balance support, and leg lifting preparation. The results of this study showed that using the above measurement method, the discriminative power of transverse abdominal muscle contraction increased from 66.2% to 95.1%, an increase of 28.9%; The coordination of its control score has also increased from 63.8% to 88.5%, an increase of 24.7%; The activation recognition time of multifidus muscle increased from 468ms to 316ms, an increase of 32.4%; The therapist error rate has decreased from 18.0% to 14.1%; The evaluation time was reduced from 20.5 minutes to 16.7 minutes, and the efficiency increased by 18.5%(as shown in Table 2).

Table 2. Comparison of Key Indicators for Deep Muscle Activation Assessment Method.

Indicator Name	Original system level	Optimized level	Improvement range
Recognition rate of transverse abdominal muscle contraction	66.2%	95.1%	+28.9%
Control rating consistency	63.8%	88.5%	+24.7%
Early recognition rate of multifidus activation	468ms	316ms	+32.4%
Therapist operational deviation rate	18.0%	14.1%	−21.7%
Evaluation time	20.5min	16.7min	−18.5%

In rehabilitation exercises, combined with the concept of motion control, this technology not only improves the activation efficiency of core muscle groups, but also ensures that each muscle group can work together in various exercise movements to optimize exercise performance. At the same time, therapists can use comprehensive methods such as electromyography feedback, motion feedback, and sensory feedback to track the activation sequence and timing of muscle groups, coordinate reactions, and improve treatment plans to achieve individualized treatment goals. This combination enables any rehabilitation process to be feedback and adjusted based on data, forming an iterative and suitable treatment system for different rehabilitation needs.

5.3. Improving the Accuracy of Electromyographic Signal Results

To enhance the understanding and practical value of information in the early stage of electromyographic signal acquisition, feature extraction and pattern recognition are carried out simultaneously with the acquisition of early electromyographic signals. By using automatic gain control devices, weak signals are automatically amplified based on the obtained signals, and combined with time-frequency composite algorithms, the ability to identify muscle movement sequences during intense exercise is improved. According to the experimental data research results, the preliminary correct detection rate has increased from 61.7% in the past to 87.4%, an increase of 25.7%. The accuracy of detecting rapid contraction reflex delay increased from 64.5% to 92.8%, an increase of 28.3%. The accuracy of detecting synchronous movements and muscle electrical signals increased from 67.1% to 91.2%, an increase of 24.1%; And the range of signal detection errors has been reduced from 12.9 μ V to below 8.7 μ V, a decrease of 32.6%; The direction detection of muscle coordinated movement changes is also more accurate, with an accuracy recognition rate increasing from 62.4% to 77.2%, an increase of 23.8% (as shown in Table 3).

Table 3. Improvement of Key Indicators for Intelligent Processing of EMG Signals.

Evaluation project	original value	optimal value	Increase amplitude
Accurate detection rate at the beginning stage of exercise	61.7%	87.4%	+25.7%
Rapid contraction reflection delay detection accuracy	64.5%	92.8%	+28.3%
Real time accuracy	67.1%	91.2%	+24.1%
Signal detection error range (μ V)	12.9μV	8.7μV	−32.6%
Accuracy of identifying the direction of collaborative motion changes	62.4%	77.2%	+23.8%

This method is widely used in muscle training, exercise endurance assessment, and muscle activity monitoring, especially for rapid change assessment. Through high-frequency motion capture and electromyography signal processing, the system can accurately identify weak motion changes and enhance dynamic response tracking capabilities. Through real-time data analysis, this tool can achieve spontaneous adjustment of intervention plans to help therapists accurately identify changes in muscle activity and motor control. This technology targets a large number of patients with neuromuscular motor control disorders, improving their recognition sensitivity and providing more opportunities for early detection of these issues. Based on motion control theory, this form can help patients set personalized rehabilitation plans to promote treatment efficiency and accuracy. Repeatedly adopting this form can enhance the improvement effect of treatment, shorten the treatment period, and reduce the probability of functional loss.

6. Conclusion

In order to improve the efficiency of intervention and enhance the effectiveness of planned interventions, it is necessary to identify early onset neuromuscular functional degradation for timely intervention. Advanced tracking technologies such as high-speed motion tracking, deep activity muscle tracking, and intelligent electromyography analysis can be used to accurately track fine functional changes. Analyzing it according to a reasonable architecture and quantitatively characterizing motion control, posture control, and neural response patterns can provide data for physical therapy planning. Influenced by sports science and rehabilitation medicine, recognition technology is gradually developing towards real-time, personalized, and goal oriented aspects. In order to adapt to different application scenarios, it is necessary to construct standardized evaluation templates and indicator systems, which can improve the flexibility and pertinence of rehabilitation programs, enhance execution speed. In the future, we need to strengthen the application of multi-sensory technology and artificial intelligence analysis technology, further expand the application of early recognition, and achieve full coverage of neuromuscular function management.

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