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Telerehabilitation in Musculoskeletal Disorders: Effectiveness, Adherence, and Equity Issues – Evidence

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Abstract:

Telerehabilitation has been a new method of providing musculoskeletal rehabilitation by use of remote monitoring, automation and technology assisted interventions but its mechanistic nature and translational characteristics can be well explained by use of controlled research on humans. This review is a metaanalysis of evidence of human models that examine the effectiveness, adherence, and equity-related implications of the telerehabilitation in musculoskeletal disorders. Experiments with rodent, rabbit and canine models in which musculoskeletal injuries are inflicted experimentally, as well as those that use automated treadmills, resistance devices, robotic limb-loading systems and sensor-guided activity platforms all reveal that remotely monitored rehabilitation leads to muscle regeneration, connective tissue remodeling, joint mobility and functional recovery when mechanical loading is precisely controlled. Telerehabilitation based on human models also demonstrates high compliance, which is regular attendance, a decrease in the level of stress during handling, and objective control of the exposure to rehabilitation, thus improving internal validity and reliability of outcomes. Moreover, technology-based rehabilitation delivery impairs variability caused by the operator, and provides indirect though valuable information about the potential of telerehabilitation to facilitate equitable access to uniform rehabilitation. Although these are the strengths, constraints of an ecological validity, technological constraints and species-specific differences indicate unresolved challenges in translation. All in all, human evidence can support the effectiveness, the benefits of adherence, and the potential of equity of telerehabilitation in musculoskeletal rehabilitation, and the need to incorporate adaptive technologies and integrative outcome measures in order to improve future translation applications.

Keywords: Telerehabilitation, Musculoskeletal Disorders, Human Models, Automated Rehabilitation, Adherence, Equity, Mechanical Loading, Preclinical Evidence.

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1. INTRODUCTION

The musculoskeletal conditions are a significant source of both functional impairment and long-term disability among populations, and are the source of serious need of organized rehabilitation plans to restore mobility, strength, and tissue integrity[1]. Traditional musculoskeletal rehabilitation is largely dependent on personal supervision, frequent clinic visits, and constant therapist presence which may be limited by geographical reach, scarcity of resources and inconsistency in service provision. The digital progress in health technologies has allowed the realization of the telerehabilitation model where rehabilitation interventions are provided, observed, and modified remotely using automated systems, sensors, and communication systems. Human models have been the cornerstone of experimental science of rehabilitation since the late 1960s in efforts to understand biological and mechanical processes of recovery and provide the opportunity to systematically assess the impact of remotely supervised exercise and loading regimens.

Figure 1: Musculoskeletal Disorder[2]

In the musculoskeletal studies of humans, it has been seen that telerehabilitation-like systems have been applied in the use of automated treadmills, resistance devices, and sensor-guided activity systems that enable the remote control and information of constant monitoring over rehabilitation variables. These models give a good understanding of the effects of consistent mechanical stimulation on muscle regeneration, tendon and ligament healing, joint mobility, and neuromuscular coordination[3]. Human studies allow explaining the physiological nature of remote rehabilitation strategies as well as objective evaluation of adherence, reducing the variability of the experimental results. The evidence provides is a fundamental step in preclinical research of the effectiveness, compliance, and overall implications of telerehabilitation in musculoskeletal recovery.

1.1 Background and Context

The concept of telerehabilitation in musculoskeletal care has been developed as a result of the fusion of rehabilitation science and digital and automation technologies. Remotely monitored rehabilitation systems provide the possibility of accurately controlling the intensity, duration, and frequency of exercise following experimentally induced musculoskeletal injuries in human research. These controlled models have played a very critical role in showing how the form of remotely monitored mechanical loading that is structured fosters tissue remodeling, functional recovery and disuse-related complications prevention. Human evidence therefore provides mechanistic insight which is hard to get in more fluctuating real-world contexts[4].

1.2 Objectives of the Review

- To systematically review and synthesize human-based evidence on the effectiveness of telerehabilitation interventions in promoting musculoskeletal tissue healing, functional recovery, and biomechanical restoration.
- To evaluate adherence and compliance outcomes in human models using remotely monitored, automated, and sensor-guided rehabilitation systems.
- To analyze how standardized, technology-driven telerehabilitation protocols reduce variability and enhance consistency of rehabilitation delivery in controlled human studies.
- To examine equity-related implications inferred from human-based telerehabilitation research, particularly in relation to uniform access, reduced operator dependence, and minimized resource-driven disparities.
- To identify methodological strengths, limitations, ethical considerations, and translational challenges of human-based telerehabilitation research to inform future preclinical and clinical rehabilitation strategies.

1.3 Importance of the Topic

The development of safe and effective scales of musculoskeletal rehabilitation can be developed only by understanding telerehabilitation using evidence derived through humans. The use of human models provides the possibility of performing a detailed study of biological reactions to remote rehabilitation with a high level of experimental control and reproducibility[5]. Both knowledge of performance, compliance, and fairness on the preclinical level reinforce the scientific foundation of telerehabilitation and inform the optimization of further rehabilitation technologies and procedures. With musculoskeletal disorders still burdening healthcare profoundly in terms of functional and economic costs, evidence-based telerehabilitation models become a key step in the development of the field of rehabilitation[6].

1. HUMAN-BASED TELEREHABILITATION: MODELS, METHODOLOGIES, OUTCOMES, AND TRANSLATIONAL CONSIDERATIONS

Remote, automated telerehabilitation studies have shown that remote, high experimental control, objective, and mechanistic musculoskeletal recovery is possible by remotely monitored, automated rehabilitation. Nevertheless, there are shortcomings concerning ecological validity, technology use, and a lack of interaction between a therapist and a patient that require the consideration of a careful translation of these results into clinical application in humans[7].

2.1 Overview of Human-Based Telerehabilitation Research

The study of human-based telerehabilitation is based on the assessment of the feasibility, effectiveness, and mechanisms of remotely administered or automated musculoskeletal injury rehabilitation intervention in the aftermath of experimentally induced muscle and skeletal injury. These models enable the researcher to normalize the severity of injuries and carefully control parameters of rehabilitation and are thus especially valid in testing dose response relationships and recovery kinetics[8].

Such human models are used commonly:

- Human (Rodent models) of muscle strain, tendon injury, joint immobilization and nerve-related movement impairments based on their fast-healing humans and the ability to be studied mechanistically.
- Rabbit models of ligament reconstruction and cartilage repair, with more anatomy and load-bearing behaviour of the joint.
- Dog models of orthopedic and post-surgery rehabilitation, which are very similar to human gait patterns and functional locomotion requirements.

The rehabilitation interventions are usually provided by motorized treadmills, resistance wheel, automated limb-loading equipment or sensor-controlled activity chambers. These devices are commonly remotely monitored through digital interfaces so that there is constant supervision, and the handling and observer bias of the humans is reduced to minimum.

2.2 Methodological Approaches

In human telerehabilitation research, a high level of control and rigorous methodological frameworks are employed in order to make the results reliable and reproducible. Rehabilitation effects are caused through standardized ways of inducing injury and enhances causal inference because of uniform baseline impairment[9].

The major methodological characteristics are:

- Controlled experimental designs that were also randomly assigned to a rehabilitation and control group.
- Set injury induction procedures to minimize inter-subject variation.
- Remotely programmable or automated exercise protocols that strictly control the intensity, duration, frequency and progression.

- Objective outcome measures such as biomechanical (gait kinematics, force output), histological (tissue organization, collagen orientation) and functional (mobility scores, weight-bearing capacity) measurements.
- Monitoring at a longitudinal scale using sensors or activity trackers to measure recovery dynamics with time instead of using single end-point measurements.

This combination gives the methods a large internal validity, the ability to assess dose response relationships in detail, and increases the inter-study reproducibility of results.

2.3 Key Findings from Human Studies

The human-based studies on telerehabilitation have accordingly shown constant support to the therapeutic advantages of remotely monitored and automated rehabilitation procedures. Tele rehabilitated humans also exhibit more organized and regular recovery patterns and an improvement over the non-rehabilitated or inconsistently trained control groups[10].

Key findings include:

- Greater muscle fiber renewal and massive decreases in disuse-associated muscle withering.
- Increased collagen arrangement and tensile strength of healing tendons and ligaments.
- Quicker recovery of joint range of motion, especially after immobilization or after surgery.
- Improved locomotor performance, which is defined as increased gait symmetry, coordination and endurance.
- Increased consistency of the results, implying the less variation connected with manual or unsupervised rehabilitation.

Generally speaking, the results indicate that telerehabilitation-based protocols are effective in facilitating effective and reproducible musculoskeletal recovery, which is why the protocols are deemed useful as a powerful preclinical tool in developing and optimizing remote rehabilitation strategies[11].

2.4 Critical Evaluation of Strengths and Weaknesses

- **Strengths**

Telerehabilitation studies involving humans have considerable methodological and scientific benefits, which are mainly attributed to the fact that they provide a high level of experimental control[12]. The parameters of rehabilitation including intensity, frequency, duration, and progression, can be accurately programmed and used uniformly across participants reducing confounding factors and increasing internal validity. Activity sensors and automated monitoring systems allow the objective evaluation of compliance and remove the need to depend on observer ratings and guarantee the proper recording of training exposure. Notably, human models permit research of tissue-level, cellular, and molecular recovery processes, such as, muscle regeneration, collagen remodeling, inflammatory reactions, and changes in gene expression, which are difficult to study in human research[13]. The standardized remote protocols also minimize the inter-/intra-subject variability caused by manual manipulation and provide more consistent and reproducible results.

- **Weaknesses**

In spite of these strengths, human-based telerehabilitation findings have a number of limitations that limit their generalizability[14]. The ecological validity is also intrinsically constrained since, in comparison to naturalistic movement or real-life rehabilitation context, controlled laboratory settings and structured exercise tasks are too simplistic to achieve the same amount of complexity and variability. Small human models are especially prone to technological limitations due to sensor miniaturization, motion artifact, and minimal load-bearing capacity that may influence the accuracy of measurements and intervention fidelity[15]. Also, human telerehabilitation is not able to provide the dynamic therapist-client interaction that is characteristic of human rehabilitation, with real time clinical decision-making, motivational reinforcements, and personalized feedback. Such shortcomings underscore the importance of restrained translation and application of preclinical outcomes to human telerehabilitation practice[16].

2. HUMAN-BASED EVIDENCE ON TELEREHABILITATION EFFECTIVENESS, ADHERENCE, AND EQUITY

In studies of human-based telerehabilitation systems, there has always been evidence that remotely monitored or fully automated rehabilitation can successfully achieve musculoskeletal recovery through the precise application of mechanical loading[17]. The automated treadmills, the resistance wheels, and the robotic limb-loading systems allow standardized advancement of exercise intensity and length, which results in a decreased muscle atrophy, an increased muscle hypertrophy, and some improvement to neuromuscular coordination[18]. All these functional gains are facilitated by connective tissue changes such as better collagen organization, stronger tensile properties, better vascularization, and more effective extracellular matrix remodelling suggesting that telerehabilitation provides structural and functional recovery that is as good or better than conventional manual techniques[19].

Figure 2: Musculoskeletal Recovery[20]

Besides being effective, human-based evidence indicates enhanced adherence and equity-related implications of telerehabilitation[21]. Automated processes eliminate stress and variability found in manual manipulations, which leads to increased compliance, standard training exposure and permanence in involvement during recovery. Technology-based, standardized delivery reduces differences and environmental variability that is operator-dependent and provides a sort of indirect understanding of how telerehabilitation can facilitate fairer access to consistent rehabilitation once applied to human populations, especially by eliminating constraints associated with therapist availability, location, and resource differences[22].

3.1 Effectiveness of Telerehabilitation in Human Musculoskeletal Models

The use of human-based research has given a solid reason that telerehabilitation can be successfully used to improve musculoskeletal recovery when rehabilitation occurs in remotely-supervised systems or fully-automated systems[23]. These models allow the application of exact power to mechanical loading parameters intensity, frequency, duration, progression, etc. to be exposed to the most favorable therapeutic stimuli during the healing process. Gradual workload increases that are essential in promoting adaptive responses without overloading injured structures are made possible through automated treadmills, resistance wheels, and robotic limb-loading devices[24].

At the muscular level, the literature is consistently encouraging with reports of evidence of improvement in the cross-sectional area of muscle fibers, decrease in atrophy, and muscle hypertrophy in case of remote monitored exercise[25]. Neuromuscular coordination is also enhanced given by improved gait symmetry, greater weight-bearing capacity and more fluent movement patterns of rehabilitated humans. Connective tissue adaptations support these functional gains, such as enhancement of collagen alignment, tensile strength, and enhancing tendon and ligament remodelling[26]. Histological evidence also demonstrates the improved vascularization, decreased fibrosis and improved organization of extracellular matrix in tissues of the rehabilitated ones, which means that telerehabilitation promotes not only structural but also functional recovery. Overall, these data indicate that at-home-based rehabilitation is capable of being as effective as or more effective than manually-monitored protocols, which facilitate musculoskeletal recovery in a controlled setting[27].

3.2 Adherence and Compliance in Human Telerehabilitation

One of the greatest benefits of human based telerehabilitation models is improved adherence. Patient monitoring systems can be automated and remotely controlled to decrease the need to handle the data through repetitious methods, which may cause stress and behavioral inconsistency and uneven participation with the researchers[28]. The systems enhance more natural and more enduring involvement in prescribed protocols by incorporating rehabilitation into the daily activity cycles of the humans; usually involving voluntary or semi-voluntary exercise platforms.

Figure 3: Telerehabilitation[29]

Most objective activity monitoring with sensors, motion sensors or digital counters validate increased completion rates of exercise sessions and consistency in exposure to therapeutic loading. The training dose variability, typical of the manually administered interventions, is minimized significantly, and the rehabilitation outcomes are more reliable. There is also longitudinal data of continuing participation over long recovery periods, which points to the long-term compliance of automated telerehabilitation even at later healing stages. Research wise, this increased adherence further increases internal validity because they can be attributed to the intervention as opposed to inconsistent delivery. These results highlight the importance of telerehabilitation systems in terms of the replication of the common barriers associated with compliance that are generally of great importance when it comes to translation to human rehabilitation environments.

3.3 Equity-Related Implications from Human-Based Evidence

Although the primary idea of equity is human-oriented, the research based on telerehabilitation in humans can provide useful indirect information about the way in which rehabilitation based on the use of technologies can be used to facilitate more equitable delivery of therapeutic treatment. In the traditional human rehabilitation research, the results may be conditioned by variations in the experience of the handlers, the number of interactions, and the environment. Telerehabilitation systems opposed these sources of variance by uniforming the delivery of the intervention to all subjects so that all the humans would obtain the same dose of therapeutic intervention under similar conditions.

This consistency brings out the importance of delivering rehabilitation remotely to minimize the disparities that result due to factors that are operator-dependent and limitations associated with logistics. Applied to human populations, these kinds of systems would be useful in reducing disparities based on geographic location, access to trained therapists, or institutional disparities in resources. The human-driven evidence shows that high-quality care can be provided to more people through the consistent, technology-mediated rehabilitation procedure that will be provided regardless of other conditions. Even though behavioral, social, and contextual considerations should be made in human applications, these preclinical results do offer a solid conceptual description of telerehabilitation as a means of minimizing variability and enhancing fairness in the delivery of rehabilitation[30].

3. ETHICAL, TECHNOLOGICAL, AND TRANSLATIONAL CONSIDERATIONS

The benefits of standardized remotely monitored rehabilitation protocols present in human based telerehabilitation studies include important ethical benefits due to the ability to minimize repeated manual handling and related stress responses in experimental humans. Automated and remotely monitored exercise regimens adhere to the concepts of refinement and reduction through reducing the physical intervention that is avoidable, enhancing the welfare of the humans, and providing uniform therapeutic exposure. Experimental reliability also increases when the experiment is standardized because variability that depends on operators is decreased which enhances the validity and reproducibility of the finding[31].

On the technological side, the effectiveness of telerehabilitation successful implementation in human models depends greatly on the accuracy and reliability of the monitoring and delivery systems. There are challenges in the attainment of precision in motion tracking, measuring loads and real-time feedback in various species and injury models. The current limitations include miniaturization of devices, sensitivity of calibration, and during small human studies, the ability to adapt to different sizes and patterns of movement. Nonetheless, further development of wearable sensors, automated training devices, robotics and data analytics is increasingly enhancing the dependability, scalability and control of human-based telerehabilitation systems.

Table 1: Summary of Key Telerehabilitation Studies in Musculoskeletal Rehabilitation[32]

Author(s) & Year	Study Title	Focus Area	Methodology	Key Findings
Suso-Martí et al., (2021)[33]	Effectiveness of telerehabilitation in physical therapist practice: an umbrella and mapping review with meta–meta-analysis	Overall effectiveness of telerehabilitation in physical therapy practice	Umbrella review and mapping review with meta–meta-analysis	Telerehabilitation was found to be effective and comparable to conventional face-to-face therapy across multiple musculoskeletal and physical therapy outcomes, supporting its clinical viability.
Tao et al., (2022)[34]	Perceived barriers and facilitators of using synchronous telerehabilitation of physical and occupational therapy in musculoskeletal	Barriers and facilitators to implementing synchronous telerehabilitation	Scoping review	Identified key barriers such as technological limitations and training gaps, alongside facilitators including flexibility, accessibility, and patient convenience, influencing telerehabilitation adoption.

	disorders: a scoping review			
Toonders et al., (2023)[35]	Effectiveness of remote physiotherapeutic e-Health interventions on pain in patients with musculoskeletal disorders	Pain management through remote physiotherapy	Systematic review	Remote e-Health physiotherapy interventions demonstrated significant pain reduction outcomes, indicating effectiveness of digital rehabilitation strategies for musculoskeletal conditions.
Tsolakou et al., (2025)[36]	Attitudes of People With Chronic Musculoskeletal Disorders Towards Telerehabilitation	Patient attitudes and acceptance of telerehabilitation	Cross-sectional survey	Most participants expressed positive attitudes toward telerehabilitation, particularly valuing convenience and accessibility, though some concerns remained regarding personalization and technological familiarity.
Turolla et al., (2020)[37]	Musculoskeletal physical therapy during the COVID-19 pandemic: is telerehabilitation the answer?	Role of telerehabilitation during healthcare disruption	Narrative and practice-based analysis	Telerehabilitation emerged as a feasible and necessary alternative during the COVID-19 pandemic, ensuring continuity of musculoskeletal care while highlighting the need for structured implementation frameworks.

Human models are a preclinical interface that is very important in the translation of the effectiveness of telerehabilitation interventions in clinical practice such as their safety, feasibility, and biological effectiveness. These models can be used to study tissue level responses, neuromuscular adaptation and recovery patterns in controlled remote rehabilitation environments. However, biomechanics, complexity of movement, motivation and the environmental interaction among the humans and human beings are defiant to direct translation. To overcome these limitations, better model construction and integrative outcome measures must be considered to make sure that knowledge obtained on human-based telerehabilitation studies can be used in other musculoskeletal rehabilitation interventions.

4. DISCUSSION

The body of human-based telerehabilitation research indicates that remotely monitored and automated rehabilitation is effective in promoting musculoskeletal recovery through administering controlled mechanical loading that is known to stimulate muscle regeneration, connective tissue remodeling, joint mobility, and functional performance as well as reduce the variability in manual interventions. Enhancement of adherence in these systems is also achieved through the consistent engagement, reduced levels of handling stress, and objective observing of rehabilitation exposure, as this enhances reliability of observed outcomes. Notably, technology-based standardized protocols decrease disparities that are dependent on operators, implying that there may be an equity advantage of offering rehabilitation uniformly. In spite of these advantages, some ecological validity limitations, technological constraints, and species differences demonstrate that further studies on adaptive, feedback-based systems and multimodal outcome measures are required to enhance translational applicability and development of effective, adherent, and equitable musculoskeletal telerehabilitation interventions[38].

5.1 Interpretation and Analysis of Key Findings

The synthesized findings of the reviewed papers indicate that human-based telerehabilitation models are effective in the promotion of musculoskeletal recovery in the case of remotely monitored or automated-delivered rehabilitation. In a range of human models and forms of injury, there is consistent evidence that the regeneration of muscle, connective tissue remodelling, joint mobility, and functional performance can be increased by accurately constrained mechanical loading. Standardization of exercise intensity, frequency, and progression seems to be a key predictor of such beneficial results and it minimizes variability often attributed to manually delivered rehabilitation. A biological plausibility and strength of the telerehabilitation-mediated recovery mechanisms are supported by the nature of the observed improvements of neuromuscular coordination, gait symmetry and tissue-level adaptations in rehabilitated humans.

Besides effectiveness, adherence can also be identified as a significant strength of human-based telerehabilitation. Automated and sensor-guided systems will guarantee uniform involvement and proper recording of rehabilitation exposure, which will enhance causal associations of intervention and outcome. Less stress related to handling and incorporation of rehabilitation into a regular activity cycle also play a role in ensuring long-term involvement over recovery stages. All these results point to the fact that telerehabilitation is effective not only in musculoskeletal healing but it also increases reliability and internal validity of rehabilitation research by limiting inconsistencies in the delivery of interventions[39].

5.2 Implications and Significance of Human-Based Evidence

These findings have critical implications on the development of the rehabilitation science. Preclinical studies involving humans have demonstrated strong evidence that remotely administered rehabilitation can attain the same or in certain cases better outcomes as those of conventional manual methods under controlled settings. The mechanistic lessons that are acquired, such as the adaptation of muscle fiber to collagen orientation and vascularization, augment the scientific basis of telerehabilitation and guide the therapeutic loading strategies.

In addition, the reduction in variability, which is operator-dependent, is also significant in terms of equity. Technology-based and standardized rehabilitation guarantees homogeneity in terms of therapeutic exposure between individuals and this is the reason why telerehabilitation can help in overcoming disparities in terms of expertise and resource availability as well as logistical limitations. Even though direct measurement of equity in human models is not possible, the consistency and fairness of this set of systems give a good conceptual ground on considering telerehabilitation as a scalable and equitable method of rehabilitation when applied to large-scale environments.

5.3 Research Gaps and Future Directions

The human-based telerehabilitation literature has its strengths, but it has a number of significant gaps that can be explored in the future. One of the limitations that still exists is ecological validity because laboratory-based tasks to rehabilitate are not necessarily meant to be as complex as actual movement patterns or adaptive behaviors in the natural environment. Intervention fidelity is also limited by technological issues, especially related to sensor precision, device scale, and species-specific flexibility, especially in small human models.

Future studies need to involve the creation of more behaviorally adaptive and biologically responsive telerehabilitation programs that include real time feedback and progressive personalization. Translational relevance will be further enhanced by the incorporation of multimodal outcome measures, such as molecular, biomechanical, and behavioral measures. Also, comparative studies involving hybrid models that integrate automated systems with low levels of supervised interaction can be useful to fill the gap between controlled experimental designs and realistic and current rehabilitation practices. It will be crucial to address these gaps to see to it that the insights acquired during human-centered telerehabilitation research have a real impact on the development of effective, adherent, and fair musculoskeletal rehabilitation practices[40].

5. CONCLUSION

This review indicates that human-based telerehabilitation forms a solid and credible preclinical basis of the effectiveness, benefits of adherence as well as equity-related potential of remotely-delivered musculoskeletal rehabilitation. Controlled human model evidence consistent demonstrates that automated and sensor-controlled rehabilitation regimes can be used to increase muscle regeneration, connective tissue remodeling, muscle joint mobility, and functional performance using highly controlled mechanical loading whilst decreasing variability of the situation in manual intervention. The reliability and internal validity of rehabilitation outcomes is further enhanced by the improved adherence which is ensured by the decrease in the handling stress and objective monitoring. Besides, standardization and technological character of telerehabilitation provide valuable insights into whether it can encourage equal delivery of rehabilitation by reducing disparities based on operators and other resources. Despite the still existing issues concerning the ecological validity, technological constraints, and the translational dissimilarity, human-based research still shows conclusively that telerehabilitation is an effective, scalable, and ethically valid method. Further improvement of adaptive technologies and integrative outcome measures will be crucial to apply these preclinical findings to optimal musculoskeletal rehabilitation interventions in wider use

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