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Biomechanical Analysis of Rehabilitation Techniques

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ABSTRACT

This paper examines the intersection of biomechanics and rehabilitation, focusing on the quantitative analysis of human movement and its application to improving therapeutic outcomes. Beginning with an introduction to biomechanics and its evolution from basic pendulum models to complex three-dimensional motion tracking systems, the study highlights the importance of accurate in vivo data for clinical and rehabilitative assessments. Emphasis is placed on the growing necessity of biomechanical training for rehabilitation professionals, given the increasing integration of robotic devices, motion capture, and sEMG-based feedback systems. Specific attention is given to rehabilitation techniques that leverage dynamic modeling, gait and kinematic analyses, and muscle activation studies to provide individualized and effective therapies. Technological advancements such as virtual reality, robotic exoskeletons, and hybrid assessment-intervention systems are discussed as catalysts for home-based and clinic-based therapy models. Through detailed case studies, the paper demonstrates the practical benefits and limitations of biomechanical rehabilitation, ultimately advocating for a standardization of biomechanical tools and training to ensure reliability, validity, and clinical effectiveness.

Keywords: Biomechanics, Rehabilitation, Gait Analysis, Kinematic Modeling, Kinetic Analysis, Muscle Activation, Semg.

INTRODUCTION

Biomechanics applies classical mechanics to study living things, focusing on rigid bodies like human bones, enabling quantitative measurement of their position and orientation. The primary method involves tracking markers placed on the skin, which must be rigidly connected to the motion segment for accurate reconstruction. However, marker-bone relationships can vary across subjects and data collections, complicating comparisons. In vivo measurement of human motion exemplifies the utility of optimization methods in 3D kinematic modeling. Initial biomechanics utilized simple pendulum estimates and basic geometric modeling of the body as a single rigid entity, measuring positions at the feet or head. With technological advancements, kinetic models with Euler angles or rotation invariants became popular, utilizing optical and magnetic tracking for rigidly mounted markers. Biomechanics has evolved to incorporate complex models that estimate joint constraints through optimization methods, analyzing 3D motion capture data. Simultaneously, dynamic analysis using inverse dynamics to compute muscle loads at joints has expanded rapidly. Ultimately, biomechanics examines mechanical laws applied to biological systems, intersecting classical mechanics with the complexities of living organisms [1, 2].

Importance of Rehabilitation

In our aging society, advancements in medicine and technology are creating new opportunities to address the deficits in movement associated with aging and disability. The traditional view of rehabilitation as a fixed process is evolving into a more adaptable approach that responds to users' changing conditions. Emerging markets are promoting integrated rehabilitation systems, cost-effective devices, and kinetic learning systems to increase access for individuals with disabilities. Innovative concepts, like a feedback training system, are promoting a shift of rehabilitation from clinics to home settings. This transition opens up numerous opportunities for implementing biomechanical analyses in clinical practice and offers new pedagogical methods for teaching biomechanics to professionals. However, the implementation of these analyses poses challenges, as many rehabilitation specialists are not adequately trained in biomechanics, with 87% reporting no formal training in the past decade. The confidence and independence in using biomechanical analyses are rated low, and over half of specialist's struggle to interpret analysis results. Furthermore, the training of physiotherapists and psychologists in biomechanics has been insufficient, with a lack of attention given to functional assessment during their education. Many specialists remain unaware of the potential of biomechanical analyses or lack institutional support [3, 4].

Overview of Rehabilitation Techniques

Rehabilitation techniques aim to resist energetic conservation principles and individually damp the mechanical energy of the biomechanical system, whilst ensuring a certain regulation of the system by the nervous system of the targeted rehabilitation tasks. A robot-aided rehabilitation approach that structurally models and individually damp the mechanical energy percentage of the involved DOFs with dimensional regularization of the potential indices of the energy balancing controllers is proposed. The approach is based on a robotic device whose passive degrees of freedom individually provide the energetic conservation mechanism of the human-robot system, and a 3D dimensionally indexed mass spring model based on the mechanical analysis of the system, which frames an individual energy balancing control per-applied DOF. The proposed approach is connected to the passive elasticity of the mechanical system and the impulsiveness of the applied perturbation. Based on these principles, the rehabilitation technique is formulated as a strategy planning problem on the human-robot system, which stabilizes the energetic equilibrium to achieve any desired motion pattern of the mechanical system. As a first example of a single DOF mechanism, the application of an adapted damping coefficient is proposed so that the scalability, robustness, and adaptability of the approach to an exoskeleton for rehabilitation of more complex effects is discussed. The recent work can be regarded as an extension of the rehabilitation technique. In the future still need to extend this approach: (i) perform a clinical study, and (ii) speed up the exercise execution based on the therapeutic recommendations [5, 6].

Biomechanical Principles in Rehabilitation

In recent decades, biomechanical models have been utilized to study movement disorders resulting from physical impairments. Muscles and soft tissues are often modeled as nonlinear springs and dampers to establish notions of normality using nonlinear dynamical systems theory. Practical rehabilitation analysis emphasizes cyclical movements found in various daily activities and sports, making cyclical motion the focal point of this work. This study considers mechanical principles for controlling 1D periodic, nonlinear physical systems. Nonlinear motions can be modeled using an analogous driving force theory with polynomial expressions, addressing challenges faced by conventional methods. Results highlight applications in human motor control, sports biomechanics, and rehabilitation, tackling issues related to the complexity and nonlinearity of biomechanical models, suitable environments for human motion, and obtaining valid data. Several gait analysis applications in rehabilitation are examined, demonstrating variability in techniques without a specific preferred protocol. The primary concern remains quantitative measurement of gait disorders and their progression over time, emphasizing high data integrity and minimal restrictions in clinical gait analysis during rehabilitation [7, 8].

Gait Analysis in Rehabilitation

Refining treatment options, decisions are based on the original gait data and follow-up data for each intervention that has been used, on the basis of six main treatment options; physiotherapy, orthoses, surgery, pharmacology, assistive devices, and the 'wait and see' approach. It is often the case that more than one option has been employed since the collection of the original data, and even since the collection of the follow-up data. For each treatment option the gait data are checked to ensure that this option was applied as prescribed, and the outcome of the rehabilitation is assessed on the basis of the agreed criteria. The data are based on kinematic sequences describing the relationship of the body segments during walking for both the baseline gait recording and the follow-up. All deviation in the follow-up data from the baseline data is clearly observed still using this design. The specific treatment is suspected to influence some of the gait data and consequently the entire outcome evaluation is confined on the gait measures uniquely modified during the selected treatment. Much research into childhood disability is wide ranging and responses can be diverse. Identifying the expected changes must take account of the treatment being used and also the possible side effects. Changes in one part of the gait cycle can impact upon other timings or amplitudes. It is clearly important to consider the nature of the treatment and how it is expected to affect the child and their walking pattern. Consideration must be made to the time scale which rehabilitation is being evaluated. Many treatments will on one hand target a specific measure as an isolated success, on the other hand they can reduce deviation in one part of the gait cycle only to worsen another [9, 10].

Kinematic Analysis of Movement

The formal study of biomechanics began in the nineteenth century with analysis of rigid bodies. Rigid bodies are mathematically treated with classical mechanics, laws of motion which have solutions in analytical form. Rigid body mechanics equations of motion are primarily expressed in terms of three linear and three angular positions. To use these equations with human motion, it is desirable to quantitively measure the pose of the human body's rigid bodies. In biomechanics, a rigid body is typically represented by the underlying bone—one of the human body's repeating anatomical entities. Similarities in position and structure allow the application of knowledge gained from one individual to another. Constant shape, mass, and density lend utility to rigid body models in many research fields, including biomedical engineering and ergonomics issues of safety, comfort, and performance. Unfortunately, rigid body models in biomechanics are challenging for several reasons. Primarily, bones are much larger than the joints that connect them. Accurate tracking of the bone as a rigid body requires attachments to points that move with the bone, typically high-density reflecting markers. In lower extremity biomechanics, a typical set of twelve markers is attached to the pelvis, four markers on each thigh, and two markers on each lower leg. Placing the tracking markers over the skin has two drawbacks. The first is that the markers do not have a repeatable relationship to the underlying bone, preventing meaningful comparison of different data sets. Markers on the bony landmarks will measure the same sequence of events on different individuals, but do not take account of the fact that the relative bones were possibly quite different. This is a source of undefined variable error in biomechanical studies. The second drawback is the invitation of Soft Tissue Artifact (STA). The rigid body approximation remains approximately valid for the bones of the human body. The bone tracking markers are placed many centimeters away from the bone, overlying the skin. Ten milliseconds after the rigid bone moves, its soft tissue envelope has not adjusted to the change, and it is the soft tissue above the bone which is tracked. Interpretation of kinematic parameter estimates is complicated by the fact that these numbers describe the motion of the overlying soft tissue and not the target rigid body [11, 12].

Kinetic Analysis of Forces

The knee joint is a critical component of the human lower limbs and plays a vital role in activities. Its structure and function are among the most complex in the body. Improper movements can lead to injuries, particularly anterior cruciate ligament injuries. Given the knee's anatomical, kinematic, and mechanical complexities—including multiaxis three-dimensional motion and simultaneous application of pressure, tensile stress, and shear force during movement—it is essential to study its mechanical system. Research in knee biomechanics focuses on how movement, joint contact, and soft tissue deformation and forces impact joint dynamics. Common analysis tools include 3D data acquisition systems like the VICON T40S motion capture system and the AMTI 3D force measurement platform, where data acquisition corresponds to the gait cycle. Visual analysis software then assesses the knee joint's biomechanical properties based on kinematic and dynamic data, particularly ground reaction force (GRF). This study presents a method that attaches five spherical markers to the thigh and shank, enabling faster and simpler geometric center detection of the knee joint compared to manual methods. GRF analysis aids in biomechanical assessments. Empirical methods for inverse dynamics (ID) analysis of resistance exercises have been developed, allowing for estimation of joint moments, forces, and muscle forces while inferring unknowns through machine learning from camera-based measurements of joint angles, rather than relying on force plates. Simulation experiments validated the forward dynamics and ID abilities regarding known motion systems, further tested using a prototype exercise device [13, 14].

Muscle Activation Patterns

While motoneuron activity is widely studied, muscle contraction assessment has not received the same attention. Surface electromyography (sEMG) identifies the functions and effectiveness of muscle contractions, serving as a basis for biomechanical analysis. Many joint movement disorders show altered muscle activation patterns due to long-term adaptations, which sEMG helps confirm. Robust sEMG data aligns with high-quality kinematic results interpreted in rehabilitation stroke analyses. Progress in sport biomechanics application of muscle activation patterns has been slow. The functional sEMG modeling of arm biomechanics is too vast for one paper. After exploring various sEMG uses in rehabilitation techniques, much of the information will be amalgamated into a network of sEMG design scripts. The paper will also provide maps of analysis design recommendations for common rehabilitation activities, including adjustments for different body parts. While only two to three motions are synthesized, the framework is adaptable for various cases. This work consolidates knowledge on muscle activation patterns for biomechanical analysis and advocates its use in rehabilitation stroke monitoring. Shoulder rehabilitation may incorporate strength screening tests for various muscle contraction types linked to total upper extremity movements, but these designs often overlook consumer needs. While multiple formats exist for stage two shoulder training and strength screening tests, examples of efficient training quality reviews using sEMG are rare. In response, this work introduces wearable sEMG-supported systems for training quality management and feedback, enhancing labor intensity, worker health, and service quality [15, 16].

Role Of Technology in Rehabilitation

Technologically supported rehabilitation enhances the rehabilitation process through various approaches. A systematic review studied available rehabilitation technologies with high applicability for physiotherapists. A total of 94 technologies were classified into three categories: Assessment, Intervention, and Hybrid. The review identified 20 rehabilitation technologies, 18 related scientific articles, and 43 rehabilitation specialists. Including these technologies in clinical practice adds significant value to rehabilitation. Assessment technologies focus on evaluating an individual's health, utilizing devices and applications that analyze biomechanical variables, posture, movement speed, and joint range of motion. Some technologies hold a dual role in both assessment and intervention, emphasizing the need to recognize their primary purpose for optimal outcomes. Intervention technologies provide tools for individualized support but often lack detailed rehabilitation procedures. Further research is necessary to enhance these technologies' clinical usability. Hybrid technologies blend assessment with intervention, using visual or auditory cues to guide users in replicating movements. Examples include virtual reality and robotic rehabilitation technologies that assist in assessing postural analysis, movement tracking, muscle assessment, gait characteristics, and joint motion analysis [17, 18].

Case Studies of Biomechanical Rehabilitation

A single leg squat task was executed by six volunteers: three female and three male, aged between 24–55 years, without known injuries. Initially, each subject without exoskeleton (0%) performed the squat task. For the next trials the exoskeleton was attached at the knee joint and five more configurations were tested: Assistance Set 1 (41% assistance at asking to flex), Assistance Set 2 (59% at 30% of flection), and Assistance Set 3 (59% at 40% flection) and a 59% resistance configuration. Gazes, body and exoskeleton angles were tracked. Overall, the maximum knee flexion angle decreases with a maximum 30% assistance configuration. Upper body movements are deeply coupled with knee angle joint motions. With the addition of exoskeletons, the observers revealed increased steadiness of knees, while to flex knee social-like movements arise, including gaze changes to the free leg and pelvis yielding changes. Human and exoskeletons knee flexion extension angles increase activation of flexor and extensor muscles, while lower activation is shown in the transitory and peak torque phases. In a clinical rehabilitation context, producing scientifically valid data is all-important. In general, the wider contexts of rehabilitation and kinetic examination are less research mature than gait analysis. Movement examination techniques have sprung up organically and have not been researched for standards of validation. As a result, practitioners do not know what are the best techniques to use; they tend to pick and choose from a disparate range of approaches without a scientific basis for ensuring that they attain their goals. Meanwhile it is increasingly obvious that in order to be effective as a clinical outcome measure and as part of multi-centre trials, biomechanical rehabilitation tests must be valid, reliable, non-ceiling, and practical. Thus, it was felt timely to consider the literature on the characteristics of biomechanical tests to get insights into the labour that lies ahead of rehabilitation researchers aiming to develop valid tests. In the same way that gait analysis is not just about motion capture and simulation but also includes data pre-processing, reconciliation etc., movement analysis is not just about vector and angular outputs but about the processes that yield these outputs [19, 20].

Measuring Rehabilitation Outcomes

It is crucial to balance performance-based and subjective measures in assessing post-stroke rehabilitation outcomes. Satisfaction with goal accomplishment is often overlooked, hindering proper evaluation in both experimental and clinical settings. This study proposes a 3-point goal-oriented measure of satisfaction for pre- and post-assessment to investigate its correlation with well-being and depression biases. The Satisfaction with Life Scale suggests increased satisfaction in achieving goals while showing less focus on failures related to stroke-unrelated tasks. Contrary to expectations, the measure proven to be a redundant yet reliable unidimensional tool, indicating a need for wider research in different mental health fields. The introduced technique for assessing subjective goal accomplishments illustrates a clear link between stroke-related degradation and future engagement. This measure has potential across various domains, promoting goal orientation in assessments of psychopathology. A patient's overarching aim in rehabilitation remains full recovery from impairments; however, success is never guaranteed, even with active involvement. Acknowledging the distinction between satisfaction and objective scoring highlights the nuanced nature of successful outcomes. Future inquiries may explore the 3-item questionnaire across multiple sciences, analyzing different evaluators' intentions. There remains a need for reflection on methodological approaches to achieve meaningful results. Despite advancements in documenting subjective engagement through dynamic motivational levels, a deficit occurs in effectively applying a versatile-science approach for comprehensive assessments [21, 22].

Challenges In Biomechanical Rehabilitation

Biomechanical intervention holds great promises in facilitating the rehabilitation of a wide variety of conditions, from sports injuries to neurological disorders or amputations. Before any interventions, patient evaluation of functional aspects of the impairment to formulate a treatment plan is necessary. Future outcomes must also be predicted and it is still a challenge that current intervention offered does not invoke significant challenges to the patients. Most current interventions are also subjective and led by the therapists and limited treatment information is available to the patients. Currently, biomechanical tools, methods and analytics are developed to obtain an objective understanding for the rehabilitation process, which also are integrated with available rehabilitation robots to enable patient-optimized rehabilitation. They sense patients' biomechanical responses during the rehabilitation process in real-time and tune the robots' assistance appropriately. These avatar-based rehabilitation robots are expected to elicit an optimal paretic limb task from each single patient. Automated biomechanical analysis of rehabilitation, comprising biomechanical analysis methods to obtain an online understanding of patients' biomechanical responses, a biomechanical modeling approach to realize patient avatars and a biomechanical unit tuning method to optimize each single patient's rehabilitation, is proposed. For a common robotic rehabilitation device, the effectiveness of the biomechanical methods for grip-force control rehabilitation and for lateral control rehabilitation is evaluated. Results demonstrate the feasibility of the automated biomechanical analysis of rehabilitation. Automated biomechanical analysis of rehabilitation robots would provide treatment information to the patients, increase the patients' engagement and thus improve the effectiveness of robotic rehabilitation. Frontal plane motion of the hip is a risk factor for knee valgus during rehabilitation by physiotherapists. During rehabilitation, physiotherapists provide verbal biofeedback aimed to correct this risky knee motion. The effectiveness of observing biofeedback versus verbal feedback for educating frontal plane knee motion in rehabilitation robots is investigated. Experimental results show that biofeedback is a more effective form of feedback than verbal feedback. Integration of the biofeedback and the inertial measurement unit-based analysis method for rehabilitation with rehabilitant robots is also discussed [23, 24].

Future Directions in Biomechanical Research

As biomechanics becomes a more ubiquitous area of study within rehabilitation techniques research, biomechanics researchers will increasingly need to collaborate with other disciplines interested in biomechanics. Researchers are encouraged to actively try to be good interdisciplinary collaborators, as success in interdisciplinary biomechanics research will require some understanding of other disciplines' terminology, research questions, and basic tenets or principles. A little background understanding is often necessary to effectively communicate with and make requests of other discipline experts. Biomechanics researchers who more effectively communicate their disciplines' experimental methods' merits, limitations, and ability to answer these questions will also have better chances of successful collaborations within biomechanics. As biomechanics becomes more widely used in rehabilitation techniques research, researchers are motivated to actively communicate with others using biomechanics in research. Scientists in other disciplines will often lack basic knowledge and understanding of biomechanics concepts and experimental methods. Biomechanics researchers are encouraged to discuss biomechanics results with other scientists early in their research to better understand how to effectively communicate with these scientists. Educating scientists on biomechanics prior to interdisciplinary projects can help set realistic expectations and goals. When forming collaborations, biomechanics researchers should strive for equal contributions and effort from both disciplines; this may involve compromising on methods or equipment needed. Additionally, scientists outside of biomechanics tend to work at a different pace than those within biomechanics; this must be taken into account when designing a research timeline [25, 26].

Ethical Considerations in Rehabilitation

Professionals in rehabilitation can access quality didactic resources for their education, covering areas like disability assessment, biomechanics, research methods, and clinical applications involving data management and AI. In-depth training in these topics, supported by literature databases, is crucial. Training should focus on disability assessment per the ICF, physics for movements and forces, and gait analysis techniques. It should also include complex concepts on evaluating functional capacity and using Big Data, Thick Data, and AI in rehabilitation. Specific focus areas include neurorehabilitation, musculoskeletal disorders, amputee rehabilitation, and spinal deformities. Establishing a network of health centers for biomechanics and internships in instrumented analysis is advisable to conduct biomechanical studies and access rehabilitation technology. Healthcare professionals should create protocols for rehabilitation and telemedicine to ensure quality care. Ethical doubts surrounding telerehabilitation have existed, which complicates its integration into healthcare. Initial criteria for resources limited the search to 1400, focusing on ethical, legal, and religious relevance. The need for reevaluation is highlighted by a three-fold increase in relevant publications since the pandemic. After eliminating duplicates, 58 resources were examined. Providers must be aware of religious norms and Islamic rulings regarding patient treatment and privacy. Addressing ethical dilemmas may involve seeking supporting evidence or precedents, yet clear protocols are essential for quality healthcare. The guidelines for sick visits must be respected in telerehabilitation. All healthcare professionals should adhere to ethical principles of autonomy, beneficence, non-maleficence, justice, veracity, fidelity, and privacy, with recommendations to deliver bad news in-person, particularly for lower socio-economic patients [27-30].

Interdisciplinary Approaches to Rehabilitation

In the past two decades, physiotherapy and rehabilitation techniques have been widely studied, focusing on areas such as general rehabilitation analysis, Transient Ischaemic Attack, anatomy-driven recovery, post-surgical care, spinal surgery rehabilitation, exercise therapy principles, biomechanics, and treatment improvements for various disorders. Numerous patented devices aimed at rehabilitating locomotor skills and upper limbs have been developed, clarifying movements and categorizing techniques. However, a detailed understanding of rehabilitation techniques remains lacking. Previous research using a unique biomechanical analysis system demonstrated 3D kinematic analysis of squash, with potential applications in biology, sports, motor development, and medical fields. The pressing issue is the biomechanical analysis of rehabilitation techniques. This initial study presents multi-joint assessments using fluid mechanics equations for 3D kinematic analysis of hand, elbow, and shoulder orientations based on clinical data. Functional adaptations are identified, addressing asymmetries in disease components and informing rehabilitation enhancements across various contexts. Understanding the uniqueness of joint angles or trajectories is crucial. A new tri-dimensional numeric representation is proposed to model joint angle variables, potentially improving adaptability and rehabilitation estimates. Future trends include optimizing technique performance, learning disabled tasks, and applying findings to advanced robotics. Recognizing the specific application areas of rehabilitation techniques is essential for their effectiveness.

Subsequent papers will analyze rehabilitation techniques within the context of invented devices, aiming to provide comprehensive insights to advance this vital field [31-35].

CONCLUSION

Biomechanical analysis has emerged as an essential tool in the evolution of rehabilitation practices, enabling a deeper understanding of human movement and the mechanics underlying functional recovery. As rehabilitation shifts from clinic-centered care to more personalized, technology-supported models, the need for reliable and quantifiable biomechanical data becomes increasingly critical. Techniques such as gait analysis, kinematic and kinetic modeling, and muscle activation mapping through sEMG have demonstrated measurable benefits in assessing and guiding therapy. However, challenges remain in terms of specialist training, standardization of methods, and clinical integration. Bridging the gap between biomechanical science and therapeutic practice requires a multidisciplinary approach, supported by technological innovation, clinical validation, and ongoing education for practitioners. Moving forward, incorporating biomechanics into mainstream rehabilitation can enhance treatment precision, patient outcomes, and the overall effectiveness of physical therapy interventions.

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