

Biomechanical Modeling in Physical Therapy: Advancing the Science of Movement to Improve Patient Outcomes

¹Dr. Sophia Tanaka, ²Dr. Hiroshi Yamamoto,

¹Tokyo University of AI & Robotics, Japan.

²Kyoto University, Quantum AI Research Center, Japan.

Abstract: Biomechanical modeling has emerged as a pivotal tool in physical therapy, enhancing the understanding of human movement and its implications for patient recovery. This modeling involves the application of principles from biomechanics to analyze and optimize movement patterns, which can significantly improve rehabilitation outcomes. By utilizing advanced technologies such as 3D motion capture and real-time biofeedback, therapists can gain insights into joint ranges of motion (ROM) and muscle dynamics during various activities. These analyses help identify underlying causes of pain and dysfunction, allowing for tailored treatment plans that address specific biomechanical issues. The integration of biomechanical modeling into physical therapy not only aids in injury prevention but also enhances the efficacy of rehabilitation programs. For instance, by assessing gait patterns and postural alignment, therapists can detect abnormalities that may lead to overuse injuries or chronic pain. Furthermore, biomechanical assessments enable practitioners to develop personalized exercise regimens aimed at strengthening weak muscles, improving flexibility, and correcting faulty movement patterns. In conclusion, biomechanical modeling represents a transformative approach in physical therapy, facilitating a deeper understanding of movement mechanics and promoting better patient outcomes through customized interventions.

Keywords: Biomechanical modeling, physical therapy, Movement, Rehabilitation, Injury prevention.

1. Introduction

The field of physical therapy has undergone significant evolution over the past few decades, driven by advancements in technology and a deeper understanding of human biomechanics. Biomechanical modeling stands at the forefront of this transformation, providing therapists with powerful tools to analyze and enhance movement. This introduction explores the importance of biomechanical modeling in physical therapy, its applications, and its potential to improve patient outcomes.

1.1. Understanding Biomechanical Modeling

Biomechanical modeling refers to the simulation and analysis of biological systems, particularly the mechanics of human movement. By applying principles from physics and engineering, biomechanical models can represent the complex interactions between muscles, joints, and bones during various activities. These models can be developed using sophisticated software that incorporates data from motion capture systems, force plates, and electromyography (EMG). The resulting insights allow therapists to visualize movement patterns, quantify joint forces, and assess muscle activation.

1.2. Importance in Physical Therapy

The integration of biomechanical modeling into physical therapy is crucial for several reasons. First, it enhances the assessment process. Traditional evaluation methods often rely on subjective observations and basic measurements, which may overlook subtle movement dysfunctions. In contrast, biomechanical analysis provides objective data that can pinpoint specific areas of concern. For example, it can reveal compensatory movements that patients may adopt to avoid pain or discomfort, leading to further injury if left unaddressed. Second, biomechanical modeling supports personalized treatment plans. Each patient presents unique challenges based on their injury history, physical condition, and lifestyle. By utilizing biomechanical assessments, therapists can tailor interventions to meet individual needs effectively. This customization may involve selecting appropriate exercises that target specific muscle groups or modifying techniques to correct faulty movement patterns.

1.3. Applications in Rehabilitation

Biomechanical modeling has a wide range of applications in rehabilitation settings. One prominent use is in gait analysis for patients recovering from lower extremity injuries or surgeries. By analyzing walking patterns through motion capture technology, therapists can identify deviations that may hinder recovery. This information allows for targeted interventions aimed at restoring normal gait mechanics. Another application is in sports rehabilitation, where athletes often face unique biomechanical challenges due to the demands of their sport. Biomechanical modeling can help identify risk factors for injuries related to specific movements or training regimens. By addressing these factors through tailored rehabilitation programs, athletes can return to their sport more safely and effectively.

2. Literature Review

Biomechanical modeling has become integral in advancing physical therapy practices, providing insights that enhance rehabilitation strategies and improve patient outcomes. This literature review synthesizes recent findings and developments in biomechanical research, focusing on its applications in rehabilitation, injury prevention, and treatment efficacy.

2.1. The Role of Biomechanical Research in Rehabilitation

Recent studies emphasize the importance of biomechanical research in developing effective rehabilitation programs. highlights how modern biomechanical investigations have transformed traditional approaches to rehabilitation physiotherapy, particularly for conditions like coxarthrosis. The integration of biomechanical data allows for the creation of personalized rehabilitation programs tailored to individual patient needs, significantly improving treatment outcomes by reducing pain and enhancing mobility. The analysis of joint movement parameters and functional capabilities provides an objective assessment of patient conditions, facilitating continuous monitoring and adjustment of treatment plans.

2.2. Predicting Injury Risk through Biomechanical Modeling

Biomechanical modeling serves as a practical tool for predicting injury risks associated with various physical activities. Research indicates that understanding the mechanics of movement can identify potential injury factors, particularly in sports settings. For instance, a study demonstrated that variations in movement patterns and strength imbalances between muscle groups play a critical role in the etiology of injuries. By employing 3D motion capture technology and biomechanical modeling, therapists can assess joint ranges of motion (ROM) and muscle dynamics during specific activities, leading to optimized training regimens that mitigate injury risks.

2.3. Enhancing Treatment Strategies for Low Back Pain

Biomechanics research has also contributed significantly to the management of low back pain (LBP). Various biomechanical models have been developed to guide treatment strategies based on sound anatomical and mechanical principles. These models facilitate a better understanding of the relationship between pain and movement patterns, informing interventions such as motor control rehabilitation exercises. Although biomechanical approaches have shown promise, recent reviews suggest that they may not always outperform other nonsurgical therapies unless applied to specific patient subgroups. This underscores the need for ongoing research to refine subgroup identification methods based on biomechanical factors.

2.4. Technological Innovations in Biomechanics

The integration of technology into biomechanics has further expanded its applications in rehabilitation. Innovations such as wearable sensors and virtual reality (VR) systems are enhancing the ability to monitor patient progress and engage them in their recovery process. Wearable devices provide real-time data on movement patterns, enabling therapists to adjust treatment plans dynamically. Meanwhile, VR offers immersive environments that can be tailored to improve balance, coordination, and mobility, thereby increasing patient motivation and accelerating recovery.

3. Biomechanical Modeling: Fundamentals

Biomechanical modeling plays a critical role in understanding human movement, particularly in its application to physical therapy and sports science. It allows for a deeper analysis of movement, helping professionals optimize performance, prevent injuries, and improve rehabilitation strategies. This section outlines the key components of biomechanical modeling, the methodologies used to analyze movement, and its significance in various fields.

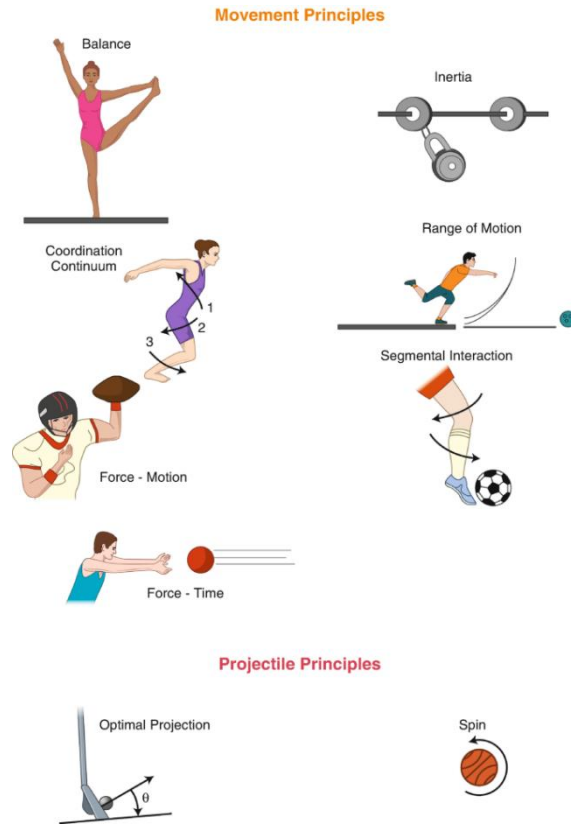


Figure 1: Biomechanical Principles in Movement and Projectile Dynamics

This image visually illustrates key biomechanical principles essential for understanding human movement and its application in physical therapy. The image is divided into two main categories: Movement Principles and Projectile Principles, each with various sub-categories that provide critical insights into how biomechanics can be used to optimize physical therapy interventions.

The Movement Principles category highlights fundamental aspects of human movement and interaction with the environment. For instance, Balance emphasizes the body's ability to maintain equilibrium, crucial for assessing and guiding rehabilitation progress. Coordination Continuum describes how different body segments synchronize during movement, a concept that is central to rehabilitation exercises targeting motor coordination. The principles of Inertia, Range of Motion, and Segmental Interaction are equally vital, as they explain the resistance to changes in movement, the flexibility of joints, and how different body segments work together to achieve efficient movement. Finally, the Force-Motion and Force-Time principles underline the connection between applied forces and motion, which are key to understanding how strength and rehabilitation exercises can influence recovery.

The Projectile Principles category focuses on the dynamics of objects in motion, such as a ball or a limb. Principles like Optimal Projection and Spin are important in physical therapy, especially for sports rehabilitation, where understanding how body segments influence the trajectory and speed of motion can help improve performance and control. These principles provide a solid foundation for biomechanical modeling, which can enhance physical therapy outcomes by helping therapists better understand and optimize patient movements for effective rehabilitation.

3.1. Understanding Biomechanical Modeling

Biomechanical modeling involves applying principles of physics and engineering to biological systems, with a focus on human movement. It explores how forces act on the body, how motion is generated, and the interactions between different segments of the body during movement. The ultimate goal is to enhance performance, reduce the risk of injury, and support rehabilitation efforts.

3.1.1. Key Components of Biomechanical Modeling

Biomechanical modeling is based on several core concepts that help to describe and analyze movement effectively:

1. **Kinematics:** This aspect of biomechanical modeling deals with the description of motion, focusing on parameters like position, velocity, and acceleration. Kinematics does not consider the forces that cause motion, but rather, how body segments move through space and time.
2. **Kinetics:** Kinetics explores the forces that cause or alter motion. This includes the analysis of ground reaction forces, joint torques, and muscle forces. Kinetic analysis is essential for understanding how different forces interact to produce movement, making it critical for injury prevention and rehabilitation.
3. **Dynamics:** Dynamics combines both kinematic and kinetic data to analyze how forces affect motion over time. By studying the dynamic relationships between force and motion, biomechanical models can predict the outcomes of specific movements and suggest improvements for therapeutic exercises.
4. **Muscle Mechanics:** This component focuses on understanding how muscles generate force and how they interact with skeletal structures during movement. The ability to model muscle mechanics is crucial for accurately simulating and predicting human movement, particularly in physical therapy interventions.

3.2. Methodologies in Biomechanical Modeling

Biomechanical modeling employs several advanced methodologies to capture and analyze human movement. These technologies and techniques provide detailed insights that aid in understanding and improving movement efficiency, injury prevention, and rehabilitation:

- **3D Motion Capture:** This technology captures real-time movement data through multiple cameras to create a 3D representation of the motion. It allows for precise analysis of joint angles, body segment motions, and overall movement patterns, making it an essential tool for both sports science and physical therapy.
- **Computer Simulations:** Advanced software tools can simulate human movement under different conditions. These simulations allow biomechanical models to predict outcomes based on factors such as load, technique, or rehabilitation strategies, enabling better decision-making in patient care.
- **Force Plates:** These devices measure ground reaction forces during dynamic activities such as walking, running, or jumping. By understanding the forces at play during these activities, clinicians can assess joint loads, gait abnormalities, and movement patterns to tailor rehabilitation plans.
- **Electromyography (EMG):** EMG records electrical activity in muscles, helping to analyze muscle activation patterns during various movements. This technique is invaluable for understanding how muscles engage during physical activities and identifying areas of weakness or imbalance in patients.

3.3. Significance of Biomechanical Modeling

The application of biomechanical modeling in physical therapy and sports science provides significant benefits that are directly linked to patient outcomes and performance optimization:

- **Injury Prevention:** By analyzing movement patterns, biomechanical models can identify potential risk factors for injury. For example, understanding how muscle imbalances or improper techniques contribute to overuse injuries allows for targeted corrective exercises and preventive measures.
- **Rehabilitation:** In physical therapy, biomechanical models help therapists design personalized rehabilitation programs. By closely analyzing movement dysfunctions, therapists can monitor progress and adjust treatment plans, ensuring a more effective recovery process for patients.
- **Performance Enhancement:** In sports science, biomechanical modeling aids athletes by optimizing their techniques. Analyzing movements like running gait, throwing mechanics, or swing techniques can help enhance performance while reducing the risk of injury. For athletes, biomechanical modeling provides insights into technique adjustments that lead to improved efficiency and results.

3.4. Anatomical segmentation of the human body for biomechanical analysis

Anatomical segmentation of the human body forms the basis of biomechanical modeling, enabling a systematic analysis of movement and force dynamics. The human body can be divided into distinct segments, such as the head, torso, pelvis, upper limbs, lower limbs, and feet. Each segment is treated as a rigid body connected by joints, allowing researchers to model the interactions between segments during various physical activities. This segmentation simplifies the complexity of human anatomy, making it easier to study how forces, torques, and motion propagate through the body.

In physical therapy, such segmentation is critical for assessing and improving patient outcomes. For instance, in gait analysis, the movement of the lower leg and foot relative to the pelvis and upper leg is closely examined to identify abnormalities or inefficiencies in walking patterns. Similarly, upper-limb segments can be analyzed to understand motor impairments caused by conditions such as stroke or musculoskeletal injuries. By breaking down the body into interconnected segments, therapists can pinpoint the source of functional limitations and tailor interventions accordingly.

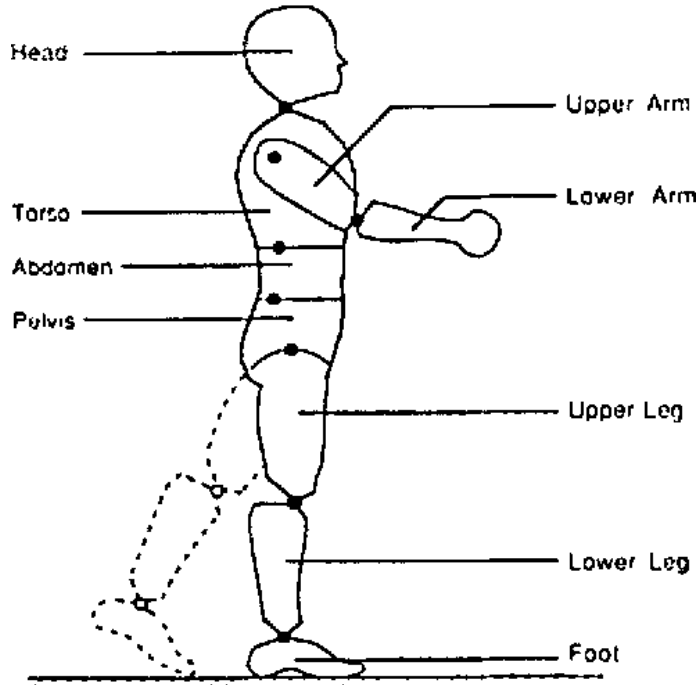


Figure 2: Anatomical segmentation of the human body for biomechanical analysis

Biomechanical modeling uses these anatomical divisions in conjunction with mathematical and computational tools to generate simulations. These simulations provide insights into joint kinematics (motion) and kinetics (forces) during dynamic activities. For example, motion capture systems can track the trajectory of markers placed on each segment, while force plates measure ground reaction forces. Together, these data sets help create accurate biomechanical models to evaluate therapy techniques or design assistive devices like orthotics or prosthetics.

Ultimately, the ability to model anatomical segments and their interactions allows for the development of evidence-based therapeutic strategies. This approach not only improves the precision of clinical assessments but also enhances the personalization of treatment plans. By leveraging biomechanical modeling, clinicians can better understand the biomechanical underpinnings of movement disorders, enabling more effective and measurable improvements in patient outcomes.

4. Applications in Physical Therapy

Biomechanical modeling plays an essential role in physical therapy by enhancing the assessment and treatment of musculoskeletal conditions. It provides a framework for understanding the mechanical aspects of human movement, which is crucial in optimizing therapy plans for injury prevention, rehabilitation, and performance enhancement. This section outlines the key applications of biomechanical principles in physical therapy, emphasizing how they contribute to these primary goals.

4.1. Injury Prevention

Injury prevention is a critical aspect of physical therapy, and biomechanical modeling offers valuable insights into movement patterns that may predispose individuals to injuries. By assessing the forces acting on the body during various activities, therapists can identify potential risk factors linked to specific movements and design interventions to prevent injuries before they occur.

4.1.1. Key Techniques for Injury Prevention

- **Motion Analysis:** One of the most effective tools for injury prevention is motion analysis, which utilizes 3D motion capture systems to observe and assess a patient's biomechanics during functional tasks. This technology enables

therapists to detect abnormal movement patterns that could lead to injuries, such as improper joint angles or asymmetries in movement.

- **Strength and Flexibility Assessments:** Biomechanical assessments also include evaluating muscle strength and flexibility, which are essential in identifying imbalances between opposing muscle groups. Correcting these imbalances can help improve overall stability, reducing the risk of overuse injuries and enhancing overall movement efficiency.
- **Customized Exercise Programs:** Based on the results of biomechanical assessments, therapists can create individualized exercise programs that focus on strengthening weak areas, improving flexibility, and enhancing neuromuscular coordination. These programs often incorporate strength training, flexibility exercises, and proprioceptive training to promote better movement patterns and injury prevention.

4.2. Rehabilitation Strategies

Biomechanical modeling is particularly beneficial in rehabilitation settings, where it provides objective data to inform treatment decisions. Personalized rehabilitation programs can be designed based on detailed biomechanical assessments, ensuring that patients receive tailored interventions that address their unique movement limitations and recovery goals.

4.2.1. Components of Effective Rehabilitation

- **Baseline Measurements:** The first step in rehabilitation is establishing baseline measurements, including range of motion (ROM), joint stability, and muscle activation patterns. These measurements serve as a starting point for tracking patient progress and determining the effectiveness of the treatment plan.
- **Progressive Exercise Regimens:** Rehabilitation programs are designed to gradually increase in intensity as the patient recovers. Biomechanical modeling helps therapists determine the appropriate progression rates to avoid overloading vulnerable areas while still challenging the patient to improve strength and function.
- **Functional Movement Training:** Incorporating functional movements that simulate daily activities is a critical component of rehabilitation. This approach helps patients regain the ability to perform routine tasks safely and effectively, enhancing their overall functionality and reducing the likelihood of re-injury.

4.3. Performance Enhancement

In addition to injury prevention and rehabilitation, biomechanical modeling also plays a vital role in enhancing athletic performance. By analyzing athletes' movement mechanics, therapists can provide personalized feedback that helps optimize performance outcomes and improve the efficiency of specific movements.

4.3.1. Strategies for Performance Enhancement

- **Technique Optimization:** Biomechanical analysis allows therapists to identify optimal movement techniques tailored to individual athletes. This involves analyzing body positioning, joint angles, and muscle recruitment patterns during specific sports activities, all of which can be adjusted to enhance performance.
- **Equipment Assessment:** Understanding how equipment interacts with the biomechanics of an athlete is essential for performance optimization. Biomechanical modeling can be used to assess the impact of footwear, sports gear, and playing surfaces on an athlete's movement, helping to reduce injury risk and maximize performance.
- **Real-Time Feedback:** With the advent of wearable sensors, athletes can receive real-time feedback during training sessions. These devices track movement patterns and provide immediate data that can be used to make adjustments in technique, promoting faster improvements and better performance outcomes.

5. Impact on Patient Outcomes

The integration of biomechanical modeling in physical therapy has profoundly impacted patient outcomes, significantly improving recovery rates, enabling personalized treatment plans, and enhancing functional abilities. This section delves into how biomechanical modeling influences patient care, offering evidence for its effectiveness in rehabilitation, injury prevention, and overall treatment strategies.

5.1. Improved Recovery Rates

Biomechanical modeling plays a pivotal role in accelerating and optimizing recovery during rehabilitation. By providing a comprehensive understanding of movement mechanics, these models allow therapists to design precise interventions that target specific impairments and recovery challenges.

5.1.1. Key Factors Contributing to Improved Recovery

1. **Precision in Assessment:** Biomechanical models allow for accurate assessments of joint movements and muscle forces, which provide critical insights into how the body is functioning during recovery. Research shows that preoperative biomechanical analysis can predict postoperative outcomes in patients undergoing spinal surgery, enabling the design of personalized surgical plans that enhance recovery rates.
2. **Customized Rehabilitation Programs:** With data from biomechanical assessments, therapists can develop individualized rehabilitation programs that focus on the patient's specific needs. These personalized approaches, guided by biomechanical analysis, have been linked to quicker recovery times and improved outcomes.
3. **Monitoring Progress:** Continuous biomechanical monitoring throughout rehabilitation helps therapists track patient progress in real-time, allowing for adjustments to treatment plans as needed. This adaptability contributes to faster recovery times and ensures that patients are on track to meet their rehabilitation goals.

5.2. Personalized Treatment Plans

One of the most significant advancements in physical therapy through biomechanical modeling is the ability to create patient-specific models that directly inform treatment plans. By customizing interventions based on a patient's unique biomechanics, therapists can optimize treatment efficacy and enhance recovery outcomes.

5.2.1. Components of Personalized Treatment

1. **Patient-Specific Simulations:** The use of finite element models enables simulations that predict how various treatment options will affect a patient's biomechanics. This predictive capability helps clinicians make more informed decisions about which interventions will be most effective.
2. **Targeting Specific Pathologies:** Biomechanical modeling aids in identifying specific pathologies that affect patient movement. For example, in patients with osteoarthritis, personalized models can simulate joint loading patterns, guiding interventions that reduce pain and improve joint mobility.
3. **Enhanced Communication:** The visual representation of biomechanical data improves communication between therapists and patients. Patients who can visualize how specific exercises or interventions will benefit them are more likely to engage in their treatment, leading to better compliance and improved outcomes.

5.3. Enhanced Functional Abilities

Beyond recovery, biomechanical modeling plays an essential role in enhancing functional abilities post-rehabilitation. By focusing on optimizing movement patterns, therapists can help patients regain independence and improve their quality of life.

5.3.1. Strategies for Enhancing Functionality

1. **Functional Movement Training:** Biomechanically optimized exercises are integrated into rehabilitation programs to help patients develop more efficient movement patterns. This is particularly valuable for restoring independence in tasks such as walking, climbing stairs, or lifting objects.
2. **Real-Time Feedback Mechanisms:** Technologies such as motion capture systems provide real-time feedback during rehabilitation sessions, allowing therapists to correct movement patterns immediately. This feedback accelerates learning and adaptation, ensuring more effective functional recovery.
3. **Long-Term Monitoring:** Biomechanical models also enable long-term monitoring of patients even after formal rehabilitation has concluded. This ongoing assessment helps identify potential issues early, ensuring that functional improvements are sustained and preventing the recurrence of problems.

6. Challenges and Limitations

Despite the significant advancements and benefits of biomechanical modeling in physical therapy, several challenges and limitations persist that can hinder its widespread application and effectiveness. One major challenge is the complexity of human biomechanics itself. The human body is a highly intricate system with numerous variables influencing movement, including anatomical differences, muscle strength, joint stability, and neurological factors. Accurately capturing and modeling these variables requires sophisticated technology and expertise, which may not be readily available in all clinical settings. Moreover, the variability in individual patient responses to treatment complicates the creation of universally applicable models, making it difficult to generalize findings across diverse populations.

Another limitation is the accessibility and cost of advanced biomechanical technologies. While tools such as 3D motion capture systems, force plates, and electromyography (EMG) provide valuable data for analysis, they often come with high costs and require specialized training for effective use. This can create barriers for smaller clinics or those in underserved areas, limiting their ability to implement biomechanical assessments in routine practice. Additionally, the integration of these

technologies into existing workflows can be challenging, requiring time for staff training and adjustments to treatment protocols. As a result, while biomechanical modeling holds great promise for enhancing physical therapy outcomes, addressing these challenges is essential for maximizing its potential benefits across various healthcare settings.

7. Future Directions

The future of biomechanical modeling in physical therapy is poised for significant advancements, driven by emerging technologies and interdisciplinary approaches. One promising direction is the integration of artificial intelligence (AI) and machine learning algorithms into biomechanical assessments. These technologies can analyze vast amounts of movement data to identify patterns and predict outcomes more accurately than traditional methods. By leveraging AI, therapists could receive real-time insights into patient progress, enabling them to make data-driven decisions that enhance treatment efficacy.

Furthermore, AI could facilitate personalized rehabilitation plans by continuously adapting exercises based on individual patient responses, thereby optimizing recovery trajectories. Another key area for future development is the expansion of wearable technology and mobile health applications. Wearable devices equipped with sensors can monitor biomechanics in real-time during daily activities, providing continuous feedback to both patients and therapists. This capability not only enhances patient engagement but also allows for more precise tracking of functional improvements outside the clinical setting. As these technologies become more accessible and affordable, they have the potential to democratize biomechanical assessments, making them available to a broader range of patients and healthcare providers. Additionally, the integration of virtual reality (VR) into rehabilitation programs offers exciting possibilities for creating immersive environments that simulate real-life scenarios, further enhancing the effectiveness of therapeutic interventions.

8. Conclusion

In conclusion, biomechanical modeling represents a transformative advancement in the field of physical therapy, offering valuable insights into human movement and its implications for rehabilitation and injury prevention. By integrating principles of biomechanics with cutting-edge technology, therapists can develop personalized treatment plans that address the unique needs of each patient. The ability to analyze movement patterns objectively not only enhances the accuracy of assessments but also allows for timely adjustments to rehabilitation strategies, ultimately leading to improved patient outcomes.

As the field continues to evolve, the incorporation of artificial intelligence, wearable technology, and virtual reality holds great promise for further enhancing the effectiveness of biomechanical modeling in clinical practice. These innovations are set to make biomechanical assessments more accessible and engaging for patients, fostering greater adherence to rehabilitation protocols. By embracing these advancements, physical therapists can optimize their interventions, reduce recovery times, and empower patients to achieve their functional goals. The future of biomechanical modeling in physical therapy is bright, with the potential to revolutionize patient care and set new standards for rehabilitation practices.

References

1. Zatsiorsky, V. M., & Prilutsky, B. I. (2012). Biomechanics of skeletal muscles. *Human Kinetics*.
2. Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed.). Wiley.
3. Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., & Whittlesey, S. (2013).
4. Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., ... & Thelen, D. G. (2007). OpenSim: Open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, 54(11), 1940-1950.
5. Rajagopal, A., Dembia, C. L., Demers, M. S., Delp, D. D., Hicks, J. L., & Delp, S. L. (2016). Full-body musculoskeletal model for muscle-driven simulation of human gait. *IEEE Transactions on Biomedical Engineering*, 63(10), 2068-2079.
6. Ackermann, M., & van den Bogert, A. J. (2010). Predictive simulation of gait at low speeds: Implications for orthotic design. *Medical Engineering & Physics*, 32(4), 326-333.
7. Seth, A., Sherman, M., Reinbolt, J. A., & Delp, S. L. (2011). OpenSim: A musculoskeletal modeling and simulation framework for in silico investigations and exchange. *Procedia IUTAM*, 2, 212-232.
8. Liew, B. X. W., Morris, S., Netto, K., & Rubenson, J. (2017). Joint-level mechanics of the human lower limb during walking and running throughout the lifespan. *Journal of Biomechanics*, 55, 1-10.
9. Mokhtarzadeh, H., Yeow, C. H., Goh, J. C. H., & Oetomo, D. (2014). Development of a subject-specific musculoskeletal model of the lower limb in gait analysis. *Computer Methods in Biomechanics and Biomedical Engineering*, 17(6), 595-600.