Chapter 3

Mechanics of Sport Movements: A Biomechanical Perspective

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Abstract

This abstract outline the core tenets of "Mechanics of Sports Movements: A Biomechanical Perspective," a text dedicated to the rigorous examination of human motor control and execution within athletic contexts. The book systematically applies principles of biomechanics to elucidate the underlying physical mechanisms that govern sport-specific movements. It posits that a comprehensive understanding of these principles is indispensable for optimizing athletic performance, mitigating injury risk, and advancing evidence-based training methodologies.

The text meticulously delineates foundational biomechanical constructs, encompassing both kinematics—the spatiotemporal description of motion—and kinetics—the analysis of forces inducing motion. Chapters are structured to address critical concepts such as force-velocity relationships, power output, impulse-momentum theorem, and work-energy relationships as they manifest in various sporting actions, including but not limited to ballistic movements (e.g., throwing, jumping), cyclical movements (e.g., running, cycling), and precision-based movements. Furthermore, the book explores the intricate interplay between neuromuscular activation patterns, anthropometric characteristics, and environmental constraints in shaping movement efficacy and efficiency. Through detailed quantitative analyses and theoretical frameworks, this work aims to provide a robust scientific foundation for researchers, practitioners, and students seeking to deepen their understanding of the complex mechanics underpinning human movement in sport.

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Introduction

Definition of Biomechanics

Kinesiology is the scientific discipline that systematically studies human movement. One of its subfields, biomechanics, focuses on understanding the causes of human motion and the mechanisms through which these movements occur. Rooted in the principles of classical mechanical physics, biomechanics analyzes the description of movement and the effects of force on that movement. Within this framework, biomechanics examines how force generates motion in living organisms, both to ensure the healthy progression of growth and development processes and to prevent injuries in tissues exposed to excessive loading (Knudson, 2003; Kanjilal & Mondol, 2017).

Applying classical mechanical principles to living systems defines the unique position of biomechanics within the natural sciences. This discipline establishes a bidirectional relationship between theoretical knowledge and practical application, grounded in measurable experimental data. Theoretical insights must be testable through practical implementations; likewise, the outcomes derived from applications should be explainable within a coherent theoretical framework (Muratlı et al., 2000).

The biomechanics of human movement can be defined as a scientific discipline that describes, analyzes, and evaluates bodily motions. This field investigates a broad spectrum of physical movement, ranging from individuals with gait impairments to elite-level athletes (Winter, 2005). Effective movement requires more than just anatomical structure; neuromuscular coordination, physical fitness level, and psychological factors also play a crucial role. Kinesiology specialists develop and teach new techniques aimed at enhancing performance. However, in technically demanding sports and movements, biomechanical knowledge becomes even more central to optimizing performance (Knudson, 2003; Hughes et al., 2019).

Biomechanics classifies forces as internal and external in order to examine the structure and quality of movement. Internal forces originate from the body's own anatomical components, while external forces arise from interactions with the environment. These external forces may act either in close proximity or at a distance. According to Newton's third law of motion, when the human body generates a force, it simultaneously applies an equal but opposite force to its surroundings. For instance, the force exerted by a person's foot on the ground is met with a ground reaction force of equal magnitude but in the opposite direction (Zatsiorsky, 2002).

Basic Concepts of Biomechanics

Force

Force is fundamentally defined as a push or pull that causes a change in the motion of an object. In accordance with Newton's third law of motion, every force is accompanied by an equal and opposite reaction force. In biomechanics (particularly within the scope of rigid body mechanics) analyses often disregard deformation and focus solely on the effects of force on motion. Force can increase or decrease the speed of an object, alter its direction, or initiate movement. According to the SI unit system, force is measured in Newtons (N), where one Newton is the force required to accelerate a one-kilogram mass at a rate of 1 m/s^2. Importantly, a force is characterized not only by its magnitude but also by its point of application, direction, and line of action—features that make it a vector quantity. In biomechanical analyses, systems are frequently modeled as particles, assuming that all forces act through a single point. Forces are categorized as either internal or external. Internal forces arise within the system's own components and serve to maintain structural integrity, but they do not generate motion at the system's center of mass; muscle forces fall into this category. In contrast, external forces result from interactions with the environment and are the primary drivers of movement. Gravity is the most fundamental non-contact external force, responsible for the weight of objects. Contact forces include the ground reaction force, which consists of a normal force and a frictional force. Friction plays a vital role in producing horizontal motion and is a foundational element in human locomotion (McGinnis, 2020; Aydos et al., 2004; Sevim, 1991; Aktüre et al., 2020).

Torque

Torque refers to the rotational effect of a force around an axis of rotation and is often used interchangeably with the term "moment." It is calculated by multiplying the force applied by the perpendicular distance from the axis of rotation to the point where the force is applied: Torque (□) = Force (F) × Moment arm (r). Torque is the angular equivalent of force in linear motion and causes an object to rotate. Its SI unit is Newton-meter (N□m) (Likens & Stergiou, 2020).

Moment

Moment refers to the rotational effect of a force around an axis and is often used interchangeably with the term torque in biomechanics (McGinnis, 2020). It is calculated by multiplying the magnitude of the force by the perpendicular distance from the axis of rotation to the point where the force is applied: Moment (M) = Force (F) × Moment arm (r). This concept is essential for understanding how body segments rotate around joints. For example, the knee extensors (quadriceps muscles) generate an extension moment around the knee joint. The direction of the moment can be either clockwise or counterclockwise, which is referred to as negative or positive, respectively (Hall, 2014). In sports biomechanics, moments are widely used to analyze joint movements. In the case of the knee, the extension moment is determined by the force produced by the quadriceps and the perpendicular distance from the point of force application on the tibia to the knee joint axis (Enoka, 2008). The net moment is the vector sum of all moments acting on a joint, including internal moments from muscles and external moments from forces such as gravity or resistance. The effect of a moment depends not only on muscle force but also on joint angle, segment position during movement, and biomechanical advantages. Therefore, moment analysis plays a critical role in training design, rehabilitation, and performance evaluation in biomechanics (McGinnis, 2020).

Acceleration

Acceleration refers to the rate at which an object's velocity changes over time and is defined as a vector quantity, meaning it includes both magnitude and direction (McGinnis, 2020). Acceleration occurs when an object starts moving, stops, speeds up, slows down, or changes direction. It is mathematically defined by the formula $a = \Delta v / \Delta t$, where a represents acceleration, Δv is the change in velocity, and Δt is the time interval. If an object moves at a constant velocity, its acceleration is zero; however, any change in speed or direction results in acceleration (Hall, 2014). In the context of sports and exercise biomechanics, acceleration is frequently used to analyze the movement patterns of body segments or the body's center of mass. For example, a sprinter's maximum acceleration during the initial phase from the starting blocks is a key parameter in evaluating sprint performance. According to Newton's second law of motion, $F = m \times a$, the net force applied to an object determines its acceleration in proportion to its mass, illustrating the direct relationship between force and acceleration (McGinnis, 2020). In kinematic analyses, acceleration is typically calculated as the derivative of velocity or the second derivative of position. Today, these calculations can be performed directly using modern technologies such as high-speed cameras, motion capture systems, or accelerometers (Enoka, 2008).

Newton's Laws of Motion

One of the fundamental pillars of the science of mechanics is the three laws of motion developed by the English scientist Sir Isaac Newton. Newton is recognized as a pioneering figure who laid the foundations of modern science—not only for his laws of motion but also for his contributions to calculus (e.g., determining the speed of a falling object or the slope of a curved path), the universal law of gravitation, and theories of light. His laws of motion provide a basic framework for understanding the physical nature of human movement (Knudson, 2003).

Newton's First Law of Motion

Newton's first law, known as the law of inertia, describes the tendency of an object to maintain its current state of motion. According to Newton, all objects will remain at rest or in uniform motion in a straight line unless acted upon by an external net force. In other words, an object changes its motion only when the net external force is unbalanced. For example, a sprinter running at a constant speed and an athlete sitting on a bench both possess the same amount of inertia if they have equal mass (Knudson, 2003). This law emphasizes that no external force is required to maintain motion; uniform linear motion arises solely from the inherent property of inertia (Knudsen & Hjorth, 2000). However, everyday experiences often lead to misconceptions that seem to contradict this law. For instance, many people believe that moving objects naturally slow down. This incorrect assumption results from overlooking external forces such as air resistance and surface friction. In reality, Newton's first law highlights that the natural state of motion is not rest, but the continuation of existing motion. In the fields of biomechanics and movement science, this law is a foundational principle that must be understood in order to conduct accurate analyses of human motion (Serway et al., 2002; Knudsen & Hjorth, 2000; Knudson, 2003).

Newton's Second Law of Motion

Newton's second law of motion is a fundamental principle in physics that describes the quantitative relationship between force and motion. This law states that the net force acting on an object is equal to the product of the object's mass and its acceleration. Mathematically, it is expressed as $F = m \times a$, where F represents the net force, m the mass, and a the acceleration. This means that the greater the net force applied to an object, the greater its acceleration. However, for the same applied force, an object with greater mass will accelerate less. This law plays a critical role in understanding dynamic systems. Structures such as the human body (with its multi-joint and musculoskeletal system) are subjected to numerous forces during movement. Newton's second law enables analysis of how these forces influence body motion. In the field of sports biomechanics, aspects such as muscular force production, ground reaction forces, and the resulting accelerations are typically evaluated based on this physical principle. As a result, this law provides a scientific foundation for assessing athletic performance, improving movement efficiency, and reducing injury risk (Knudson, 2003; Serway et al., 2002).

Newton's Third Law of Motion

Newton's third law of motion is known as the principle of action and reaction. It is defined as: "For every action, there is an equal and opposite reaction." This law emphasizes that forces never act in isolation but always occur in pairs. When one object applies a force to another, the second object simultaneously applies an equal force in the opposite direction. For example, when you push against a wall with a horizontal force, the wall pushes back with an equal force in the opposite direction. This demonstrates that force interactions occur not on a single object alone but always between two objects (Knudson, 2003). This law is not limited to everyday experiences; it also applies to large-scale systems, such as planetary interactions. For instance, the gravitational pull that the Earth exerts on the Moon is matched by an equal and opposite gravitational pull from the Moon on the Earth. This mutual attraction plays a central role in generating tidal movements in Earth's oceans (Knudsen & Hjorth, 2000; Serway et al., 2002).

Technological Measurement Systems in Biomechanics

Force Platforms

Force plates are among the most widely used measurement tools in sports biomechanics, playing a critical role in the quantitative assessment of ground reaction forces (GRF). These systems measure the forces exerted by an individual on the ground during activities such as standing, walking, running, or jumping, capturing data in three dimensions with high temporal precision. The collected force data can be integrated with kinematic variables such as acceleration, velocity, and displacement to perform dynamic analyses of movement. Through this integration, biomechanical parameters such as force-time curves, jump height, balance strategies, and performance indicators can be derived. Force plates are also commonly used in motor control and neuromuscular performance assessments. However, the high cost of commercial force platforms (often exceeding 20,000 USD) limits accessibility in developing regions. To address this challenge, low-cost and portable alternatives using piezoelectric sensors have been developed. These alternative systems can provide sufficiently accurate data for basic biomechanical analysis and serve as valuable tools for educational and research purposes in the field of sports science (Barela et al., 2023; Wardoyo et al., 2016; Challis & Challis, 2021; Miller et al., 2023).

IMU Sensors

Inertial and Magneto-Inertial Measurement Units (IMUs) have become widely used wireless sensor technologies in the field of sports biomechanics in recent years. These systems typically include tri-axial accelerometers and gyroscopes, and in some versions, tri-axial magnetometers for magnetic field measurement as well (Fong & Chan, 2010). IMUs can be used either as standalone sensors or as part of multi-sensor systems to capture the linear and angular movements of individual body segments. However, current technological capabilities still fall short in reliably estimating energy-related parameters of center of mass motion using IMUs (Pavei et al., 2020). Sensors can be attached directly to the skin or integrated into belts and tight-fitting garments. Sport-specific placements (such as on the heel of a shoe, the tongue, or behind the ear) have also enabled customized applications (Camomilla et al., 2018). This diversity, however, introduces variability in measurement accuracy and reliability due to differences in sensor placement, device specifications, anatomical calibration methods, and data processing algorithms (Macadam et al., 2019; Vitali & Perkins, 2020). IMU-based outputs can generally be categorized into five key areas: (1) physical activity monitoring, (2) estimation of biomechanical loading at external or segmental levels, (3) dynamic balance assessments, (4) technical performance analysis (e.g., angular velocity, segment orientation), and (5) hybrid applications combining multiple categories (Picerno, 2017). For technical analysis in particular, raw sensor data must be transformed into an anatomically meaningful reference system. This transformation can be performed using simple manual alignment techniques or functional calibration movements such as walking. Nonetheless, a universally accepted measurement protocol for different types of movement, sensor positions, and biomechanical models is still lacking. Moreover, issues such as inappropriate filtering parameters, the absence of drift correction algorithms, or magnetic disturbances may negatively affect measurement validity (Ligorio & Sabatini, 2016; Mendes Jr. et al., 2016). Therefore, the establishment of minimum technical standards (encompassing sensor selection, placement, calibration, and data processing) is critically needed to ensure reliable data generation in sports and exercise science (Hughes et al., 2024).

Smartphone Sensors and Application Software

Modern smartphones are equipped with internal sensors such as tri-axial accelerometers and gyroscopes, allowing them to measure movement. While the idea of using these sensors to monitor human motion during sports activities has been around for some time, it is only in recent years that their potential has been fully explored (Hummel et al., 2013; Hughes et al., 2024). Developers have created innovative applications that transform smartphones into wearable tools for biomechanical analysis. For example, the Dorsiflex app, which uses the phone's gyroscope as an inclinometer to measure ankle dorsiflexion range of motion, has been validated for clinical use (Balsalobre-Fernández et al., 2019). Similarly, the TiltMeter© app is used to assess sagittal plane spinal range of motion (Pourahmadi et al., 2016). According to a systematic review by Keogh et al. (2019), such applications have the potential to replace traditional goniometers; however, more reliable and valid protocols are needed (Keogh et al., 2019). Most of these apps currently measure only static range of motion, where the joint is held at the end range, limiting their applicability in dynamic sports scenarios. Although some apps (such as Phyphox, which provides real-time tilt tracking, or ForceData, which estimates force using the phone's accelerometer) aim to capture dynamic metrics, there is limited scientific validation supporting their accuracy. Moreover, the technical specifications of built-in smartphone sensors can vary significantly between devices, leading to differences in measurement accuracy even when using the same application. Therefore, it is essential to examine the specific sensor characteristics of a smartphone before using it for biomechanical assessments (Chen et al., 2018; Hughes et al., 2024)

3D Motion Capture

3D motion capture systems are advanced technologies used in biomechanical analysis to measure human movement with high precision. These systems determine the position and orientation of body segments in three dimensions, enabling the calculation of biomechanical variables such as joint angles, movement velocity, and temporospatial parameters. Traditional marker-based systems use reflective markers attached to the skin and infrared cameras to identify joint centers. However, these systems require controlled environments and skilled personnel to operate effectively. Motion capture is widely applied in sports science for performance analysis, in clinical settings for evaluating gait disorders, and in monitoring rehabilitation processes. Despite their high accuracy, the cost and setup time associated with marker-based systems can limit their use, particularly in clinical contexts. When combined with force plates and IMU sensors, motion capture systems allow for comprehensive analysis of both the kinematic and kinetic aspects of movement. This integration provides valuable insights across a wide range of applications—from assessing athletic performance to identifying neuromuscular disorders (Wade et al., 2022; Veirs et al., 2022).

EMG (Electromyography)

Surface electromyography (sEMG) is an advanced technology that provides critical data for movement control and performance assessment by measuring muscle activity in a non-invasive manner within sports biomechanics. Using bipolar electrodes placed on the skin, sEMG captures the electrical potential differences generated by muscle contractions, enabling analysis of neuromuscular activation coordinated by the central nervous system. This method is employed across various sports (such as running, cycling, swimming, and weightlifting) to evaluate muscle amplitude, timing, and frequency characteristics. sEMG plays a key role in identifying muscle synergies, revealing common activation patterns among muscle groups through techniques such as non-negative matrix factorization (NMF), thereby offering deeper insights into motor control mechanisms. However, factors like electrode placement and ambient noise can affect signal quality, making standardized protocols essential for accurate data acquisition. When integrated with force plates and inertial measurement units (IMUs), sEMG contributes to a comprehensive biomechanical analysis, combining kinematic, kinetic, and electromyographic data. This integration enhances the understanding of athletic performance and aids in the assessment of injury risk and movement efficiency (Kotov-Smolenskiy et al., 2021; Taborri et al., 2020; Soderberg et al., 1984).

Modelling and Simulation Techniques in Biomechanics

In the field of biomechanics, modeling and simulation techniques developed to quantitatively analyze human movement have advanced significantly in recent years. A key methodological approach driving this progress is Multibody System Dynamics (MBS), which is widely used in modeling the skeletal (SK), musculoskeletal (MSK), and neuromusculoskeletal (NMSK) systems. While SK models represent only bones and joints, MSK models incorporate muscle-tendon units to estimate muscle forces and joint moments. NMSK models go further by integrating the neural control of muscle activation, capturing excitation–contraction dynamics for a more comprehensive depiction of human movement. These MBS-based models have a broad range of applications, including understanding movement mechanics, estimating muscle forces and joint loads, designing prosthetic devices, and optimizing athletic performance. During simulation, phenomenological Hill-type muscle models are often preferred due to their low computational cost. However, more complex biophysical models may be employed when higher physiological accuracy is required. Crucial factors affecting model accuracy and individualization include the representation of muscle paths, methods used to define joint centers, anthropometric scaling strategies, and optimization techniques used to resolve the muscle redundancy problem. Addressing these elements appropriately ensures that simulations not only reflect general biomechanics but also capture subject-specific variability, which is essential for both clinical and sports applications (Roupa et al., 2022; Yeadon & King, 2008; Alexander, 2003).

Types of Biomechanical Analysis

A quantitative biomechanical analysis involves the collection and interpretation of numerical data. When aspects of a movement are measured (such as velocity, force, or angle) and described using numerical values, the analysis falls under this category. It is grounded in objective measurement and typically relies on instruments and technology. In contrast, a qualitative biomechanical analysis relies on sensory observations rather than numerical data. The evaluator assesses movement characteristics based on visual or auditory cues, drawing on experience and perceptual judgment without formal measurements (McGinnis, 2020).

Qualitative Biomechanical Analysis

Qualitative biomechanical analysis involves the breakdown of a movement or motor skill into its fundamental components and the evaluation of these elements through observational judgment rather than numerical measurement. In this approach, the observer relies on sensory perceptions instead of objective data, making it particularly suitable for coaches and physical educators. Descriptions such as "faster," "more stable," or "higher" are commonly used to assess performance. Visual observation forms the foundation of this method, allowing for an accessible and low-cost means of evaluation. In contrast, quantitative biomechanical analysis requires specialized equipment, technical expertise, and significant financial investment, and is therefore more frequently used in the performance evaluation of elite athletes. According to McGinnis (2020), an effective qualitative analysis follows a four-step process: (1) theoretically defining the ideal technique, (2) systematically observing the athlete's performance, (3) identifying discrepancies by comparing the observed performance with the ideal model, and (4) providing instruction and feedback to correct the identified errors. The goals of biomechanical analysis are not limited to improving technique; they also encompass training planning, injury prevention, and equipment design optimization. For the analysis to be meaningful, the purpose of the movement must be clearly defined and, where possible, articulated using mechanical terms. For example, in tennis, the goal of a serve is not only to win a point but also to put the opponent in a disadvantageous position—parameters such as serve speed and accuracy become indicators of that goal. In sum, qualitative biomechanical analysis offers a structured, practical, and conceptually grounded approach that is especially valuable in educational and coaching settings (McGinnis, 2020).

Quantitative Biomechanical Analysis

Comprehensive quantitative biomechanical analyses are mostly applied to the performances of elite-level athletes. However, coaches may sometimes carry out limited quantitative analyses by taking basic performance measurements. Simple tools such as a stopwatch and a measuring tape can be used to quantify several biomechanical variables. For example, counting the number of steps and measuring the time it takes to complete them can provide a measure of step frequency. Measuring a fixed distance and timing how long it takes to cover that distance allows for the calculation of speed. If assistants mark the location of each footfall, step length can also be determined. These types of measurements allow for a basic level of quantitative analysis; however, collecting such data often prevents the coach from observing the full performance in real time. In contrast, a comprehensive quantitative analysis requires specialized and often expensive equipment to accurately record and measure key biomechanical parameters. These detailed assessments are typically conducted not by coaches, but by trained biomechanists or technicians (McGinnis, 2020).

Biomechanic with Artificial Intelligence and Machine Learning

The convergence of Artificial Intelligence (AI) and biomechanics has emerged as a transformative force in the scientific analysis of human movement. In recent years, AI (particularly Machine Learning (ML) techniques) has enabled the interpretation of complex, high-dimensional biomechanical data in ways previously unattainable using traditional methods. Supervised algorithms such as Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and k-Nearest Neighbors (k-NN), along with unsupervised learning and deep learning models, have demonstrated exceptional performance in modeling nonlinear and temporal relationships within movement data. As highlighted by Molavian et al. (2023), AI applications in biomechanics support real-time monitoring, performance prediction, and automated classification of gait disorders. Among these tools, Convolutional Neural Networks (CNNs) have gained prominence for their ability to extract biomechanical features directly from video and wearable sensor data, enabling tasks such as pose estimation and player detection in sports analytics. Additionally, clustering algorithms contribute to gait pattern recognition and the identification of pathological deviations, which are crucial in clinical decision-making and rehabilitation planning. By integrating AI-driven analytics into biomechanical workflows, researchers and practitioners can achieve not only improved accuracy and efficiency but also the development of intelligent, adaptive support systems for performance optimization and patient care (Molavian et al., 2023).

Application Areas and Future Perspectives in Biomechanics

Biomechanics encompasses a broad range of applications spanning from sports sciences and healthcare to engineering and ergonomics. In sports biomechanics, it is employed to optimize athletic performance, refine techniques, and minimize injury risk. For instance, running analyses using force plates and 3D motion capture systems enable detailed evaluation of step mechanics and joint loading, facilitating the development of more efficient running techniques. In clinical biomechanics, it plays a vital role in diagnosing gait abnormalities, designing prostheses, and monitoring rehabilitation progress. Analyzing joint moments before orthopedic surgery improves surgical planning, while tools like surface electromyography (sEMG) help assess neuromuscular disorders. Industrial biomechanics focuses on improving ergonomics and safety in the workplace by analyzing workers' movement patterns to prevent injuries caused by repetitive motions. Biomechanical principles also inform the design of robotic and biomimetic technologies, such as robotic prosthetics and exercise equipment that mimic human movement. Looking ahead, the evolution of biomechanics is closely tied to its integration with Artificial Intelligence (AI) and Machine Learning (ML). Deep learning algorithms can analyze large datasets to identify movement patterns, predict performance outcomes, and deliver personalized training programs. Convolutional Neural Networks (CNNs) can accurately extract athlete positions and biomechanical parameters from video data. Wearable technologies, especially IMU sensors and smartphone-based applications, are making biomechanical analyses more accessible and affordable, supporting real-world, portable assessments. Advances in simulation technologies, including multibody system dynamics (MBS) and neuromusculoskeletal (NMSK) models, will enhance the accuracy of individualized movement analyses. Tools like Virtual Reality (VR) and Augmented Reality (AR) will offer interactive environments in sports training and rehabilitation, enriching movement analysis experiences. The combination of biomechanical data with big data analytics holds the potential to create predictive models for athlete health and performance. However, the success of these technologies depends on establishing standardized protocols and ensuring data reliability. Ultimately, as an interdisciplinary science, biomechanics has the potential to revolutionize our understanding and optimization of human movement when fused with emerging technologies.

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