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Integration of Biomechanics and Kinesiology in Improving Athlete Performance: Physiological and Biomechanical Perspectives

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Abstract. This study aims to analyze the integrative role between biomechanics and kinesiology in improving athletic performance from a physiological and biomechanical perspective. The study was conducted using a literature review method of scientific articles from the PubMed, ScienceDirect, BMC, SpringerLink, BMJ, and Google Scholar databases for the period 2020–2026. The results of the review show that the integration of these two disciplines contributes significantly to improving movement efficiency, explosive strength, and injury prevention. Biomechanics plays a role in analyzing force, joint moments, and muscle-tendon stiffness, while kinesiology explains motor control, movement coordination, and physiological adaptation to training loads. The reviewed studies confirm that exercises such as plyometrics and high loads increase tendon stiffness and energy transfer efficiency, while the use of wearable sensors enables real-time biomechanical monitoring to support coaching decisions. This integration also needs to consider biological factors such as gender, fitness level, and tissue condition in the design of training programs. Overall, the research results confirm that the biomechanics-kinesiology approach can create a more scientific, personalized, and adaptive training model, thereby supporting optimal athlete performance and reducing the risk of injury.

Keywords: Athlete Performance; Biomechanics; Injury Prevention; Kinesiology; Neuromuscular Adaptation.

1 Intriduction

An athlete's performance depends not only on physical abilities such as VO_2max, muscle strength, and energy systems, but also on the effectiveness of movement techniques that can reduce energy loss and tissue stress. Biomechanics offers a foundation for understanding forces, joint moments, and the interaction between the body and the surface during an activity, aiming to explain the efficiency of the movement and the risk of injury (Applied Biomechanics

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in Sports Performance) (Penichet-Tomas, 2024). Kinesiology, on the other hand, highlights how neuromuscular control, coordination, and tissue adaptation can influence safe and efficient movement patterns. By combining these two disciplines, coaches and researchers can link technical variables (such as joint angles, ground contact duration, and force distribution) with physiological outcomes including metabolic efficiency, contraction frequency, and muscle fatigue. This integration offers a more comprehensive training approach that focuses not only on muscle strengthening but also on refining technique within the framework of tissue adaptation. In today's sports practice, linking laboratory research findings with field applications is crucial.

The development of wearable sensors has opened up numerous opportunities for monitoring movement and load on the field. A comprehensive review by Rebelo and colleagues (2023) showed that wearable devices and force plates are now being used to monitor performance, provide training program information, and support injury prevention strategies across a variety of sports (Rebelo et al., 2023). Another review also indicated that wearable technology can provide real-time data that underpins immediate technique feedback and performance improvement (Seçkin et al., 2023). However, challenges remain in integrating and interpreting data in real-world situations due to device diversity, accuracy, and standardized procedures. Sensors without context and processing can provide confusing or misunderstanding information. Therefore, sensor use needs to be supported by robust, reliable, and easily understood analytical models for coaches and athletes. The integration of sensors, biomechanics, and kinesiology is crucial to ensure that movement data is not just numbers but can inform training decisions.

A fundamental element of this integration is an understanding of muscle and tendon stiffness, which acts as a link between external forces and tissue adaptation. A meta-analysis of plyometric training programs showed that these programs significantly improve tendon stiffness and performance variables, such as jumping ability and lower limb strength (Ramírez-delaCruz et al., 2022). However, stiffness-related adaptations are not linear and can vary based on initial fitness level, muscle type, and training stage. In situations of injury or recovery, changes in stiffness over time can be an indicator of improvement or risk, rather than simply an absolute target value. Therefore, long-term monitoring of stiffness and its relationship to movement patterns and neuromuscular control is crucial. Kinesiology explains how motor regulation and tissue adaptation mediate the biomechanical impact of training. Adjustments to technique or training dosage should be based on each individual's tissue stiffness profile.

Gender differences are also crucial factors in the interaction of biomechanics and kinesiology. A systematic review and meta-analysis have identified biomechanical differences between male and female runners, such as hip adduction angle, ground reaction force, and vertical oscillation, that impact movement efficiency and the likelihood of injury. By understanding these differences, training programs can be adapted to more accurately meet the biological needs of men and women. When it comes to integration, coaches need to consider that strategies that are most effective for one gender may not be applicable to another. Tissue adaptations, neuromuscular control, and response to load can also vary. Therefore, recent research highlights the importance of subgroup-based study design and analysis (gender, athlete level). This suggests that integration between biomechanics and kinesiology must be sensitive to biological variations and cannot be generalized.

Conventional practical implementations typically occur in laboratory settings using optical motion capture systems and force plates, although their implementation in the field faces challenges related to cost, time, and environmental conditions. An article discussing improved wearable sensors and automated analytics for injury prevention noted that wearable sensors are now capable of continuously recording kinematics and kinetics on the field, with automated algorithms estimating injury risk based on specific biomechanical variables (Kovoor et al., 2024). In the broader context of sports science, advances in smart testing, big data, and artificial intelligence are beginning to bring sports biomechanics into the digital dimension (Chenglin et al., 2023). However, applying laboratory findings to real-world situations remains challenging, especially when faced with unpredictable surface conditions, fatigue, and interactions. Therefore, it is essential to design hybrid protocols: measurements taken in the laboratory for model calibration and validation, and sensors used on the field for routine monitoring. Kinesiology techniques, such as movement control analysis, play a role in understanding sensor data within the framework of body system adaptation. This integration enables coaches to make technique and loading decisions based on scientific evidence.

One specific application is hamstring injury prevention through sprint mechanics assessment. Recent research has linked sprint mechanics scores to the incidence of hamstring injuries in elite soccer clubs, making running mechanics a significant risk indicator. Running techniques such as pelvic control, back mechanics, and horizontal push application are central to biomechanical interventions. Kinesiology supports that neuromuscular adaptations, such as muscle synchronization and contraction velocity, are crucial factors in ensuring effective running technique without exceeding tissue capacity. With the help of sensors and modeling, coaches can identify potentially harmful technique deviations. A tailored training program can include structured sprint volume, hamstring eccentric training, and technique drills as part of an overall performance ecosystem. This integration contributes to reducing risk while maintaining speed.

As a guide to research and challenges, research from 2020 to 2025 shows that while a significant amount of research on sensor technology and biomechanical modeling is emerging, there is still a paucity of technical interventions examining long-term impacts on athlete performance and injury. A review by Rebelo et al. (2023) stated that the majority of research on sensors is still descriptive and does not sufficiently contribute to decision-making in training programs (Rebelo et al., 2023). Furthermore, issues of protocol standards, data compatibility, and validity across various sporting conditions continue to be major challenges (Chenglin et al., 2023). Future research designs require prospective studies linking technique-based interventions, derived from biomechanical insights, to physiological outcomes and athlete performance. At the practical level, coaches and professionals must be equipped with a comprehensive framework so that sensors and models are not merely static information but can serve as tools for decision-making in daily training. In conclusion, the integration of biomechanics and kinesiology offers a path to more comprehensively optimize athlete performance by integrating technique, tissue adaptation, and physiological capacity, while reducing injury risk in the era of data-driven sport.

2 Method

This study uses a literature review approach to analyze the relationship and integration between biomechanics and kinesiology in improving athlete performance from a physiological and biomechanical perspective. The objective of this method is to collect, critically assess, and synthesize the latest research findings explaining how biomechanical factors (such as forces, joint moments, and muscle-tendon stiffness) and kinesiological factors (such as motor coordination, neuromuscular control, and physiological adaptation) contribute to improved sports performance and injury prevention.

Literature data was obtained from leading international academic databases, including PubMed, Google Scholar, ScienceDirect, BMC, SpringerLink, BMJ Open Sport & Exercise Medicine, and The Lancet. The search was conducted using a combination of keywords such as "Athlete Performance," "Biomechanics," "Injury Prevention," "Kinesiology," and "Neuromuscular Adaptation." The search focused on articles published between 2020 and 2025 to ensure relevance to the latest developments in motion analysis methodology and sports technology.

3 Result

A search of various academic articles shows that the application of an integrative approach between biomechanics and kinesiology in the field of sports is very broad and diverse. Various models, methods, and analysis systems have proven effective in improving athlete performance, optimizing movement efficiency, and reducing the risk of injury through a deeper understanding of body mechanics and physiological functions. Recent literature research also identifies that the synergy between movement analysis (biomechanics) and neuromuscular adaptation (kinesiology) plays a crucial role in developing more scientific, personalized, and sustainable training strategies. The following is the result of the identification and synthesis of literature on biomechanics and kinesiology in improving athlete performance in sports:

No.	Integration of Biomechanics and Kinesiology in Improving Athlete Performance	Source (Researcher, Year)
1	Skor mekanika sprint (S-MAS) berkorelasi signifikan dengan risiko cedera hamstring; tiap kenaikan satu poin meningkatkan risiko 33%.	(Bramah et al., 2025)
2	Sprint memicu stres tinggi pada hamstring; teknik lari seperti postur panggul dan fase ayun akhir menjadi kunci pencegahan cedera.	(Bramah et al., 2024)
3	Terdapat konflik antara performa cutting yang cepat dan peningkatan beban sendi lutut; diperlukan keseimbangan biomekanik dan kontrol neuromuskular.	(Dos'Santos et al., 2021)

4	Latihan plyometrik meningkatkan kekakuan otot–tendon dan kekuatan eksplosif secara signifikan, terutama setelah ≥6 minggu latihan.	(Ramírez-delaCruz et al., 2022)
5	Latihan plyometrik meningkatkan *leg stiffness* dan efisiensi biomekanik; efek paling besar pada atlet tingkat menengah.	(Moran et al., 2023)
6	Tendon Achilles bersifat adaptif terhadap beban dan frekuensi latihan; keseimbangan adaptasi otot–tendon penting untuk efisiensi elastik.	(Finni & Vanwanseele, 2023)
7	Penurunan kekakuan tendon patela selama rehabilitasi meningkatkan hasil klinis; kekakuan berlebih tidak selalu menguntungkan.	(Breda et al., 2022)
8	Wearable sensors efektif untuk pemantauan biomekanik, tetapi implementasi "data-to-decision" masih terbatas di lingkungan latihan nyata.	(Rebelo et al., 2023)
9	Sensor berbasis IMU dan EMG akurat mendeteksi pola gerak abnormal; standarisasi dan validasi lintas cabang olahraga masih diperlukan.	(Kovoor et al., 2024)
10	Latihan neuromuskular adaptif meningkatkan koordinasi dan efisiensi biomekanik dibanding model repetisi statis tradisional.	(Murphy et al., 2024)
11	Algoritme IMU terbukti valid untuk mengukur parameter langkah; efektif menggantikan sistem *motion capture* di lapangan.	(Kvist et al., 2024)
12	Desain pelat karbon pada sepatu mengubah distribusi tekanan dan gaya kaki; desain pelat menentukan stabilitas dan efisiensi lari.	(Song et al., 2023)
13	Peningkatan kekakuan sepatu (LBS) meningkatkan efisiensi energi lari, tetapi adaptasi biomekanik tubuh tetap diperlukan untuk mencegah cedera.	(Ortega et al., 2021)
14	Penggunaan sepatu berpelat karbon tanpa adaptasi progresif dapat meningkatkan risiko cedera stres tulang pada pelari kompetitif.	(Tenforde et al., 2023)
15	Perempuan memiliki sudut lutut dan beban frontal lebih besar saat *cutting* dibanding pria, meningkatkan risiko cedera ACL.	(Donelon et al., 2024)

Mendiguchia et al. (2025) in a prospective cohort study of 126 elite soccer players found that Sprint Mechanics Assessment Score (S-MAS) scores were significantly correlated with new hamstring injuries, with each one-point increase in S-MAS score increasing the risk of injury by 33% (IRR = 1.33) over a 6-month period (Bramah et al., 2025).

Dos'Santos et al., (2021) investigated the 90° cut and reported that biomechanical variables such as center-of-mass velocity, peak propulsive force, braking force at the penultimate/final step, and internal foot angle explained approximately 64% of the variation in cutting completion time. However, the fastest strategy often conflicted with knee loading variables (KAM, rotational moment). Sprint mechanics, including stride length, joint angle, and posture, influence the magnitude of mechanical strain on the hamstrings, suggesting that injury prevention efforts should incorporate technique modifications beyond eccentric training (Bramah et al., 2024).

Through a systematic review and meta-analysis of over 30 studies, this research demonstrated that plyometric training significantly improves muscle-tendon stiffness, explosive strength, and mechanical efficiency of movement. The greatest adaptations occurred after at least six weeks of intensive training. Furthermore, changes in tendon structure and muscle architecture contributed to an increase in the rate of force development (RFD), which is crucial for athletes' explosive performance (Ramírez-delaCruz et al., 2022).

This study assessed the effects of plyometric training on lower limb stiffness and demonstrated significant improvements in young athletes. This increase in stiffness was directly related to improved sprint and vertical jump performance. However, the greatest adaptations were found in athletes with intermediate fitness levels, while elite athletes showed a plateau in adaptation. These results emphasize the importance of managing training intensity and variation in sports kinesiology programs (Moran et al., 2023).

This article examines the biomechanical and physiological properties of the Achilles tendon, including its elastic behavior and energy storage capacity. The Achilles tendon has been shown to adjust its stiffness and viscoelasticity according to training load patterns. However, an imbalance between muscle and tendon adaptation can lead to tissue stress accumulation and injury risk. Therefore, training programs must balance muscle strength and tendon elasticity to maintain biomechanical efficiency (Finni & Vanwanseele, 2023).

This longitudinal study found that decreasing patellar tendon stiffness during rehabilitation was associated with improved clinical outcomes, such as reduced pain and improved knee function. These results challenge the long-held paradigm that tendons must be “stiffer” to be stronger, as structural flexibility actually supports tissue healing and adaptation. From a biomechanical perspective, reduced stiffness helps reduce shear loads during eccentric activities (Breda et al., 2022).

Wearable sensors such as IMUs, GNSS, and foot pressure sensors have been widely used to monitor athlete performance. However, most research stops at the data collection stage and has not yet been applied to real-time decision-making. This study emphasizes the importance of converting biomechanical data into concrete actions for training optimization, injury prevention, and individualized load monitoring (Rebelo et al., 2023).

Through a systematic review, this study concluded that accelerometer- and EMG-based sensor technology has great potential for analyzing movement and detecting injury risk. The accuracy of detecting abnormal movement patterns such as knee valgus and gait asymmetry reached over 85% compared to optical systems. However, differences in algorithms and measurement parameters between devices remain a major obstacle. The authors emphasize the need for integration of biomechanical data and kinesiological interpretation for clinical and performance applications (Kovoor et al., 2024).

An adaptive neuromuscular training approach focuses not only on the number of sets and repetitions. Variations in intensity, tempo, and external cueing have been shown to improve motor coordination and movement efficiency. This approach allows the nervous and muscular systems to optimally adapt to the mechanical demands of exercise. Thus, the integration of kinesiology principles into biomechanical training planning is key to improving performance (Murphy et al., 2024).

Another study validated an Inertial Measurement Unit (IMU) algorithm for measuring spatiotemporal parameters in gait analysis. The results showed that the system's accuracy approached that of laboratory motion capture systems at a lower cost. The IMU application allows coaches to monitor gait patterns and motion loads in real time on the field. This technology provides a bridge between theoretical biomechanics and everyday kinesiology practice (Kvist et al., 2024).

This computational study evaluated the effect of carbon plate design in running shoes on pressure distribution and deformation of the instep. It was found that variations in the shape and thickness of the carbon plate can alter ground reaction forces and torques at the metatarsal joints. These results explain why shoes with carbon plates can improve running efficiency but also potentially increase structural load when used without proper biomechanical adaptations (Song et al., 2023).

The effect of increasing shoe longitudinal stiffness (bending stiffness) on running energy and economy. Shoes with carbon plates increase mechanical efficiency by up to 4%, but their use must be accompanied by biomechanical adjustments to prevent recurrent injuries. The authors assert that footwear design is an external factor that directly influences an athlete's biomechanical performance (Ortega et al., 2021).

Through case studies and expert opinion, this study reports an increased risk of bone-stress injury (BSI) in runners using carbon-plated shoes without a progressive adaptation period. Repetitive stress resulting from force redistribution can lead to tibial or metatarsal microfractures. Therefore, kinesiological adaptation and load management are crucial steps when integrating new footwear technology into training (Tenforde et al., 2023).

Differences in ACL biomechanics between male and female athletes during change-of-direction (COD) movements are noted. Women have a greater knee angle and a tendency toward valgus collapse, which increases frontal loading on the knee joint. These findings emphasize the importance of gender-specific technique training and neuromuscular strengthening to prevent ligament injuries (Donelon et al., 2024).

4 Discussion

Research by Quarmby et al. (2023) showed that athletes with Achilles tendinopathy exhibited significant biomechanical changes compared to healthy controls. These changes included differences in lower limb kinematics and neuromuscular control, including load distribution, joint angles, and muscle activation patterns. This confirms that tendon pathology is not solely structural but also involves motor system adaptations. This supports the notion that interventions solely targeting tendon structures (e.g., weight training) are inadequate without considering the integration of neuromuscular control. From a kinesiological perspective, optimal movement pattern adaptations need to be applied alongside structural stimuli to improve mechanics and function. These findings emphasize that in the integration of kinesiological biomechanics, tissue (tendon) impairments and motor control should be viewed as interconnected systems, not separate elements (Quarmby et al., 2023).

Another study investigated how mechanical loading triggers tendon adaptations in terms of stiffness, modulus, and cross-sectional area (CSA) (Lazarczuk et al., 2022). They found that increases in tendon stiffness were driven more by changes in CSA than by changes in material modulus, particularly when the applied load was greater and the training duration was longer. This means that training program design needs to consider both load volume and intensity to stimulate tendon remodeling, not only in material properties but also in structural properties. In an athletic context, these structural adaptations help tendons cope with dynamic motion stress while maintaining efficient elastic energy transfer.

In a clinical intervention trial for Achilles tendinopathy, the Evidence-Based High-Loading Tendon Exercise for 12 Weeks study reported that a high-load program resulted in greater mechanical and morphological adaptations, such as increased tendon stiffness, maximum strain, and cross-sectional area, compared to standard eccentric training or passive therapy (Radovanović et al., 2022). From a biomechanical perspective, these adaptations enhance the tendon's capacity to withstand repetitive strain, and from a kinesiological perspective, they enable the muscles and tendons to perform under higher load conditions with a lower risk of injury. These results provide empirical support that high-load stimuli, when administered appropriately, are an effective strategy that integrates structural and functional aspects of movement.

A review of research studies concluded that chronic exercise, particularly mild to moderate eccentric exercise, can improve the mechanical properties (stiffness, stress, and endurance) of the Achilles tendon, moderated by more balanced muscle-tendon adaptations (Yu et al., 2022). They also noted that adaptation results tend to be inconsistent due to variations in training intensity, subject baseline status, and contraction type. From an integrative perspective, this emphasizes the need for individualized training interventions based on the athlete's biomechanical response and neuromuscular capacity.

A correlational study in runners by Konrad et al. (2023) found that passive compression stiffness of the Achilles tendon was negatively correlated with oxygen consumption during running, meaning that athletes with stiffer Achilles tendons tended to have better energetic efficiency (Konrad et al., 2023). This relationship was not significantly found for the patellar tendon or quadriceps muscle. These findings provide empirical evidence that tendon mechanical characteristics (which can be influenced by training and adaptation) are directly related to an athlete's metabolic performance. Within the framework of integrating biomechanics and kinesiology, this underscores the importance of monitoring tissue properties (e.g., stiffness) as mediators of physiological efficiency in athletes

5 Conclusion

The integration of biomechanics and kinesiology has been proven to improve athletes' overall performance through the integration of body mechanics analysis and neuromuscular adaptation. This approach focuses not only on increasing strength and physiological capacity, but also on technical efficiency, motor control, and muscle-tendon balance. Technological advances such as wearable sensors further enhance the application of this science in the field, enabling real-time monitoring of load and motion for injury prevention and performance optimization. Thus, the integrative application of biomechanical kinesiology provides a scientific basis for coaches and researchers to design more precise, adaptive, and long-term performance-oriented training programs.

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