

GENETIC AND ANATOMICAL DETERMINANTS OF MUSCULOSKELETAL PERFORMANCE: IMPLICATIONS FOR PHYSICAL FITNESS, EXERCISE ADAPTATION, AND SPORTS PERFORMANCE

Simreet Singh^{1*}, Dr Anuj Prasad², Dr Rahul Taye Gam³, Shachi Tayal⁴, Disha Bansal⁵, Mary Jida⁶

¹Assistant Professor In Physical Education, Department of Physical Education, Ganga Degree College, Dhabi Gujran, Punjab, khanauri mandi/148027. ORCID ID:- <https://orcid.org/0009-0009-7538-5105>, Email ID: simreetsingh4@gmail.com

²Senior Resident, ABVIMS & DR RML HOSPITAL, Guru Gobind Singh Indraprastha University, Delhi. Email ID: divergent1005anuj@gmail.com, Department of Orthopaedics, ORCID ID: 0009-0004-6196-6199

³Assistant Professor, Department of Community Medicine, Lakhimpur Medical College, Assam, Lakhimpur, 787051 ORCID ID : 0000-0001-9962-4099, Email ID: dr.rahul.gam@gmail.com

⁴Resident 2nd year MS Anatomy, Department of Anatomy, Maharana Pratap Government Medical College, Pali, Rajasthan, JODHPUR, 342001. Email ID: shachit08@gmail.com ORCID ID: <http://orcid.org/0009-0008-1760-3429>

⁵Former Postgraduate Student, ISIC Institute of Rehabilitation Sciences, New Delhi, India, Guru Gobind Singh Indraprastha University, New Delhi, India. Email ID : drdishabansalpt@gmail.com, ORCID ID : 0009-0005-6718-5876

⁶Assistant Professor, LNIPE, ASSAM, Department of Physical Education Email ID: maryjida2017@gmail.com ORCID ID: 0009-0007-3988-915X

ABSTRACT

Musculoskeletal performance is fundamental to human movement, physical fitness, and athletic achievement, arising from the complex interplay between genetic, anatomical, physiological, and environmental factors. Advances in sports genomics have demonstrated that physical performance is influenced by the cumulative effects of multiple genetic variants regulating muscle development, energy metabolism, connective tissue integrity, and exercise responsiveness. Simultaneously, anatomical characteristics—including skeletal morphology, muscle architecture, tendon properties, body composition, and neuromuscular organization—determine the mechanical efficiency required for force production and movement. This review synthesizes current evidence on the genetic and anatomical determinants of musculoskeletal performance and examines their implications for physical fitness, exercise adaptation, and sports performance. It further discusses how interactions between inherited biological characteristics and external factors such as training, nutrition, and mechanical loading contribute to inter-individual variability in exercise responses and injury susceptibility. Emerging technologies, including multi-omics approaches, artificial intelligence, wearable sensors, and digital twin systems, are also explored for their potential to support personalized exercise prescription, injury prevention, rehabilitation, and precision sports medicine. Despite substantial scientific progress, important challenges remain, including limited population diversity, inconsistent phenotyping, and the need for standardized longitudinal research. Future investigations integrating genetics, anatomy, biomechanics, and advanced computational approaches are expected to improve individualized performance optimization while enhancing musculoskeletal health and functional capacity across athletic and general populations.

KEYWORDS: musculoskeletal performance, sports genomics, exercise adaptation, physical fitness, precision sports medicine

INTRODUCTION

Functioning of the musculoskeletal system serves as the foundation for any kind of activity that can be undertaken by people, from simple daily activities to competitive sport events. Functioning of bones, muscles, tendons, ligaments and nervous system allows to generate, transfer and control forces required for locomotion, stabilization and sport maneuvers. Biomechanics as a science is providing essential information on the effect of mechanical forces on the efficiency of movement, loads on tissues and performance outcomes; hence it is considered to be the basis for physical fitness and athletic capability evaluation [1]. Further development of the research has shown that the functioning of the musculoskeletal system is the result of complex biological processes.

New technologies have greatly changed the analysis of human performance by combining biomechanics, computer modeling, digital health, and artificial intelligence. Newer technologies like digital twin allow for the integration of physiological, biomechanical and environmental data to simulate the individual response to training, injury and rehabilitation. These innovations provide an unprecedented opportunity to optimize performance in a personalised manner and to predict and recover from injuries [2]. Likewise, improvements in the evaluation of muscle function have furthered the knowledge of how muscles generate force, how they are coordinated to act as a unit and how they are strong in the first place, and how they become stronger when challenged by exercise [3].

Concurrently, there has been great advances in molecular genetics which have identified that genetic variation plays a significant role in individual differences in musculoskeletal traits, exercise responsiveness and athletic potential. From studying just one or a handful of candidate genes, sports genomics has advanced to genome-wide association studies, polygenic risk assessments and multi-omics analyses, which indicate that phenotypes related to sports performance are caused by the interplay between many genetic variants and environmental factors [4]. Building on these discoveries, next-

generation sports medicine is coming with the use of genomics, transcriptomics, metabolomics and digital health technologies, to enable precision exercise prescription, exercise individualization and long-term athlete health management [5].

In addition to genes, there is increasing evidence to show that other factors, such as nutrition, metabolism, endocrine regulation and physiological adaptation interact with genes to determine athletic performance. These systems are interdependent and can integrate together to better understand how exercise adaptations occur and why personalized training and recovery is important [6]. Moreover, the field of sports physiology has seen continuous evolution over time, with the advent of new technologies and research in the field of exercise science, wearable technology, and personalized monitoring systems that allow for evidence-based decision-making within the context of both recreational and elite sports [7].

Despite these advances, there is still a lot of difference in people's responses to exercise training, vulnerability to musculoskeletal injuries and attainment of elite performance. These differences are not just due to genetics or anatomy but are an interplay of each of these and the additional factors of environmental exposures, lifestyle and training history. Hence, for musculoskeletal performance in health, fitness and sport, an integrated approach in studying the genetic and anatomical determinants is necessary. In this review, we summarize the existing evidence on these determinants, examine their roles in physical fitness and adaptations to exercise, review their use in the field of sports and precision medicine, and consider future research directions that could impact personalized exercise science.

2. Genetic Determinants of Musculoskeletal Performance

Musculoskeletal performance is a multifactorial phenotype, where the interaction among a number of genetic variants, environmental exposures and training stimuli play a role. The heritability of traits like muscle strength, aerobic capacity, power output, flexibility and susceptibility to injury is moderate to high, with expression, however, significantly influenced by lifestyle factors and exercise history, as evidenced by twin and family studies. As a result, the importance of the continuous dialogue between genetic predisposition and environmental factors such as quality of coaching, nutrition and training has been recognized in the achievement of athletic success, rather than recognizing the athlete as simply a product of their genetics [8].

Sports genetics has progressed from the study of individual candidate genes towards the study of complex architectures of polygenes. Current evidence suggests that there are hundreds of genetic sites that play a small part in performance aspects, with their combined effects influencing muscle fibre type, cardiovascular function, energy metabolism, motion co-ordination and recovery ability. All genes linked to variants in structural proteins, mitochondrial function, angiogenesis, inflammation and connective tissue remodeling contribute to individual responses to the various types of exercises and responses to long-term training [9]. The results show that the genetic makeup of elite athletes is far too complex to be determined by any one gene; therefore, whole-genome screening is important.

There have been significant advances in the understanding of exercise biology with the incorporation of genome-wide association studies (GWAS), polygenic risk scores and multi-omics technologies. Today, the modern sports genomics is about integrating the information of the genome, transcriptome, proteome and metabolome in order to describe the pathways involved in physical performance. These methods can aid in determining biological markers of endurance, strength, recovery and resilience, and in creating customizable exercise interventions that align with each person's genetic makeup [10]. On the back of these developments, there is a recent trend towards multi-trait genetic panels, which are used to assess training response in conjunction with rehabilitation potential and long-term disease protection. While these methods demonstrate good clinical potential, their use in everyday practice needs to be further verified in a variety of populations and sports modalities [11].

The genetic control of musculoskeletal performance is not limited to muscle contractile proteins, but also involves signalling molecules which coordinate communication between skeletal muscle and the nervous system. Myokines, or muscle-derived factors, control metabolic adaptations, motor neuron characteristics and neuromuscular efficiency during exercise. These molecular interactions help to improve oxidative metabolism, endurance capacity and functional adaptations after repeated physical activity [12]. Similarly, genes involved in the synthesis of collagens, extracellular matrix organization and connective tissue remodeling also impact tendon and ligament integrity which impact force transmission, joint stability, and predisposition to musculoskeletal injuries [13].

There is also growing evidence that the adaptations resulting from exercise are not due to the actual alteration of DNA sequence but rather to epigenetic changes. Exercise alters DNA methylation, histone modifications and non-coding RNA expression, leading to dynamic changes in the expression of genes involved in muscle growth, mitochondrial biogenesis, inflammation and tissue remodeling [14]. These reversible molecular changes are likely to play a role in exercise memory, and may account for some of the variation in training responsiveness that is observed across the lifespan. Moreover, epigenetic changes associated with exercise have become a subject of growing interest, alongside their possible role in healthy ageing processes, musculoskeletal function and to minimise risk of functional decline with age; this further solidifies the argument that both genetic and environmental factors play a role in determining musculoskeletal function [15]. The main genetic and epigenetic mechanisms that influence musculoskeletal performance are listed in Table 1. There is evidence that suggests that several genes are involved in determining an athlete's performance and that these genes interact with environmental factors and training.

Table 1. Major genetic and epigenetic determinants of musculoskeletal performance

Genetic factor	Primary biological function	Influence on musculoskeletal performance	Clinical/Sports relevance	Sources
----------------	-----------------------------	--	---------------------------	---------

Polygenic architecture	Combined action of multiple genes	Influences strength, endurance, power, and trainability	Explains individual variability in athletic performance	[8–10]
Muscle growth regulatory genes	Regulate muscle development and protein synthesis	Affect muscle mass, hypertrophy, and regeneration	Relevant for strength and resistance training adaptation	[9–11]
Metabolic genes	Control mitochondrial function and energy metabolism	Improve aerobic capacity and fatigue resistance	Important for endurance performance	[9,10]
Connective tissue-related genes	Regulate collagen synthesis and tissue remodeling	Influence tendon stiffness and injury susceptibility	Useful for injury prevention strategies	[11,13]
Exercise-induced epigenetic mechanisms	Modify gene expression through DNA methylation and histone regulation	Enhance exercise adaptation, recovery, and muscle remodeling	Basis for personalized exercise prescription	[14,15]

3. Anatomical Determinants of Musculoskeletal Performance

Anatomical characteristics represent the structural bases of musculoskeletal performance, which affects the efficiency of force generation, transmission and control in movement. While it is accepted that training can change a number of anatomical characteristics, inherited skeletal structure, muscle architecture, connective tissue characteristics, body composition and neuromuscular organization determine the mechanical capacity for physical performance. These characteristics vary between people, thus affecting their strength, power, endurance, movement economy and risk of injury.

One of the main anatomic factors that affect the mechanics of movement is skeletal morphology. Mechanics of locomotion and sport-specific activities are influenced by bone geometry, joint configuration, limb proportions and pelvic architecture, which in turn influences leverage and joint stability. The difference exists in terms of the anatomy between the two sexes, where the difference will be noted in such areas as the size of the pelvis, the angles of limbs, joints mobility, and muscle placement. Such differences in anatomy play an important role concerning the body loading process, the movement technique, as well as the risks associated with the occurrence of musculoskeletal injuries and have to be considered while working out and rehabilitation [16]. Also, there is a strong connection between the alignment of the spine and the pelvis that changes considerably depending on the person's age. The alteration in the thoracolumbar sagittal alignment will affect such aspects as posture, balance, weight-bearing capacity, and movement mechanics, resulting in the development of musculoskeletal degenerative disease [17]. Finally, new possibilities offered by three-dimensional anatomical modeling proved that there is a great difference in the form and orientation of the female sacrum [18].

The second important factor, which influences the physical performance of a person, is the architecture of the muscle. The development of force and velocity of muscle contraction depends on such elements as the length of muscle fibers, physiological cross-section of muscles, the pennation angle, muscle volume, and the site of tendon insertion. Thus, the bigger the physiological cross-section of muscles (PCSA) is, the more the force will be generated. However, the longer the fascicle is, the faster shortening and movement of the muscle take place. It was revealed through detailed investigation of anatomy of hamstrings that there are great differences in fascicle arrangement and muscle architecture, which corresponds to different functions of these muscles in sprinting, jumping, and braking. Thus, it is clear that the architecture of the muscle influences its mechanical properties and must be taken into consideration while developing training programs aimed at a certain sport [19].

In addition to this, the mechanical properties of tendons, ligaments, and other types of connective tissues play an essential role in the performance of the musculoskeletal system. The connective tissues transmit the forces produced by muscles to bones and help store and release the elastic energy. The mechanical properties of the tissue greatly depend on the extracellular matrix composition, which includes fibrillar collagen and proteoglycans and helps regulate the stiffness, elasticity, and mechanical load of the tissue. Good CT structure contributes to efficient movement, while poor structure causes overuse injuries [20].

Body composition also plays a role in the musculoskeletal function through its impact on force production and economy of movement. In general, lean muscle mass is associated with higher strength and power production while overweight/obesity could lower mechanical efficiency and increase loading of the joints. Further, there is a strong relationship between regional body composition (and in particular between appendicular lean mass) and bone mineral density, which indicates the interdependency between skeletal muscle and bone adaptation. Thus, a good body composition will benefit the athlete, as well as the maintenance of healthy skeletal structures and injury prevention in the long-term [21].

The ability to function effectively musculoskeletal systems is the ultimate integration of the anatomy with the nervous system. The coordinated interaction of upper and lower motor neurons, peripheral nerves, neuromuscular junction and skeletal muscle results in motor control. Motor unit activation, synchronization and firing rates are regulated by neural recruitment patterns, which affects muscle strength, precision of movement, balance and coordination. Appropriate neuromuscular control allows for the successful execution of complex motor skills with minimal wasted movement, energy and risk of injury [22].

All of the above features (skeletal morphology, muscle architecture, connective tissue characteristics, body composition, neuromuscular organization) are interrelated and together create the anatomical basis for an individual's mechanical ability to move. Knowledge of these structural determinants gives an important foundation for interpreting the variance in physical fitness, exercise adaptation, athletic performance and musculoskeletal injury risk. The main anatomical factors

determining the performance of the musculoskeletal system are shown in Figure 1. The forces that are produced and the efficiency of the movement and risk for injuries are impacted by various factors, including the skeletal morphology, muscle architecture, connective-tissue properties, body composition, and neuromuscular control.

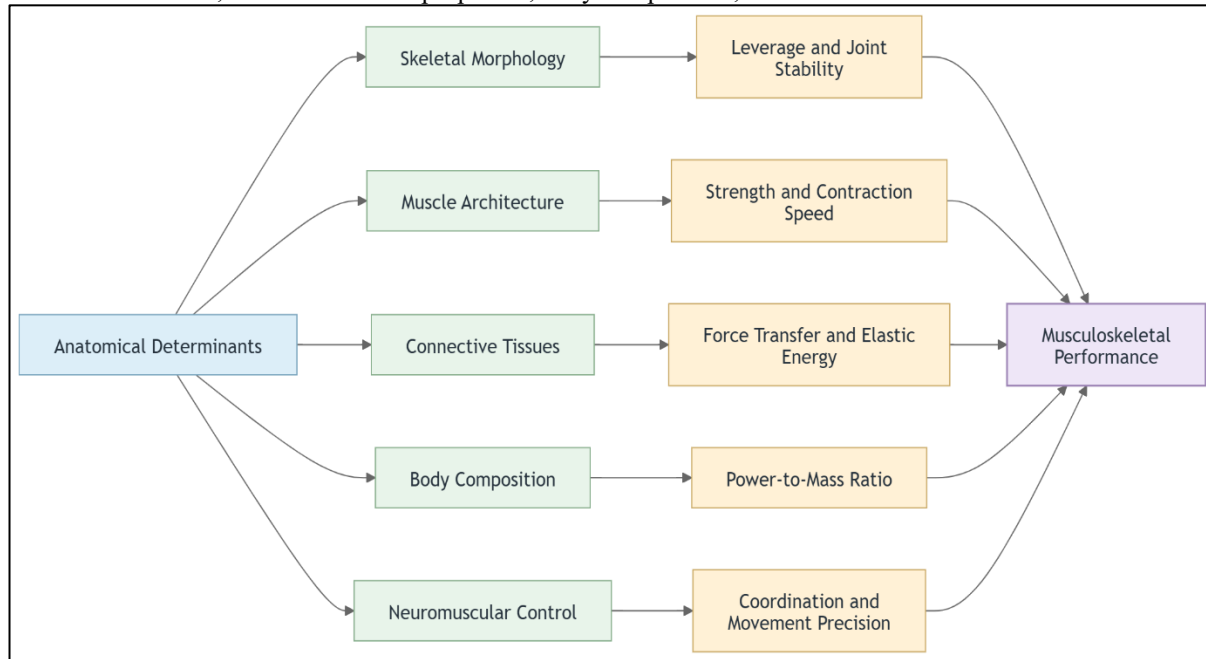


Figure 1. Anatomical determinants of musculoskeletal performance.

4. Interaction Between Genetics and Anatomy

Musculoskeletal performance is not dependent on either genetic regulation or anatomical development, but is the result of an ongoing relationship between the two. Bones, muscles, tendons and connective tissues develop, grow and maintain according to genetic information, which is modified by mechanical loading, nutrition, hormonal status and physical activity throughout the life course. This reciprocal relationship is the reason why there can be significant variation in the structural adaptations and performance of people with similar training programs.

Many genes control the growth and development of muscle and skeletal tissue, including the proliferation, differentiation and maturation of the tissues. These genes have an effect on myogenesis, which is regulated by their role in satellite cell activation, muscle fiber formation, protein synthesis, and tissue remodeling, affecting muscle size, muscle protein composition, and muscle regeneration. While much of the evidence for these mechanisms comes from animal studies, many mechanisms are evolutionarily conserved and can offer valuable insight into the biological mechanisms involved in human skeletal muscle development and adaptations [23]. Thus, environmental influences act on an inherited genetic variation that sets up the structural environment.

Another example of close relationship between genetics and anatomy is bone morphology. Skeletal structure is influenced by genetics, as well as by physical activity and muscle activity throughout life. Weight-bearing exercise helps stimulate the activity of osteoblasts and promotes skeletal strength and bone mineralization by processes of adaptation and remodeling. The extent of these adaptations is related to the level of mechanical stimulation as well as the ability of the individual to control bone formation and repair, which indicates that there is an interaction between genetics and environment [24]. These are similar mechanisms for the age-related skeletal adaptation, which is genetically regulated and physical activity is an important determinant of bone quality and skeletal structure throughout adulthood [25].

Mechanical loading also has a complex molecular mechanism of action for bone adaptation which coordinates the communication between bone cells, skeletal muscle and connective tissue. Mechanical strain stimulates mechanosensitive receptors and intracellular signaling pathways that stimulate osteogenesis and inhibit hyper-resorption of bone. Such adaptive responses diminish over time with aging and osteoporosis, and cause a decline in the resilience of the bones and an increase in fracture risk. However, the right kind of exercise is still one of the most powerful physiological cues to keep the skeletal system healthy through regulation of these molecular mechanisms and a favorable structural remodeling process [26].

The recent developments in systems biology also serve to reinforce that musculoskeletal adaptation be thought of as a biological network rather than as individual molecular events. The use of multi-omics analysis is based on the integration of genomic, transcriptomic, proteomic and metabolomics analysis combined with computer modeling to reveal the regulation of complicated biological processes involved in tissue formation and adaptation. Although these techniques have been widely used in other areas of biology, they can provide some important ideas for studying the regulation of musculoskeletal tissues in humans. The use of integrative computational techniques could be very helpful in revealing biological pathways and the link between genetic diversity and phenotypic features of anatomy and response to physical activity [27].

Generally speaking, the biology behind the musculoskeletal performance is genetics/anatomy. The properties of the structure result from the genetically regulated processes of development and are affected by mechanical load and environment in a highly significant way. It is important to understand the interplay between these factors to get an insight into the reasons for the individual variations in terms of physical fitness, adaptation to exercises, injury proneness and

athletic performance. Table 2 presents the interplay between genetic regulation and anatomical adaptation and their influence on musculoskeletal development.

Table 2. Interaction between genetics, anatomy, and environmental factors

Biological component	Genetic regulation	Environmental influence	Functional outcome	Sources
Skeletal muscle	Controls muscle fiber formation and growth	Exercise, nutrition, hormones	Muscle size and functional capacity	[23]
Bone tissue	Regulates bone formation and remodeling	Weight-bearing physical activity	Bone strength and mineral density	[24–26]
Mechanotransduction	Activates cellular signaling pathways	Mechanical loading during exercise	Skeletal adaptation and structural remodeling	[24–26]
Aging process	Alters remodeling efficiency	Regular exercise delays decline	Preservation of musculoskeletal function	[25,26]
Multi-omics integration	Coordinates biological pathways across tissues	Lifestyle and environmental exposure	Individual differences in exercise adaptation	[27]

5. Implications for Physical Fitness and Exercise Adaptation

Physical fitness can be considered a multidimensional concept including muscular strength, muscular endurance, flexibility, power, coordination, and cardiorespiratory fitness. The degree to which these variables are increased through exercise is based on the combination of a person's genetic makeup, anatomy, previous experience, and environment. While exercise will increase musculoskeletal performance in any individual, there is a high degree of variability in the amount and rate of improvement possible.

Muscular strength and endurance constitute two of the most trainable aspects of physical fitness. Resistance training leads to muscle hypertrophy, neuromuscular adaptations, and restructuring of connective tissue that ultimately lead to better force generation and fatigue resistance. It has been shown that through strength-training exercises that include exercises for the core muscles and progressive resistance training, muscular strength, endurance, and flexibility are greatly increased in young athletes. Core stabilization makes the force generated by the upper body and lower body efficiently transferred between each other during exercise [28].

Muscle flexibility, stability of posture, and endurance can also be achieved using alternative methods of exercise. The mind-body techniques like Tai Chi have been shown to enhance muscle strength, balance, flexibility, and physical endurance through the incorporation of coordinated movement with neuromuscular coordination and stabilization of posture. Such adaptations are especially significant in terms of injury prevention, healthy aging, and performance, indicating that exercise-based musculoskeletal adaptations do not necessarily have to rely on traditional forms of exercise. Exercise specificity is an important factor in terms of adaptation. Programs that have been created specifically to address sport-related movement have better outcomes than those programs that are general in nature. As an example, kinetic chain strength training helps improve the proximal core endurance, the transmission of power from the trunk to the arm and the bat swing speed. This proves how improvements in the functional anatomy and neuromuscular coordination result in improved athletic performance [29].

Although many positive effects of physical activity have been confirmed, people do not react to the same training regimen in the same way. Scientific evidence has found that there were "responders" and "non-responders." It means that adaptation to exercises depends on such factors as genetic predispositions, initial physical fitness level, age, gender, nutrition, recovery, and commitment to the training program. Non-response does not mean the total lack of adaptation; it can indicate the lack of training stimulus, wrong exercise prescription or differences in physiology [30].

The concurrent training program, which includes the combination of resistance and endurance training in one training session, is an appropriate method for improving the performances of athletes involved in complex sports. Scientific studies have revealed that a proper organization of the concurrent training program allows one to improve the strength, power, cardiorespiratory fitness, and sport-related skills of the athletes without any problems associated with interference of physical activities [31].

Further research has also shown that concurrent training at relatively low volumes but very high intensities is highly effective for improving physical fitness and physiological robustness. This is especially beneficial in situations where the amount of time available for training is minimal, yet physical readiness is essential, such as in the military, occupation, and sports. These results support the concept that training quality and individualized programs may matter more than training volumes in terms of musculoskeletal adaptations and performance benefits [32].

In general, the process of exercise adaptation is regulated by the interactions between biological characteristics and training variables. The knowledge about the processes behind such biological differences can be used for an accurate prescription of physical exercises, which will help achieve maximum physical fitness while reducing the risk of injuries. As is seen from Figure 2, exercise adaptation is the result of the interaction between the biological characteristics of a person and training variables.

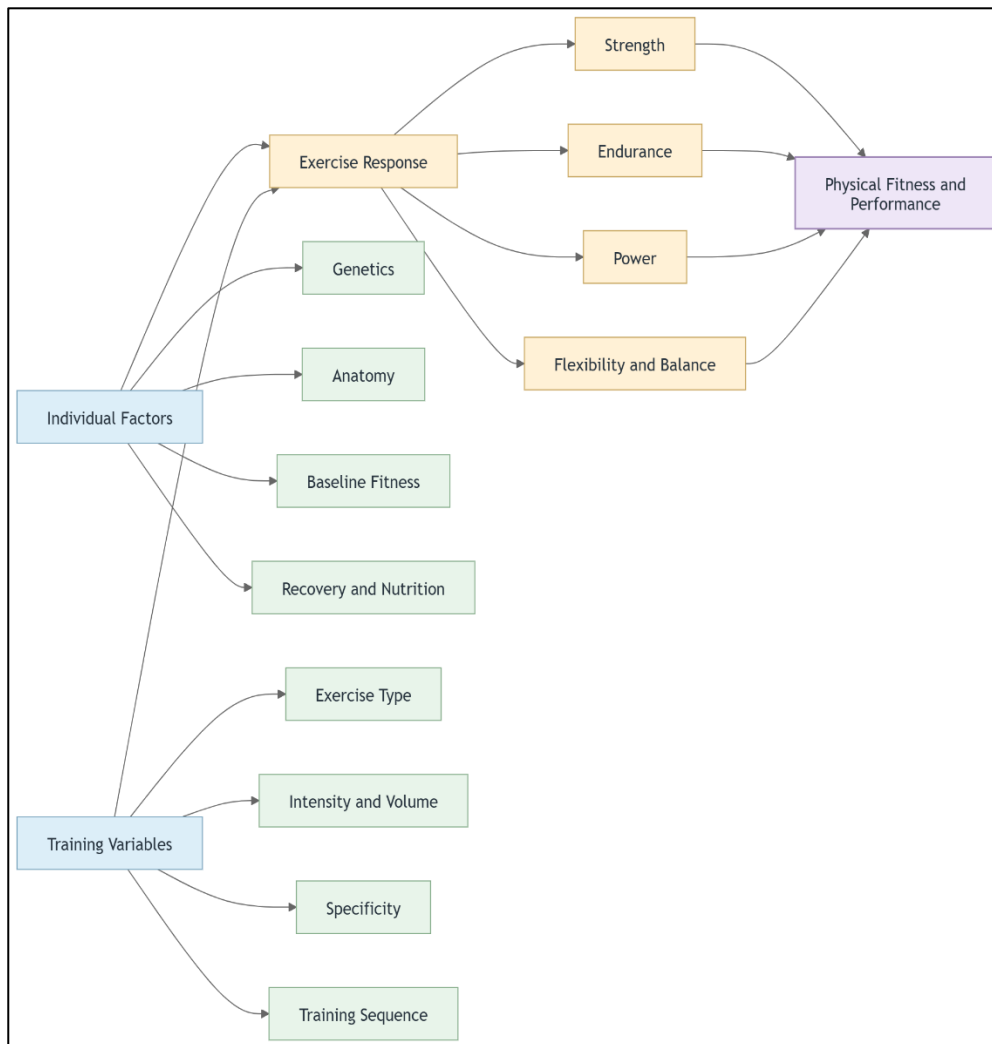


Figure 2. Integrated determinants of physical fitness and exercise adaptation.

6. Applications in Sports Performance

By combining genetics, anatomy, physiology and technology, the way in which we approach sports performance is radically changed and we can now do more tailored approaches to athlete development. Today, instead of only following standard training programmes, the importance of evidence-based strategies that take into account individual athlete structural, functional and adaptive capabilities is stressed. This individualized approach not only enhances performance, but also helps to minimize the risk of injury and promote long-term athletic development.

The importance of sport-specific training is a solid foundation of performance enhancement as physiological adaptations are greatly affected by the requirements of the sport activity. Youth soccer training programs targeting the development of technical skills and/or small sided games have been shown to markedly improve speed, agility, endurance and technical skills. The choice of training methods however, should be related to the developmental status of the athlete, tactical aims, and physical needs to maximize performance gains. Similarly, repeated sprint training has been shown to be beneficial in sports that require repeated high intensity sprints. Structured programs of sprint based exercises led to an enhancement of aerobic endurance, anaerobic power, agility and explosive strength in collegiate badminton players, showing how specificity of exercise in sports can enhance performance [33].

In addition, optimal sports performance is dependent on a healthy nutritional status as body composition, available energy and hydration, and micronutrient balance directly impact training adaptations, recovery, and injury resistance. Whilst identifying the deficiencies and understanding the potential impact on musculoskeletal function or athletic readiness is difficult, comprehensive nutritional assessment frameworks can help practitioners. The use of nutritional evaluation coupled with physical and physiological monitoring will lead to a more comprehensive assessment of athlete health and capacity to perform [34].

The use of digital technologies has improved recently and these have helped speed up the delivery of personalised training programmes. Machine learning algorithms, coupled with wearable devices and smartwatches, can track body reaction, activity levels, and indicators of recovery that can continuously be used to modify exercise prescription based on individual activity trends. Such systems provide real-time feedback, improve training compliance, and support evidence-based decision-making, thereby ensuring their vital importance for precision sports science [35]. The same approach becomes relevant in the field of rehabilitation when designing personalized exercise regimes in relation to characteristics of the disease, functional impairments and molecular reactions. Precision rehab consists in the optimization of the intensity and dynamics of exercise in relation to biological and clinical profile of the patient, which ensures maximum functional recovery and effectiveness of the treatment [36].

Injuries' prevention and rehabilitation have become equally important questions for sports performance. The repeated injuries to lower extremities suffered by athletes involved in competitive sports have become an essential issue since insufficient recovery, improper loading and unloading and premature return to training and competition considerably increase the likelihood of injuries. Current evidence favors comprehensive rehabilitation protocols that account for biomechanical assessment, progressive strength training, neuromuscular training, sports-specific loading and retraining, and objective criteria for return to play to minimize re-injury and maximize optimal return to play [37].

Moreover, the budding science of sports genomics is also responsible for managing the athlete through genetics in that they affect the probability of the occurrence of musculoskeletal injury, high-performance capabilities, and response to training. However, while no one would want to rely purely on genes in identifying talent and choosing athletes for teams, it can be used in conjunction with other physiological, anatomical, and functional evaluations to determine the training and injury prevention programme. Genes have shown variations amongst soccer players depending on the performance characteristics and injury proneness and hence indicating that sports success is not only determined by genetics but also through physiology, training, and environment [38].

In conclusion, precision medicine approaches and integrative strategies involving sport-specific training, nutrition, technology, rehabilitation, and genomics are increasingly prevalent in modern sport performance. Such multidisciplinary strategies represent a more holistic approach to achieving high performance, prolonging the life of the athlete, and reducing the chances of injury. The applications of personalized musculoskeletal assessment in sports performance are presented in Table 3. Physiological, nutritional, technological, and genetic data can be used to complement evidence-based management of the athlete.

Table 3. Practical applications of personalized assessment in sports performance

Application	Assessment focus	Practical benefit	Sources
Sport-specific training	Strength, agility, endurance, movement skills	Improves performance according to sport demands	[33]
Nutritional assessment	Body composition, dietary intake, hydration	Optimizes recovery and physical performance	[34]
AI and wearable technologies	Training load, physiological responses, recovery	Enables personalized exercise monitoring	[35-36]
Precision rehabilitation	Functional capacity and clinical status	Improves recovery and individualized exercise prescription	[37]
Return-to-play and genetic assessment	Injury risk, tissue healing, genetic predisposition	Supports safer rehabilitation and individualized athlete management	[38]

7. Emerging Technologies and Future Perspectives

The field of sports science is undergoing transformation thanks to technological advancements, which now incorporate biomechanics, artificial intelligence (AI), wearable devices, and computer modeling into the monitoring and optimization of athletes' performance. These developments enable parameters of physiology and biomechanics to be assessed on a continuous basis, which helps practitioners to leave general training programs behind and move towards precision-based training, taking into account the individual differences. Digital technologies are expected to take talent development, injury prevention, rehabilitation, and long-term athlete management to the next level as they become more advanced.

One of the major breakthroughs in the field of sports medicine has been the proper use of integrated rehabilitation approaches based on objective assessment of the patient's performance. Improvements in biomechanical analysis, neuromuscular and functional tests have led to better decision-making processes regarding the return to playing for athletes after their musculoskeletal injuries. Progressive overload, movement analysis and sport-specific functional tests are used in comprehensive rehabilitation programs to ensure safe and smooth return to play of an athlete, avoiding the risk of re-injury while developing the physical condition of the athlete before return to play.

AI is another tool that has helped sports medicine to move forward and develop due to its ability to perform a quick analysis of large sets of complicated data. The machine learning algorithms will reveal the relationships between different biomechanical variables, physiological responses, medical history and training loads which would be impossible for conventional statistics to identify. Such models would help to detect athletes who are likely to get an injury at a very early stage and prevent the development of such an injury through precautionary measures [39].

A further possible direction of personalized sports science includes the emergence of digital twin technology for humans. Digital twin is a dynamic model of an athlete created by using data from motion capture, biomechanical modeling, physiological indicators, and sensor data. They are able to help in simulating movement patterns, conducting tests and training interventions, predicting the biomechanical response to different situations without exposing an athlete to any physical stress. Such technologies have already been proven to be useful in the design of individual training programs, rehabilitation and improving athletic performance [40].

Outside of sports applications, a number of advances in AI in the health care industry are helping to usher in precision exercise medicine. AI systems are becoming more capable of integrating clinical records, imaging data, wearables' output, genetic data, and physiology measurements to help make personalized clinical choices. These technologies have potential to utilize in sports medicine for individual exercise prescription, constant monitoring of health condition, and early discovery of health problems that are likely to affect performance. However, to achieve desired outcomes, there is a need for thorough validation, collaboration among various disciplines, and careful application and understanding of the algorithm's suggestions in clinical and sports settings.

These new technologies have significant ethical and legal issues, but they also have great potential. The vast amount of data collected and analyzed with athletes also raises issues with athlete privacy, informed consent, data ownership, cybersecurity, and algorithmic bias. Additionally, the availability and use of these advanced analytical tools might result in disparities in competitive sports, and over-trusting in predictive technology could impact athlete selection and opportunities. Transparent regulation of technology and ethical guidelines are thus needed to ensure that technology contributes to the well-being of athletes while maintaining fairness, integrity, and public trust in sport [41].

In conclusion, this newfound synergy between artificial intelligence, digital twins, motion analysis and precision health in sports is shaping the future of sports science. These technologies could revolutionize the improvement of athletic performance as well as the optimization of rehabilitation and minimisation of the risk of injury by providing very personalised interventions. Ongoing investigations, ethical oversight, and careful application will all play significant roles in developing safe, effective, and fair applications of these innovations for athletes and physically active populations. Figure 3 shows a precision sports-science paradigm where wearable sensors, artificial intelligence, motion analysis and digital twins are used to translate the data of the athlete into personalized decisions for training, injury prevention, and recovery.

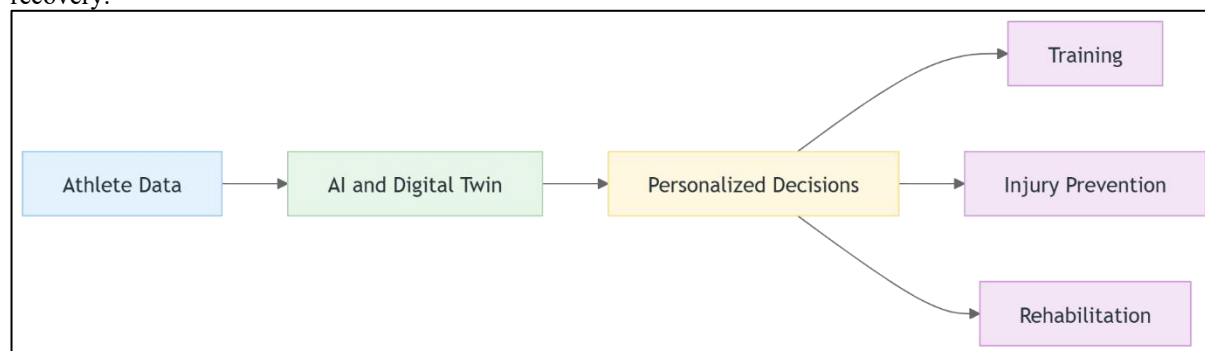


Figure 3. Emerging technology framework for precision sports science.

8. Current Challenges, Knowledge Gaps, and Future Research Directions

Although there has been significant advances in sports genomics, and musculoskeletal research, a number of methodological and translational issues still hinder the implementation of available knowledge in clinical practice and sports. Main concerns involve the bias that could be introduced into genomic research due to the lack of population diversity, variability in phenotype definitions, and lack of sample size, as well as underrepresentation of specific demographic groups. These restrictions diminish the applicability of the genetic results and highlight the importance of more comprehensive and uniform research designs [42].

The other problem is that of non-standardized longitudinal data which can integrate data on genetics and anatomy, physiology, biomechanics, and medicine. The role of standardized data structures in improving the reproducibility of scientific studies, for multicenter studies, and the creation of predictive models for adaptation and the risks of injuries in the long term, and musculoskeletal health are discussed in this essay [43]. Furthermore, the influence of molecular quantitative trait loci and sex-specific differences in biology needs to be taken into account as they may explain the performance of an individual, recovery capacity and vulnerability to disease.

Moreover, future studies need to follow a more holistic approach by linking genomic information with other components of the exposome including the exposure itself, nutrition, lifestyle and other variables [44]. The use of these approaches for translation will assist in increasing our knowledge on the relationship between genes and environment and also facilitate faster development of precision exercise medicine using individual biological and environmental information [45]. Multimodal diagnostic techniques (such as imaging, functional assessment, biomarkers, wearables and omics technologies) offer future approaches to the early diagnosis of sarcopenia, frailty and musculoskeletal conditions limiting performance.

In the future, large, ethnically diverse longitudinal cohorts with standardized phenotyping approaches, multi-omics analyses, and sophisticated computational analysis should be sought to improve the translation of basic science to practical applications in sports performance, rehabilitation, and precision musculoskeletal medicine.

9. CONCLUSION

The musculoskeletal function is a highly complicated phenotype, which includes a combination of genetic, anatomical features, adaptation and environment. The anatomical factors are responsible for the mechanical effectiveness of movement, muscle strength and endurance, while the genetic ones determine the muscle structure, connective tissue condition and reaction to exercise training. Both the biological features are affected by training, nutrition, aging and lifestyle, pointing at the necessity of adopting a holistic approach to it. Precision medicine for athletes is now within reach due to such innovations as genomics in sport, multi-omics methods, artificial intelligence, wearable technology and digital twins. Nevertheless, there are serious limitations in the currently available literature because of the methodological issues, differences in study designs, as well as lack of longitudinal studies, thus emphasizing the importance of standardization of phenotyping and population-based studies of various types. Further research involving genetics, anatomical, biomechanical and sophisticated computer analysis might assist in the progress of understanding the variations between fit individuals and individuals adapted to exercise. This research would help in improving the performance of athletes and also give insight into developing individual health care programs for ensuring musculoskeletal fitness and functionality.

REFERENCES

1. Devar M. Core concepts of biomechanics. Educoback Press; 2025 Feb 20.
2. Sédiri A, Barbaria S, Ceylan H, De Giorgio A, Puce L, Stefanica V, Bragazzi N, Dergaa I, Rahmouni H. Digital twins in sports science: applications for performance enhancement, injury prevention, and rehabilitation through advanced big data analytics and deep learning methodologies—a comprehensive narrative review. *Biology of Sport*. 2025;43(1):1271-91.
3. Rios IJC. Introduction to muscle strength and force in sports science. In: *Functional Electromechanical Dynamometry*. Routledge; 2025. p. 3-22.
4. Ginevičienė V, Utkus A, Pranckevičienė E, Semenova EA, Hall EC, Ahmetov II. Perspectives in sports genomics. *Biomedicines*. 2022;10(2):298.
5. Juginović A, Kekić A, Aranza I, Biloš V, Armanda M. Next-generation approaches in sports medicine: the role of genetics, omics, and digital health in optimizing athlete performance and longevity—a narrative review. *Life (Basel)*. 2025;15(7):1023.
6. Spanakis M, Fragkiadaki P, Renieri E, Baliou S, Fragkiadoulaki I, Vakonaki E, et al. Exploiting interrelated genomic, biochemical, nutritional and pathophysiological data to optimize athletic performance. *World Acad Sci J*. 2025;7(4):52.
7. Saadati SA. Recent innovations in sports physiology: shaping the future of athletic performance. 2023.
8. McAuley AB, Baker J, Kelly AL. How nature and nurture conspire to influence athletic success. In: *Birth Advantages and Relative Age Effects in Sport*. Routledge; 2021. p. 159-183.
9. Semenova EA, Hall EC, Ahmetov II. Genes and athletic performance: the 2023 update. *Genes (Basel)*. 2023;14(6):1235.
10. Imperatore A, Mennitti C, De Fonzo G, Amitrano R, Gentile A, Calvanese M, et al. Toward a multi-trait genetic panel targeting training, rehabilitation, and chronic disease prevention: a narrative review. *Genes (Basel)*. 2025;16(11):1309.
11. Correia JC, Kelahmetoglu Y, Jannig PR, Schweingruber C, Shvaikovskaya D, Zhengye L, et al. Muscle-secreted neurturin couples myofiber oxidative metabolism and slow motor neuron identity. *Cell Metab*. 2021;33(11):2215-2230.
12. Al Makhzoomi AK. From anatomy to pathology: an evidence-based guide to ligament, tendon and fracture evaluation. 2026.
13. Zheng X, Liu X, Guo Y, Lv Y, Lin C, Wang D, et al. Physical exercise and epigenetic modifications in skeletal muscle, brain, and heart. *Epigenetics Chromatin*. 2025;18(1):12.
14. Yang Q, Hu Y, Zhang B, Hong W. Exercise-induced epigenetic modifications: implications for healthy aging. *Int J Sports Med*. 2025.
15. Petrie KA, Burbank K, Sizer PS, James CR, Zumwalt M. Considerations of sex differences in musculoskeletal anatomy between males and females. In: *The Active Female: Health Issues Throughout the Lifespan*. Cham: Springer International Publishing; 2023. p. 3-24.
16. Prost S, Charles YP, Ilharreborde B, Riouallon G, Pesenti S, Blondel B. Thoracolumbar sagittal shape varies with pelvic morphology and aging. *Spine (Phila Pa 1976)*. 2023;48(24):1726-1732.
17. Van Hauwermeiren L, Audenaert E, Van Houcke J, Matthews H, Claes P, Delrue L, et al. A statistical shape model of the human female sacrum: an integrative analysis of form. *J Anat*. 2026.
18. Takeda K, Kato K, Ichimura K, Sakai T. Unique morphological architecture of the hamstring muscles and its functional relevance revealed by analysis of isolated muscle specimens and quantification of structural parameters. *J Anat*. 2023;243(2):284-296.
19. Silver FH, Kelkar N, Deshmukh T. Molecular basis for mechanical properties of ECMs: proposed role of fibrillar collagen and proteoglycans in tissue biomechanics. *Biomolecules*. 2021;11(7):1018.
20. Lin Y, Wang X, Wu R, Zhou J, Feng F. Association between segmental body composition and bone mineral density in US adults: results from the NHANES (2011–2018). *BMC Endocr Disord*. 2023;23(1):246.
21. de Carvalho M, Swash M. Upper and lower motor neuron neurophysiology and motor control. In: *Handbook of Clinical Neurology*. Vol. 195. Elsevier; 2023. p. 17-29.
22. Mohammadabadi M, Bordbar F, Jensen J, Du M, Guo W. Key genes regulating skeletal muscle development and growth in farm animals. *Animals (Basel)*. 2021;11(3):835.
23. Nowak A, Ogurkowska M. Bone health and physical activity: the complex mechanism. *Aging Dis*. 2024;16(6):3400.
24. Valeria C, Costa V, Daniele B, Veronesi F, Simona C, Milena F, Gianluca G. Bone's response to mechanical loading in aging and osteoporosis: molecular mechanisms. *Calcif Tissue Int*. 2020;107(4):301-318.
25. Kundu BK, Tanti B. Decoding plant physiology through systems biology: integrative multi-omics and computational perspectives for next-generation crop design. *Plant Commun*. 2026;7(3).
26. Kumar R, Zemková E. The effect of 12-week core strengthening and weight training on muscle strength, endurance and flexibility in school-aged athletes. *Appl Sci*. 2022;12(24):12550.
27. Wehner C, Blank C, Arvandi M, Wehner C, Schobersberger W. Effect of Tai Chi on muscle strength, physical endurance, postural balance and flexibility: a systematic review and meta-analysis. *BMJ Open Sport Exerc Med*. 2021;7(1).
28. Palmer TG, McCabe M. The effect of a novel weight-supported kinetic chain resistance training program on proximal core muscular endurance, trunk-to-arm muscular power, and bat swing speed. *J Strength Cond Res*. 2023;37(11):2130-2140.
29. Mattioni Maturana F, Soares RN, Murias JM, Schellhorn P, Erz G, Burgstahler C, et al. Responders and non-responders to aerobic exercise training: beyond the evaluation of. *Physiol Rep*. 2021;9(16):e14951.
30. Seipp D, Quittmann OJ, Fasold F, Klatt S. Concurrent training in team sports: a systematic review. *Int J Sports Sci Coach*. 2023;18(4):1342-1364.

31. Burley SD, Drain JR, Sampson JA, Nindl BC, Groeller H. Effect of a novel low volume, high intensity concurrent training regimen on recruit fitness and resilience. *J Sci Med Sport*. 2020;23(10):979-984.
32. Karahan M. Effect of skill-based training vs. small-sided games on physical performance improvement in young soccer players. *Biol Sport*. 2020;37(3):305-312.
33. Wei C, An J, Lin Y, Yang S, Zhu Q, Zhou L. The effects of 8 weeks of repeated sprint training on aerobic endurance, anaerobic power, agility and explosive strength in college badminton players. *PeerJ*. 2026;14:e21111.
34. Zambrano-Villacres R, Arteaga-Pazmiño C, Guevara Castillo WD, Herrera-Fontana ME, Domínguez Brito LD, Becerra Granados LM, et al. The seven methods for the evaluation of nutritional status—ABCDEFG: a narrative review. *Appl Sci*. 2026;16(2):845.
35. Jubair H, Mehenaz M. Utilizing machine learning algorithms for personalized workout recommendations and monitoring: a systematic review on smartwatch-assisted exercise prescription. *Digit Health*. 2025;11:20552076251355365.
36. Yu YS, Ming H. Personalized rehabilitation exercise effects in chronic diseases: from molecular mechanisms to precise exercise prescription. *Sci Sports*. 2026
37. Murtagh CF, Hall EC, Brownlee TE, Drust B, Williams AG, Erskine RM. The genetic association with athlete status, physical performance, and injury risk in soccer. *Int J Sports Med*. 2023;44(13):941-960.
38. Palermi S, Vittadini F, Vecchiato M, Corsini A, Demeco A, Massa B, et al. Managing lower limb muscle reinjuries in athletes: from risk factors to return-to-play strategies. *J Funct Morphol Kinesiol*. 2023;8(4):155.
39. Musat CL, Mereuta C, Nechita A, Tutunaru D, Voipan AE, Voipan D, et al. Diagnostic applications of AI in sports: a comprehensive review of injury risk prediction methods. *Diagnostics (Basel)*. 2024;14(22):2516.
40. Zhou H, Wang L, Pang G, Shen H, Wang B, Wu H, Yang G. Toward human motion digital twin: a motion capture system for human-centric applications. *IEEE Trans Autom Sci Eng*. 2024;22:619-630.
41. Chong PL, Vaigeshwari V, Mohammed Reyasudin BK, Noor Hidayah BRA, Tatchanaamoorti P, Yeow JA, Kong FY. Integrating artificial intelligence in healthcare: applications, challenges, and future directions. *Future Sci OA*. 2025;11(1):2527505.
42. Najjar MC. Legal and ethical issues arising from the application of data analytics and artificial intelligence to traditional sports. *Alb Law J Sci Technol*. 2023;33:51.
43. Agler CS, Divaris K. Sources of bias in genomics research of oral and dental traits. *Community Dent Health*. 2020;37(1):102-106.
44. Rojas JC, Lyons PG, Chhikara K, Chaudhari V, Bhavani SV, Nour M, et al. A common longitudinal intensive care unit data format (CLIF) for critical illness research. *Intensive Care Med*. 2025;51(3):556-569.
45. Hernangómez Laderas A. Use of molecular quantitative trait loci for the understanding of complex disease sex bias and biomarker discovery. 2025.