

# Athlegentics: Athletic characteristics and musculoskeletal conditions (Review)

NIKOLAOS PANAGIOTOU, ALEXIS SAGONAS, EFFIE SALATA, THANOS FOTIS and ELENI NTOUMOU

iDNA Laboratories, Athens 145 64, Greece

Received November 29, 2024; Accepted March 6, 2025

DOI: 10.3892/wasj.2025.332

**Abstract.** Innovative elite athlete evaluation can now incorporate novel genetic profiling strategies alongside traditional biochemical and modern ergophysiological monitoring. This genotype-empowered approach aims to broadly assess the performance capabilities, risk of injury and recovery needs of elite athletes, in order to effectively reach maximum performance, as well as to achieve successful longevity in the sport. An analysis of the genetic makeup of an athlete delves into specific genetic variations linked to athletic performance, injury susceptibility, musculoskeletal conditions and recovery requirements, thus facilitating personalized training strategies and interventions to maximize the potential of an athlete. Genetic testing can also be combined with a series of diverse traditional and novel phenotypic evaluations, including ergophysiological assessment, biochemical testing, metabolomics profiling, micronutrient analysis, echocardiography and burnout testing, among others, to produce a multidimensional understanding of the health of an athlete. The present review discusses this athlegentics strategy in an aim to pave the way for personalized interventions in training, nutrition and supplementation, for injury prevention, faster recovery and mental well-being support. This scientific approach holds significant promise for enhancing athletic performance and the longevity of an athlete in their associated sport, through evidence-based, personalized interventions that advance sports performance optimization.

## Contents

1. Introduction
2. Athlegentics
3. A combined strategy for athletes
4. Synopsis and future perspectives

---

*Correspondence to:* Dr Nikolaos Panagiotou, iDNA Laboratories, T. Kavalieratou 7, Kifissia, Athens 145 64, Greece  
E-mail: panagiotoun10@gmail.com

*Key words:* sports medicine, genotype, athletic performance, athlegentics

## 1. Introduction

Sports coaches and their organizations constantly aim to improve their practices so that their elite athletes reach their maximum athletic potential, remain healthy, recover from injuries promptly and maintain their ability to perform competitively at the highest level for a long period of time (1,2). Understanding the biology of exercise, including the mechanisms through which the bodies of athletes function, how they respond to different nutrients and supplements, and how they can maintain fitness and avoid injuries, is essential for assisting them achieve their maximum potential (3). Currently, the top organizations in sports use a plethora of equipment to generate metrics, both physiological and biomedical, to assess the current level of performance, nutrient needs, sleep quality, injury risk and recovery status of their athletes. Sports competitiveness is driving further scientific knowledge and breakthroughs constantly making their way within the sports industry to help coaches and organizations achieve this more precisely and accurately (4). Recently, genomics, combined with more traditional metrics, can be leveraged in various sports settings to personalize training regimes, nutrition, supplementation and estimate injury risk associated with musculoskeletal conditions (5,6). Further advancing this notion, other multi-omics-based holistic approaches have been proposed, comprising metabolomics, proteomics, transcriptomics and even microbiome analysis (7).

Analyzing the genetic profile of an athlete, to understand how the body processes nutrients to generate energy can help develop nutrigenetic strategies that personalize diet plans based on the needs of an individual (8). Such genetic information can allow predictions about the performance of elite athletes and their increased needs in different athletic categories; thus, any decisions can be based on what type of exercise, diet, treatments and lifestyle changes may be more effective for preventing musculoskeletal injuries and improving the ability of the athlete to perform at the maximum organismal capacity. This notion is influenced by similar advances employed in personalized medicine approaches to prevent disease and improve overall health (9-11). This genetics-empowered multi-omics approach may be a game-changer in sports medicine, helping athletes perform at their optimal level while remaining healthy in the long run (12).

The present review comprehensively summarizes data from the existing literature on the interplay between genetics

and athletic performance, focusing on the utility of genetics in sports. Analyzing key genetic markers associated with athletic performance, specifically in endurance and power sports, aims to highlight their potential application of genetic testing in optimizing personalized training plans and mitigating exercise-related injury risk.

## 2. Athlegentics

Athlegentics (genetics and sports) is defined as the study of how genetics influence athletic performance, including factors such as endurance, strength, muscle composition, aerobic capacity, oxygen consumption, metabolism, musculoskeletal injuries susceptibility and recovery needs (13,14). Researchers in this field examine how common variations in genes referred to as single nucleotide polymorphisms (SNPs) can affect the predisposition of an individual to excel in certain sports categories or athletic activities. While genetics play a crucial role in controlling the potential of an athlete, it is important to note that environmental factors, such as training, nutrition, sleep and mental health can significantly affect athletic performance. Hence, genetic testing is not meant to be used to determine what type of sport a young athlete should take up (15). Instead, genetic testing should be used to inform and personalize training intensity, nutrition, supplementation and other sport-related interventions necessary for the athlete to achieve maximum potential in the selected sport, in combination with traditional metrics and novel biomarkers used more recently.

Moreover, systems biology research is aiding in the better understanding of the bodies of athletes in sports medicine (16). This type of research involves an analysis of their genes, how these are affected by their lifestyle, and how the bodies of athletes appear and function. Different variations in their genes can affect factors, such as how long they can continue with the sport, their strength, and the speed at which they can move (17). By studying the genes of athlete and examining how their bodies function, further information can be obtained about the factors responsible for their optimal performance in their sport and can help determine the factors that may render them more likely to sustain injuries. Scientists have found ample genetic markers that may be linked to the ability of an individual to excel in sports; however, further information remains to be obtained about the mechanisms of action of these genes (18).

To date, >250 genetic markers have been found that may be connected to characteristics found in sports. However, only up to 128 of these markers have been investigated in several studies (19). Nevertheless, the available data remain limited, and further investigations are required to properly comprehend the mechanistic aspects of genetic variation (19).

For example, there is a specific gene known as alpha-actinin-3 (ACTN3) that affects the speed and strength at which muscles function. Specifically, the ACTN3 protein, encoded by the ACTN3 gene, is predominantly expressed in fast, type II muscle fibers, enabling fast and powerful muscle contractions. A particular ACTN3 variation in SNP rs1815739 involves a C-to-T transition. This results in the replacement of an arginine with a stop codon at amino acid 577 (R577X), leading to the absence of functional  $\alpha$ -actinin-3 protein (20).

An over-representation of the ACTN3 RR genotype and an under-representation of the ACTN3 XX genotype in strength/sprint athletes has been observed (20). In simpler terms, this SNP variation in the ACTN3 gene can predispose individuals to be better at strength. In other words, these athletes may require less effort to build muscle and may thus be inherently better. Others who carry the alternative SNP genotype may not be as good at these activities. However, this only means that they would require more effort to build similar muscle strength. This example demonstrates how genes can play a role in athletic abilities and that the main role of genetic testing is to provide information about the effort required to achieve a certain goal and thus, guide personalized exercise, diet and supplementation plans (15).

Genetic testing can also help prevent potential injuries at an early stage by identifying genetic predisposition and the risk of developing certain musculoskeletal conditions. For instance, there is a protein known as growth differentiation factor 5 (GDF5) that helps bones, muscles, and tendons grow and stay healthy. There are three different versions of the gene that makes this protein: CC, CT and TT. Individuals with the TT version may have lower levels of the GDF5 protein and a higher risk of sustaining sports injuries (21).

Genetic profiling can also prove vital in cases of indicating if an individual may have underlying heart conditions, including arrhythmias or whether an individual is susceptible to sudden death (22). For instance, there is a gene termed myosin-binding protein C3 (MYBPC3) that appears to affect how well elite athletes can perform; however, certain versions of the MYBPC3 gene can also cause a heart condition known as hypertrophic cardiomyopathy (23).

The adrenoceptor beta 3 (ADRB3) gene is linked to  $VO_2$  max, a key indicator of aerobic capacity, with studies suggesting its role in predicting oxygen utilization thresholds during exercise (24). A specific variant of the ADRB3 gene (rs4994) may affect the aerobic capacity of an athlete. Similarly, CKM rs8111989 (c.\*800A>G) is associated with anaerobic performance, where the GG genotype may favor power/strength athletes due to increased creatine kinase-M activity, although conflicting evidence exists regarding its endurance-related effects (25). The HFE rs1799945 GG variant is associated with iron metabolism efficiency, potentially enhancing aerobic capacity in endurance athletes by optimizing oxygen transport (26). Likewise, HIF1 $\alpha$  rs11549465 (Pro582Ser) involves the T allele, which is protective and linked to improved endurance performance through enhanced oxygen utilization (27).

For muscle-related traits, leptin receptor (LEPR) rs1137101 (Gln223Arg) influences leptin receptor signaling, which may indirectly affect muscle mass development through metabolic regulation (28), while myostatin (MSTN) rs1805086 (K153R) is strongly tied to muscle strength, with the R allele associated with hypertrophic muscle response and overrepresentation in strength-oriented athletes (29). NFIA-AS2 rs1572312 is connected to elite endurance performance, as the C allele correlates with higher  $VO_2$  max values and is more prevalent in endurance athletes (30), with peroxisome proliferator activated receptor (PPAR)A rs4253778 (intron 7 G/C) favoring anaerobic power output, with C allele carriers demonstrating advantages in speed-strength tasks (31).

Table I. Genetic markers of athletic functions.

Gene	Full name	Function	Polymorphism	(Refs.)
ACE	Angiotensin I converting enzyme	Endurance	rs4343	(34)
ACTN3	Alpha actinin 3	Endurance	rs1815739	(35)
ADRB3	Adrenoceptor beta 3	VO <sub>2</sub> max ability	rs4994	(36)
CK-MM	Creatine kinase M-type	Endurance	rs8111989	(37)
GDF5	Growth differentiation factor 5	Power	rs143384	(38)
HFE	Homeostatic iron regulator	Endurance	rs1799945	(26)
HIF1 $\alpha$	Hypoxia inducible factor 1 subunit alpha	Endurance	rs11549465	(39)
LEPR	Leptin receptor	Ability to develop muscle mass	rs1137101	(40)
MSTN	Myostatin	Strength	rs1805086	(29)
MYBPC3	Myosin binding protein C3	Endurance	rs1052373	(23)
NFIA-AS2	NFIA antisense RNA 2	Endurance	rs1572312	(30)
PPARA	Peroxisome proliferator-activated receptor alpha	Strength	rs4253778	(31)
PPARG	Peroxisome proliferator activated receptor gamma	Strength	rs1801282	(32)
SOD2	Superoxide dismutase 2	Muscle damage	rs4880	(33)

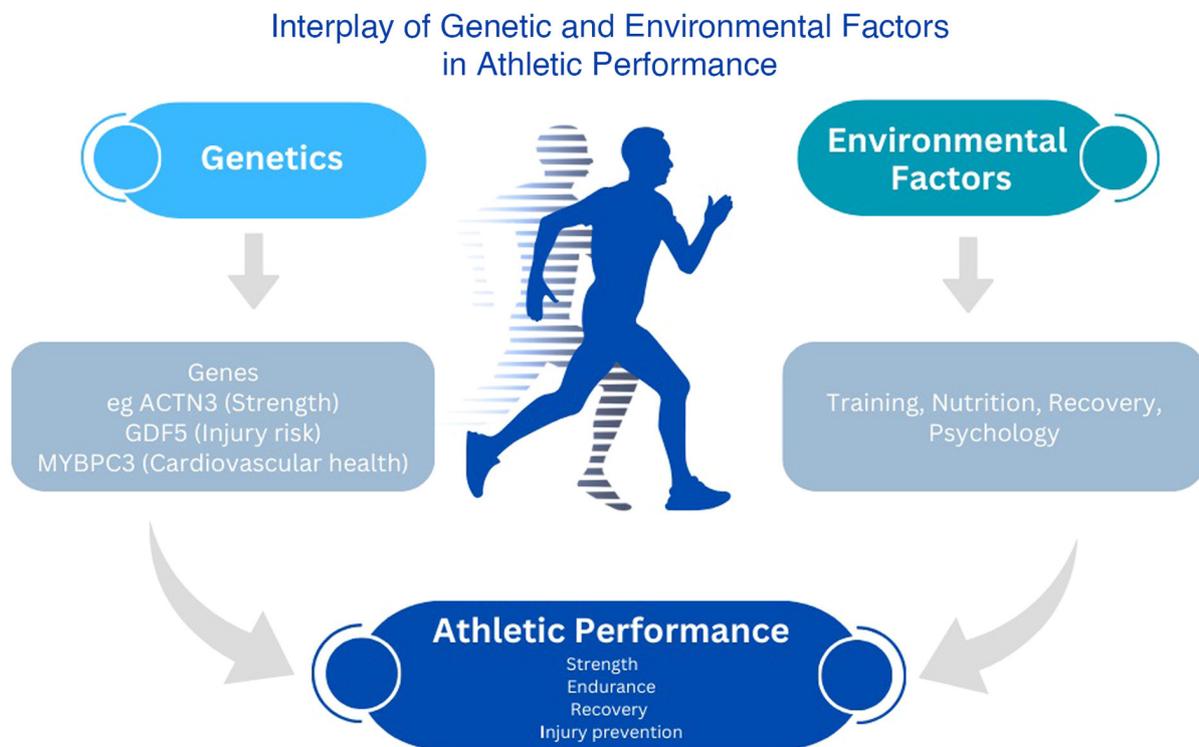


Figure 1. Schematic diagram illustrating the association between genetics, environment and athletic performance. ACTN3, alpha actinin 3; GDF5, growth differentiation factor 5; MYBPC3, myosin-binding protein C3.

As regards muscle damage and recovery, PPARG (rs1801282) has been demonstrated to influence muscle fiber composition and strength potential; genetic predisposition may determine susceptibility to muscle damage (32). A variant in the superoxide dismutase 2 (SOD2) gene (rs4880) has been shown to be associated with increased oxidative

stress, which can impact muscle recovery and injury risk (33) (Table I). While environmental factors such as training and nutrition continue to play a crucial role, understanding the genetic profile of an individual can help create personalized strategies for optimizing performance and reducing the risk of sustaining injuries.

### 3. A combined strategy for athletes

The combination of different technologies can help enhance the performance of elite athletes throughout the season and can prolong their healthy and successful longevity in the sport. A personalized plan that includes training, nutrition, supplements, recovery and mental health support, provided by combining genetic testing with other tests and assessments, is a promising strategy for achieving this.

Repetitive testing throughout the season can reveal how an athlete is progressing and provide recommendations to make changes to the personalized plans as required. This process helps athletes improve their performance, minimize the risk of sustaining injuries, and may also help them keep performing at an optimal level in the long run (Fig. 1). An end of season evaluation can reveal recovery needs and allow for planning in order to help the athlete prepare for the following season (6).

### 4. Synopsis and future perspectives

The combination of genetic profiling with conventional evaluation methods represents a transformative shift in optimizing athletic performance, mitigating the risk of sustaining injuries and improving recovery processes. The information discussed in the present review underscores the potential of using genetic markers alongside phenotypic assessments to develop a more comprehensive understanding of the strengths and limitations of an athlete.

By analyzing specific genetic variations related to traits, such as endurance and power, this method can help identify the genetic predispositions of athletes and may provide valuable insight into their potential for success in various sports. For instance, genes, such as ACTN3, which affects fast-twitch muscle fibers, and ACE I/D, which influences cardiovascular endurance, are associated with performance in power and endurance sports, respectively (20,41,42).

It is important to remember that genetic predisposition is not the only driver of athletic achievement. Environmental and lifestyle variables also play a critical role in shaping the final phenotype (43). In this sense, whereas genetic analysis is required only once, the continuous examination of phenotypic expression for certain features (i.e., metabolites) is essential throughout the career of an athlete (44). Mental health, socioeconomic variables, personal motivation and well-structured athletic programs with excellent coaching and scientific assistance all play key roles in the development and ability of an athlete to maintain high performance and reach their goals (19). Recent research estimates the degree of genetic heritability contributing to athletic performance to be ~50%. Accordingly, other factors, such as the environment, different training methods, diets, etc. account for the remaining variation of performance between athletes (43). Despite the potential benefits of genetic profiling in sports, there are ethical considerations that need to be addressed before personalized plans can be implemented accurately and successfully. Specifically, further research is required to enhance the current understanding and assess the effectiveness of tailored therapies and plans based on clinical, physiological and biological data. Lastly, refining data analysis approaches is critical in order to efficiently combine

big data from diverse sources and provide outputs that can be directly translated into meaningful personalized recommendations. The use of genetic information in athlete selection and training raises concerns about potential biases and discrimination, particularly if certain genetic profiles are deemed more desirable than others. Safeguards need to be implemented to protect the privacy of athletes and prevent the misuse of genetic data for unfair competitive advantages or exclusionary practices (45). Accessibility to genetic testing also presents a challenge. While elite athletes may have access to cutting-edge genetic technology, the cost of testing and the infrastructure required may not be available to athletes at all levels. This disparity could lead to inequities in the application of genetic data across the sports spectrum, limiting the benefits to only the most financially privileged athletes. Efforts should be made to make genetic testing more accessible to a broader range of athletes, particularly those in underrepresented groups.

In summary, while genetic profiling offers immense potential to optimize athletic performance, enhance recovery and prevent injuries, its practical application in sports needs to be approached with caution. The present review highlights the importance of ongoing research in genetics and sports science, as well as the need for a holistic approach that considers the complex interplay of genetics, epigenetics, environmental factors and psychosocial influences; this is paramount for optimizing athlete development and performance while upholding ethical principles. With these considerations in place, genetic profiling may prove to be a powerful tool for improving athletic outcomes, enhancing performance and promoting longevity in sports, while also addressing health challenges in broader populations.

#### Acknowledgements

Not applicable.

#### Funding

The present study was privately funded by iDNA Laboratories.

#### Availability of data and materials

Not applicable.

#### Authors' contributions

NP, ES, TF, AS and EN performed the literature review. NP, ES, TF, AS and EN wrote the manuscript. All authors reviewed and edited the manuscript. Data authentication is not applicable. All authors have read and approved the final manuscript.

#### Ethics approval and consent to participate

Not applicable.

#### Patient consent for publication

Not applicable.

## Competing interests

The authors declare that they have no competing interests.

## Use of artificial intelligence tools

During the preparation of this work, AI tools were used to improve the readability and language of the manuscript or to generate images, and subsequently, the authors revised and edited the content produced by the AI tools as necessary, taking full responsibility for the ultimate content of the present manuscript.

## References

- Lee EC, Fragala MS, Kavouras SA, Queen RM, Pryor JL and Casa DJ: Biomarkers in sports and exercise: Tracking health, performance, and recovery in athletes. *J Strength Cond Res* 31: 2920-2937, 2017.
- Staff HC, Solli GS, Osborne JO and Sandbakk Ø: Long-term development of training characteristics and performance-determining factors in elite/international and world-class endurance athletes: A scoping review. *Sports Med* 53: 1595-1607, 2023.
- Hawley JA, Hargreaves M, Joyner MJ and Zierath JR: Integrative biology of exercise. *Cell* 159: 738-749, 2014.
- Ferraz A, Duarte-Mendes P, Sarmiento H, Valente-Dos-Santos J and Travassos B: Tracking devices and physical performance analysis in team sports: A comprehensive framework for research-trends and future directions. *Front Sports Act Living* 5: 1284086, 2023.
- Sun BB, Kurki MI, Foley CN, Mechakra A, Chen CY, Marshall E, Wilk JB; Biogen Biobank Team; Chahine M, Chevalier P, *et al*: Genetic associations of protein-coding variants in human disease. *Nature* 603: 95-102, 2022.
- Spanakis M, Fragkiadaki P, Renieri E, Vakonaki E, Fragkiadoulaki I, Alegakis A, Kiriakakis M, Panagiotou N, Ntoumou E, Gratsias I, *et al*: Advancing athletic assessment by integrating conventional methods with cutting-edge biomedical technologies for comprehensive performance, wellness, and longevity insights. *Front Sports Act Living* 5: 1327792, 2024.
- Nieman DC: Multiomics approach to precision sports nutrition: Limits, challenges, and possibilities. *Front Nutr* 8: 796360, 2021.
- Bush CL, Blumberg JB, El-Sohehy A, Minich DM, Ordoñas JM, Reed DG and Behm VAY: Toward the definition of personalized nutrition: A proposal by the American nutrition association. *J Am Coll Nutr* 39: 5-15, 2020.
- Hood L, Balling R and Auffray C: Revolutionizing medicine in the 21st century through systems approaches. *Biotechnol J* 7: 992-1001, 2012.
- González JR, Cáceres A, Ferrer E, Balagué-Dobón L, Escribà-Montagut X, Sarrat-González D, Quintás G and Rodas G: Predicting injuries in elite female football players with global-positioning-system and multiomics data. *Int J Sports Physiol Perform* 19: 661-669, 2024.
- Brazier J, Antrobus MR, Herbert AJ, Callus PC, Khanal P, Stebbings GK, Day SH, Heffernan SM, Kilduff LP, Bennett MA, *et al*: Gene variants previously associated with reduced soft-tissue injury risk: Part 2-Polygenic associations with elite status in Rugby. *Eur J Sport Sci* 23: 1779-1788, 2023.
- Sellami M, Elrayess MA, Puce L and Bragazzi NL: Molecular big data in sports sciences: State-of-art and future prospects of OMICS-based sports sciences. *Front Mol Biosci* 8: 815410, 2022.
- Lippi G, Longo UG and Maffulli N: Genetics and sports. *Br Med Bull* 93: 27-47, 2010.
- Varillas-Delgado D, Del Coso J, Gutiérrez-Hellín J, Aguilar-Navarro M, Muñoz A, Maestro A and Morencos E: Genetics and sports performance: The present and future in the identification of talent for sports based on DNA testing. *Eur J Appl Physiol* 122: 1811-1830, 2022.
- Camporesi S and McNamee MJ: Ethics, genetic testing, and athletic talent: Children's best interests, and the right to an open (athletic) future. *Physiol Genomics* 48: 191-195, 2016.
- Ginevičienė V, Utkus A, Pranckevičienė E, Semenova EA, Hall ECR and Ahmetov II: Perspectives in sports genomics. *Biomedicines* 10: 298, 2022.
- Bongiovanni T, Pintus R, Dessì A, Noto A, Sardo S, Finco G, Corsello G and Fanos V: Sportomics: Metabolomics applied to sports. The new revolution? *Eur Rev Med Pharmacol Sci* 23: 11011-11019, 2019.
- Tanisawa K, Wang G, Seto J, Verdouka I, Twycross-Lewis R, Karanikolou A, Tanaka M, Borjesson M, Di Luigi L, Dohi M, *et al*: Sport and exercise genomics: The FIMS 2019 consensus statement update. *Br J Sports Med* 54: 969-975, 2020.
- Semenova EA, Hall ECR and Ahmetov II: Genes and athletic performance: The 2023 update. *Genes (Basel)* 14: 1235, 2023.
- Roth SM, Walsh S, Liu D, Metter EJ, Ferrucci L and Hurley BF: The ACTN3 R577X nonsense allele is under-represented in elite-level strength athletes. *Eur J Hum Genet* 16: 391-394, 2008.
- McCabe K and Collins C: Can genetics predict sports injury? The association of the genes GDF5, AMPD1, COL5A1 and IGF2 on soccer player injury occurrence. *Sports (Basel)* 6: 21, 2018.
- Ackerman MJ, Priori SG, Willems S, Berul C, Brugada R, Calkins H, Camm AJ, Ellinor PT, Gollob M, Hamilton R, *et al*: HRS/EHRA expert consensus statement on the state of genetic testing for the channelopathies and cardiomyopathies this document was developed as a partnership between the Heart Rhythm Society (HRS) and the European Heart Rhythm Association (EHRA). *Heart Rhythm* 8: 1308-1339, 2011.
- Riguene E, Theodoridou M, Barrak L, Elrayess MA and Nomikos M: The relationship between changes in MYBPC3 single-nucleotide polymorphism-associated metabolites and elite athletes' adaptive cardiac function. *J Cardiovasc Dev Dis* 10: 400, 2023.
- de la Iglesia R, Espinosa-Salinas I, Lopez-Silvarrey FJ, Ramos-Alvarez JJ, Segovia JC, Colmenarejo G, Borregon-Rivilla E, Marcos-Pasero H, Aguilar-Aguilar E, Loria-Kohen V, *et al*: A potential endurance algorithm prediction in the field of sports performance. *Front Genet* 11: 711, 2020.
- Ginevičienė V, Jakaitienė A, Utkus A, Hall ECR, Semenova EA, Andryushchenko LB, Larin AK, Moreland E, Generozov EV and Ahmetov II: CKM gene rs8111989 polymorphism and power athlete status. *Genes (Basel)* 12: 1499, 2021.
- Thakkar D, Sicova M, Guest NS, Garcia-Bailo B and El-Sohehy A: HFE genotype and endurance performance in competitive male athletes. *Med Sci Sports Exerc* 53: 1385-1390, 2021.
- Al-Shajrawi OM, Alwardat S, Alwardat N, Tengku Din TADAA, Hussain Abdulrazak M, Musa I and Mussa A: Exploring the complex relationship between HIF-1 (rs11549465) and NFκB1 (rs28362491) variations and obesity (Review). *World Acad Sci J* 6: 71, 2024.
- Supti DA, Akter F, Rahman MI, Munim MA, Tonmoy MIQ, Tarin RJ, Afroz S, Reza HA, Yeasmin R, Alam MR and Hossain MS: Meta-analysis investigating the impact of the LEPR rs1137101 (A>G) polymorphism on obesity risk in Asian and Caucasian ethnicities. *Heliyon* 10: e27213, 2024.
- Kruszewski M and Aksenov MO: Association of myostatin gene polymorphisms with strength and muscle mass in athletes: A systematic review and meta-analysis of the MSTN rs1805086 mutation. *Genes (Basel)* 13: 2055, 2022.
- Ahmetov I, Kulemin N, Popov D, Naumov V, Akimov E, Bravy Y, Egorova E, Galeeva A, Generozov E, Kostryukova E, *et al*: Genome-wide association study identifies three novel genetic markers associated with elite endurance performance. *Biol Sport* 32: 3-9, 2015.
- Petr M, Stastny P, Pecha O, Šteffl M, Šeda O and Kohlíková E: PPARA intron polymorphism associated with power performance in 30-s anaerobic wingate test. *PLoS One* 9: e107171, 2014.
- Maciejewska-Karłowska A, Sawczuk M, Cieszczyk P, Zarebska A and Sawczyn S: Association between the Prol2Aa polymorphism of the peroxisome proliferator-activated receptor gamma gene and strength athlete status. *PLoS One* 8: e67172, 2013.
- Ahmetov II, Naumov VA, Donnikov AE, Maciejewska-Karłowska A, Kostryukova ES, Larin AK, Maykova EV, Alexeev DG, Fedotovskaya ON, Generozov EV, *et al*: SOD2 gene polymorphism and muscle damage markers in elite athletes. *Free Radic Res* 48: 948-955, 2014.
- Gayagay G, Yu B, Hambly B, Boston T, Hahn A, Celermajer DS and Trent RJ: Elite endurance athletes and the ACE I allele-the role of genes in athletic performance. *Hum Genet* 103: 48-50, 1998.

35. Papadimitriou ID, Lucia A, Pitsiladis YP, Pushkarev VP, Dyatlov DA, Orekhov EF, Artioli GG, Guilherme JP, Lancha AH Jr, Ginevičienė V, *et al*: ACTN3 R577X and ACE I/D gene variants influence performance in elite sprinters: A multi-cohort study. *BMC Genomics* 17: 285, 2016.
36. Xie C, Hua W, Zhao Y, Rui J, Feng J, Chen Y, Liu Y, Liu J, Yang X and Xu X: The ADRB3 rs4994 polymorphism increases risk of childhood and adolescent overweight/obesity for East Asia's population: An evidence-based meta-analysis. *Adipocyte* 9: 77-86, 2020.
37. Chen C, Sun Y, Liang H, Yu D and Hu S: A meta-analysis of the association of CKM gene rs8111989 polymorphism with sport performance. *Biol Sport* 34: 323-330, 2017.
38. Guilherme JPLF, Semenova EA, Larin AK, Yusupov RA, Generozov EV and Ahmetov II: Genomic predictors of brisk walking are associated with elite sprinter status. *Genes (Basel)* 13: 1710, 2022.
39. Gabbasov RT, Arkhipova AA, Borisova AV, Hakimullina AM, Kuznetsova AV, Williams AG, Day SH and Ahmetov II: The HIF1A gene Pro582Ser polymorphism in Russian strength athletes. *J Strength Cond Res* 27: 2055-2058, 2013.
40. Wang Y and Ashokan K: Physical exercise: An overview of benefits from psychological level to genetics and beyond. *Front Physiol* 12: 731858, 2021.
41. Sommers L, Akam L, Hunter DJ, Bhatti JS and Mastana S: Role of the ACE I/D polymorphism in selected public health-associated sporting modalities: An updated systematic review and meta-analysis. *Int J Environ Res Public Health* 21: 1439, 2024.
42. Kujala UM, Palviainen T, Pesonen P, Waller K, Sillanpää E, Niemelä M, Kangas M, Vähä-Ypyä H, Sievänen H, Korpelainen R, *et al*: Polygenic risk scores and physical activity. *Med Sci Sports Exerc* 52: 1518-1524, 2020.
43. Konopka MJ, Sperlich B, Rietjens G and Zeegers MP: Genetics and athletic performance: A systematic SWOT analysis of non-systematic reviews. *Front Genet* 14: 1232987, 2023.
44. Qiu S, Cai Y, Yao H, Lin C, Xie Y, Tang S and Zhang A: Small molecule metabolites: Discovery of biomarkers and therapeutic targets. *Signal Transduct Target Ther* 8: 132, 2023.
45. Salardi S: Sport and enhancement in the age of human rights: Genetic testing as a case study. *Philosophies* 6: 17, 2021.



Copyright © 2025 Panagiotou et al. This work is licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) License.