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# Genetic Influences on Athletic Performance: A Review of ACTN3, ACE, and the Limits of Prediction

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**Abstract:** ***A person's physique is strongly influenced by genetics. Traits such as muscle type, endurance, and strength are shaped by specific genes, making genetics a key factor in sports science. This study investigates two genes prominent in athletic performance, ACTN3 and ACE, and evaluates their role within the emerging field of sports genomics. The research aims to examine how variations in these genes influence physiological traits related to power, speed, and endurance, and to assess their predictive value in identifying athletic potential. Variations in the ACTN3 gene affect the function of fast-twitch muscle fibres, essential for power and sprint performance. ACE gene variants are associated with cardiovascular efficiency and muscle endurance. The study further examines broader factors, including environmental influences, training conditions, and the ethical implications of genetic testing and talent identification in youth sports. Furthermore, it reviews research on genetic links to injury susceptibility. The genes are influential to some extent but not determinative of any athletic performance. A detailed analysis of existing literature, review articles was done. These observations support the conclusion that while ACTN3 and ACE genes provide useful information about physiological predispositions, athletic success ultimately depends on a combination of factors like genetics, environment, and training***.

**Keywords:** ACTN3; ACE; sports genomics; athletic performance; genetic testing

## 1. Introduction

At the 2012 London Olympics, the Jamaican men's 4x100m relay team, anchored by Usain Bolt, broke the world record with a time of 36.84 seconds, showcasing their extraordinary sprinting dominance.[1]Such performances raise important questions about the factors behind their consistent success and what distinguishes them from athletes worldwide. Many attribute their achievements to genetics, which, while influential, do not alone determine athletic performance

ACTN3, commonly known as the speed gene, is associated with the function of fast-twitch muscle fibres.[2]Both professional sprinters and amateurs may carry this gene; however, it is their surrounding environment, training regimen, and personal dedication that ultimately shape elite performance outcomes. Genetics alone cannot explain why some athletes reach exceptional levels while others with similar potential do not.

A study comparing 116 elite Jamaican sprinters with 311 non-athlete controls from Jamaica showed that the presence of the XX variant of the ACTN3 gene was very low (about 2–3%), indicating no significant difference between athletes and non-athletes. [3]Most Jamaicans naturally have a higher proportion of the R allele, which is the more favourable variant associated with sprinting ability. These findings suggest that although an athlete's success may be influenced by favourable genes, it largely depends on quality training, environmental factors, and consistent effort.

Building on this understanding, the most widely studied genes related to athletic performance are ACTN3 and ACE, as these were among the first genes investigated that directly affect human physiology and muscle performance. The ACE gene influences blood flow and oxygen delivery to muscles, thereby impacting endurance, while the ACTN3 gene affects fast-twitch muscle fibres, contributing specifically to power and speed. Understanding how these genes, in combination with training and environmental factors, impact athletic performance is essential for interpreting their overall influence.[4]

This literature-based study was conducted to address several key questions: how are ACTN3 and ACE variants associated with sprint and power versus endurance, how consistent are findings across different sports and populations, and what are the limits and ethical concerns of genetic testing in youth sports? Examining these questions provides a clearer understanding of the balance between genetics and environment in shaping elite athletic performance.

## 2. Literature Review and Background

While studying any gene, it is essential to have a clear understanding of the fundamental concepts of genetics in order to examine genes from all perspectives. Genetics is a branch of biology that focuses on understanding genes: specific sequences of nucleotides on a chromosome that encode proteins, which are expressed as particular traits. A gene acts as the basic unit of heredity in humans.

Alleles are alternative forms of the same gene that occupy the same position on a pair of homologous chromosomes, influencing the same characteristic in different ways. [5]For example, the gene for hair type has two alleles: curly and straight hair. The genotype refers to the genetic constitution of an organism or the set of genes it carries, inherited from both parents. The phenotype, on the other hand, represents the observable characteristics or physical expression of those genes, like height or eye colour. Environmental factors also may influence the phenotype of a gene, which is a great

example of the genes and the surroundings working in tandem to produce variation within a species.[6]

A gene variant is an alteration in the DNA sequence that can affect a gene's function or how it is expressed. Everyone carries gene variants — they are what make individuals unique in appearance, metabolism and even immunity. Some variants may affect how our body responds to medicines or environmental factors, causing different reactions among individuals. If a specific variant occurs in more than 1% of the population, it is called a polymorphism and it is considered a normal variation. However, if it occurs in less than 1%, it is classified as a mutation, which can have a harmful, beneficial or neutral impact. [7]

Though they are similar in name, Single Nucleotide Variants (SNVs) and Single Nucleotide Polymorphisms (SNPs) are slightly different concepts in genetics. An SNV is a broad term for a variation in which a single nitrogenous base (A, T, C, or G) is altered at one position in the genome, and this change can be rare or common. SNVs can occur anywhere in the genome, including coding and non-coding regions, and may or may not affect gene function. An SNP, however, is a specific type of SNV that occurs more frequently in the population— typically in more than 1% of individuals — and is often used in genetic research to study inheritance and disease risk.[8]

The central dogma describes the fundamental process by which genetic information flows from DNA to RNA through transcription and from RNA to protein through translation. This process dictates how the information in genes is converted into functional molecules inside the cell. The proteome represents the complete set of proteins expressed by an organism, reflecting the active expression of its genome. Proteins perform most biological functions, therefore scientists study the proteome to understand how genes translate into physical traits and how changes in gene expression can lead to diseases or adaptive differences among organisms.[9]

One of the genes examined in this paper, ACTN3, is discussed for its relevance to athletic performance and its influence on the functioning of muscle fibres. Understanding muscle fibre structure and types is equally important when studying athletic ability. The diagram below illustrates the various components of a muscle fibre.

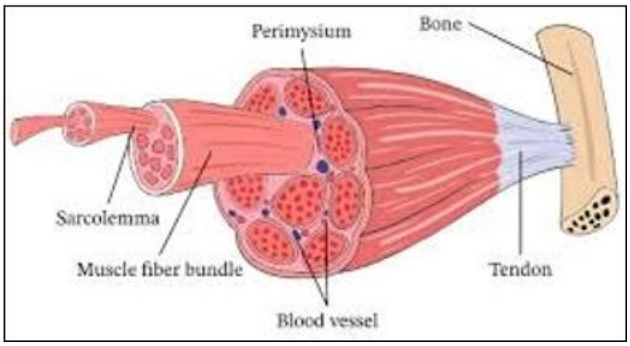


**Figure 1:** Structure of a Muscle Fibre [10]

There are three main types of muscle fibres:

1) Type I: Slow-twitch fibres: These fibres have a higher oxidative capacity as they contain more myoglobin and are surrounded by a greater number of blood capillaries. They also contain more mitochondria, providing a steady energy supply. These features contribute to their high fatigue resistance, which supports endurance-based sports such as long-distance running or cycling.
2) Type IIa: Fast-twitch oxidative: These muscle fibres are considered the intermediate fibres. They have characteristics of both the type I and type IIx. They generate more power than type I but can sustain activity longer than type IIx. They are ideal for high intensity activities or moderate duration, like swimming.
3) Type IIx: Fast-twitch glycolytic: This type of muscle fibre is capable of generating maximum power but is quickly fatigued. Due to its low oxidative capacity and limited number of mitochondria, it is not well-suited for endurance activities. Instead, these fibres are primarily associated with explosive, power-driven sports such as sprinting, jumping, and weightlifting.[11]

The ACTN3 and the ACE genes influence athletic performance through their effects on muscular contraction and cardiovascular function. ACTN3 encodes the α-actinin-3 protein found in fast twitch muscle fibres, enabling rapid and powerful contractions. The 'R' allele supports sprint and power performance, while the 'X' allele is linked with reduced muscle efficiency. [12] The ACE gene regulates blood pressure and oxygen delivery. Its 'I' allele enhances endurance and the 'D' allele supports strength and power. Together, they influence an athlete's potential in a sport.[13]

**Table 1:** Summary of Key Genetic Variants Linked to Athletic Performance

| Gene and Allele | Effect on muscle fibre type | Phenotypic impact | Sport-specific relevance |
|---|---|---|---|
| 1. ACTN3: R allele | Presence of α-actinin-3 increases efficiency of Type II (fast-twitch) muscle fibres which enhances rapid and powerful contractions. | Rapid muscle contractions and increased power output. This supports short and explosive movements | Sprinting, powerlifting, jumping and other explosive sports. |
| 2. ACTN3: X allele | Absence of α-actinin-3 causes reduced efficiency of Type II (fast-twitch) muscle fibres which moves towards oxidative or endurance performance. | Lower explosive power but improved fatigue resistance and metabolic efficiency. | Long-distance running, endurance swimming and cycling. |
| 3. ACE: I allele | Reduced ACE enzyme activity supports dominance of Type I (slow-twitch fibres) muscle fibres and oxygen utilisation. | Increased endurance, fatigue resistance and aerobic efficiency. | Marathon running, triathlon, cycling, mountaineering and distance swimming. |
| 4. ACE: D allele | Higher ACE enzyme activity may promote Type II (fast-twitch) fibre strength and power output. | Greater anaerobic output and increased muscle strength which supports peformance in shorts bursts. | Sprinting, weightlifting, and other short, hight intensity sports. |

| | | | |
|---|---|---|---|
| 5.ACE A22982G: (A allele) | Linked with lower ACE enzyme activity, it enhances Type I (slow-twitch) fibre efficiency and endurance-related activities. | Improved aerobic capacity, better endurance performance and lesser fatigue. | long-distance running, endurance swimming, cycling and high altitude activities. |
| 6. ACE A22982G: (G allele) | Associated with higher levels of ACE activity, supporting Type II (fast-twitch) fibre power and strength. | Improved anaerobic performance, improved strength response and increased power output. | Sprinting, powerlifting, and short distance swimming. |

## 3. Methodology

This study was designed as a narrative literature review analyzing the influence of ACTN3 and ACE gene polymorphisms on athletic performance and injury susceptibility. Scientific databases including PubMed, ScienceDirect, Scopus, and Google Scholar were searched for peer-reviewed articles published between 2000 and 2025 using combinations of keywords such as *"ACTN3," "ACE," "athletic performance," "endurance," "power,"* and *"sports genomics."* Only studies involving human subjects that discussed genotype distribution, physiological implications, or associations with performance outcomes were included. Review articles, meta-analyses, and primary studies with clear sample descriptions were prioritized to ensure scientific credibility and reproducibility.

Extracted data were compared and summarized thematically to identify consistent trends across populations and sports disciplines. Emphasis was placed on the R577X polymorphism (rs1815739) of the ACTN3 gene and the I/D variant (rs1799752) of the ACE gene, as well as other relevant markers influencing endurance and strength traits. Findings were critically evaluated in terms of population diversity, methodology, and reported limitations. The analysis also incorporated ethical considerations of genetic testing in youth sports, acknowledging that while genetics provides valuable insights into physiological predispositions, environmental and training factors play equally significant roles.

## 4. Results & Discussion

ACTN3 is the gene that encodes α-actinin-3, a structural protein found exclusively in fast-twitch muscle fibres. A common polymorphism, R577X, involves the substitution of cytosine (C) with thymine (T) in the genetic sequence, resulting in a premature stop codon that prevents the production of functional α-actinin-3. This polymorphism produces three possible genotypes: RR, with two functional copies; RX, with one functional and one nonfunctional copy; and XX, with two nonfunctional copies.[14]

The R allele is associated with power and sprint athletes, such as sprinters and weightlifters, as it supports rapid and powerful muscle contractions. Conversely, the X allele produces a nonfunctional protein, leading to reduced muscle efficiency and power output. While it may contribute to aspects of endurance physiology, its primary effect is reduced muscle power. Elite athletic performance, however, is polygenic – influenced by multiple genes – and ACTN3 alone has a modest effect, increasing the likelihood of certain performance traits but not determining them.[15]

Research suggests that the XX genotype may be associated with higher risk of injury. A study shows incredible statistics: football players with the XX genotype were found to have a 2.66-fold higher injury risk, and a 2.13-fold higher risk of severe injury, compared to the RX or RR genotype. The RX genotype showed a 1.63-fold higher risk of injuries. However, these associations can vary depending on factors like the type of sport or training. This indicates that injury risk relies on the context.[16]

The ACE gene encodes the angiotensin-converting enzyme, which regulates blood pressure, vascular tone and oxygen delivery through the renin-angiotensin system.

A common polymorphism of the gene, the insertion and the deletion is caused by the presence or absence of a 287 base pair sequence. This gives rise to the two alleles, the I allele and the D allele. Individuals with I allele have lower ACE activity, due to which they experience enhanced vasodilation and oxygen transport, traits which are favourable for improved endurance performance. In contrast, individuals with the D allele have higher ACE activity, which promotes vasoconstriction and quick muscle contraction. These features are important for power-based sports. [17]

Population studies indicate some variability in these associations. The relations made were mainly applicable for Europeans. In African population, the A22982G variant seemed to be more reliable in terms of a genetic predictor. It involves the substitution of adenine(A) with guanine(G) in a genetic sequence. The genotypes, AA and AG have a lower level of ACE activity than GG which has the highest level of activity. Lower ACE activity is related with improved endurance performance, while higher activity supports strength-related activities. Overall, ACE influences on athletic ability in a polygenic and is context-dependent. Its effect is further dependent on other factors like environment and training regimen.[18]

As discussed earlier, athletic ability is a polygenic trait, influenced by multiple genes. Genes such as MSTN (myostatin), which regulates muscle growth, and EPAS1, which supports oxygen regulation at high altitudes, interact with ACTN3 and ACE to shape performance. Genetics, together with environmental factors, collectively impact athletic ability—an interplay known as gene–environment interaction. Epigenetic mechanisms, including DNA methylation and histone modification, can alter gene expression without changing the DNA sequence in response to environmental stress. This demonstrates that training not only builds muscle but can also alter gene expression over time. [19], [20]

Injury susceptibility is also affected by genetic factors. Genetic variations related to connective tissue structure such as COL1A1, COL5A1, MMP3 and TNC have been associated with a higher risk of soft-tissue injuries. Similarly, polymorphisms in the APOE gene, especially the APOE4 have been associated with increased concussion risk and slow recovery. However, these findings preliminary and

inconsistent, indicating that while genetics may contribute to injury risk, they do not dictate it entirely. [21] [22]

An analysis of the ACTN3 and ACE variants and their influence on specific aspects of athletic performance. ACTN3 shows a strong association with power output and strength, while ACE shows more variable links to endurance, emphasizing that no single gene can determine athletic ability. The R allele of the ACTN3 gene supports rapid muscle contractions, whereas the X allele reduces power output but may benefit endurance. The ACE I/D and A22982G variants influence vascular function and oxygen delivery. These variants show more inconsistent trends: I and AA/AG genotypes are generally associated with endurance, and D and GG genotypes with power. These links however, differ by ethnicity, sport type and environment. These inconsistencies suggest that ACE's effect is context-dependent unlike ACTN3's influence which is more predictable.

**Table 2:** Comparative Findings from Major Studies on ACTN3 and ACE in Athletes

| Gene and variant | Key findings from major studies | Performance Association | Notes and Limitations |
|---|---|---|---|
| 1. ACTN3 (R577X) | The R allele produces the functional α-actinin-3, whereas the X allele produces the nonfunctional protein. RR genotype is associated with the highest power output, and XX allele is associated with reduced power output but may support endurance physiology. | RR and RX are associated with sprinting, power, and strength. XX is sometimes associated with endurance traits. | Its effect is modest and does not determine performance. Polygenic influences and training override the genotype. |
| 2. ACE (I/D polymorphism) | The I allele is associated with less ACE activity and improved vasodilation and oxygen transport. The D allele is linked to higher ACE activity due to which it is associated with vasoconstriction and faster muscle contractions. | I allele is associated with endurance performance and D allele with strength and power. | Effects vary by population. ACE contributes but does not determine performance. |
| 3. ACE (A22892G variant) | In some African populations, A22982G is a more reliable predictor than I/D. AA & AG show lower ACE activity; GG highest. | AA and AG are linked with endurance traits and GG is linked with power and strength. | There are ethnicity-dependent effects which are inconsistent across studies. Strongly context-dependent. |
| 4. Polygenic and Epigenetic factors (MSTN, EPAS1, etc.) | Multiple genes interact with ACTN3 & ACE. Epigenetic changes (methylation, histone modification) alter expression in response to training. | Athletic ability emerges from combined genetic and environmental factors. | Reinforces that no single gene predicts athletic ability and training induces gene-expression differences. |
| 5. Injury-related genes (COL1A1, COL5A1, MMP3, TNC, APOE4, etc.) | Variants in connective-tissue genes associated with soft-tissue injuries. eg. APOE4 is linked to higher concussion risk and slower recovery. | There is increased injury susceptibility linked with some genes. | Evidence is preliminary and inconsistent. Genetics alone do not dictate injury outcomes. |

Contrary to popular belief, the XX genotype of ACTN3 does not result in a 'poor athlete.' While ACTN3 XX individuals are sometimes perceived as less capable, evidence shows many excel, particularly in endurance-focused sports, highlighting that genetic variants do not rigidly determine outcomes. Another myth, is that ACE directly affects the contraction of the muscle. However, it actually affects the vascular pathways and oxygen delivery which are traits that are associated with endurance performance.

## 5. Conclusion

Genetic information can be used to guide training plans. It gives insight on areas in training that require attention or emphasis. Although useful for informing training strategies, this information should not determine a child's involvement in sports or restrict their opportunities. While the information can give us a good idea of how individuals respond to different types of training, these genetic tendencies should not dictate participation or talent identification. These genetic insights should serve as tools for personalized training rather that determinants of athletic potential. The use of genetic testing raises privacy and misuse concerns. Commercial genetic talent identification in children is scientifically premature and can cause ethical complications. Misinterpretation of the genetic data could lead to psychological pressure or limit participation in a sport due to discrimination and excessive reliance on the information acquired. Therefore, any use of genetics in talent identification should be regulated and researched.

Most studies are narrative review with various designs, small sample sizes and the possibility of publication bias. Many did not include original genotyping, and their findings often applied to only certain populations. Due to this, the evidence is limited and premature.

Future studies should incorporate ethnically diverse athlete cohorts and detailed polygenic scoring to better characterise how ACTN3, ACE, and related variants collectively influence performance traits. Longitudinal, training-based research is also needed to clarify gene–environment and epigenetic interactions, particularly their roles in endurance adaptation, power development, and injury susceptibility.

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