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Association of the ACTN3 R/X Genotype with Injury Risk, Power, and Strength in Elite Male Competitive Badminton Athletes

[1,2]Muhammad Iqbal Shaharudin, [1]Ahmad Munir Che Muhamed, [1]Ernest Mangantig, [1]Hazwani Ahmad Yusof*

[1]Department of Community Health, Advanced Medical and Dental Institute, Universiti Sains Malaysia, 13200 Kepala Batas, Pulau Pinang, Malaysia.
[2]Faculty of Health Sciences, Universiti Teknologi MARA, Cawangan Pulau Pinang, Kampus Bertam, 13200 Kepala Batas, Pulau Pinang, Malaysia.
***. Corresponding Author: Hazwani Ahmad Yusof**; **E-mail:** hazwanihanafi@usm.my

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Badminton Performance, ACTN3 R/X Polymorphism, Genetic Prediction, Athlete Performance.

ABSTRACT

Background. The *ACTN3 R* allele is associated with normal *ACTN3* expression in fast-twitch muscle. **Objectives.** This study investigates whether the *ACTN3 R* allele, which is associated with normal ACTN3 expression in fast-twitch muscle fibers, is linked to performance and injury susceptibility in well-trained male badminton players. **Methods.** A total of 101 well-trained male badminton players (mean age: 20.72 ± 6.72 years) were genotyped for this polymorphism using DNA extracted from buccal cells. Training history, injury incidence, and severity over the past year were recorded. Strength and power were assessed via handgrip, back strength, vertical leap, standing long jump, and a 40-meter sprint. **Results.** Positive correlations were observed between the RR genotype and both back strength ($r = 0.283$, $p = 0.004$) and handgrip strength ($r = 0.320$, $p = 0.001$). Multinomial logistic regression indicated that the *RR* genotype was associated with a higher likelihood of minor injuries (OR = 0.351) and superior back and handgrip strength (OR = 1.036, 1.202). ANOVA results further confirmed that *RR* and *RX* genotypes exhibited greater back and handgrip strength. **Conclusion.** *ACTN3 R/X* polymorphism may influence physical performance attributes relevant to badminton, particularly strength and injury susceptibility.

INTRODUCTION

Badminton is a high-intensity, intermittent sports activity that uses both aerobic and anaerobic systems (1). Badminton players must compete with fast running, unexpected acceleration, abrupt stops, change of direction, and a constant high intensity of several rallies (1). A range of factors, including motivation, training load, and environmental conditions, influences peak performance in competition (2). Previous research suggests that the intrinsic factor, a genetic component, is more responsible for determining human innate potential, which in turn leads to higher performance (3). A recent study stated that a total of 251 DNA polymorphisms have been linked to athletic status, with 128 genetic markers exhibiting a positive association with this status, with the alpha-actinin-3 (*ACTN3*) gene suggested as the most vital candidate gene with the highest number of positive findings related to strength and power performances (4, 5). The nonsense mutation *ACTN3 R/X* gene polymorphism (rs1815739) is found in codon 577

of exon 16, where the translation [specifically, a cytosine (C) is replaced by a thymine (T)] at nucleotide position 1,747 changes the synthesis of arginine codon (*R* allele) to a premature stop codon (*X* allele) (6). The *R* allele codes for a fully functional *ACTN3* gene, resulting in the creation of the *ACTN3* protein, whereas the *X* allele codes for a truncated protein, which prevents the production of that protein (6). Possessing the *R* allele of the *ACTN3 R/X* gene polymorphism may offer additive effects on strength and power performance in explosive and high-intensity sports such as sprinting, weightlifting, and jumping events, as the *RR* genotype (two copies of the *R* allele) was observed more frequently in strength or power-oriented athletes (7-9). Individuals with the *R* allele have been shown to have higher strength and power capability than those with the *X* allele (10-12). Possession of the *R* allele has also been linked to increased vulnerability to muscle injury (10) and reduced muscle thickness (13) in response to training.

Given that strength, power, and susceptibility to injury are critical components of badminton performance, focusing on the *ACTN3 R/X* gene polymorphism is particularly relevant. The possession of the *R* allele has been shown to have beneficial effects on strength and power (10-12), which are crucial for the high-intensity and explosive movements required in badminton. Most existing studies in the field of badminton have focused on environmental factors, including training, footwear, and nutrition (14). However, there is a significant gap in research addressing the innate genetic factors, such as an athlete's genetic profile. A recent study on elite badminton players that linked *ACTN3* to the *RR* and *RX* genotypes may provide an edge in becoming a world-class badminton player, particularly in the top ten rankings (15). The current literature on the effects of the *ACTN3 R/X* gene polymorphism on physical performance, particularly in badminton players, is limited. The specific influence of the *ACTN3 R/X* gene polymorphism on strength performance and injury risk in badminton remains unclear due to a lack of research. However, a current study suggests that sports injury could be a major factor in determining whether young athletes continue their careers after entering the professional ranks. The risk of injuries is a major concern because of the selection procedure for young athletes and the longevity of their careers. The repercussions of an injury could determine whether an athlete advances, quits, or reaches the competitive level (16).

Previous studies have investigated *ACTN3* in sprinters, endurance athletes, and team-sport players (7-9), but limited research has explored its role in racket sports such as badminton, which requires a combination of speed, agility, and muscular endurance. Given the high prevalence of injuries in badminton players due to rapid directional changes and explosive movements, understanding the genetic influence of *ACTN3* on performance and injury risk is crucial. The *ACTN3* gene is known to play a role in determining muscle fibre composition (17), which can impact an individual's athletic performance in sports like badminton. By examining how this gene influences muscle strength, power, and endurance, researchers can gain insight into its potential role in contributing to success in badminton. Additionally, understanding the genetic factors that influence an athlete's abilities in this sport can help coaches and trainers tailor training programs to optimize performance based on each individual's genetic profile. This knowledge can also be used to identify potential talent in young athletes and guide them towards sports where they may have a genetic advantage. Ultimately, understanding the role of genetics in athletic performance can lead to more personalised and effective training strategies for badminton players. For example, if a player has a genetic predisposition for fast-twitch muscle fibres, coaches can focus on developing explosive power and speed in their training regimen.

Additionally, if a player has a genetic advantage in hand-eye coordination, they may excel in the technical aspects of the sport, such as making accurate shots and responding quickly to the court. In badminton, coaches can use genetic information to tailor training programs for athletes. For instance, players with fast-twitch muscle fibres can benefit from drills that focus on explosive power and speed. Individuals with a genetic advantage in hand-eye coordination may excel at executing accurate shots and responding quickly to situations during gameplay. Understanding genetics in athletic performance can lead to more personalised and effective strategies for badminton players, ultimately enhancing their overall performance on the court.

Identifying the right genes will enable scientists to predict the likelihood of players

developing sports-related injuries and assess their performance in practice and competition. Thus, this new area or focus area is warranted for exploration, as the outcome of the investigation may yield exciting and beneficial information for all badminton players. With the information expected to be provided through this study, a new approach to training the more personalized badminton player, while reducing injury risk to athletes, could be explained by the association between genetic factors and athlete performance. Avoiding injuries can help athletes focus more on their training and aim to win in the competition. The potential to use genetic information is beneficial to maximise the innate potential of the athlete. It is still not possible to determine the precise genes that may give benefits to badminton players of different skill levels. To resolve this discrepancy, our study was conducted to examine how the *ACTN3 R/X* genetic variation affects the strength and endurance performance of badminton players. In addition, this study aims to investigate the relationship between the ACTN3 R/X polymorphism and injury susceptibility in well-trained badminton players, providing insights that could inform personalized training strategies and injury prevention. The findings derived from this study will provide a preliminary understanding of the association between this genetic variation and performance in badminton. Identifying the appropriate genes will enable coaches, sports scientists, and athletic trainers to assist badminton players more effectively in reaching their maximum potential.

MATERIALS AND METHODS

Study Design. A descriptive and retrospective cross-sectional study design was used in the present study. The training information, history of injury, anthropometric measurements, and physical performance tests of badminton players were compared across *ACTN3 R/X* genotype groups. The study was designed in accordance with the STROBE guidelines (18) and was approved by the research ethics committee, adhering to the principles outlined in the Declaration of Helsinki (USM/JEPeM/22080547). The selection of physical performance indicators was based on the well-established role of *ACTN3* in muscle function and athletic performance. The *ACTN3* gene encodes α-actinin-3, a protein predominantly expressed in type II (fast-twitch) muscle fibres, which are crucial for explosive strength, sprinting, and rapid directional changes, key components of badminton performance. Prior research has shown that the *RR* genotype is associated with greater power output, increased muscle force production, and superior sprinting ability, whereas the *XX* genotype is linked to reduced muscle strength but potentially enhances endurance capacity (19). Given the demands of badminton, this study included performance tests such as handgrip strength, back strength, vertical leap, standing long jump, and a 40-meter sprint to evaluate the relationship between *ACTN3* genotype and relevant athletic traits. By integrating both genetic and performance data, this study aimed to explore the potential influence of *ACTN3* polymorphism on badminton-specific attributes, thereby contributing to a better understanding of genotype-based performance variations and injury susceptibility.

Procedure. The athletes received a detailed explanation of the technique, and their written consent was obtained before data collection. Subsequently, the participants underwent a screening process to determine their eligibility, which was based on specific criteria for inclusion and exclusion. The participants were then instructed to complete a comprehensive form that contained the subject's demographic profile, training details, and injury history from the previous 12 months. Injuries were classified according to the number of days lost from sport participation: Slight: no time lost; Minimal: 1–3 days lost; Mild: 4–7 days lost; Moderate: 8–28 days lost; Severe: >28 days lost. Afterwards, the DNA sample was collected by swabbing the inside of the cheek using a sterile swab applicator to analyze the *ACTN3*. The athlete's height was measured using a stadiometer (Seca 213, Seca Corporation, United States), while their body weight and hemodynamic parameters (systolic and diastolic blood pressure) were measured using an Omron KARADA Scan Body Composition & Scale (HBF-362, Omron Corporation, Japan) and a non-invasive, passive brachial oscillometer measured B*P-values* (Omron HEM907XL, Omron Healthcare, Inc., USA), respectively. The athletes then underwent a series of physical assessments conducted by the same researcher, including a hand grip test, a back and leg dynamometer test, a vertical jump, a standing long jump, and a 40-meter sprint test. The total duration of data collection for each participant was approximately 2 hours.

Established research sources support the validity and reliability of the tests used in this study. Strength was assessed using the Hand Dynamometer (Takei A5401, Takei Scientific Instruments Co., Ltd., Japan) and the Leg Dynamometer (Takei A5402, Takei Scientific Instruments Co., Ltd., Japan), both of which have been validated in previous studies (9, 20). Power was measured using multiple tests, including the Vertical Jump Height Tester (PB 7460, Sports Imports Inc., United States), the Standing Long Jump Mat (PB 5039, Sports Imports Inc., United States), and the 40-meter Sprint Test (using a timer, stopwatch, and tape), with validation and reliability established by previous studies (21, 22) Cognitive-motor performance was evaluated using PsyToolkit (Gijsbert Stoet, United Kingdom), which has been validated by Kim et al. (23). These tools have been widely used in research, ensuring the accuracy and consistency of the measurements in assessing strength, power, and cognitive-motor performance. Figure 1 illustrates the general flowchart of the research study.

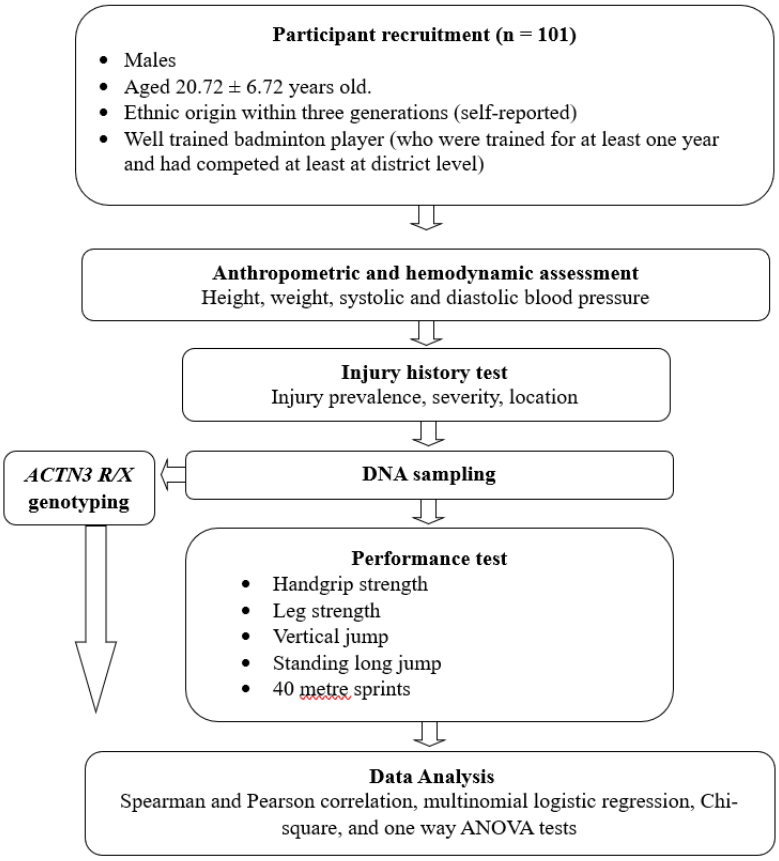

Figure 1. Flow chart of study design

Participants. The sample for this study consisted of 101 well-trained male badminton players of ethnic origin, spanning three generations, as reported on the Phylogeny and Phylogeographic Analysis form. The average age of the players was 20.72 ± 6.72 years, and they had been training for at least one year, having also competed at the district level. Participants with physical limitations or disabilities that would impede their ability to complete the measured test, as well as those with mixed or ambiguous ethnicity, are excluded from fulfilling the criteria. Individuals who violate the study protocol are subject to withdrawal from the study. Their systolic and diastolic blood pressure were approximately 122.36 ± 13.12 mmHg and 74.68 ± 11.47 mmHg, respectively. The players had an average height of 166.46 ± 11.43 cm and a body weight of 63.23 ± 15.52 kg. This study excluded athletes who claimed to have mixed ancestry within three generations and those with physical limitations, such as injuries, that would prohibit

them from executing the evaluated tests. The total number of participants for this study is based on a sample size calculation using the ANOVA test in G*Power version 3.0.10 software, informed by findings from previous studies (24). With three genotype groups, the power of the study was at 0.80, an alpha level of 0.05, and the estimated effect size of 0.25, the minimal required sample size is 101 [sample size/ (1-dropout rate: 91/ (1-0.10) = 91/ 0.90 = 101 participants]. For participants who were minors, informed consent was obtained from their legal guardians or parents, in accordance with ethical guidelines and Institutional Review Board (IRB) requirements. Additionally, assent was obtained from the minors to ensure their voluntary participation in the study.

Handgrip Strength Test. The handgrip test utilizes a hand dynamometer (Takei A5401, Takei Scientific Instruments Co., Ltd., Japan) to assess an athlete's isometric handgrip strength. The researchers employed a conventional method to evaluate grip strength (in kilograms) using a hand dynamometer (25). The device was calibrated following the manufacturer's instructions by suspending calibration weights from the dynamometer's handle. The dynamometer was operated by the dominant hand, while the arm was positioned at a 90-degree angle, and the elbow was kept alongside the body. The dynamometer handles were modified based on the athlete's grip size. The dynamometer's dial was adjusted to zero, and the athletes exerted maximum force on it, sustaining the pressure for around 5 seconds. During the test, verbal support was provided. The athlete performs three trials, with a 10- to 20-second resting period between each test.

Back And Leg Strength Test. The measurement of isometric leg strength was conducted using a back and leg dynamometer manufactured by Takei Scientific Instruments Co., Ltd., Japan (model A5402). This test adhered to the established protocol outlined in the prior investigation (26). The dial was adjusted to a value of zero, and the participants were in an upright position with both feet firmly planted on the base of the equipment. The dynamometer chain was calibrated while the athletes' knees flexed at an angle of 110 degrees. Subsequently, the athlete was instructed to exert maximum force on the handlebars by pulling them upwards for 5 seconds. The maximum reading was documented on the dynamometer display. The exam was conducted three times, with a 10-20 second rest period between each test.

Vertical Jump. The vertical jump height tester (PB 7460, Sports Imports Inc., United States) was used to quantify the athletes' explosive power. This test adhered to the protocol outlined in a previous investigation (27). Before the test, the athlete performs a warm-up. The athlete was required to stand upright next to the vertical jump flag, ensuring that all the vanes were fully extended and aligned. They were then instructed to lightly tap the tallest vanes with their dominant arm while keeping their feet flat on the ground. This measurement was recorded as their standing reached a height of centimeters. Then, the reset tool was employed to displace all the vanes, up to and including the vane that was touched the highest, to a different position. The athlete was instructed to initiate the jump from a crouched position. The athlete achieves maximum vertical height by leaping with a knee angle of 90 degrees and touching the highest vane within reach. The athlete's highest recorded jump height was measured in centimeters. The vertical jump height score (in centimeters) is determined by subtracting the standing reach height from the jump height. The athlete conducted the test on three occasions, with a resting period ranging from 10 to 20 seconds between each attempt.

Standing Long Jump. The standing long jump test was employed to assess the athletes' power in a horizontal direction. This test adhered to the methodology outlined in the preceding investigation (28). The athlete positioned themselves on the standing long jump mat (PB 5039, Sports Imports Inc., United States) by standing with their feet approximately shoulder width apart and their toes positioned directly behind the take-off line. Next, the athletes flexed their knees and oscillated their arms in a backward and forward motion to prepare for the jump. The jump must be executed cleanly, with both feet completely behind the take-off line, without any additional hop or step beforehand. The athletes executed a countermovement and propelled themselves as far as feasible, with the requirement of landing on their feet to achieve a score for the leap. The jump distance was determined by measuring the distance in centimeters from the take-off line to the point where the feet touched the mat closest to the take-off line. The test was repeated three times with

10-second intervals of rest, and the mean score of the three trials was utilized for data analysis.

40-Meter Sprint. Sprint performance was assessed using a 40-meter sprint time (s) measured with photocell timing gates. No direct calculation of mechanical power was performed. The method of administering the test followed the procedure outlined in a previous study (28). The procedure required the participant to perform a warm-up routine. When ready, the participant was asked to assume a starting position by lowering their center of gravity and leaning slightly forward, with their leading foot positioned behind the starting line. On the command "Go," the participant sprints to the 40-meter finish line as fast as possible. The participants were encouraged throughout the test to get the best result. The time the participant crossed the finish line was recorded. The test was repeated three times with 5-minute resting intervals.

Genotyping. DNA samples were collected from all participants using a sterile swab applicator (Swab and bud plastic stick in PP tubes, LTC, Malaysia) through a buccal swab. The samples were air-dried and then placed in sterile 1.5 mL microcentrifuge tubes, which were stored at -20°C until used for DNA isolation. Genomic DNA was isolated from the swab samples using the Presto Buccal Swab gDNA Extraction Kit (Geneaid Biotech Ltd., Taiwan) according to the manufacturer's protocol. For *ACTN3 R/X* genotype determination, polymerase chain reaction (PCR) was carried out using 2X Taq PCR master mix (Thermo Scientific, United States), primer (forward: 5'-CTGTTGCCTGTGGTAAGTGGG-3': reverse: 5'-TGGTCACAGTATGCAGGAGGG-3') (29), sterilized distilled water, and genomic DNA were amplified using a PCR machine (C1000TM Thermal Cycler). In the restriction fragment length polymorphism (RFLP) method, the amplified PCR product was digested with DdeI restriction enzyme (New England Biolabs, Beverly, MA, United States) and 10X NEBuffer3 (New England Biolabs, Beverly, MA, United States). The *ACTN3* genotype was identified by the presence of 205 bp and 86 bp bands, indicating the R allele, while the absence of 108 bp, 97 bp, and 86 bp bands indicates the *X* allele. The primers' sequences were verified by sending the amplified samples to a sequencing company for analysis. To minimize potential errors in the PCR process and RFLP analysis, stringent controls were implemented, including the use of negative controls, optimization of annealing temperatures, verification of enzyme activity, and replication of experiments to ensure consistency and reproducibility.

Statistical Analysis. Statistical evaluations were performed using IBM SPSS Statistics version 28.0.0.0 (Armonk, New York, United States), with a significance level set at $p < 0.05$. The descriptive data are presented as mean ± standard deviation (SD). Allele frequencies of the *ACTN3 R/X* gene polymorphism are determined by direct counting. The normality of each variable was initially tested with the Kolmogorov-Smirnov test, and parametric/ non-parametric statistics were performed for normally/ non-normally distributed variables, respectively. We examine the correlation between athletes with different genotypes and badminton performance metrics using the Spearman or Pearson correlation test. Multinomial regression analyses were conducted to assess the predictive power of the genetic polymorphisms on badminton performance. Variables with significant *p*-values ($p < 0.05$) indicate statistically significant associations with the respective genotypes. The 95% confidence intervals for odds ratios provide insights into the strength and direction of the associations between each variable and the genotypes. In addition, we performed a chi-square test to determine the association between the genotype and the badminton player's history of injury and reaction time level. Analysis of variance (ANOVA) and t-tests, followed by Tukey or Games-Howell post-hoc test when appropriate, have also been used to determine if there are statistically significant differences in performance metrics between individuals with different genotypes or alleles.

RESULTS

Characteristics of participants. All participants were male badminton players who participated in at least district-level competitions for the past year, aged 14-49 years old. A total of 102 volunteers were screened and met all the inclusion and exclusion criteria. However, one participant was excluded after refusing to participate further in the middle of the assessment. The remaining 101 participants completed all assessments, including the demographic profile, training information, history of injury, anthropometric measurements, and physical performance tests.

Table 1 provides a summary of the sample population's characteristics, focusing on various demographic, genetic, and performance-related attributes. Out of the total population sample, almost half of the participants were Malay, followed by Other Bumiputra, Chinese, and Indian. Genotyping analysis of the *ACTN3 R/X* genotype indicates that the *RX* genotype is the most common, while *RR* and *XX* are also significantly represented. The allele frequencies of the *ACTN3 R/X* allele reflect a nearly equal distribution of the *R* and *X* alleles in the sample population, with the *R* allele being slightly more prevalent. The genotype distribution of the *ACTN3 R/X* polymorphism was assessed for Hardy-Weinberg Equilibrium (HWE). The results showed a deviation from HWE (p = 0.02), which may be attributed to factors such as population stratification, selection bias due to the athletic nature of the cohort, or limitations in sample size. The overrepresentation of the RX genotype in our sample may suggest that this variant confers potential advantages for sustaining participation in competitive badminton; however, caution is warranted when generalizing this finding to other populations. Given that the study focuses on well-trained badminton players rather than the general population, this deviation does not necessarily invalidate the observed genotype-performance associations; however, it should be taken into account when interpreting the findings.

Regarding the level of play in badminton, most athletes compete locally at the district and state levels, while a smaller number have competed at national and international competition levels. Most participants have a moderate amount of experience, with the largest group playing for 5 to 10 years. Additionally, most participants are relatively new to competitive play, with the majority having less than five years of tournament experience.

Table 2 provides an overview of the injury history among a sample of badminton players over the past 12 months, detailing the frequency, severity, and types of injuries, as well as the recurrence and chronic nature of these injuries. Over the past 12 months, 72.3% (n = 73) of badminton players reported experiencing an injury, while 27.7% (n = 28) did not. The severity of these injuries varied, with 34.2% (n = 25) classified as slight (no time lost), 30.1% (n = 22) as minimal (1–3 days lost), 21.9% (n = 16) as mild (4–7 days lost), 11.0% (n = 8) as moderate (8–28 days lost), and 2.7% (n = 2) as severe (over 28 days lost). Injuries occurred most frequently during single matches (56.2%, n = 41), followed by doubles (30.1%, n = 22), mixed doubles (1.4%, n = 1), and warm-up/cool-down/practice sessions (12.3%, n = 9). The most common injury locations were the ankle (34.2%, n = 25), foot (17.8%, n = 13), knee (13.7%, n = 10), shoulder and thigh (11.0%, n = 8 each), hand (5.5%, n = 4), neck (4.1%, n = 3), back and elbow (1.4%, n = 1 each). Regarding the types of injuries, muscle cramps were predominant (52.1%, n = 38), followed by blisters and sprains (17.8%, n = 13 each), with bruises, knee injuries, tendonitis, and other types each constituting 1.4% (n = 1), and others making up 6.8% (n = 5). Recurring injuries, reported 2-5 times, affected 70.0% (n = 51) of the players, with muscle cramps being the most common (62.7%, n = 32), followed by blisters (13.7%, n = 7), sprains (11.8%, n = 6), tendonitis (3.9%, n = 2), bruises (5.9%, n = 3), and knee injuries (2.0%, n = 1). Chronic injuries, reported six or more times, were experienced by 56.9% (n = 29) of players, with muscle cramps again being the most frequent (45.5%, n = 10), followed by blisters (27.3%, n = 6), and sprains and tendonitis each at 9.1% (n = 2). Chronic knee injuries and lower back issues were each reported by 4.5% (n = 1).

Correlation between the *ACTN3 R/X* gene polymorphism and badminton players' physical performances. As presented in Table 3, for physical performance, back strength (kg) has a significant positive correlation with the *ACTN3 R/X* polymorphism (r = 0.283, p = 0.004), indicating that this variant is associated with greater back strength. Handgrip strength (kg) also shows a significant positive correlation with the *ACTN3 R/X* polymorphism (r = 0.320, p = 0.001), showing that *ACTN3 R/X* genotypes are related to stronger handgrip strength. However, no significant correlations are observed for long jump (r = -0.040, p = 0.691), vertical jump (r = 0.042, p = 0.674), 40-meter sprint (r = 0.090, p = 0.368), speed (r = -0.091, p = 0.366), or power (r = -0.086, p = 0.392).

Predictive analysis of badminton players' demographic, injury history, and physical performances based on *ACTN3 R/X* genotypes. The findings in Table 4 indicate a negative association between the number of years playing badminton and participating in competitions and the *RR* genotype. Specifically, players with the

RR genotype tend to have fewer years of experience in playing badminton. Players with the *RR* genotype had a decreased likelihood of playing badminton for longer years (OR = 0.833, 95% CI = 0.696 to 0.998, p = 0.047). This suggests that players with the *RR* genotype are 16.7% less likely to have more years of badminton playing experience compared to those without the *RR* genotype.

Additionally, players with the *RR* genotype had a significantly decreased likelihood of playing in tournaments for more years (OR = 0.716, 95% CI = 0.566 to 0.906, p = 0.005). This indicates that players with the *RR* genotype are 28.4% less likely to have more years of tournament play experience compared to those without the *RR* genotype. This suggests that players with this genotype might either start playing later or possibly have shorter badminton careers. Similar to the *RR* genotype, the *RX* genotype also exhibits a negative association with the number of years playing badminton and the number of years playing in tournaments. Players with the *RX* genotype had a significantly decreased likelihood of playing badminton for more years (OR = 0.802, 95% CI = 0.665-0.967, p = 0.021). This indicates that players with the *RX* genotype are 19.8% less likely to have more years of badminton playing experience compared to those without the *RX* genotype. Players with the *RX* genotype also had a significantly decreased likelihood of playing in more tournaments (OR = 0.713, 95% CI = 0.561 to 0.905, p = 0.005). This means that players with the *RX* genotype are 28.7% less likely to have more years of tournament play experience compared to those without the *RX* genotype.

Table 1. The frequency of ethnicity group, *ACTN3 R/X* genotype, level of playing badminton, years playing badminton, and in tournaments (N = 101)

Characteristics	n (%)
Ethnicity	
Malay	49 (48.5)
Chinese	16 (15.8)
Indian	2 (2.0)
Others Bumiputera	34 (33.7)
***ACTN3 R/X* genotype**	
RR	33 (32.7)
RX	39 (38.6)
XX	29 (28.7)
***ACTN3 R/X* allele**	
R	51 (52.0)
X	49 (48.0)
Level of playing badminton	
District	44 (43.6)
University	4 (4.0)
State	36 (35.6)
National	16 (15.8)
International	1 (1.0)
Years playing badminton	
< 5 years	29 (28.7)
5 years to 10 years	51 (50.5)
11 years to 20 years	19 (18.8)
> 20 years	2 (2.0)
Years playing in tournaments	
< 5 years	54 (53.5)
5 years to 10 years	41 (40.6)
11 years to 20 years	6 (5.9)

n: Frequency

Table 2. The history of injury among badminton players

Characteristics	n (%)
Report injury in the past 12 months (n = 101)	
Yes	73 (72.3)
No	28 (27.7)
Severity of injury (n = 73)	
Slight (no time lost)	25 (34.2)
Minimal (1–3 days lost)	22 (30.1)
Mild (4–7 days lost)	16 (21.9)
Moderate (8–28 days lost)	8 (11.0)
Severe (>28 days lost)	2 (2.7)
Event that incurred injury (n = 73)	
Single	41 (56.2)
Double	22 (30.1)
Mixed double	1 (1.4)
Warm up/ cool down/ practice	9 (12.3)
Location injury (n = 73)	
Ankle	25 (34.2)
Back	1 (1.4)
Elbow	1 (1.4)
Foot	13 (17.8)
Hand	4 (5.5)
Knee	10 (13.7)
Neck	3 (4.1)
Shoulder	8 (11.0)
Thigh	8 (11.0)
The type of injury from playing badminton (n = 73)	
Ankle	1 (1.4)
Blister	13 (17.8)
Bruises	1 (1.4)
Knee injuries	1 (1.4)
Muscle cramps	38 (52.1)
Sprains	13 (17.8)
Tendonitis	1 (1.4)
Others	5 (6.8)
Report recurring injuries from playing badminton (reported 2-5 times) (n = 73)	
Yes	51 (70.0)
No	22 (30.0)
No. Reporting recurring injuries from playing badminton (reported 2-5 times) (n = 51)	
Blister	7 (13.7)
Bruises	3 (5.9)
Knee injuries	1 (2.0)
Muscle Cramps	32 (62.7)
Sprains	6 (11.8)
Tendonitis	2 (3.9)
Report chronic injuries from playing badminton (reported injuries six or more times) (n = 51)	
Yes	29 (56.9)
No	22 (43.1)
No. Reporting chronic injuries from playing badminton (reported injuries six or more times) (n = 22)	
Blister	6 (27.3)
Knee injuries	1 (4.5)
Lower back	1 (4.5)
Muscle cramps	10 (45.5)
Sprains	2 (9.1)
Tendonitis	2 (9.1)

n: Frequency

Table 3. The correlation between the *ACTN3 R/X* gene polymorphism and physical performance.

Characteristics	Correlation Coefficient	*p-value*
Back strength (kg)	0.283	0.004*
Handgrip strength (kg)	0.320	0.001*
Long jump (cm)	-0.040	0.691
Vertical jump (cm)	0.042	0.674
40-meter sprint (s)	0.090	0.368
Speed (m/s)	-0.091	0.366

* Significant at $p < 0.05$ (2-tailed)

There is a significant negative association between the severity of injury and the *RR* genotype. Players with the *RR* genotype had a significantly lower likelihood of experiencing severe injuries (OR = 0.351, 95% CI = 0.137-0.898, $p = 0.029$). This indicates that the odds of having severe injuries are 64.9% lower in players with the *RR* genotype compared to those without this genotype. The reported odds ratio of 0.351 suggests a strong protective effect of the *RR* genotype against severe injuries among badminton players, as individuals with this genotype are less likely to suffer from severe injuries.

For back and handgrip strength, there are positive associations observed between the *RR* genotype and both back strength and handgrip strength. Higher back strength was significantly associated with the *RR* genotype (OR = 1.036, 95% CI = 1.006-1.068, $p = 0.018$). This means that players with the *RR* genotype are 3.6% more likely to have superior back strength. Increased handgrip strength was also significantly associated with the *RR* genotype (OR = 1.202, 95% CI = 1.046 to 1.380, $p = 0.009$). This suggests that players with the *RR* genotype are 20.2% more likely to have superior handgrip strength.

For other variables, such as the number of recurring injuries, the number of chronic injuries, long jump, vertical jump, 40-meter sprint, speed, and power, the odds ratios did not reach statistical significance ($p > 0.05$) for the *RR* genotype. Meanwhile, severity of injury, number of recurring injuries, number of chronic injuries, back strength, handgrip strength, long jump, vertical jump, 40-meter sprint, speed, and power showed no significant association with the *RX* genotype ($p > 0.05$).

Association analysis between the *ACTN3 R/X* gene polymorphism and badminton players' demographic, injury history, and physical performances. The association between the *ACTN3 R/X* genotype and injury severity among badminton players reveals significant differences, as shown in Table 5. The Chi-square test indicates a significant association ($p = 0.023$). Specifically, slight injuries are most frequent in the *RR* genotype (14 players), followed by *the RX genotype (6 players) and the XX genotype* (5 players). The most frequent injuries are minimal in the *RX* genotype (14 players), followed equally by *RR* (4 players) and *XX* (4 players). Even distribution across all genotypes, with 6 in *RR*, 5 in *RX*, and 5 in *XX*, was found in the mild injuries category. Moderate injuries are more common in the *RX* genotype (4 players), followed by *the XX genotype (3 players) and the RR genotype* (1 player). Meanwhile, severe injuries are observed only in the *XX* genotype (in 2 players), with none reported in the other genotypes. Overall, our study suggests that the *RR* genotype may be associated with less severe injuries, while the *XX* genotype is linked to more severe injuries that require extended recovery times.

Table 6 presents the results of a one-way ANOVA analysis examining the association between *ACTN3 R/X* gene polymorphism and various performance metrics in badminton players. The metrics include back strength, handgrip strength, reaction times, jumping ability, sprinting speed, and power. The results showed a significant effect of *ACTN3 R/X* genotype on back strength ($F(2, 98) = 4.766$, $p = 0.012$). A Games-Howell post hoc test revealed that back strength was statistically significantly higher among RR genotype carriers (109.30 ± 29.53 kg, $p = 0.009$) compared to *RX* genotype individuals (88.89 ± 26.58 kg). There is also a significant effect of *ACTN3 R/X* genotype on handgrip strength ($F(2, 98) = 8.657$, $p = 0.000$). A Games-Howell post hoc test revealed that back

strength was statistically significantly higher among RR genotype carriers (36.79 ± 6.73 kg, p = 0.000) compared to *RX* genotype individuals (35.37 ± 5.56 kg). In contrast, there is no significant difference in long jump (F (2, 98) = 0.512, p = 0.601), vertical jump (F (2, 98) = 0.133, p = 0.876), 40-meter sprint (F (2, 98) = 0.329, p = 0.721), speed (F (2, 98) = 0.284, p = 0.753), and power (F (2, 98) = 0.222, p = 0.801) between the *ACTN3* genotypes.

Table 4. The association of badminton players' demographic, injury history, and physical performances with *ACTN3 R/X* genotypes using multinomial logistic regression.

Variable	Coefficient	Odds ratio (95% confidence interval)	*p* value
***RR* genotype**			
Years of playing badminton	-0.183	0.833 (0.696 to 0.998)	0.047*
Years of playing in tournaments	-0.334	0.716 (0.566 to 0.906)	0.005*
Severity of injury	-1.047	0.351 (0.137 to 0.898)	0.029*
No of recurring injury	-0.678	0.508 (0.097 to 2.650)	0.421
No of chronic injuries	1.074	2.928 (0.391 to 21.917)	0.295
Back strength (kg)	0.024	1.036 (1.006 to 1.068)	0.018*
Handgrip strength (kg)	0.184	1.202 (1.046 to 1.380)	0.009*
Long jump (cm)	-0.005	0.995 (0.983 to 1.006)	0.365
Vertical jump (cm)	0.010	1.010 (0.965 to 1.057)	0.667
40-meter sprint (s)	-0.007	0.993 (0.567 to 1.739)	0.980
Speed (m/s)	-0.088	0.916 (0.441 to 1.900)	0.814
***RX* genotype**			
Years of playing badminton	-0.220	0.802 (0.665 to 0.967)	0.021*
Years of playing in tournaments	-0.339	0.713 (0.561 to 0.905)	0.005*
Severity of injury	-0.737	0.479 (0.211 to 1.086)	0.078
No of recurring injury	-0.046	0.955 (0.172 to 5.293)	0.958
No of chronic injuries	0.776	2.173 (0.326 to 14.492)	0.423
Back strength (kg)	0.003	1.003 (0.975 to 1.031)	0.844
Handgrip strength (kg)	0.020	1.020 (0.902 to 1.155)	0.706
Long jump (cm)	-0.008	0.992 (0.979 to 1.004)	0.176
Vertical jump (cm)	0.009	1.009 (0.964 to 1.055)	0.706
40-meter sprint (s)	-0.441	0.644 (0.363 to 1.140)	0.131
Speed (m/s)	0.430	1.538 (0.716 to 3.304)	0.270

The reference category for *ACTN3* is the *XX* genotype. * Significant at $p < 0.05$

Table 5. The association between *ACTN3 R/X* and injury history (N = 73)

Variable	*ACTN3 R/X* genotype			X^2	*p* value
	RR	***RX***	***XX***		
Severity of injury (n = 73)					
Slight (no time lost)	14	6	5	15.824	0.023*
Minimal (1–3 days lost)	4	14	4		
Mild (4–7 days lost)	6	5	5		
Moderate (8–28 days lost)	1	4	3		
Severe (>28 days lost)	0	0	2		

*** Significant at $p < 0.05$**

DISCUSSION

Genetic variations play a significant role in athletic performance, influencing factors such as strength and endurance abilities (30). The *ACTN3* gene has been identified as a potential marker for athletic performance due to its role in muscle function (31). Therefore, this study was conducted to investigate how variations in the *ACTN3 R/X* polymorphism may predict performance outcomes among badminton players. Our findings suggest that the *ACTN3 R/X* gene polymorphism is linked to several key aspects of badminton performance. Based on the genotypes identified in the study, it was possible to calculate the probability of

different injury severities. Polymorphism results in variations in muscle strength across different genotypes (31). The present study employed correlation, multinomial regression, and ANOVA analyses to establish a comprehensive framework for examining the influence of the *ACTN3 R/X* gene polymorphism on athletic performance and injury profiles. The correlation analysis was first used to establish a foundational relationship between the *ACTN3 R/X* gene polymorphism and various measures of athletic performance. Further analysis using the multinomial regression added depth by predicting the likelihood of different injury severities based on genotype, while ANOVA confirmed significant differences in muscle strength across genotypes. These combined findings underscore the role of the *ACTN3 R/X* gene polymorphism in influencing both performance and injury resilience among badminton athletes.

Table 6. The association between the *ACTN3 R/X* genotype with badminton players' demographic, injury history, and performance using one-way ANOVA (N = 101)

Variables	Genotype	n	Mean ± SD	F (2, 98)	*p* value	*Partial ETA Squared*
Years of playing badminton	*RR*	33	9.62 ± 5.80	3.837	0.025*	0.072
	RX	39	7.24 ± 0.91			
	XX	29	6.06 ± 0.64			
Years of playing in tournaments	*RR*	33	7.31 ± 4.22	8.706	<0.01*	0.159
	RX	39	4.16 ± 3.64			
	XX	29	3.74 ± 2.52			
Severity of injury	*RR*	33	2.10 ± 1.88	2.631	0.077	-0.006
	RX	39	1.85 ± 1.14			
	XX	29	1.32 ± 1.15			
No of recurring injury	*RR*	33	0.48 ± 0.51	0.369	0.693	0.007
	RX	39	0.56 ± 0.50			
	XX	29	0.47 ± 0.51			
No of chronic injuries			0.17 ± 0.38	0.439	0.646	0.009
	RR	29				
	RX	33	0.26 ± 0.44			
	XX	39	0.26 ± 0.42			
Back strength (kg)	*RR*	33	109.30 ± 29.53	4.766	0.012*	0.089
	RX	39	88.89 ± 26.58			
	XX	29	94.53 ± 20.98			
Handgrip strength (kg)						
	RR	33	40.35 ± 4.63	7.202	0.001*	0.129
	RX	39	35.37 ± 5.64			
	XX	29	36.79 ± 6.73			
Long jump (cm)	*RR*	33	213.14 ± 52.16	0.512	0.601	0.010
	RX	39	206.56 ± 56.60			
	XX	29	219.43 ± 45.30			
Vertical jump (cm)	*RR*	33	54.50 ± 15.05	0.133	0.876	0.003
	RX	39	52.79 ± 14.73			
	XX	29	54.20 ± 15.43			
40-meter sprint (s)	*RR*	33	6.67 ± 1.00	0.329	0.721	0.007
	RX	39	6.53 ± 1.13			
	XX	29	6.80 ± 1.81			
Speed (m/s)	*RR*	33	6.11 ± 0.81	0.284	0.753	0.006
	RX	39	6.27 ± 0.90			
	XX	29	6.15 ± 1.08			

*** Significant at $p \leq 0.05$**

The distribution analysis of the *ACTN3 R/X* genotypes reveals interesting patterns in the sample population. For the *ACTN3 R/X* genotype, the *RX* genotype is the most common among participants, with *RR* and *XX* genotypes also represented, indicating a varied distribution of *ACTN3* genotypes (24). This distribution aligns with previous studies on athletic populations,

though variations exist across different ethnic groups. For example, studies on Chinese sprinters have reported a lower prevalence of the *XX* genotype, suggesting population-specific genetic influences on sprint performance (32). However, the current findings differ notably from those of a previous study on European badminton players (15). While the *RX* genotype is the most common in the sample population, the *RR* genotype is more prevalent among professional badminton players, particularly those at the elite level (15). The discrepancy in genotype distribution between the current population and elite athletes in the previous study (15) may be due to differences in experience and competition level, where most athletes in the sample population compete locally at district and state levels, with fewer athletes competing at national and international levels. Most participants have a moderate amount of experience, with the largest group having played for 5 to 10 years.

Additionally, most participants are relatively new to competitive play, with the majority having less than 5 years of tournament experience. Nonetheless, both findings indicate that the expression of functional α-actinin-3, particularly those associated with the *R* allele of *ACTN3*, may be more advantageous in sports requiring explosive power and fast-twitch muscle performance, such as badminton. These results underscore the need for further large-scale studies across different ethnic backgrounds to confirm the association between the R allele and badminton performance, and to explore the underlying mechanisms.

Correlation and multinomial regression analysis demonstrate a significant negative correlation between the *RR* genotype and the number of years playing badminton, both overall and in tournaments. This suggests that individuals with the *RR* genotype tend to start playing badminton later or have shorter careers in competitive play. Previous research has consistently shown that the presence or absence of α-actinin-3 (encoded by the *ACTN3* gene) can significantly influence muscle fiber composition and performance characteristics (6). The observed negative correlation between the *RR* genotype and the duration of badminton involvement in this study could imply several potential factors. Firstly, the *RR* genotype, associated with α-actinin-3 presence, generally favors fast-twitch muscle fibers suited for explosive movements but may be less advantageous in sports requiring prolonged endurance, such as badminton. These muscle fibres may fatigue more quickly, potentially affecting long-term endurance and career longevity in sports like badminton that require sustained effort over matches and tournaments. Secondly, athletes with the *RR* or *RX* genotypes might excel initially due to their genetic predisposition for explosive muscle performance. However, factors such as training intensity, recovery strategies, and susceptibility to injury could influence their ability to maintain long-term participation in competitive environments. Thirdly, it is also possible that athletes with these genotypes make career decisions influenced by their physical attributes and performance trajectories. They might choose to specialize in sports or activities where explosive power provides a more significant competitive advantage over endurance. In brief, the correlations observed between the *RR* and *RX* genotypes and the duration of badminton involvement support existing literature on genetic influences in sports. These findings highlight the potential benefits of personalized training approaches and career planning for athletes, tailored to their genetic predispositions and performance dynamics.

This suggests that individuals with specific *ACTN3* genotypes (likely *RR* or *RX*, given the negative correlation) may experience less severe injuries compared to those with other genotypes. The presence of α-actinin-3, particularly in *RR* and *RX* genotypes, may contribute to improved muscle performance and potentially reduce the risk of severe injury during physical activities. A study among professional football players also indicates that individuals with the *ACTN3 XX* genotype had a higher risk of severe injuries in comparison to those with other genotypes (33). In addition, the study indicates that individuals with the *ACTN3 XX* genotype were more likely to suffer from severe injury (33). The possible explanations for the current observations are that individuals with the *RR* or *RX* genotype produce α-actinin-3, which may contribute to more efficient muscle function during physical activities, such as sports. Enhanced muscle function in *RR* and *RX* genotypes could potentially lead to better coordination, strength, and agility, thereby reducing the likelihood of sustaining severe injuries during athletic endeavours.

In contrast, α-actinin-3 deficiency (in individuals with the *XX* genotype) has been associated with reduced muscle performance in activities requiring rapid, forceful contractions (10). This deficiency may predispose individuals to muscle strains, tears, or other injuries due to compromised muscle function and performance under strenuous conditions. Individuals with *RR* or *RX* genotypes, characterized by the presence of α-actinin-3, may experience less severe injuries due to enhanced muscle performance and resilience.

Recurring injuries typically refer to injuries that happen repeatedly in the same area or due to similar activities, suggesting that the variations in the *ACTN3 R/X* genotypes do not appear to influence the likelihood of experiencing recurring injuries among athletes. Similarly, there is no statistically significant association between the *ACTN3 R/X* polymorphism and chronic injuries, which are injuries characterized by long-term or persistent symptoms. Chronic injuries often result from overuse, repetitive stress, or underlying biomechanical issues rather than acute events, and the lack of correlation suggests that *ACTN3* genotypes may not play a prominent role in predisposing individuals to chronic injury risk. The absence of significant correlations between the *ACTN3 R/X* polymorphism and recurring or chronic injuries may be due to the fact that injuries, especially recurring and chronic ones, are influenced by a multitude of factors beyond genetics, including biomechanics, training history, environmental conditions, and individual behaviour. Different types of injuries, such as acute and chronic injuries, may have distinct underlying mechanisms and risk factors (34) that interact differently with genetic predispositions. Furthermore, while α-actinin-3 deficiency in the *XX* genotype has been linked to reduced muscle performance and potentially increased injury susceptibility in certain contexts, its direct association with recurring or chronic injury patterns may be less pronounced. The genetic variations in *ACTN3* may primarily influence the severity of acute injuries rather than the frequency or persistence of injuries over time.

This suggests that individuals with certain genotypes, likely *RR* or *RX*, tend to exhibit greater back and handgrip strength compared to those with the *XX* genotype. This finding underscores a consistent trend observed across various studies (24, 35) highlighting a genetic predisposition for greater muscular power and performance in individuals with the *R* allele. In the meantime, the lack of significant correlations on long jump, vertical jump, 40-meter sprint, speed, or power suggests that while *ACTN3* genotype influences strength-related metrics (back and handgrip strength), it may not play a significant role in other performance domains measured in this study. Performance in activities such as reaction time, agility, and speed involve a combination of neural factors, biomechanics, and skill acquisition, which factors beyond the ACTN3 genotype may influence. Genetic variations in *ACTN3* may exert more pronounced effects on specific aspects of physical performance that heavily rely on muscle strength and power rather than pure speed or reaction time. The significant positive correlations between back strength and handgrip strength with the *ACTN3 R/X* polymorphism suggest a role for this genetic variant in influencing muscle strength performance. However, the lack of significant correlations with other physical performance measures underscores the selective impact of the *ACTN3* genotype on specific facets of physical performance. Future research could further explore these relationships across diverse athletic populations to better understand how genetic factors contribute to variations in physical capabilities and performance outcomes.

In terms of injury severity, the *RR* genotype is most commonly seen in cases of minor injuries, followed by those of minimal injuries. However, it is rarely observed in cases of moderate injuries and is completely absent in cases of severe injuries, indicating potentially better injury resilience or recovery capabilities. Conversely, individuals with the *RX* genotype exhibit a higher occurrence in cases of minimal injuries, while moderate injuries are noted, and no instances of severe injuries have been reported. The *XX* genotype is the most prevalent in cases of severe injuries, although there have also been reports of this genotype in cases of moderate and minor injuries, implying greater vulnerability to injuries that require extended recovery periods. The significant association between *ACTN3 R/X* genotype and injury severity suggests distinct injury profiles among genotypes. The current study's observations align with earlier research demonstrating the significant impact of the *R* allele on athletic capabilities and recovery (10). In a detailed study examining race performance and

post-competition recovery, it was found that at the end of the race, *X*-allele carriers had higher serum CK-MM concentrations, indicating more significant muscle damage (36). There was also a tendency for higher self-reported lower limb muscle pain among *X*-allele carriers. Hence, these findings emphasize that the *X*-allele of the *ACTN3 R577X* polymorphism exhibits greater signs of exercise-induced muscle damage during a half-ironman race compared to *RR* homozygotes. This supports the notion that the *R* allele is associated not only with enhanced muscle performance but also with better resilience and recovery capabilities, which are critical for high-performance athletes. The consistency of these results with previous studies (36) highlights the significant role of the *ACTN3* genotype in determining athletic performance and recovery profiles, offering valuable insights for personalized training and injury prevention strategies.

This difference is attributed to the presence of α-actinin-3, a protein abundant in fast-twitch muscle fibres, which are crucial for generating power and stability in movements like those required in badminton (12). Fast-twitch muscle fibres, enriched with α-actinin-3, enable quicker and more forceful contractions, contributing to enhanced back strength. This strength is vital in badminton for executing powerful smashes, quick changes in direction, and maintaining posture during intense rallies. Similarly, *RR* genotype carriers demonstrated higher handgrip strength compared to those with the *RX* genotype. Handgrip strength is crucial in badminton for racket control, especially during shots that require precise grip adjustments, as well as overall upper body strength, which influences various aspects of gameplay, such as serving, net play, and defensive manoeuvres. The presence of α-actinin-3 in individuals with the *RR* genotype likely contributes to superior muscle performance in the hands and upper body, enhancing their ability to execute technical manoeuvres with greater control and power. The results highlight the impact of genetic variants in *ACTN3* on characteristics of muscle strength that are relevant to badminton play. Individuals with the *RR* genotype, who benefit from α-actinin-3 expression, may have a natural advantage in generating and controlling force during gameplay, potentially contributing to better overall performance outcomes.

In contrast, no significant differences were observed between *ACTN3* genotypes in the long jump, vertical jump, 40-meter sprint, speed, or power events. The lack of significant differences in reaction times, jumping ability, sprinting ability, speed, and power between *ACTN3* genotypes suggests that while *ACTN3* influences specific aspects of muscular strength (such as back and handgrip strength), its impact on these other performance metrics in badminton players may be less pronounced or influenced by additional factors such as training, technique, and individual variability in athletic development. This underscores the complexity of athletic performance, which is influenced by a combination of genetic predispositions and environmental factors. For example, jumping ability, including both the long jump (horizontal) and vertical jump (vertical), relies on explosive power generated by fast-twitch muscle fibres. Despite the influence of α-actinin-3 on fast-twitch muscle fibres and muscular strength, the study did not find significant differences in jumping performance between *ACTN3* genotypes. Other factors, such as technique, coordination, and neuromuscular efficiency, may play a larger role in determining jumping ability compared to the genetic influence of *ACTN3* alone. Sprinting ability, including short-distance speed, relies heavily on fast-twitch muscle fibres for explosive acceleration and top speed. Like jumping ability, the *ACTN3* genotype influences muscular strength, which can contribute to sprinting performance; however, the study did not detect significant differences in sprinting ability or speed between genotypes. Factors such as technique, stride length, and training specificity may have a more pronounced impact on sprinting performance compared to genetic variations in *ACTN3*. Power, in the context of sports performance, encompasses the ability to generate force quickly, often measured in movements such as throws or rapid changes in direction. Despite the role of α-actinin-3 in fast-twitch muscle fibres, which are crucial for power production, the study did not find significant differences in power output between *ACTN3* genotypes. The multifaceted nature of power production, including both muscular strength and neuromuscular coordination, may involve factors beyond the influence of the *ACTN3* genotype alone.

Regardless of the *ACTN3 R/X* gene polymorphism, the findings on the severity of the

injury and its proportion of injuries were similar to those of past studies, where most players had slight injuries, followed by moderate and severe injuries (37, 38). The location of injury primarily occurs in the lower extremities, a region that has also been well-reported in previous studies (37-39). Badminton is a sport that places significant demands on the body's biomechanics, requiring frequent and rapid changes in speed and direction. Therefore, this places a significant eccentric load on the lower extremities, risking strains, sprains, and ligament injuries (37). It was found that the ankle, foot, and knee regions were the most frequently reported injuries in the lower extremities, a finding that has been well-documented in past studies among badminton players (38-40). Quick and repetitive lunges and jumps in badminton have been associated with generating substantial impact loading on the lower extremities of players, which can lead to overuse injuries to the knees (40). In addition, it was discovered that most players executed the jump smash by using their same-side foot (the foot on the side holding the racquet) to jump and then landing with their opposite-side foot. The researchers determined that the single-leg technique could contribute to injuries in the ankle and knee joints (37, 41). A review study also indicates that the shoulder is the most common location of injuries in the upper extremities. A characteristic of badminton is that it requires an increased range of shoulder mobility, which puts considerable stress on the shoulder joint (37).

Additionally, there is a significant amount of repetitive over-the-shoulder movement in badminton, particularly in shoulder abduction and rotation, which leads to injury (42-44). Additionally, muscle cramps were reported as one of the most common types of injury in previous retrospective studies conducted in Indonesia (45). A study on the survey of badminton injuries also indicates that blisters, muscle cramps, and sprains are the most common injuries reported among badminton players (46). The classification of injuries based on event type also yields similar findings to past studies, where single and double injuries were reported to be more prevalent (46).

This study presents a thorough and multifaceted investigation into the influence of the *ACTN3 R/X* gene polymorphism on athletic performance and injury profiles among badminton players. Several key elements contribute to the strength of this research. Firstly, the present study integrates correlation, multinomial regression, and ANOVA analyses to provide a strong methodological foundation for understanding the impact of genetic variations. The correlation analysis establishes foundational relationships, multinomial regression predicts the likelihood of injury severities based on genotype, and ANOVA confirms significant differences in muscle strength across genotypes. This multi-layered analytical approach enhances the robustness and reliability of the findings. Secondly, the study's detailed examination of the distribution of *ACTN3 R/X* genotypes within the sample population offers valuable insights. The varied distribution observed aligns with patterns seen in different athletic populations, highlighting the relevance and applicability of the findings. The discrepancy between the current population and elite athletes underscores the influence of experience and competition level on genotype prevalence.

Overall, the findings observed in the present study highlight the potential relevance of genetic testing in sports medicine for tailoring injury prevention strategies and optimizing athletic performance based on individual genetic profiles. However, it is essential to note that while genetics may influence injury severity, other factors, such as nutrition, training periodization, sleep quality, psychological issues, conditioning, and environmental factors, also play critical roles in overall injury risk management for athletes. These findings not only deepen our understanding of the genetic basis of muscle function but also have practical implications for training strategies tailored to optimize athletic performance based on an individual's genetic profile. The practicality of utilizing *ACTN3 R/X* genotype analysis in everyday training and player selection involves several key considerations. Firstly, implementing genetic testing into training programs can be relatively straightforward since it typically requires a simple saliva or blood sample. This minimal invasiveness makes it feasible to integrate into existing routines without major disruptions. Coaches can leverage these results to tailor training to each athlete's unique genetic profile, potentially enhancing performance and reducing the risk of injury. However, the effectiveness hinges on the coach's ability to interpret and apply the data, which may require additional training. The costs associated with genetic testing have decreased, making it more

accessible, yet it still represents an additional expense that tangible benefits must justify. To maximize its impact, conducting genetic assessments early in an athlete's career allows for the creation of personalized training regimens from the outset, while periodic reassessment can refine programs as athletes mature and their needs evolve. This systematic approach could significantly enhance training and performance strategies, offering a valuable tool for optimizing athletic potential. These findings highlight the complex and varied elements that contribute to the risk of injury in sports, underscoring the importance of comprehensive strategies for preventing injuries that consider genetic, biomechanical, and behavioral aspects. Additional investigation is necessary to clarify the precise connections between genetic profiles, muscle physiology, and injury patterns, thereby enhancing individualized injury treatment strategies for athletes.

The study acknowledges several limitations that impact its generalizability and robustness, necessitating caution in interpreting the results. The study's sample population may not represent the diversity of all ethnic backgrounds and populations, potentially skewing the applicability of the results due to genetic variations across different groups. Participants' experience levels, predominantly at local and district levels, may not accurately reflect the genetic profiles of elite athletes, who often exhibit distinct genetic characteristics. While the average age is reported, the large standard deviation (6.72 years) indicates significant variability. This variability might influence the results, as physiological responses can differ widely between younger and older athletes within this range. Moreover, environmental factors such as training intensity, recovery strategies, and coaching quality, which significantly influence athletic performance and injury risk, were not controlled, potentially confounding the results. The study's focus on the *ACTN3 R/X* polymorphism overlooks the complex interplay of multiple genes that influence athletic performance and susceptibility to injury.

Furthermore, injury reporting and classification methods may introduce biases, as self-reported injuries can be subjective, and the severity of injuries may vary. The study also measured specific performance metrics, such as back strength and handgrip strength, but did not find significant correlations with other important performance indicators, including reaction time and jumping ability, which limited the scope of the findings. Additionally, ancestry-matched controls are absent, justifying focusing on a homogeneous competitive cohort.

To overcome these limitations, future research should focus on larger, more ethnically diverse sample populations, including elite athletes, to explore how genetic variations, particularly in *ACTN3*, influence performance and injury susceptibility across different groups. Including more elite-level athletes could provide insights into genetic profiles associated with top-tier performance. A multifactorial approach, considering various environmental, training, and genetic factors, would offer a better understanding of the complex interactions influencing athletic performance and injury risk. Broadening genetic analysis to encompass multiple genes and polymorphisms associated with athletic performance and injury susceptibility can offer a more holistic insight into genetic influences. Implementing standardized methods for injury reporting and classification can reduce biases and improve the accuracy of injury data. Future research should also encompass a broader range of performance metrics to capture various aspects of athletic ability, including agility, endurance, and skill-related components. Employing longitudinal studies would enable the monitoring of performance and injury trends over time, facilitating a deeper understanding of how genetic factors interact with training regimens and career trajectories. Lastly, the findings suggest the potential for personalized training and injury prevention programs based on genetic profiles, enabling coaches and trainers to tailor training regimens that optimize performance and minimize injury risk for individual athletes. The use of genetic information in sport raises several ethical considerations that warrant careful attention. First, privacy is a major concern, as genetic data are highly personal and sensitive; inappropriate access or sharing could lead to discrimination or stigma. Second, the predictive value of genetic markers for athletic performance is currently limited. While certain variants may be associated with traits such as endurance or power, they cannot reliably determine an individual's potential, and overreliance on such information could be misleading. Finally, there is a risk of

misuse, including genetic discrimination in talent identification, selection processes, or even the encouragement of unethical practices such as gene doping. Therefore, any application of genetic information in sports settings should be approached with caution, adhering to strict ethical guidelines and respecting the rights of athletes.

CONCLUSION

The present study underscores the significant role of genetic variations, particularly the *ACTN3 R/X* polymorphism, in athletic performance and injury profiles among badminton players. Our findings highlight that the *RX* genotype is the most common among participants, although the RR genotype is more prevalent among elite badminton players. Key insights from the study reveal that the *ACTN3 R/X* polymorphism is associated with specific aspects of badminton performance, particularly in muscle strength. Individuals with the *RR* genotype exhibit greater back and handgrip strength, which is critical for the power and control required in badminton. However, no significant differences were found in reaction time, jumping ability, sprinting speed, or overall power, suggesting that factors beyond the *ACTN3* genotype may influence these performance domains. Our results also indicate a significant negative correlation between the RR genotype and the number of years playing badminton, suggesting that while these individuals may excel initially, their careers in competitive play may be shorter due to various factors, including training intensity and susceptibility to injury.

Additionally, the study found that the *ACTN3 R/X* polymorphism has a significant impact on the severity of injuries. Individuals with the RR genotype experience less severe injuries, possibly due to better muscle performance and resilience. Conversely, the *XX* genotype is more associated with severe injuries, aligning with previous research on the increased susceptibility of *XX* genotype carriers to muscle damage and injuries. Despite the observed associations, the study did not find a significant correlation between the *ACTN3 R/X* polymorphism and the frequency of recurring or chronic injuries. This suggests that while the *ACTN3* genotype may influence the severity of acute injuries, recurring and chronic injuries are likely influenced by a broader range of factors, including biomechanics, training history, and environmental conditions.

In conclusion, our findings underscore the intricate relationship between genetic factors and athletic performance. The *ACTN3 R/X* polymorphism has a significant impact on muscle strength and injury severity, but does not appear to influence other performance metrics, such as reaction time and speed. These insights underscore the importance of considering genetic profiles in designing personalized training and injury prevention strategies for athletes. Further large and longitudinal scale studies across diverse populations are needed to confirm these associations and explore the underlying mechanisms in greater detail. While *ACTN3 R/X* polymorphism may contribute to performance variation, the small effect sizes observed in this cohort make it inappropriate to base individualized training or selection decisions solely on genetic testing.

APPLICABLE REMARKS

- The present study revealed that the *ACTN3 RR* genotype was associated with superior back and handgrip strength among well-trained male badminton players, indicating a potential advantage in explosive strength-related movements required in the sport.
- Players with the *RR* genotype also experienced less severe injuries, although they tended to have shorter badminton experience, which may suggest that genetic factors play a role even in early athletic development.
- A genetic screening for *ACTN3* polymorphism may support coaches and sports scientists in designing individualized strength and injury prevention programs, thereby optimizing training outcomes and athlete performance.

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AUTHORS' CONTRIBUTIONS

Study concept and design: H. Ahmad Yusof. Acquisition of data: M.I. Shaharudin; A.M. Che Muhamed; H. Ahmad Yusof. Analysis and interpretation of data: E. Mangantig; H. Ahmad Yusof. Drafting of the manuscript: M.I. Shaharudin; H. Ahmad Yusof. Critical revision of the manuscript for important intellectual content: H. Ahmad Yusof. Statistical analysis: E. Mangantig; H. Ahmad Yusof. Administrative, technical, and material support: H.

Ahmad Yusof. Study supervision: H. Ahmad Yusof; E. Mangantig; A.M. Che Muhamed.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

There is no financial interest related to the material in the manuscript.

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ETHICAL CONSIDERATION

All participants provided written informed consent to participate in this study. They were fully informed about the purpose, procedures, potential risks, and benefits of the research and were made aware of their right to withdraw from the study at any time without consequences. The study obtained ethical approval from the research ethics committee and was conducted in accordance with the Helsinki guidelines, under the ethics approval code: USM/JEPeM/22080547.

ROLE OF THE SPONSOR

The funding organizations are NGO institutions and had no role in the design and conduct of the study, the collection, management, and analysis of the data, or the preparation, review, and approval of the manuscript.

ARTIFICIAL INTELLIGENCE (AI) USE

The authors of the present study did not utilize any artificial intelligence-based software for the conceptualization, data analysis, or writing of the paper, except for general-purpose language models used for proofreading or editing assistance, where applicable.

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