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DO GENES DETERMINE CHAMPIONS?

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KEY POINTS

- The genotype is the total combination of all the inherited genes within the body. It represents an individual's genetic potential and plays a major role in determining many of that individual's anatomical, biochemical, physiological, and behavioral characteristics or phenotypes (e.g., brown eyes, a body mass of 75 kg, or a maximal oxygen intake of 50 mL• kg^{-1} • min^{-1}).
- Except for identical twins, people vary in how their genotypes are expressed in various characteristics, (e.g., strength, body weight, blood pressure), and how those characteristics respond to training, to a low-calorie diet, to medication, or to other environmental factors.
- The major sources of variation in training seem to be the state of certain complex characteristics (phenotypes) before training and the ability of these phenotypes characteristics to adapt to training.
- Elite athletes are probably those who begin with high levels of the characteristics needed for success in their sport and who exhibit superior adaptations in those characteristics after training.
- By knowing the genotype, it is not possible to accurately predict how an individual will respond to training or to any other stimulus or whether that individual will become a champion athlete.
- It is unlikely that genetic engineering or any other technology can be used to reliably produce champion athletes.

INTRODUCTION

It is well known that brothers and sisters with the same parents inherit different traits from different ancestors on both sides of the family. For example, there may be differences in eye color, height, cholesterol level, fitness level, or the ease with which one loses or gains weight. Only identical twins, those developed from the same egg, have the same genetic background because they are duplicates of the same person. Non-identical or fraternal twins develop from two eggs and are as different genetically as any other two siblings.

Athletes and coaches are curious about the possible role of genetics in determining who will be a champion. Coaches would like to know if an athlete's genetic background could be used to help select those who have a better chance of succeeding. Athletes wonder if the genes they have inherited might help or limit their abilities to perform at high levels in various sports. This article will address these issues.

RESEARCH REVIEW

Basic Concepts

Genes are parts of DNA molecules in every cell of the body that carry information responsible for the subsequent production of specific chains of amino acids, which are then used to develop a specific proteins. The genotype is the total combination of the thousands of genes within the body, that is, the genetic potential of a person. However, not all of the genes are used or expressed to their full potential. The anatomical, biochemical, and physiological, and behavioral characteristics of a person at any given time represent the extent to which the various genes are expressed; these characteristics are known as phenotypes. Examples of phenotypes include brown hair, green eyes, a resting heart rate of 60 beats/min, a maximal oxygen intake (VO_2max) of 50 mL • kg^{-1} • min^{-1} min, or a body weight of 180 pounds.

Genes affect how a phenotype is expressed now, as well as how it will respond to a change in environment. While one's eye color is set for life, one might reduce blood pressure with medication, increase VO_2max with training, and lose weight by dieting. The speed and the extent to which changes in phenotypes occur are affected by one's genetic background. For a particular phenotype, there are people who are superior responders, average responders, poor responders, and non-responders to a change in the environment. Thus, there are people who lose weight or who improve their fitness more easily than others.

It is this variation in phenotypes and how they respond to changes in the environment that allows scientists to study the role of genes. For instance, if all participants improve their VO_2max by 14-16% after 12 wk of standardized exercise training, then it is clear that genes play a minor role and it is only the change in environment (training) that is important. On the other hand, if there is a large variation in adaptations to the same training program, genes may be important.

The variation within a given phenotype in a population is influenced by the variation due to genes, the variation due to environment, and the interaction between these two sources of variation. One way to study variation is to study families with biological and adopted children to see the influence of genes on various phenotypes when the environment is similar. If there is little difference among these children before or after an intervention, then environment is more important. On the other hand, if the responses of biological children are similar to those of the parents but the responses of adopted children are not, then genes are more important. Another way to compare variations is to study twins living in the same home. With identical twins, the genetic background is the same and the environment is similar, whereas fraternal twins have a similar (but not identical) genetic background and a similar environment. If there is less difference between identical twins than there is between fraternal twins, this suggests that genes play a big role. But if the differences between identical twins and between fraternal twins are similar, then genes are less important. One can also look at identical twins separated early in life and living in different environments. Regardless of the environment, research shows that identical twins tend to be more similar before and after an intervention than are fraternal twins or other siblings, showing that genes have an important influence (Bouchard, Malina & Pérusse, 1997).

To better understand the roles of genes and the environment, consider their effects on three factors; physical activity, fitness, and health. The genotype can influence the extent to which one is physically active, physically fit, and healthy. Environment (physical and social environment, as well as one's lifestyle) also can affect activity, fitness, and health. In addition, there is an interaction among these factors because 1) activity can affect fitness, 2) fitness can affect activity, 3) activity can affect health, 4) health can affect activity, 5) fitness can affect health, and 6) health can affect fitness. Moreover, one's genes can influence these interactions, e.g., how physical activity affects fitness or health and the degree to which this occurs.

Examples of Genetic Effects

There are many phenotypes for which the effects of the genes have been determined (Bouchard, Malina & Pérusse, 1997; Bouchard et al., 1992). Genes have a large effect on height, length of trunk, and length of arms and legs. It is known, for example, that tall parents tend to have tall children. Of course, within a family of tall parents, one child may be shorter because his/her height was inherited from the maternal grandmother's side of the family. In contrast, there is only a small-to-moderate effect of genes on circumferences, girths, and breadths of various body parts because the environment can play a larger role in determining these measures. For example, waist circumference can be changed by diet or exercise.

Genes have a large influence on muscle size and composition (percentage of fast-twitch and slow-twitch fibers). Because muscle strength is closely related to fiber composition, genes have a large effect on strength, too. On the other hand, the activities of enzymes important in energy metabolism and the number of mitochondria within a given amount of muscle tend to be less influenced by genes because they can be modified by different types and amounts of physical activity. To summarize, the effect of the genes in muscles is great relative to structure (e.g., contractile proteins and size) but not necessarily to function. In the case of the phenotype "muscular endurance," which is affected by both structural and functional factors, the genetic effect is only moderate.

Similarly, size of the lungs (a structural measure) is affected greatly by the genes, but such functional measures as rates of airflow are not. In the cardiovascular system, there are large genetic effects on the size of the heart, as well as the size and structure of the coronary arteries. Blood pressure tends to be less affected by genes because it can be modified by body weight, diet, stress, and other factors.

Relative to exercise, genes have a large effect on VO_2max, maximal heart rate, and maximal lung ventilation. Evidence suggests that cardiovascular endurance (e.g., the total amount of work that one can perform in 90 min) is even more strongly affected by genes than is VO_2max; this is probably because many physiological and biochemical variables are involved in endurance exercise, and genes can affect each of them (Bouchard et al., 1992).

There are people who genetically have a high or low level of fitness (as indicated by VO_2max), but they may or may not be physically active. In other words, fitness and activity are not necessarily the same. There are people who train regularly but are not very fit, whereas others do little regular activity but are reasonably fit. It is true that people must be very active to have high levels of fitness and that people with very low levels of fitness tend to be very inactive. However, for most of us in the middle of these two extremes, fitness cannot be judged by an individual's level of physical activity and vice versa. Nevertheless, persons who are regularly active are capable of doing more exercise than inactive persons, even though both may have the same VO_2 max or the same level of strength, because training by itself produces changes in the various systems of the body.

Genetics and Training

Depending on the sport or activity, many systems in the body are involved. For example, distance running involves the cardiovascular, respiratory, neuromuscular, metabolic, hormonal and thermoregulatory systems. Each of these systems can be affected by a number of genes. Also, there are many interactions among the genes and between these genes and the environment. Because of this complexity, it is unlikely that scientists can make champions by altering only one or two genes.

Identical twins with similar levels of activity tend to have similar levels of fitness. When identical twins undergo the same aerobic or anaerobic training program, they exhibit similar adaptations to the training (Bouchard et al., 1986). On the other hand, fraternal twins or siblings with similar levels of activity vary more in their fitness and have a greater variation in their adaptations to training.

To examine VO_2max adaptations to different types of training, we carried out a standardized, 12-wk endurance training study with 29 male university students (Dionne et al., 1991). Subjects trained three times a week for 30-45 min on a bicycle ergometer at a constant intensity of 75% VO_2max. After training, the rise in VO_2max ranged from 40 mL/min to almost 1,000 mL/min. This study was done in the fall semester, after which students went home for 4 wk. We asked the nine students who had the greatest improvement in VO_2max (~ 9 mL • kg^{-1} • min^{-1}) to return for another 12 wk of training. For the second program, subjects did interval training three times per week at an average intensity of 75% VO_2max (3 min at 60% VO_2max and 3 min at 90% VO_2max) for 30-45 min. During the 4 wk of inactivity, the VO_2max values of the four superior responders who agreed to return had decreased and were similar to the levels when they began the first training program. After the interval-training program, these students again showed a superior training response. Thus, there are phenotypes that respond differently to continuous or interval training.

The HERITAGE Family Study (Bouchard et al., 1995) was a very large investigation of how genes influence adaptations to exercise training and involved 484 Whites from 99 families and 260 Blacks from 105 families at four centers. All subjects were healthy and sedentary. After taking many tests associated with fitness and risk factors for cardiovascular disease and diabetes, subjects trained and were retested. The standardized training program consisted of exercise on a cycle ergometer three times a week for 20 wk. Subjects began training for 30 min at the heart rate associated with 55% VO_2max. Each two weeks thereafter, either duration or intensity increased so that they trained during the last 8 wk for 50 min at the heart rate associated with 75% VO_2max (Skinner et al., 2000).

One question asked was whether the families had similar levels of VO_2max and other phenotypes before training began. Relative to VO_2max, there were families in which all members had lower values, average values or higher values. In this case, heredity explained about 40% of the variation (Bouchard et al., 1998).

There was a large variation in response to training. Although the average increase in VO_2max was 19% and was similar at all four centers, about 5% of the subjects had little or no change, and about 5% had an increase of 40-50%. This large variation occurred at all ages and at all levels of initial VO_2max and was similar for Blacks and Whites and for women and men (Skinner et al., 2001). In other words, there were superior, average and poor responders to training at all ages (17 to 65 years), in both races, in both sexes, and at all levels of initial VO_2max. There was essentially no relation between initial fitness and its response to training, as the correlation between VO_2max before training and the change in VO_2max after training was only 0.08. It appears that one set of genes affects the initial level of VO_2max and another set of genes affects the VO_2max response to training.

When we looked to see if families responded in a similar manner, we found that families tended to have superior responders, average responders, or poor responders. In this case, 47% of the variation in the response of VO_2max to training was explained by heredity (Bouchard et al., 1999). We also examined whether there were any non-genetic variables measured before training that would differentiate between superior responders and poor responders. We found no variable or combination of variables that would distinguish between these two groups (Skinner et al., unpublished). Because we have DNA samples from all subjects, we are now screening for genetic markers that may be associated with responses to training.

Based on the information available now, it is not possible to predict how a given individual will respond to training. Breeders of racehorses have tried for many years to predict which horses will be successful. What they say is that "we take the best, mate them with the best, and hope for the best." In other words, out of 10 offspring of two excellent horses, a few will be excellent, a few will be above average, and a few will be below average. Horse breeders cannot predict which horses will be in which category. Of course, we do not breed humans for competition, so the possibility of accurately predicting which humans will be champion athletes is even lower.

Many athletes reach a point at which they must train more and harder to obtain fewer and fewer benefits in terms of performance. When athletes reach this point, it is possible that they are approaching their genetic limits. As mentioned before, there is no way to predict where this limit is.

Whether a given person will be a champion appears to be associated with 1) the actual state of a number of complex phenotypes before training, 2) proper training, rest, and nutrition, and 3) the ability of these phenotypes to adapt to the training, rest, and nutrition. Thus, a person can begin with low, average or high values of VO_2max and other phenotypes and have poor, moderate or superior responses to training, rest, and nutrition. It is probable that elite athletes are those who begin with high levels of the characteristics (phenotypes) needed for success in their particular sports and also have superior adaptations in those characteristics after training. Only a small percentage of the population has genetically high levels of the phenotypes needed for success, not all of these will train, and only a small percentage of those who do train will be superior responders.

PRACTICAL APPLICATIONS

- Genes do influence the initial level of one's characteristics (phenotypes), as well as how fast and how much they can change in response to training, nutrition, and other environmental factors. Athletes who have immediate success in a new sport probably have relatively high qualities of at least some of the genetically determined phenotypes required to be a champion in that sport.
- Superior responders to sports participation probably have early success and positive feedback from competition.
- Potential athletes should try various sports to see which ones they enjoy and in which ones they have success. These factors are probably a better guide for selection than any laboratory analysis of one's genetic background.
- It is not possible to predict who will be a champion. Nevertheless, coaches can and do select candidates based on the characteristics required for success in that sport. The genes influence many of these characteristics.
- The genes do not affect other aspects of some sports (e.g., tactics and technique). Champions at the elite level must be experts at tactics and technique in addition to possessing the necessary genetically determined attributes for success in their sports. Still, less genetically gifted athletes who are talented in tactics and technique may be champions at non-elite levels of competition.

SUMMARY

As a general rule, genetic influences are stronger on the structural components of the body than on the functional components, which can be influenced more by training and other environmental factors. Although genetic background—heredity—can influence one's success in a particular activity or sport, this background is probably too complex to be fully known or understood. The possibility of a magical altering of the genes by genetic engineering is very unlikely because many genes are involved, there are interactions among different genes, and there are interactions among genes and the environment.

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GENES AND SPORT: ARE YOUR PARENTS RESPONSIBLE FOR YOUR WINS AND LOSSES?

We all know of champion athletes whose parents and perhaps grandparents were also champions. Moreover, racehorse owners spend millions of dollars on stud fees to breed winners. This seems to tell us that champions are born and that if you don't have the "champion gene," you can never be truly successful, no matter how hard you train. In other words, you must be wasting your time practicing your favorite sport if your parents were not champions themselves. But if champions can be bred, why don't all racehorses bred for performance become champions? The reason is that there are factors other than heredity that play important roles in performance, too.

Genes Are More or Less Important

There is no getting around it; genes determine our potential for developing many of the structural and functional characteristics important in determining sport performance. For instance, to be a successful center in the National Basketball Association, you must inherit the gene for tall stature. For other characteristics, though, diet, training, and other environmental factors play a huge role in how your genetic potential is expressed. For example, you may have the genetic potential for a low body weight, but eating too much and exercising too little can overcome that genetic message and cause you to become obese. Thus, some characteristics—like height—are strongly influenced by genes, whereas others—like abdominal girth—are less affected by the genes and are more likely to be influenced by the environment. Table 1 illustrates how strongly the genes typically affect some of the structural, functional, and performance characteristics of the body. Those characteristics in the table for which the genes have only a low to moderate effect (e.g., balance, reaction time, accuracy of movements) are likely to be more powerfully influenced by training, diet, and other environmental factors than are characteristics like strength and flexibility, for which the genes have a large effect.

The genes also determine the speed and extent to which your body's performance characteristics respond to training, diet, and other environmental factors. For a given characteristic, such as aerobic endurance or muscular strength, some people are strong responders to training and others are moderate or weak responders to the same training. What this means, for instance, is that even though your genetic potential for distance running may be less impressive than that of a competitor, you may be able to develop that potential more quickly and completely by training hard so that you can always beat your opponent. There is insufficient published research on how strongly genes affect an individual's response to training to be certain, but Table 2 lists some of the early conclusions from this research.

It is likely that the small genetic effect on the response of strength to resistance training will be greater when studies are completed with larger numbers of subjects. The training effect on power output in 10 seconds was only weakly affected by the genes, possibly because technique and reaction time—both little affected by

TABLE 1. Effects Of Genes On Structure, Function, And Performance

CHARACTERISTIC	EFFECT OFGENES
Height, Length of Arms	Large
Waist Girth	Small to Moderate
Muscle Size	Large
Muscle Fiber Composition (Fast- and Slow-Twitch)	Large
Mitochondria/Gram of Muscle	Small
Heart Size	Large
Lung Size And Volume	Large
Activities of Muscle Enzymes Used to Produce Energy	Small to Moderate
Resting Heart Rate	Large
Blood Pressure	Moderate
Air Flow in Lungs	Moderate
Muscular Strength	Large
Muscular Endurance (e.g., pushups, pull-ups)	Moderate to Large
Movement Speed	Moderate
Balance	Small
Flexibility of Joints	Large
Reaction Time	Small to Moderate
Accuracy of Movements	Small to Moderate
Aerobic Endurance (e.g., distance running or cycling)	Moderate to Large
Anaerobic Power (maximal cycling power output in 10 seconds)	Moderate

TABLE 2. Effects Of The Genes On Responses To Exercise Training	
RESPONSE TO TRAINING	EFFECT OFGENES ON RESPONSE
Strength	Small
10-Second Maximal Power Output—Bicycle Ergometer	Small
90-Second Maximal Power Output—Bicycle Ergometer	Large
Aerobic Endurance	Moderate to Large

genes—are more important than raw strength, more strongly affected by the genes.

Tactics and techniques—such as drafting and using an aerodynamic body posture in cycling—are critical to success in many sports but are not affected by the genes. Champions at the elite level must be experts at tactics and technique in addition to possessing the necessary genetically determined attributes for success in their sports. Still, less genetically gifted athletes who are talented in tactics and technique may become champions at non-elite levels of competition.

SUMMARY

Whether you can be a champion is determined by 1) many of your structural, functional, and performance characteristics before training, 2) proper training, rest, and nutrition, 3) the speed and extent to which these characteristics adapt to training, and 4) your mastery of tactics and techniques in your sport. It is probable that elite athletes are those who begin with high levels of the characteristics needed for success in their particular sports, have large responses to training in those characteristics, and have mastered the necessary tactics and techniques. However, at a less than elite level of competition, you can compensate for a “non-gifted” genetic potential with optimal training and nutrition and by mastering the tactics and skills required for excellence in your sport.

For a given individual, it is not possible to predict whether or not or the extent to which a characteristic such as vertical jumping ability will respond to training. Moreover, many athletes reach a point where they have to train more often and harder to obtain fewer and fewer performance benefits. When athletes reach this point, it is possible that they are approaching their genetic limits.

Although your genetic background can influence how successful you might become in a particular activity or sport, this background is probably too complex to be fully known or understood. The possibility of a magical altering of the genes by genetic engineering is very unlikely because many genes are involved, there are interactions among different genes, and there are interactions between genes and the environment.

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