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INFLUENCE OF GENETIC FACTORS ON EXERCISE AND TRAINING

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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 have the same genetic background because they are duplicates of the same person. Non-identical or fraternal twins are as different genetically as any other two siblings.

Genes are part of DNA molecules in every cell of the body. 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 in the genotype are necessarily used or expressed to their full potential. The anatomical, biochemical, 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 $ml\bullet min^{-1}\bullet kg^{-1}$, and a body weight of 75 kilograms.

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 of any change 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-

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responders to a change in the environment. Thus, there are people who gain or lose weight or who improve their fitness faster and to a greater extent 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 the genes. For instance, if all participants improve their VO_2max by 14-16% after 12 weeks of standardized exercise training, then it is clear that genes play a minor role and the change in environment (training) is more 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. On the other hand, if the differences between identical twins are similar to differences between fraternal twins, 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 (6).

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. The genotype also can influence these interactions, e.g., how much and how fast physical activity affects fitness or health.

Examples of genetic effects

There are many traits (phenotypes) for which the effects of the genes have been determined (3,6). 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 its 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, and weight training or inactivity can change muscle size.

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 also have a large effect on strength. 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 (3).

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 people 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, anaerobic, or strength training program, they exhibit similar adaptations to the training (5). 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 the different types of training.

To examine VO_2max adaptations to different types of training, we carried out a standardized, 12-week endurance training study with 29 male university students (7). Subjects trained three times a week for 30-

45 minutes on a cycle ergometer at a constant intensity of 75% VO_2max. After training, the rise in VO_2max ranged from 40 ml•min^{-1} to almost 1000 ml•min^{-1}. This study was done in the fall semester, after which students went home for four weeks. We asked the nine students who had the greatest improvement in VO_2max (~9 ml•min^{-1}•kg^{-1}) to return for another 12 weeks 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 minutes. During the four weeks of inactivity, the VO_2max 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. Of the nine students in the first study who had the smallest improvement in VO_2max (~3 ml•min^{-1}kg^{-1}•min^{-1}), only one agreed to return for more training. His VO_2max also had decreased over the vacation, and he again had a very poor response to the additional interval-training program. Thus, there are phenotypes that respond differently to continuous or interval training.

The HERITAGE Family Study (4) 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 weeks. Subjects began training for 30 minutes 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 eight weeks for 50 minutes at the heart rate associated with 75% VO_2max (9).

The first 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, average or higher values. In this case, heredity explained about 40% of the variation (2).

Because there was a large variation in the response to training, the second question asked was whether families responded similarly 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 (8). 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. In this case, 47% of the variation in the response of VO_2max to training was explained by heredity (1).

The third question asked was whether the changes in VO_2max were related to the initial values. There was essentially no relation between initial fitness and its response to training, as the correlation coefficient 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 response of VO_2max to training.

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, 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 these phenotypes 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.
- Other aspects of some sports (e.g., tactics and technique) 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. Nevertheless, less genetically gifted athletes who are talented in tactics and technique may be successful at non-elite levels of competition.

CONCLUSION

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 effect of a magical altering of one or two genes by genetic engineering probably will be low because many genes are involved, there are interactions among different genes, and there are interactions among genes and the environment. Thus, it is unlikely that genetic engineering can reliably produce champion athletes.

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