Muscular Strength Development in Children and Adolescents

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This review builds on earlier reviews and considers the development of strength characteristics from childhood through adulthood. Since strength is associated with size and biological maturation, these associations are also discussed. Finally, genetic determinants of strength and tracking of strength components over time are also reviewed.

Strength characteristics follow the general type of growth curve that is observed for most external body dimensions. In boys, a clear adolescent growth spurt is observed 3 months to 1 year after age at PHV for static, and explosive strength, and for muscular endurance of the upper body. In girls, a less pronounced adolescent growth spurt is seen for static strength. In preadolescents as well as in adolescents of both sexes, biological maturity is positively associated with static strength. Similarly in adolescent boys, from 13 years onwards, explosive strength and muscular endurance of the upper body and lower trunk are positively associated with biological maturity even after controlling for variation in chronological age, stature, and body mass. Furthermore, in adolescents, the interaction between stature, body mass, and biological maturity explains significant proportions of the variation in strength. In preadolescents, body mass and stature are more important predictors than the interactions. During growth, strength components are under fairly strong genetic control, with evidence for dominance and reduced genetic transmission from one generation to the next. Strength gain after a weight training program is only partially genetically determined. During childhood and adolescence, tracking coefficients for strength are low to moderately high and tend to decrease with increasing time interval. Coefficients, however, show considerable variation between age levels studied and between different research projects.

Muscle strength is an important fitness component essential for the execution of a variety of daily activities and sport activities throughout the life span. Various indicators of strength have been used, but in the context of epidemiological studies of growth and development, the following strength factors are considered: static or isometric strength, explosive strength or power, and dynamic (or functional) strength. Static or isometric strength is the maximal voluntary force produced against an exter-
nal immovable resistance without change in muscle length. Explosive strength or power is the ability of the muscles to release force in the shortest possible time. Outside the laboratory, jumping tasks are often used as indicators of this ability. Dynamic strength (sometimes called functional strength in the context of physical fitness studies) is the force generated by repetitive contractions of the muscle; it is closely linked to muscular endurance, which is the ability to maintain or repeat muscular contractions over time. Field tests of muscular endurance or dynamic strength include push-ups, pull-ups, sit-ups, curl-ups, and flexed arm hang. Factor analytic studies of a variety of strength indicators observed in adolescents of both sexes demonstrate that the above mentioned strength components are identified as separate factors, and these factors are fairly independent components of the motor ability domain (40, 41).

The present review considers the development from childhood through adulthood of these four strength components. Since strength is associated with size and maturation, these associations are also discussed. Finally genetic determinants of strength and tracking of strength characteristics over time are also reviewed.

The review builds on earlier reviews (4, 7, 8, 10, 20) and is limited to large fitness studies.

In this overview, childhood is viewed as the period from about 3 years to puberty. Puberty is the period when sexual maturation takes place and adolescence encompasses the period of sexual maturation until adulthood is reached. Adulthood is the period after which final stature is reached. Note also that growth refers to size attained and growth velocity (i.e., changes in size over a period of time, usually 1 year). It includes increase in cell number (hyperplasia), increase in cell size (hypertrophy), and increase in intercellular substances or accretion. Maturity refers to the distance that has been travelled along the way to adulthood and includes cell differentiation, mostly during prenatal life, and qualitative and proportional changes. Important indicators of maturation are tempo and timing of the process. Maturity, however, varies with the biological system considered (sexual, morphological dental, and skeletal maturity are most often used; ref. 34). Development is a very broad term and includes growth, maturation, learning, training, and a variety of daily experiences. As such the use of development in strength is appropriate, since it includes growth in muscle, brain and nerve cells, maturation of the brain and neuro-motor control, and a variety of exercise and daily experiences that result in specific strength levels.

**Development of Strength Characteristics**

Information on attained levels of strength is not as extensive for early childhood, or approximately the preschool years, as for middle childhood and adolescence. Between 3 and 6 years, mean levels of isometric strength increase gradually. Sex differences are small, and there is considerable overlap. These changes probably reflect the qualitative improvement in fundamental motor skills such as running, jumping, and throwing (34).

In boys, static strength increases fairly linearly with chronological age from 6 years onward to about 12 or 13 years of age, when there is a marked acceleration through the late teens. This is seen for several muscle groups of the lower and upper extremities and consequently also for composite strength scores. In girls, strength improves linearly with age through about 15 years, with no clear evidence for an adolescent spurt (2, 34). Some evidence suggests, however, a development
peak in static strength, as measured with the arm pull test (5, 26). The development in isometric strength (handgrip) is nicely demonstrated in a large fitness study of Flemish youths 7 to 17 years of age (Figures 1a and 1b). In boys, median values increase from about 12 kg (117.6 N) at 7 years to 48 kg (470.7 N) at 17 years, whereas, in girls, the grip strength increases from 10 kg (98 N) to 30 (294 N), indicating the considerably larger increase in boys.

Only longitudinal studies can provide precise information about the individual growth process. But even in a large cross-sectional study of Flemish girls, Beunen and Simons (5) demonstrated a clear acceleration in arm pull performance between 12 and 14.5 years. In contrast to what has been observed by Faust (19) in a longitudinal study of Oakland girls, Kemper and Verschuur (26) identified a clear adolescent spurt in static strength (arm pull) in a longitudinal study of Dutch girls. The peak strength spurt in these Dutch girls occurred 0.5 years after peak height velocity. Evidence from longitudinal studies in boys (4) suggests that the adolescent spurt in isometric strength begins 1.5 years before age at peak height velocity (PHV) and reaches a peak about 0.5 years after age at PHV (Figure 2a). The estimated velocity of strength development in Belgian boys is about 30% of attained strength at this time and indicates the marked increase in static strength at this time. Further, it is noteworthy that only 6 of the 444 boys followed longitudinally during the year of PHV show a negative velocity in arm pull scores (4). Similar spurts are also found for upper-body strength (the average of shoulder extension, wrist flexion, and extension elbow flexion and extension) and lower body strength (average of hip flexion and knee extension) in a sample of 99 Canadian boys (13).

Strength is related to body size and muscle mass, and associations vary between 0.30 and 0.60. Highest associations are found between 13 and 15 years, reflecting variation in the timing of the adolescent growth spurt (34). When chronologically and skeletally homogeneous groups are considered, controlling for maturity differences, correlations between strength and body mass vary between 0.44 and 0.54 in boys 12 to 18 years. These associations are consistently higher then those with stature or other body dimensions (8). Sex differences in strength might relate to the size advantage in boys. During childhood and adolescence boys have greater strength per unit of body size, especially in the upper body and trunk, than girls. There are, however, negligible sex differences in lower body strength when controlled for body size (34).

An interesting approach to analyze proportional development that takes into account the concomitant changes in body dimensions is to use allometric equations. If strength increases in proportion to muscle area, then the theory of geometric similarity predicts that strength improves to height to the second power. (Muscle area is a surface—i.e., a length dimension to the second power.) Before adolescence the isometric strength in both sexes in most muscle groups increases more than theoretically predicted by geometric similarity. The observed allometric coefficients are generally larger than the predicted value of two. Also in adolescent boys the observed allometric coefficient exceeds two, but in adolescent girls the coefficient is less than predicted (7, 20). The higher than expected increase in isometric strength is explained through quantitative changes (greater increase in muscle cross-sectional area than expected from increase in height) and qualitative changes (biochemical changes and improvement in neuro–motor control with increasing experience and age; ref. 20).
Figure 1 — Percentile distributions of Flemish boys and girls aged 6.0 to 18.0 for a. handgrip, in kg, boys; b. handgrip, in kg, girls; c. standing long jump, in cm, boys; d. standing long jump, in cm, girls; e. flexed arm hang, in s, boys; f. flexed arm hang, in s, girls; g. sit-ups, number, boys; h. sit-ups, number, girls (after ref. 30). In each age category 300 or more subjects were measured.
Performance in explosive strength as measured by standing long jump or vertical jump increases fairly linearly in both sexes between 6 and 12 to 13 years (2, 5, 34). Thereafter, standing long jump scores level off in girls and, in contrast, a larger increase is observed in boys. In a previous study (observations made in 1980) on a large sample of Flemish girls, Beunen and Simons (5) observed a gradual

![Graphs](https://example.com/graphs.png)

Figure 2 — Median velocities of several strength tests aligned on age at PHV, from the Leuven Growth Study of Belgian Boys. a. arm pull, b. vertical jump, c. bent arm hang (after ref. 2).
curvilinear increase in vertical jump. This difference in growth pattern is probably
explained by a secular decline in performance characteristics, especially in late
adolescent girls (8). Large interindividual differences were observed, as can be
seen from the percentile distributions for both sexes of the standing long jump
(Figures 1c and 1d).

In Belgian and Canadian boys, a clear adolescent growth spurt has been
demonstrated (2, 16). Maximum velocity in standing long jump (15 cm/year in
106 Canadian boys) coincides with PHV, whereas the maximum velocity in veri-
tical jump (5 cm/year for 222 Belgian boys) coincides with the maximum velocity
in static strength 0.5 years after peak height velocity (Figure 2b). The difference in
the timing of the adolescent spurt in explosive strength in both longitudinal studies
probably reflects analytical strategies. In the Belgian study, semiannual velocities
were calculated, whereas in the Canadian study annual velocities were used. Only
7% of the 446 boys followed during the year of the adolescent height spurt show a
negative velocity in vertical jump during the year of PHV. Interestingly, those who
showed a negative velocity in vertical jump obtained higher scores at the begin-
ing of the year of PHV than those who showed positive velocities in vertical
jump. This signifies that, for explosive strength, there is absolutely no indication
of the notion of adolescent awkwardness or a boy outgrowing his strength.

Correlations between body mass, fatness, endomorphy, and explosive strength
scores are consistently negative, whereas mesomorphy is positively associated.
When biological maturity is controlled, correlations between vertical jump scores
and several body dimensions are low but positive, ranging from 0.00 to 0.22, while
 correlations between fatness and vertical jump scores are negative and vary be-
tween −0.19 and −0.31 (8).

Changes in muscular endurance or dynamic (functional) strength are shown
in Figures 1e, 1f, 1g, and 1h. In boys, flexed arm hang scores increase curvilinear
with a marked increase after 12 years. In girls, the median scores fluctuate be-
tween 4–8 s. (Flexed arm hang score is the duration the subject can hold the flexed
arm position until the child’s eyes drop below the level of the horizontal bar.) The
percentile distributions show enormous interindividual differences. In boys, for
example, the score of the 10% best performers at 6 years (about 20 s) is the same
as the median score of 14-year-old boys.

Only in boys has a clear adolescent spurt been demonstrated. Maximum
increments in flexed arm hang scores follow PHV and coincide with peak static
strength (2). For functional strength, 30.5% of the 444 boys followed during the
year of the PHV show a negative velocity in bent arm hang scores, and 26% show
a negative velocity for sit-ups during the year of PHV. But for both muscle endur-
ance tests, those who show negative velocities during the year of PHV outperform
those who show positive velocities. Again this demonstrates that for all strength
characteristics discussed herein, there is no indication of an adolescent awkward-
ness or a boy outgrowing his strength (4).

The number of sit-ups increases in boys, but the increase gradually declines;
in girls, scores increase until 13 years and thereafter decrease. Leg lifts does not
show a clear adolescent spurt in Belgian boys (2).

Body mass, endomorphy, and adiposity are negatively associated with mus-
cular endurance. When biological maturity is partialled out, the associations be-
tween body dimensions and fatness, on the one hand, and muscular endurance test
scores, on the other hand, vary between 0 and −0.47 (8).
Maturity-Associated Variation in Strength

In the following section, only maturity-associated variation in strength in the general population will be considered. For reviews about maturity characteristics of elite athletes, who represent only a very small percentage of the general population, extensive reviews have been recently published (7, 35).

It is also beyond the scope of this review to describe the different indicators of biological maturation (e.g., 34). Skeletal age and indicators of sexual maturity are most often used in performance studies. In analyzing associations between performance characteristics and indicators of biological maturation, mainly two major approaches have been used. First, contrasting maturity groups of early, average, and late maturing boys and girls using one of the biological maturity indicators and, second, calculating age-specific correlations between performance characteristics and biological maturity.

Malina and Bouchard (34) summarize the findings from the Oakland Adolescent Growth Study. Boys and girls aged 11 to 18 years were grouped as average, early, and late maturers. In early maturers, skeletal age was advanced by 1 year and delayed by 1 year in late maturers. Chronological and skeletal age were, generally, the same in the average group. From 11 to 18 years, early maturing boys outperform average and late maturing boys for grip strength and shoulder pushing strength. There are no consistent differences among the three maturity groups of girls across adolescence. In early adolescence, early maturing girls tend to be slightly stronger, but as adolescence continues, the differences between the maturity groups are reduced considerably. Similar comparisons are made based on data of Belgian youths of both sexes classified as early, average, and late maturing based on skeletal age (34). Even after controlling for body-size differences, early maturing boys perform better for static strength, explosive strength, and muscular endurance of the upper-body and trunk than average- and late-maturing boys. Differences are small at 12 and 13 years, but from 14 through 18 years, late maturers consistently lag behind the early maturing boys. In Belgian girls, differences in static strength between early, average, and late maturers are similar to those in boys. With few exceptions differences between the three maturity categories are small for explosive strength and muscular endurance.

In preadolescents of both sexes, age-specific correlations between skeletal age and static strength are significant, but low, ranging between 0.21 and 0.39. With few exceptions correlations between explosive strength and skeletal age are nonsignificant in preadolescents. And small (<-0.20) but negative associations are found between skeletal age and muscular endurance (3). In Table 1, age-specific correlations between skeletal age and strength indicators are summarized for adolescent boys and girls. In girls, correlations between skeletal age and static strength characteristics vary between 0.17 and 0.39. Associations are higher in early adolescence than in late adolescence. For boys, associations with static strength are generally higher, and range from 0.43 to 0.65. Highest associations are found at 14–15 years at the time of the growth spurt. In adolescent girls, associations between skeletal age and explosive strength are nonsignificant or low (0.07 to 0.11), whereas, in boys, from 12 years onward, associations are higher (0.20 to 0.40). For muscular endurance, correlations are nonsignificant or low, but negative (−0.12 to −0.26) with the exception of the very low but positive correlation for leg lifts in boys aged 13 to 15.
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Table 1  Correlations Between Skeletal Age and Strength Characteristics in 11- to 15-Year-Old Girls and Boys

<table>
<thead>
<tr>
<th>Factor</th>
<th>Test</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girls</td>
<td>Static strength</td>
<td>Arm pull</td>
<td>.39</td>
<td>.35</td>
<td>.39</td>
<td>.26</td>
</tr>
<tr>
<td></td>
<td>Explosive strength</td>
<td>Vertical jump</td>
<td>n.s.</td>
<td>.11</td>
<td>.08</td>
<td>.07</td>
</tr>
<tr>
<td></td>
<td>Muscular endurance</td>
<td>Bent-arm hang</td>
<td>-.26</td>
<td>-.19</td>
<td>-.13</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leg lifts</td>
<td>-.21</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Boys</td>
<td>Static strength</td>
<td>Arm pull</td>
<td>.43</td>
<td>.55</td>
<td>.65</td>
<td>.63</td>
</tr>
<tr>
<td></td>
<td>Explosive strength</td>
<td>Standing broad jump</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.39</td>
<td>.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vertical jump</td>
<td>n.s.</td>
<td>.20</td>
<td>.32</td>
<td>.38</td>
</tr>
<tr>
<td></td>
<td>Muscular endurance</td>
<td>Bent-arm jump</td>
<td>-.19</td>
<td>-.14</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leg lifts</td>
<td>-.15</td>
<td>-.12</td>
<td>.04</td>
<td>.13</td>
</tr>
</tbody>
</table>

$p < .05$.

The association between skeletal maturity and strength indicators declines considerably when stature and weight are considered, leading to the conclusion that in preadolescents, skeletal age, as an indicator of the biological maturation process, is not an important predictor of strength. Among adolescent boys, however, correlations between skeletal age and static and explosive strength were significant at all chronological ages between 13 and 17 years, even when chronological age, stature, and weight were statistically controlled. Third-order partial correlations were considerably lower than the zero-order correlations. However, corresponding third-order partial correlations were higher than the zero-order correlations for muscular endurance (7).

Based on the data of the Leuven Longitudinal Study of Belgian Boys, Lefevre et al. (30) demonstrated that the strength advantage of early maturers disappears at adult age. Performances of 30-year-old men grouped on the basis of their age at PHV do not significantly differ for static strength and for muscular endurance of the lower trunk. For explosive strength and muscular endurance of the upper-body, late maturers outperform the early maturers at the age of 30.

Another important observation stems from further statistical analyses of strength, body mass, stature, and skeletal age of Belgian boys and girls. Since biological maturation, size and mass are confounded in their effects on strength, it is of interest to verify if interactions between skeletal age, stature, and body mass explain more of the variation in strength characteristics than each of the explaining variables themselves. These interaction terms (e.g., interaction skeletal age by body mass) give information about the question whether those who are heavy for their skeletal age outperform those who are light for their skeletal age. In adolescent boys and girls the interaction terms explained most of the inter-individual variation in
Figure 3 — Explained variance of strength characteristics in: a. boys and girls of 13 years, and b. boys and girls of 7–8 years. HT: height, MA: body mass, CA: chronological age, SA: skeletal age, CAXSA: interaction term between chronological and skeletal age (after refs. 1, 9, 25).
strength characteristics. The explained variance is, however, considerably higher in static strength (52% in boys and 31% in girls) than in the other strength indicators (Figure 3a). The explained variance is also higher in boys then in girls (9). These observations could not be confirmed in preadolescent boys and girls (Figure 3b). At this developmental phase, height and body mass explain most of the variation in isometric strength and long jump (25).

Although the above observations are mainly based on associations between skeletal maturity, age at PHV, and strength indicators, similar results are found when other indicators of biological maturity are considered (3, 7, 34).

**Genetic Determinants of Strength and Tracking**

In this section genetic determinants and tracking of strength characteristics will be explored. The analyses of the genetic determinants of strength not only provide insight in the importance of the contribution of genes but also in the contribution of environmental factors. With regard to strength, physical activity and weight training are probably the most important environmental factors. It is beyond the scope of this review to give an overview of the effects of training in preadolescents and adolescents. Furthermore, interaction effects between genes and environment can be studied. One of the interaction effects of interest is the gene by training interaction. This poses the question: Is the training effect (i.e., the strength gain during a weight training program) under genetic control? Tracking, or the maintenance of the relative position in a group over time, is another important issue that can only be analyzed when longitudinal observations are available. Tracking is of course partially determined by genetic factors but does not necessarily reflect genetic factors. Since tracking can also occur if the environment is relatively stable and/or if the interplay between genetic and environmental factors leads to the maintenance of the relative position.

**Methodological Issues and Muscular Strength Phenotypes**

It is not the purpose of this review to deal in depth with the methodological issues involved in the study of genetic determinants of muscular strength; however, some aspects can be revealed. The distribution of strength measures in a population shows mostly a Gaussian or skewed distribution, which is typical for quantitative, multifactorial phenotypes that are influenced by both multiple genes (polygenic) and environmental factors. The search for the genetic basis of muscular strength in humans can be studied by two basic approaches: the unmeasured genotype, or top-down approach, and the measured genotype, or bottom-up approach (11, 42).

When the genotype is not available, inferences of the genetic influences are made from the phenotype, which is mostly based on the statistical analysis of the distributions in strength measures in related individuals and families. The studied populations are twins (monozygotic [MZ] and dizygotic [DZ]), families, or twin/sibling adoption studies. The selection of the samples determines which contributing factors can be estimated. Parameters that are estimated in these epidemiological studies are familial aggregation and heritability and if more sophisticated statistical analyses are done, contributions of environmental factors, measurement of specific twin environment, assortative mating, and so on, can be obtained. Intraclass correlations between family members (father-daughter, father-son, mother-daugh-
ter, mother-son, sister-sister, brother-brother, sister-brother, mid-parent-offspring, and spouses) provide insights about the relative importance of genetic and environmental factors in strength phenotypes. Taking into account several assumptions, the ratio of intraclass correlations of groups of different degrees of genetic relatedness are indicative for the sources, which will explain the observed variability of the trait in the population. When the observed similarity in strength performance, expressed as an intra-pair correlation, is 1.0 in pairs sharing all their genetic material (MZ twins), 0.5 in pairs sharing on average 50% of their genes (DZ twins, parent-offspring, sibs), 0.25 in pairs sharing 25% of their genes (grandparent-grandchildren), and no correlation is observed in nonrelated random pairs—all of the observed variance would be caused by additive genetic factors (variance due to the action of several genes, with codominant allelic effects). When no perfect similarity is found in MZ twins (e.g., $r = 0.80$) but the similarities in other pairs of relatives follow the ratios, according to the ratios in genetic relationship (half in DZ, $r = 0.40$), one fourth in grandparents-grandchildren ($r = 0.20$), then, two factors will be causing the phenotype: additive genetic factors and environmental factors, contributing in a unique way to the individual phenotype. In this case additive genes would contribute for about 80% to the variation and unique environmental factors for 20% of the variation. In the case when one finds a similarity in pairs that is higher than the expected similarity based on their genetic similarity, part of the variation in the phenotype will be contributed to common environmental factors, which are shared by both members of the pairs under study (family environment). More sophisticated analyses of different familial covariances can be done using path analysis in which several of the indicative measures as mentioned above can now be quantified by testing a hypothetical model to the observed familial variation/covariation matrices (15, 37).

In the basic genetic model, the total variation ($V_{\text{tot}}$) in a multifactorial trait like muscular strength is partitioned into genetic ($V_{G}$) and environmental ($V_{C}$, $V_{E}$) variation components ($V_{\text{tot}} = V_{G} + V_{C} + V_{E}$; ref. 37). Heritability ($h^2$) refers to the proportion of the total variation that can be attributed to genetic effects ($V_{G}/V_{\text{tot}}$). In a similar manner, the contribution of environmental factors shared by family members (common environmental factors, $c^2 = V_{C}/V_{\text{tot}}$) and the proportion of environmental factors that act on an individual level, can be estimated ($e^2 = V_{E}/V_{\text{tot}}$).

When using this additive model of sources of variation, several presumptions should be met: no interaction between gene action and environment (different genotypes all react equal to similar environmental factors), no gene $\times$ environment correlation (similar exposure of environments for different genotypes), no gene $\times$ gene interaction and no assortative mating. Influences on strength characteristics probably do not follow these assumptions. The heritability coefficient is further a population parameter and is specific for the studied population. Designs to estimate the heritability fall into twin studies, adoption studies and family studies. Several simple but less accurate formulas have been used to estimate the heritability coefficient in the past. More flexibility and accuracy in modeling different factors that influence the phenotype can be achieved by using path analysis (15, 23). This method constructs correlational and causal paths from and between latent and observed variables and expresses these relations in linear equations. Alternative models can be tested and the goodness of fit evaluated. An iterative procedure estimates the contributions of each causal path, and confidence intervals can be calculated for all contributing factors.
All these methods only provide a measure of importance of genetics, and more specific segregation models can give indications on the action of major genes, mode of inheritance, and so on. To identify specific genes that contribute to a multifactorial phenotype, one needs to proceed with the measured genotype methods.

Two major strategies are available in humans to identify genes that explain variability in muscular strength. A first strategy concerns association studies in which one studies the co-occurrence of a specific polymorphic marker or a candidate gene and the mean strength performance level in groups of carriers or noncarriers of the specific allele. If there is a significant association of an allele with a stronger or weaker strength phenotype, almost all carriers of this allele will have a high strength level, and only a few of the carriers will have a weak strength profile. Positive association results should be carefully interpreted. Association can be positive because the studied marker does cause the major gene effect, but it might also be that the marker is in linkage disequilibrium with the real gene causing the effect. Association might also be found due to chance because of population heterogeneity; any allele most frequent in a subgroup of the population will show association with all phenotypes studied in a mixed population. Association studies do not need genetically related subjects (e.g., parents); however, family data can be included in the analyses (21).

In linkage studies parametric and nonparametric methods are available to prove that a marker is in linkage with a gene causing the phenotype under study. In the parametric method, one tests whether the recombination fraction between a marker and a causal gene is significantly smaller than 0.5. This can be tested by a Lod score, with a value of three (1000:1 odds in favor of linkage), indicating significant linkage between a marker locus and a locus causing the phenotype. The mode of inheritance has to be known to perform this type of model-based analysis on family data. The sib-pair linkage method based on the principle of Haseman and Elston is a nonparametric method (22). It is based on the relationship of the number of alleles shared at a marker locus (number of alleles shared by descent in pairs of sibs) and the squared differences in observed phenotypes. Evidence for linkage is found when the squared sib-pair trait differences decreases with an increase in the proportion of alleles shared at the marker locus. Multipoint linkage mapping (using all available markers at one time) is applicable and will allow mapping and identifying loci affecting strength phenotypes (48).

Genetic and Environmental Influences

The overview of literature on genetic and environmental influences on muscular strength in childhood and adolescence is restricted to the results from unmeasured genotype approaches. Results on positive or negative linkage or association of genes with the muscular strength phenotype are not yet extensive and are to be expected to explode in the near future as the phenotypes of large family studies and more candidate genes and polymorphisms become available.

Racial differences are reported to be absent in 6- to 12-year-old black and white siblings in four static strength tests (32). Brother-brother similarities are higher than sister-sister or brother-sister similarities for right and left grip, static pull, and push strength. Heritability estimations \( h^2 = 2 \cdot r_{sib-sib} \) vary from 0.44 to 0.58. Correction for body weight differences between siblings reduced the estimates, but correcting for reliability of the measurements raised the heritabilities to
the raw estimates. Similar sib correlations were found for a sample of 162 Polish sibs (3–10 years) and 11–17-year-old sibs ($n = 259$). Sib correlations were somewhat higher in childhood age than in adolescence (44, 45).

Montoye et al. (36), comparing siblings for arm strength, summed grip strength, and a relative strength index based on the two measurements corrected for body size and fatness, reported a significant similarity in strength scores for siblings. In this family study, significant parent-child similarities were found for arm strength, grip strength, and relative strength, with similar resemblances for both older and younger children-parent relations. In contrast, Wolanski and Kasprzak (53) found decreasing parent-offspring correlations during puberty for grip strength, and only significant shoulder pull back and back lift similarities in mother-daughter relations. Szopa (44) observed on the contrary higher assortative mating corrected heritability estimates based on parent-offspring data of 347 families in the children of the older age group compared to the younger age group. In a large family study of 375 families, Pérusse et al. (38) applied the BETA path-analytic model to maximal isometric knee extension data and found a total parent-offspring variance transmissibility of 63%, of which 30% was biological (genetic) and 31% cultural. The non-transmissible variance accounted for 37% of the variation. Gender effects from sib and family studies more frequently point to a higher male similarity (heritability) than female similarity within the studied relationships.

About 14 studies have been found in the literature studying a form of static strength measurement in twins during childhood or adolescence. Most of these studies have only small samples with an age range over the total growth period, sometimes with or without age regression on the strength variables. Heritability estimates therefore vary from .24 to .83. Results of studies within a smaller age range or with a longitudinal design will be discussed.

Skad (43) measured biannually 23 DZ and 27 MZ twins from 11 to 18 years of age on a composite strength score of arm, leg, and back force. Heritability estimates were stable in boys ranging from 0.74 to 0.79, and ranged from 0.63 to 0.73 in girls. The higher genetic component in boys seem to be less variable in course of ontogenesis in boys; however, intra-pair variance increased in both MZ and DZ twins in the period of accelerated adolescence and growth spurt. Strength heritability indices are lower in girls, tended to decrease with age, and became more variable in adolescence.

Among 48 pairs of male twins measured prepubertal (9–11 years) and at adolescence (15–17 years), Venerando and Milani-Comparetti (50) report heritabilities for right and left grip strength of 0.32 and 0.45, respectively, and 0.49 for back extension strength. In a later study, heritability estimates range from 0.76 to 0.86 for several torque measurements in different muscle groups (51). A high contribution of genetic factors was also found by Engström and Fishbein (17) in a sample of young adult twins (18–19 years) for a composite strength score per unit of squared height (based on hand grip, knee stretch, and arm bent tests). Intra-pair correlations in a subset of twins with concordant amounts of leisure-time physical activity were lower for DZ twins (decrease from 0.47 to 0.33); however, in MZ twins the effect was minor (decrease from 0.83 to 0.80), pointing to the importance of activity as a factor of increasing DZ correlation, as can be detected in a factor of common environmental variation.

Data on explosive strength are less extensive. The only study with no evidence for genetic influences comes from Komi (28) who reported no differences in
intrapair variances in static, concentric, and eccentric isotonic arm force in a small sample of MZ and DZ 10–14 year-old twins. Studies of larger age ranges found high contributions of genetic factors in maximal muscle power of the elbow flexors ($h^2 = 0.97$ in 11–17-year-old twins; ref. 24), high midparent-offspring correlations also indicated important genetic influences for vertical jump performances (44, 45).

Functional strength and muscular endurance is mostly evaluated by tests like bent arm hang, chin-ups, sit-ups, leg lifts, or more specified endurance tests. Pérusse et al (38) report comparable transmissibility estimates for push-ups (0.44) and sit-ups (0.37–0.55) based on parent-child and sibling correlations. The estimates for the transmissible variance, obtained from the application of the path analysis to nuclear family data includes both biological inheritance (0.21) and cultural inheritance (0.33). In 10-year-old German twins, genes determined 85% of the variation in a pull-up test (52). Skad et al. (43) report on two studies investigating forearm and finger flexor force until exhaustion in MZ and DZ twins. The capacity to carry out a prolonged strength effort is determined by genetic factors for 83 and 84%, respectively, in both studies. Both muscular force decay and time of depletion of energy substrates were very similar in MZ twins and highly differentiated in DZ twins. In 11–25-year-old Czechoslovakian twins (29), heritability estimates of 45 and 22% for sit-up test and push-up test were noted by Malina (33), and for bent arm hang a heritability of 60% was found.

Most of the reviewed studies use one type of study, twins or family data, to explore or quantify the contribution of genetic factors in individual differences of muscular strength performances in youth, in which most of the studies span the whole growth period; therefore, limited information on time specific effects are found. In general, heritability estimates from sibling or family studies tend to be lower than those from twin studies. Static and dynamic or explosive strength seem to be under stronger genetic control than muscular endurance or functional strength. Gender differences are not always clear, but genes seem to play a more prominent role in male than in female strength determination.

Questions on the effects and timing of action of prepubertal versus adult genetic and environmental influences on strength can be answered in a combined twin-parent design of the Leuven Longitudinal Twin Study. As this longitudinal project is approaching its end in the adult stage of the twins, longitudinal genetic models will be tested in the near future to explore the questions of genetic and environmental factors over the period of growth to maturity into greater detail.

Table 2 gives the descriptive statistics and intra-pair correlations in strength measurements for 10.3 ± 0.3-year-old twins and their parents (31). Boys outperformed girls in arm pull, vertical jump, and bent arm hang both at 10 years of age and as adults. Comparing MZ and DZ twins within each gender revealed a greater static strength for MZ boys and a larger variance of DZ boys for leg lifts. Twin correlations split up by gender give an indication of the heterogeneity of the genetic determination. Parent correlations are indicative for assortative mating and possible increased genetic influences in the children. Parent-child correlations can give information on cultural versus genetic transmission. The gender-specific MZ correlations exceed the DZ correlations; however, for arm pull, the DZ correlation in males was markedly lower than half the MZ correlation, possibly indicating the existence of genetic dominance. In girls, the DZ correlations for arm pull and leg lifts were almost equal to the MZ correlations, possibly resulting from common
Table 2  Descriptive Statistics of Strength Fitness Scores in 10-Year-Old Twins and Their Parents, and B. Maximum Likelihood Correlations of Strength Fitness Scores Between First Born and Second Born Twins by Zygosity and Gender of the Twins, and Correlations Between Parents and Children

<table>
<thead>
<tr>
<th>A. Descriptives</th>
<th>MZM</th>
<th>MZF</th>
<th>DZM</th>
<th>DZF</th>
<th>Fathers</th>
<th>Mothers</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>42</td>
<td>44</td>
<td>63</td>
<td>59</td>
<td>84</td>
<td>97</td>
</tr>
<tr>
<td>Arm pull (kg)</td>
<td>26.9 (3.8)</td>
<td>24.4 (3.9)</td>
<td>25.2 (4.2)</td>
<td>23.6 (4.5)</td>
<td>75.6 (12.5)</td>
<td>43.0 (7.8)</td>
</tr>
<tr>
<td>Vertical jump (cm)</td>
<td>29.8 (4.1)</td>
<td>28.7 (4.8)</td>
<td>29.0 (4.0)</td>
<td>28.3 (4.2)</td>
<td>43.6 (5.7)</td>
<td>29.9 (4.8)</td>
</tr>
<tr>
<td>Leg lifts (no)</td>
<td>14.1 (2.0)</td>
<td>14.7 (2.5)</td>
<td>13.6 (3.3)</td>
<td>14.4 (3.0)</td>
<td>14.8 (2.7)</td>
<td>12.8 (3.6)</td>
</tr>
<tr>
<td>Bent arm hang(s)</td>
<td>19.0 (17.0)</td>
<td>9.1 (6.5)</td>
<td>14.3 (12.5)</td>
<td>9.6 (7.2)</td>
<td>18.4 (11.4)</td>
<td>6.6 (6.4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Correlations</th>
<th>MZM</th>
<th>MZF</th>
<th>DZM</th>
<th>DZF</th>
<th>DZMF</th>
<th>FM</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>21</td>
<td>22</td>
<td>21</td>
<td>19</td>
<td>21</td>
<td>79</td>
<td>168</td>
</tr>
<tr>
<td>Arm pull</td>
<td>.805</td>
<td>.657</td>
<td>.187</td>
<td>.601</td>
<td>.176</td>
<td>.034</td>
<td>.21</td>
</tr>
<tr>
<td>Vertical jump</td>
<td>.509</td>
<td>.770</td>
<td>.253</td>
<td>.434</td>
<td>.028</td>
<td>.088</td>
<td>.09</td>
</tr>
<tr>
<td>Leg lifts</td>
<td>.601</td>
<td>.733</td>
<td>.256</td>
<td>.616</td>
<td>.304</td>
<td>.260</td>
<td>.34</td>
</tr>
<tr>
<td>Bent arm hang</td>
<td>.767</td>
<td>.775</td>
<td>.416</td>
<td>.375</td>
<td>.351</td>
<td>.016</td>
<td>.25</td>
</tr>
</tbody>
</table>

**p < .01.  
Note. MZ = monozygotic twins, DZ = dizygotic twins, m = males, f = females, os = opposite sex, FM = father-mother, FC = father-child, MC = mother-child.
environmental factors or the genetic effects of assortative mating. Assortative mating was only significant for trunk strength (0.26). No significant differences were found between father-child and mother-child coefficients, and as parent-child correlations were lower than the DZ twin correlations, it was not likely that positive cultural transmission would be significant. The twin-parent model that was applied is explained in more detail in Maes et al. (31) and allows for testing a variety of models and assumptions, not feasible in twin data alone. Shared environmental influences were tested to distinguish the impact of the parents’ phenotypes (cultural transmission) from the twin-specific nonparental-shared environment. Also, mate selection based on phenotype (assortative mating) was tested. Because of the age difference in twins and their parents, a model was tested that did not constrain the genes operating in adults to be the same as those in 10-year-old children; however, the total heritability is the same in both generations. The model was further extended to include tests for gender heterogeneity. The results of this model fitting are presented in Figure 4 where percentages of explained variance per component are given.

For arm pull, vertical jump, and bent arm hang, three models seem to fit the parent-twin data equally well and in such a way as to confirm the lower parent-child versus DZ correlations: (1) a model including genetic dominance effects (D), since these factors correlate 0.25 in DZ twins, but 0 in parent-offspring pairs; (2) negative cultural transmission, but not expected to be present in these phenotypes; and (3) different genes acting in children and adults (G). Additive genetic effects and specific environmental effects were present in all strength phenotypes. For arm pull, vertical jump, and bent arm hang, the two most plausible alternative hypotheses are presented. For leg lifts, assortative mating contributed significantly to the interindividual differences in performance. The estimated explained variance in the twin and parent data owing to the (broad) genetic component was high

![Figure 4](image-url)
for functional strength (77%) as well as for static strength (74%). Genetic factors contributed 65% in vertical jump and 63% in leg lifts. No gender heterogeneity was found at this age. The observed twin and parent offspring correlations could be explained by either a 52, 34, and 40% dominance variance for functional, static, and explosive strength, respectively, or by a reduced genetic correlation between generations of 0.31, 0.56, and 0.38, respectively. Including the data of adult twins will allow relaxing the constraint of equal heritability in both generations and will be able to provide proof for genetic heterogeneity between generations. For leg lifts, 10% of the genetic variance was due to positive assortative mating.

**Genetic Factors in Trainability of Strength**

Physical activity and more specific, high resistance strength training are environmental factors that contribute or add to the observed differences between individuals both at young ages and in adult life. The question whether responses to strength training are variable in the population and whether this observed heterogeneity in trainability is related to the genotype is referred to as Genotype × Training interaction. This Genotype × Training interaction effect has only been studied in young adult populations for aerobic and anaerobic performances (11) and for muscular strength in two studies (46, 47). In a 10-week knee flexion/extension isokinetic strength training protocol, 5 monozygotic twins (17–26 years) were tested for responses in maximal strength and muscle fiber metabolites (46). Despite significant strength increases and considerable variation in training responses (24 ± 12%), evidence for genotype-dependent changes were only found in muscle oxoglutarate dehydrogenase concentrations but not for strength increases in peak torque output or other muscle enzymes. In a 10-week high resistance strength training study of arm flexors in 25 MZ and 16 DZ male twins (22.4 ± 3.7 years), responses in static and dynamic arm flexor strength and arm cross-sectional area were analyzed by bivariate genetic models (47). The increase in one-maximal repetition load (1RM) was high, 45.8% of the pretraining value, with large interindividual differences (CV = 34%). Also isometric and concentric arm flexor strength increased by about 20% of pretraining values, and small hypertrophic effects were found as arm cross-sectional area increased on average by 4.4%. Evidence for genotype-environment interaction was found for the increase in 1RM (see Figure 5), static strength, and concentric flexion at 120°/s. In the ANOVA approach, 3.5 times more variation was found between pairs of identical genes (between MZ pairs) than within pairs of identical genetic background (within MZ pairs). From bivariate pre- and posttraining analysis of both MZ and DZ twin data, it was observed that about 20% of the variation in strength (1MR, static and concentric flexor strength) at posttraining evaluation was explained by genetic factors that did not contribute to the genetic variability in strength prior to strength training. Trainability in muscular strength is therefore found to be highly variable in young adults, with some evidence for the importance of training-specific genes coming into action by impulse of the imposed training load. However, variation in strength outcome attained after strength training is largely explained by the same genetic factors that act prior to strength training.

**Tracking in Strength**

In fitness studies, auto-correlations—namely, the correlations between observations in the same children measured at different ages—have been used to quantify
changes in 1 RM (kg)

Figure 5 — Intra-pair resemblance in monozygotic (■) and dizygotic (○) twins for strength training increases in 1RM load after 10 weeks of strength training (r%Z = 0.49, p < .01; rDZ = 0.22, n.s.; from ref. 47).

Tracking. As already mentioned, longitudinal observations on the same subjects are required to verify if youths tend to keep their relative position in the age group over time. In other words, are those who are the strongest at 10 years also the strongest at 18 years?

In Figures 6 and 7, the results of tracking in strength are summarized. Auto-correlations are given for strength characteristics covering different intervals, 1 through 5 years for preadolescents or children, and 1 through 9 years for adolescents. The interval distinction is made, since it has been observed that, in general, tracking coefficients tend to decline with increasing interval. With larger time intervals between two observations, the auto-correlations, as indicators of the maintenance of the relative position, tend to decrease. Also, given the differences in the developmental patterns in strength between preadolescence and adolescence, the two periods are considered separately. The bars in Figures 6 and 7 indicate the range of the auto-correlations stemming from different studies, different tests, and also different age levels. For example, for a 2-year interval, auto-correlations can be calculated for the age range 6–8 years, 7–9 years, 8–10 years, and all other 2-year combinations.

Auto-correlations in upper body and lower body isometric strength tend to decrease from a 1-year interval to a 5-year interval (Figures 6a and 6b). For a 1-year interval, generally high tracking is found (0.60 or above); for a 3-year interval, coefficients vary between 0.20 and 0.80; and for a 5-year interval, most coefficients vary between 0.20 and 0.50, indicating low to moderate tracking. It should be noted that for several intervals, the coefficients show large variability indicating a lack of consistency between age groups (e.g., 6–9 years vs. 8–11 years, between muscle groups and between studies). This lack of consistency is still more apparent in tracking of explosive strength. With increasing time interval, coefficients tend to decrease (Figure 6c). In boys, coefficients vary between 0.40 and 0.80,
Figure 6 — Tracking coefficients (auto-correlations), for time intervals of 1 to 5 years, in strength of preadolescents. a. lower body static strength (data from 14, 39), b. upper body static strength (from refs. 14, 39), c. explosive strength (from refs. 6, 16, 18, 27, 39, 49), d. muscular endurance (from refs. 12, 16).
indicating moderately low to high tracking. In girls, still more variability in the tracking coefficients is seen.

In preadolescents, tracking coefficients for muscular endurance are limited. Tracking is high, about 0.70, for a 1-year interval and drops to about 0.40 for intervals of 2 to 4 years. For a 5-year interval, tracking in muscular endurance is low (Figure 6d).
Age-to-age correlations for static strength in adolescent boys are moderate to high (0.40 to 0.70) for a 1-year interval. Coefficients vary considerably for a 5-year interval, and are low to moderate (0 to 0.50) for a 9-year interval (Figure 7a). In both sexes, the tracking coefficients for explosive strength vary between 0.40 and 0.90 over intervals of 1, 3, and 5 years. For a 9-year interval, the coefficients are still high (0.70 to 0.80) in girls but are considerably lower and more variable in boys (0.15 to 0.55). For muscular endurance, the correlations range from 0.50 for a 5-year interval to 0.80 for a 1-year interval. (Note that all coefficients mentioned above are rounded to 0.05.)

In the Leuven growth study of Belgian Boys and subsequent follow-up at 30 years, tracking was also studied between adolescent strength and strength at 30 years. For arm pull (static strength), correlations between observations made at 13, 14, and 15 years and at 30 years are about 0.30 to 0.35. Thereafter, coefficients increase to 0.55 between 18 and 30 years. For explosive strength, the correlations increase from 0.52, between 13 and 30 years, to 0.69 between 18 and 30 years. For muscular endurance of the upper body and lower trunk, tracking coefficients range from 0.35 to 0.55, indicating low to moderate tracking for this strength component (6).

In conclusion, strength characteristics follow the general type of growth curve that is observed for most external body dimensions. In boys, a clear adolescent growth spurt is observed 3 months to 1 year after age at PHV for static and explosive strength, and for muscular endurance of the upper body. In girls, a less pronounced adolescent growth spurt is seen for static strength. In preadolescents as well as in adolescents of both sexes, biological maturity is positively associated with static strength. In adolescent boys, from 13 years onwards, also explosive strength and muscular endurance of the upper body and lower trunk are positively associated with biological maturity even after controlling for variation in chronological age, stature, and body mass. Furthermore, in adolescents, the interaction between stature, body mass, and biological maturity explains significant proportions of the variation in strength. In preadolescents, body mass and stature are more important predictors than the interactions. During growth, strength components are under fairly strong genetic control with evidence for dominance and reduced genetic transmission from one to the next generation. Strength gain after a weight training program is only partially genetically determined. During childhood and adolescence, tracking coefficients for strength are low to moderately high and tend to decrease with increasing time interval. Coefficients, however, show considerable variation between age levels considered and between different studies.

References


42. Sing, C.F., and E.A. Boerwinkle. Genetic architecture of inter-individual variability in apolipoprotein, lipoprotein and lipid phenotypes. In: *Molecular Approaches to Human*