Maximal Power Across the Lifespan

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Background. Previous investigators have reported that maximal power increases during growth and decreases with aging. These age-related differences have been reported to persist even when power is scaled to body mass or muscle size. We hypothesized that age-related differences in maximal power were primarily related to differences in muscle size and fiber-type distribution rather than to age per se.

Methods. Maximum cycling power ($P_{\text{max}}$) and optimal pedaling rate ($V_{\text{opt}}$, a surrogate measure for muscle fiber type) were determined for 195 boys and men, 8–70 years of age, by using inertial load cycle ergometry. Anthropometric dimensions were used to estimate lean thigh volume (LTV$_{\text{est}}$) of all subjects, and magnetic resonance imagery was used to determine thigh and hip muscle volume (MRI$_{\text{th}}$) for 24 subjects.

Results. $P_{\text{max}}$ was highly related to the product of LTV$_{\text{est}}$ and $V_{\text{opt}}$ (LTV$_{\text{est}} \times V_{\text{opt}}$; $r^2 = .83$). Multiple regression revealed that $P_{\text{max}}$ was significantly related to both LTV$_{\text{est}} \times V_{\text{opt}}$ and age ($r^2 = .84$). Power scaled by LTV$_{\text{est}} \times V_{\text{opt}}$ was stable during growth and exhibited a small but significant decrease with aging. MRI$_{\text{th}}$ was highly correlated with LTV$_{\text{est}}$, and the ratio of LTV$_{\text{est}}$ to MRI$_{\text{th}}$ was independent of age.

Conclusions. These results suggest that muscle volume and optimal pedaling rate are the main determinants of maximal power across the lifespan and that the contractile properties of muscle are developed early in childhood and remain nearly intact late into the lifespan.

Maximal muscular power changes across the lifespan: it increases during childhood, reaches a peak during adulthood, then declines with old age. Production of maximal power may be required for many daily activities; climbing stairs, crossing a busy street, and recovering balance may represent short-term maximal efforts, particularly in young children and older adults. The ability to produce sufficient power to perform these types of activities may have a major influence on the development of children and the independence of older adults. At a more basic level, maximal power represents the integration of neural and muscular function, and serves as an indicator of the integrity of the neuromuscular system. It is therefore important to understand the time course of development, and subsequent decline, of maximal power.

Previous investigators have reported that the maximal power of young adults is two- to threefold higher than the power of 8- to 10-year-old children (1–5). Such a difference is not unexpected because adults are more than twice as large as 8-year-old children (6). However, the power of adults has been reported to be 35–50% greater than that of children when scaled to body mass (1–5) and 20–53% greater when scaled to muscle size (7–9). From young adulthood to older age, total power and power scaled to body mass have been reported to decrease by 6–11% per decade (8,10–13) and by 6%–8% per decade when scaled to muscle size (11,14). Some previous investigators have discussed possible mechanisms for these age-related differences in maximal power (1,3,4,9,11), but the exact mechanisms remain unknown.

One mechanism known to affect maximal power is total ATPase activity (15), which is a function of muscle size and fiber type. Indeed, maximal cycling power has been reported to be highly related to lean thigh volume (16) and to muscle fiber-type distribution (12,17,18). Additionally, optimal pedaling rate has been shown to be highly related to muscle fiber type (18) and thus may serve as a surrogate measure for muscle fiber-type distribution.

We hypothesized that age-related differences in maximal power were primarily related to differences in muscle size and fiber-type distribution rather than to age per se. To test that hypothesis, we measured the maximum cycling power, lean thigh volume, and optimal pedaling rate of males aged 8 to 70 years; we then analyzed those data to determine what portion of the variability in maximal power was related to the product of muscle size and optimal pedaling rate and what portion was related to age. An additional purpose was to determine if anthropometric dimensions provide a valid estimate of muscle volume in active males of different ages.

Methods

A total of 195 males, 8 to 70 years of age, were recruited from schools and from a list of licensed competitive cyclists. Subjects under 18 years of age were physically active and enrolled in physical education classes. Subjects between the ages of 18 and 30 years were either physically active or were competitive cyclists. All subjects over 30 years of age were competitive cyclists. Prior to testing, the subjects had the procedures explained verbally and the test demonstrated. Each minor provided written assent, and his parent or guardian provided written consent. Subjects over 18 years of age provided written informed consent. This study was approved by the Institutional Review Board of The University of Texas at Austin.

Cycling power was measured using the inertial load method (16), which determines maximal power across a range of pedaling rates in one short exercise test. The ergometer was fitted with bicycle-racing handlebars, cranks, ped-
als, and seat and was fixed to the floor. Each subject wore cycling shoes fitted with a cleat that locked into a spring-loaded binding on the pedal. The ergometer frame was modified to accommodate the lower seat position required by the younger subjects, and three handlebar stems were available to provide a comfortable position for each subject.

This method has been described previously (16). Briefly, the trajectory of an ergometer flywheel was determined by means of a slotted disc mounted on the flywheel and an infra-red photodiode on the ergometer frame. The slots were spaced at an angle (\(\Delta \theta\)) of \(\pi / 8\) radians and alternately passed or interrupted the infra-red beam. Time between consecutive interrupts (\(\Delta t\)) was recorded by a microprocessor with a clock accuracy of \(\pm 0.5 \mu\)s. Flywheel angular velocity was calculated as \(\Delta \theta / \Delta t\). The time–angular velocity data were low-pass filtered at 8 Hz by using a 5th order spline (19). Power was calculated as the rate of change of kinetic energy for each revolution of the cranks, and no frictional resistance was applied to the flywheel. Maximum power (\(P_{\text{max}}\)) was identified as the apex of the power–pedaling rate relationship. Optimal pedaling rate (\(V_{\text{opt}}\)) was the pedaling rate at which \(P_{\text{max}}\) occurred. The inertial load was varied to accommodate the various sizes of the subjects. Loads were 3.2 kg \(\times\) m\(^2\) for body masses of 24–39 kg, 5.24 kg \(\times\) m\(^2\) for masses of 40–49 kg, 8.6 kg \(\times\) m\(^2\) for masses of 50–69 kg, and 9.5 kg \(\times\) m\(^2\) for masses of 70 kg and above.

Leg circumference (C) and length were measured at gluteal furrow, mid-thigh, and proximal patella. Skin-fold thickness (SF) was measured using a Harpenden skin-fold caliper. Lean limb circumference (LC) was estimated as \(LC = C - SF \times \pi\) (20). Lean limb diameter (LD) at gluteal furrow, mid-thigh, and proximal patella was estimated from the circumference (\(LD = LC / \pi\)). Lean cross-sectional area was estimated as \(\pi LD^2 / 4\). Lean thigh volume (LTV\(_{\text{est}}\)) was estimated as the sum of two truncated cones (21).

Magnetic resonance imagery was used to obtain precise measures of hip and thigh muscle volume (MRI\(_{\text{ig}}\)) in a subset of 24 subjects. T1 images were recorded by a General Electric Signa (Milwaukee, WI) system at 16 kHz with 10-mm slice thickness from the knee to the iliac crest. Images were cropped to remove the background and most non-muscular tissue by using image processing software (Adobe Photoshop 5.0, San Jose, CA). Muscle area within each image was determined using National Institutes of Health image processing software (Scion Image for Windows), which determined the number of pixels in each image within a range of gray-scale density that was characteristic of muscle tissue. Incremental volumes were calculated as the product of cross-sectional area and slice thickness. Total MRI\(_{\text{vol}}\) was calculated as the sum of incremental volumes from the origin of glutaeus maximus to the knee joint.

Subjects who were not cycling-trained performed three days of practice prior to experimental data collection, whereas the trained cyclists performed only the experimental trials. This procedure has been previously shown to produce reliable results in active men and cyclists, respectively (22). During all practice and experimental trials, subjects performed a 5-minute warm-up of cycling at 100–120 rpm and then rested for 2 minutes prior to performing four power tests with 2 minutes resting recovery between tests. Subjects began each test from rest and accelerated maximally for approximately 3–4 seconds on a verbal command with standardized encouragement. For the cyclists, seat height (measured from the top of the saddle to the pedal axle when the pedal was at its lowest point) was set to match their accustomed riding position, which was found to average 108.5% of leg length (i.e., height minus seat height). Seat height for the active subjects was likewise set at 108.5% of leg length. Subjects remained seated throughout each bout, and feedback regarding \(P_{\text{max}}\) was provided after each power test.

Subjects were grouped by age: 8–11, 12–19, and each decade to age 70. The effects of training on \(P_{\text{max}}\) scaled by LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\) were determined by comparing the active (\(n = 25\)) and cycling-trained subjects (\(n = 25\)) ages 18–30 with a Student’s t test. If scaled \(P_{\text{max}}\) of those subjects did not differ, the data for active and cycling-trained subjects were combined for subsequent analyses. Values for body mass, LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\), LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\) and \(P_{\text{max}}\) (absolute and scaled to body mass, LTV\(_{\text{est}}\) and LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\)) were analyzed using analysis of variance, and Bonferroni post hoc procedures were used to determine which age groups differed (\(p < .05\)) from the young adults (20–29 years of age). Linear regression was performed to determine the relationship of \(P_{\text{max}}\) with LTV\(_{\text{est}}\) and LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\). Multiple linear regression of \(P_{\text{max}}\) with LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\) and age was performed to determine what additional portion of the variability in \(P_{\text{max}}\) was related to age per se. Linear regression of LTV\(_{\text{est}}\) with MRI\(_{\text{ig}}\) was performed to determine how well the anthropometric estimate predicted the actual muscle volume of the leg. Linear regression was also performed on the ratio of LTV\(_{\text{est}}\) to MRI\(_{\text{ig}}\) versus age to determine if an age-related increase in intramuscular fat might bias the accuracy of the anthropometric estimate. Linear regression of \(P_{\text{max}}\) versus LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\), and \(P_{\text{max}}\) versus MRI\(_{\text{ig}}\) \(\times\) \(V_{\text{opt}}\) were performed to determine ifMRI\(_{\text{ig}}\) was more predictive of \(P_{\text{max}}\) than was LTV\(_{\text{est}}\).

**Results**

Age, body mass, LTV\(_{\text{est}}\), and \(V_{\text{opt}}\) for each age group are presented in Table 1. Members of the youngest group were significantly less massive than were the young adults (20–29 years). LTV\(_{\text{est}}\) of the two youngest groups were significantly less than that of the young adults. \(V_{\text{opt}}\) of the youngest and oldest groups were significantly less than that of the young adults. LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\) of the two youngest and the oldest groups were significantly less than that of the young adults.

\(P_{\text{max}}\) scaled by LTV\(_{\text{est}}\) \(\times\) \(V_{\text{opt}}\), of young active (2.22 \(\pm\) 0.06) and cycling-trained (2.25 \(\pm\) 0.05) men did not differ. Therefore, active and trained subjects were combined for analysis.

Absolute and scaled values for \(P_{\text{max}}\) are presented in Table 2. Absolute \(P_{\text{max}}\) (Figure 1) of the young adults was approximately 220% greater than that of the youngest boys, whereas \(P_{\text{max}}\) of men in the oldest age group was 30% less than that of the young adults; age groups 8–11, 12–19, 50–59, and 60–70 had significantly lower \(P_{\text{max}}\) than the young adults. \(P_{\text{max}}\) scaled to body mass (Figure 2) of the young adults was approximately 40% greater than that of the
youngest boys, whereas scaled $P_{\text{max}}$ of men in the oldest age group was 30% less than that of the young adults; age groups 8–11, 40–49, 50–59, and 60–70 had significantly lower scaled $P_{\text{max}}$ than the young adults. $P_{\text{max}}$ scaled to $\text{LTV}_{\text{est}}$ (Figure 3) of the young adults was not different than that of the youngest boys, whereas scaled $P_{\text{max}}$ of men in the oldest age group was 19% less than that of the young adults; age groups 50–59 and 60–70 had significantly lower scaled $P_{\text{max}}$ than the young adults. Finally, $P_{\text{max}}$ scaled to $\text{LTV}_{\text{est}} \times V_{\text{opt}}$ (Figure 4) of the young adults was not different than that of the youngest boys, whereas scaled $P_{\text{max}}$ of men in the oldest age group was 12% less than that of the young adults; age groups 50–59 and 60–70 had significantly lower scaled $P_{\text{max}}$ than the young adults.

Regression analyses indicated that $P_{\text{max}}$ was highly related to $\text{LTV}_{\text{est}}$ and to $\text{LTV}_{\text{est}} \times V_{\text{opt}}$, and that age accounted for a small but significant portion of the variability.

$$P_{\text{max}} = 232.7 \times \text{LTV}_{\text{est}} + 53.7,$$

$$r^2 = .755, F = 595, p < .001$$

$$P_{\text{max}} = 1.835 \times \text{LTV}_{\text{est}} \times V_{\text{opt}} + 97.5,$$

$$r^2 = .826, F = 913, p < .001$$

$$P_{\text{max}} = 1.906 \times \text{LTV}_{\text{est}} \times V_{\text{opt}} - 2.68 \times \text{age} + 160,$$

$$R^2 = .843, F = 516, p < .001$$

For the 24 subjects in the magnetic resonance imaging portion of this study (Figure 5), $\text{LTV}_{\text{est}}$ was highly correlated to $\text{MRI}_{\text{vol}}$ ($r^2 = .914$). The ratio of $\text{MRI}_{\text{vol}}$ to $\text{LTV}_{\text{est}}$ was independent of age ($r^2 = .03, F = .71, p = .41$). $\text{MRI}_{\text{vol}} \times V_{\text{opt}}$ was more predictive of $P_{\text{max}}$ ($r^2 = .86, F = 134$) than $\text{LTV}_{\text{est}} \times V_{\text{opt}}$ ($r^2 = .79, F = 87$).

**Discussion**

The main finding of this study is that the product of muscle size and optimal pedaling rate, an indicator of muscle fiber type, accounted for 82% of the variability in $P_{\text{max}}$ across six decades of age, whereas age accounted for less than 2% of the variability. When $P_{\text{max}}$ was scaled by $\text{LTV}_{\text{est}} \times V_{\text{opt}}$, the previously observed age-related increase from childhood to young adulthood was eliminated and the decrease in the older groups was reduced to 12% over four decades (approximately half as large as the previously reported age-related decrease). The stability of $P_{\text{max}}$, scaled by $\text{LTV}_{\text{est}} \times V_{\text{opt}}$, suggests that the contractile properties of muscle of any specific fiber type are developed early in childhood and remain nearly intact late into the lifespan.

Obtaining valid measures of maximal muscular power from the diverse subjects in this investigation required that the protocol be safe and that the subjects be highly motivated. We chose cycling as our power measurement technique because the chance of injury was minimal and the test was of such short duration (3–4 seconds) that it was not influenced by cardiovascular fitness. During the testing of our younger subjects, other children from their physical education
tion class cheered for the boy performing the test, providing high motivation. The cyclists volunteered primarily because they hoped to learn something that would help them with their racing. Indeed they were so highly motivated that most of them traveled several hours just to perform our testing. Another advantage of recruiting cyclists was that no practice trials were necessary (22), so our older subjects were only required to visit the laboratory one time. This one-time visit allowed us to recruit subjects who might not have volunteered to make several visits. Finally, because the older subjects were trained at cycling, they were confident and able to exert a truly maximal effort.

An important difference between this investigation and previous investigations of age and power was the use of optimal pedaling rate as a surrogate measure for muscle fiber-type distribution. It is well known that muscle fiber type affects maximal power (23,24); however, the relationship of optimal pedaling rate with muscle fiber type has only recently been reported by Hautier and colleagues (18). They reported that $V_{\text{opt}}$ is strongly related to the proportion of type II muscle fiber area ($r^2 = .77$). Prior to that investigation, McCartney and colleagues (25) reported that the maximum pedaling rate of a subject with 72% type II fibers was 380 rpm compared with 225 rpm for a subject with 53% type II fibers, suggesting a relationship between fiber type and maximum pedaling rate. Conversely, Sergeant and colleagues (26) reported that optimal pedaling rate was similar in four subjects with similar muscle fiber–type distribution.

Figure 2. Power scaled to body mass versus age. Scaled power increased 40% across the young age groups and decreased approximately 7.6% per decade with aging.

Figure 3. Power scaled to $\text{LTV}_{\text{est}}$ versus age. Scaled power increased 10% across the young age groups and decreased approximately 5% per decade with aging.

Figure 4. Power scaled to $\text{LTV}_{\text{est}} \times V_{\text{opt}}$ versus age. Scaled power did not change across the young age groups and decreased approximately 3% per decade with aging.

Figure 5. Magnetic resonance images of the mid-thigh of 9- (upper left), 20- (upper right), 40- (lower left), and 61-year-old (lower right) subjects.
Our use of optimal pedaling rate as a surrogate measure for muscle fiber type is, therefore, well supported. The composite variable \(LTV_{\text{est}} \times V_{\text{opt}}\) was used to account for the combined effects of muscle size and fiber-type distribution. Another method to account for two independent variables is multiple linear regression, which would be appropriate if muscle size and fiber-type distribution affected muscular power via additive mechanisms. However, Swoap and colleagues (23) reported that rat soleus, a muscle that is 95% slow twitch, produced 26 W/kg of muscle mass during cyclic contraction, whereas the plantaris, which is 95% fast twitch, produced 144 W/kg. Because fiber type affects the power a muscle can generate per unit mass, the effects of muscle size and fiber-type characteristics are multiplicative. Thus, use of the product of \(LTV_{\text{est}}\) and \(V_{\text{opt}}\) as a single independent variable is appropriate and based on physiological principles.

To investigate the effects of age, without confound associated with sedentary lifestyle, we sought out men who maintained vigorous training late into the lifespan. We were unable, however, to obtain a sufficient sample of cycling-trained boys. Therefore, we determined the effects of training in 50 men 18–30 years of age. In those men, \(P_{\text{max}}\) was nearly identical when scaled by \(LTV_{\text{est}} \times V_{\text{opt}}\). This equivalence in scaled power suggests that at least for our power test, the effects of training are manifested in muscle size and optimal pedaling rate. Therefore, we believe it was appropriate to pool data for the young men and to compare the active boys with the trained men. Even if the data were not pooled, our conclusions would persist because the same results could be shown during growth for the active subjects, and the same results for aging could be shown for the trained men.

The observation that \(V_{\text{opt}}\) differed across age groups suggests an age-related difference in the percentage of cross-sectional area occupied by type II muscle fibers. Lexel and colleagues (27) reported a decrease in the percentage of type I fibers from 68% at age 5 to 50% at age 20. Additionally, atrophy of type II fibers in the elderly has been reported (28,29), which would result in a decrease in the proportion of muscle cross-sectional area occupied by type II fibers. Thus, our data for \(V_{\text{opt}}\) are supported by studies that used rigorous methods to determine muscle fiber characteristics.

Magnetic resonance imagery was performed because anthropometric estimates of thigh volume do not account for intramuscular fat, which is thought to be higher in older adults (11,30). If intramuscular fat were higher in the older subjects, the anthropometric technique would overestimate the lean thigh volume of the older men and bias the scaled power in favor of the younger subjects. However, in data from 24 subjects ranging in age from 9 to 69 years, the ratio of \(MRI_{\text{vol}}\) to \(LTV_{\text{est}}\) was independent of age. Thus, intramuscular fat did not increase with age, and consequently the anthropometric estimate of muscle size seems valid for all of the subjects in this study. We believe that this finding has major implications for research because it suggests that field studies in which only simple anthropometric techniques are logistically possible can provide valid results in exercise-trained males of any age.

An important difference between \(LTV_{\text{est}}\) and \(MRI_{\text{vol}}\) is that \(MRI_{\text{vol}}\) included muscle volume at the hip (from gluteal furrow to iliac crest) that was not included in \(LTV_{\text{est}}\). This volume includes gluteus maximus, which is known to be a powerful hip extensor. The inclusion of this additional muscle volume may be the reason that \(MRI_{\text{vol}}\) more accurately predicted \(P_{\text{max}}\) in these subjects.

Previous investigators have reported that the power of males increases 27–50% during growth when scaled to body mass (1–5) and 20–53% (7–9) when scaled to muscle size. The present data indicate a similar increase in power scaled to body mass (40%) but less of an increase in power scaled to muscle volume (10%). Previous investigators of power and aging have reported that age-related decreases in power range in magnitude from 6% to 11% per decade in absolute power and power scaled to body mass or muscle size (8,10,11,13). The present data indicate a similar decrease of 30% over four decades (7.5% per decade) for total power and power scaled to body mass, and 20% over four decades (5% per decade) for power scaled to estimated lean thigh volume. Indeed, when expressed as power scaled to body mass (Figure 2), data from the present study are strikingly similar to data reported by Margaria and colleagues (13) in Figure 5 of that study. When \(P_{\text{max}}\) was scaled by \(LTV_{\text{est}} \times V_{\text{opt}}\), the growth-related increase was eliminated and the decrease with aging was reduced to 12% over four decades (3% per decade; Figure 4). Thus, our results suggest that previously reported differences in power during growth are primarily related to muscle size and fiber type. Additionally, when those variables are taken into account, the age-related decrease was less than half of what has been previously reported.

The youngest subjects in this study (ages 8–12) produced 417 ± 24 watts or 12.4 ± 0.3 W/kg. That value was higher than previously reported values of 5.9–10.2 W/kg (1–5,31) for boys of similar age. These higher values may be due to differences in measurement techniques (16) or to the 3 days of practice performed by our subjects. During the 3 practice days, the power of 13 of the youngest subjects was monitored to evaluate ergometer settings. Their power increased 44% from 275 ± 18 watts (8.3 ± 0.4 W/kg) on the first practice test to 394 ± 27 watts (8.3 ± 0.4 W/kg to 11.9 ± 0.5 W/kg) during experimental data collection. That 44% learning-related increase is much larger than the increases of 11%–13% that have been previously reported for adults (22,32). Thus, the high power of our young subjects is at least partially due to the practice bouts that allowed them to produce truly maximal power. This finding suggests that investigators who do not provide adequate practice may obtain power data that are biased by learning effects.

Our data indicated that 1.7% of the variation in \(P_{\text{max}}\) was accounted for by age. That 1.7% might be ascribed to age per se; however, an alternative explanation is an increase in the proportion of connective tissue within the muscle as a person ages. Specifically, the volume of intramuscular connective tissue of the older subjects in this investigation might have been maintained even though the muscle fibers experienced some atrophy, thus decreasing the proportion of muscle volume occupied by contractile elements. This mechanism was not measured in the present investigation,
but it may be responsible for some portion of the decrease in scaled power.

In summary, these data demonstrate that the primary determinants of muscular power are the muscle characteristics: volume and optimal pedaling rate (as a surrogate measure for muscle fiber type). Across six decades of age, these muscle characteristics accounted for over 82% of the variation in $P_{max}$. Indeed, even the effects of training are accounted for by those variables. Conversely, age per se only modestly affected $P_{max}$. Magnetic resonance imagery indicated that the exercise-trained older men in this study did not exhibit higher levels of intramuscular fat in their upper legs. Consequently, anthropometric dimensions provide a valid estimate of muscle volume in trained older men and active boys. Practice dramatically affected the maximal power of the boys in this investigation, suggesting that previously reported age-related changes in maximal power may have been influenced by a lack of familiarity with the testing protocol. These results should not be extended to the generally sedentary population. Rather, our findings represent a best case scenario for active growth and aging and serve to separate what is possible from what is assumed to be inevitable.

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