J Musculoskelet Neuronal Interact 2005; 5(3):225-231

Hylonome

Review Article

Examining the developing skeletal muscle: Why, what and how?

O. Fricke[1,2] and E. Schoenau[1]

[1]Children's Hospital of the University of Cologne, Cologne, Germany,
[2]Department of Child and Adolescent Psychiatry, University of Cologne, Cologne, Germany

Abstract

This review focuses on methodological concepts in the evaluation of skeletal muscle function, taking into account classical muscle physiology, the developing motor system in children and anthropometric parameters. Thereby, the classical concept of kinetic and thermodynamic description of muscle function is discussed in relation to data pertaining to human physiology. Emphasis is given to the specific problems that arise when assessing muscle function during development. Two important factors influencing muscle function are discussed in detail: changes in anthropometric characteristics and changes in co-ordinative skills in the developing individual. Finally, we discuss currently available methods for the evaluation of anaerobic muscle function in children and adolescents (maximal isometric grip force, peak jump force, peak jump power, Wingate test, Bosco test).

Keywords: Maximal Isometric Grip Force, Peak Jump Force, Peak Jump Power, Wingate Test, Bosco Test

Introduction

Each generation challenges the health care system with new demands, as the prevalence of medical problems requiring preventive and curative approaches is constantly changing. In Western industrialized countries most individuals have replaced previously common motor activities of daily life with the technical assistance provided by a mechanized and computerized world. Because the musculoskeletal system is adapting to biomechanical challenges and environmental conditions, the body composition of the average child and adolescent has dramatically changed in Western societies[1,2]. Insulin-resistance, obesity, osteopenia and sarcopenia are now typical challenges facing health care providers dealing with disease prevention and health education. Until a few decades ago, pediatric health care in Western societies focused on the prevention of rickets and malnutrition due to low caloric intake. Nowadays, the urgent issues are an atrophic musculoskeletal system caused by low motor activity and malnutrition due to high caloric intake. In addition, the improved care of chronically ill children introduced the issue of secondary musculoskeletal diseases. Therefore, knowledge and know-how on the evaluation of muscular function will become more of an issue in pediatrics. Knowledge on the development of the musculoskeletal systems and the assessment of this process will become important topics for those who are responsible for improving the level of medical care in our societies. This review discusses mechanical properties of the skeletal muscle (e.g., the generation of force, work and power) in children and adolescents taking into account classical muscle physiology, neuromuscular co-ordination and individual anthropometric characteristics. We will also deal with reference data on muscle function that have recently become available.

Why is classical muscle physiology still important today?

Muscle physiology of the second part of the 19th century and the first half of the 20th century mainly used kinetic and thermodynamic methods of physics to describe the process of muscle contraction and the development of muscle force. Results of these classical experiments still serve as a basis for the interpretation of kinetic parameters of muscle function

---

The authors have no conflict of interest.

Corresponding author: Oliver Fricke, M.D., Department of Child and Adolescent Psychiatry, Robert-Koch-Str. 10, D-50924 Cologne, Germany
E-mail: frickeo@rockefeller.edu

Accepted 20 April 2005

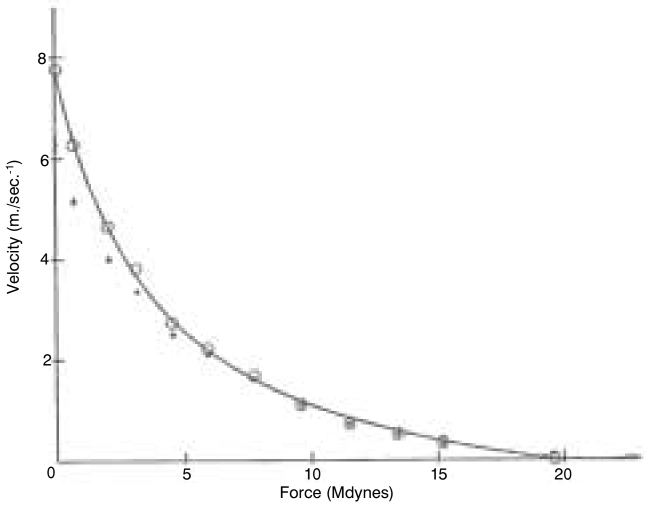

Figure 1. Experimental relation between force and velocity of contraction of muscles of the human arm. The relationship between force and velocity of contraction follows the Hill equation and is a rectangular hyperbola. Essentially, the more rapidly a muscle is allowed to shorten the less is the force developed [the figure was originally published by Wilkie, 1949].

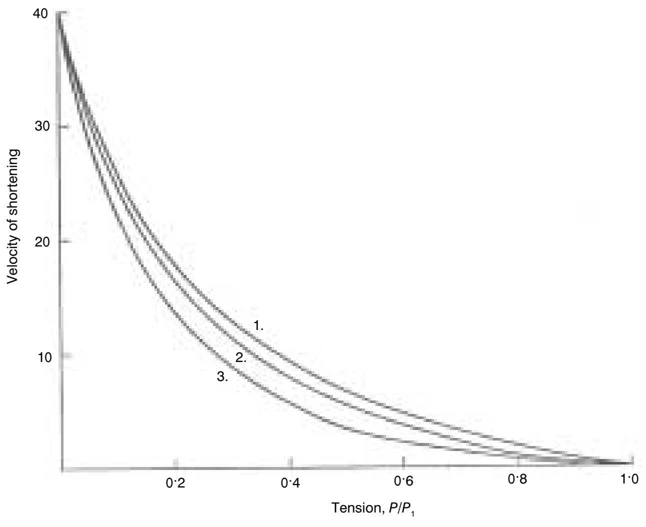

Figure 2. Calculated force velocity relation: 1. for a muscle fiber with similar sarcomeres throughout; 2. for a muscle fiber in which half the sarcomeres have maximum tension P1, the other half maximum tension 0.8 P1; 3. for a muscle fiber in which half the sarcomeres have maximum tension P1, the other half maximum tension 0.5 P1 [from Hill, 1970].

in human physiology, because those data describe biophysical characteristics of muscle work and muscular heat generation in general. Most experiments were performed on the isolated frog satorius muscle using electrical currents for the stimulation of muscle contraction. Muscle kinetics were described in terms of velocity and force. The classical force-velocity relationship of muscle contraction is based on the Fenn-effect which says that muscle force is inversely related to the velocity of muscle contraction[3]. Fenn and Marsh showed that this relationship between force and velocity was not linear, but could be described by the equation[4]:

$$\text{force} = \text{maximal force x } e^{-\text{constant}_1 \text{ x velocity}} - \text{constant}_2 \text{ x velocity}$$

Later Hill found experimentally that the relationship described by Fenn et al. could be described by a simpler equation when introducing a parameter called ‘rate of extra energy’[5,6]. Hill divided muscular heat production into three separate parts. First, ‘shortening heat’ is liberated by the process of shortening under muscle contraction and independent from the load lifted and the velocity of contraction[7]. Shortening heat is a simple linear function of the degree of shortening. Second, ‘maintenance heat’ is the heat developed in the isometric contraction, where force is developed without shortening. The amount of maintenance heat is linearly dependent on time. Third, the ‘rate of extra energy’ is liberated when the muscle contracts and lifts a load. The rate of extra energy is a linear function of the tension developed. The higher the tension, the lower the liberated rate of extra energy. Thus, extra energy is the sum of mechanical work and shortening heat. This concept leads us to the Hill equation, which illustrates the relationship between mechanical load and contraction velocity as a rectangular hyperbola (Figure 1):

$$\text{velocity x } (\text{constant}_a + \text{force}) = \text{constant}_b \text{ x } (\text{maximal force} - \text{force}).$$

Hill introduced two constants in his classical equation, describing the heat produced per cm shortening and the relation between extra energy and force, which is characteristic for different types of muscles. The ratio

$$\text{constant}_b \,/\, \text{standard degree of shortening}$$

is a parameter to compare the intrinsic contraction speed of different muscle types. The maximal contraction force determines the slope of the Hill equation. It has been determined experimentally that the mechanical efficiency of muscle peaks at about one-fifth of its no-load (maximum) contraction speed (power is peaking at around 30% of maximum velocity)[8].

Hill calculated the force-velocity relationship for muscle fibers that differ in the maximal forces that can be generated by their sarcomeres (Figure 2)[6]. Differences in maximal force may either reflect differences in the activation rate of contractile filaments or differences in muscle fiber type (I, IIa or IIb). During the same length of activation time, atrophic muscles should therefore generate a lower force than eutrophic muscles. Muscle compliance [muscle compliance = Δ(muscle length)/Δ(elastic force)] is not explicitly mentioned in this model. With regard to muscle compliance, we have to distinguish between parallel elastic forces of the inactive muscle and the immediate stiffness of the contracting muscle[9]. Myofibrils do contribute to immediate stiffness, but they do not contribute to parallel elastic forces. Considering the compliance of the muscle, Jewell and Wilkie integrated a term in the Hill equation describing elastic properties of the muscle[10,11]. Thereby, immediate stiffness is dependent on the degree of shortening of the muscle. Elastic forces contributing to mechanical work therefore eventually influence the amount of liberated extra energy, depending on the degree of shortening.

All the relationships discussed so far refer to short-term muscular contraction (time frame of seconds). What about longer time frames? Meyerhof and collaborators elucidated the fundamentals of energy conversion in muscle[12]. Muscle fibers can achieve maximum contraction for less than 30 seconds when using creatine-phosphate for energy supply. This process of energy turnover is primarily anaerobic and has to be distinguished from muscular work deriving from oxygen consumption.

The type I muscular fiber (which make up the bulk of muscles like the biceps or the *vastus medialis*) is the anaerobic working muscle fiber performing the fast twitch with a high maximal force. In contrast, the type II muscular fiber is characterized by a slow twitch and aerobic metabolism (present for example in the deltoid, gastrocnemius and soleus muscles). Type IIb fibers are characterized by aerobic and anaerobic energy generation, which have twitch characteristics between type I and IIa fibers. In the setting where maximum force generation occurs after a few seconds, mainly anaerobic generated energy supply has to be assumed. Interestingly, in rodents, the normal ontogenetic development of a postural muscle is highly dependent on the gravitational environment even during the early postnatal period, when full weight-bearing activity is not routine[13].

The mechanism underlying age-related slowing in fibers (e.g., slowing of musculus soleus fibers) is not known, but it has been suggested that there could be more than one beta/slow myosin heavy chain (MHC) isoform and that there is an age-related transition within these isoforms[14]. Therefore, the adaptation of the molecular muscle structure to environmental biomechanical conditions is a process immediately starting with the birth in mammals.

In pediatrics, muscle function can be evaluated by the measurement of maximal isometric grip force (MIGF), short-term cycling (30-s Wingate test) and forces deriving from jumping. The evaluation of MIGF, jumping forces and forces in the Wingate test are maximal forces developed in seconds and therefore, those forces are assumed to be generated in an anaerobic way, mainly by type II fibers. Thus, muscle force and power should be related to auxological characteristics (age, body weight or height) to reflect age-dependent molecular characteristics of the skeletal muscle structure. Below, this aspect is discussed in detail.

An additional interesting aspect is the efficiency of muscular work (relation between mechanical work and generated energy). Regarding the efficiency of anaerobic work, de Vries[15] concluded that the decrease in muscular efficiency with aging is slight – perhaps dropping 2 or 3% from measured efficiency values of around 22% in the 20-29 age group to around 20% in the 50-65 age group of adults. After puberty, this gives a lifetime average of around 21% efficiency, which is in line with values of around 22% experimentally obtained by Komi[16].

How non-muscular factors influence the functional muscle examination

Nervous system and muscle force. Muscle fibers are activated by peripheral nerves, which are under the control of the central nervous system. The recruitment of muscle fibers by the nervous system is a major factor for the generation of muscle force, because the velocity of shortening depends on fiber-recruitment. The functional ensemble of parts of the peripheral nerve (one motoneuron) and innervated muscle fibers are called motor unit (MU). Human MUs vary in twitch force, contractile speed, axonal conduction velocity, fatigue resistance, recruitment thresholds, firing rates and firing patterns. The smallest (soma size, axon diameter, muscle fiber size) MUs have the smallest twitch force, the slowest contraction speed, the slowest conduction velocity, the greatest resistance to fatigue, the lowest recruitment thresholds, and the lowest minimum and maximum firing rates. The converse applies to the largest MUs. Between the extremes are MUs with intermediate characteristics. In some muscles MUs recruitment occurs throughout the range of contraction force, whereas in other muscles most if not all MUs are recruited by about 50% of maximum contraction force, which is characteristic of small muscles performing precise movements. The recruitment order of MUs according to size is based on the inverse relation between susceptibility to discharge and motoneuron size. Smaller motoneurons will begin to fire before larger motoneurons due to increasing excitatory synaptic input. Which type of fibers is recruited also depends on how fast maximal force has to be generated for a given motor performance[17].

Ballistic and slow ramp contractions can be distinguished. The majority of evidence from human experiments indicates that the recruitment order is not reversed in ballistic contractions[18]. Multi-joint movement (e.g., jumping) requires the co-ordination of many muscles in an efficient way. The inefficient use of a combination of muscles in a complex motor movement might liberate a small amount of energy for the intended kinetic parameter (e.g., weight force applied on a jumping platform), even when the mechanical work performed by the participating muscles is much higher. The purpose of co-ordinative training, mainly in sports disciplines with a high technical impact e.g., track and field disciplines such as the high jump or long jump, is to improve the efficiency of the interaction between different muscles in multi-joint movements. Studies have shown that increases in peak force development are associated with increased activation of prime mover muscles and better co-ordination in the activation of all relevant muscles, thereby effecting a greater net force in the intended direction of movement[19].

In pediatrics, milestones of child development are typically related to the development of motor skills. Therefore, the assessment of motor performance serves as a useful measure for the evaluation of brain development in the first year of life[20]. For example, typical milestones are the ability to turn around the body axis at the age of 3-7 months, sitting at 5-10 months and standing freely at 10-17 months[21]. In contrast to the first year of life, the next steps of the human development are characterized by the development of motor skills in the vertical position (walking, running, jumping etc.). Thereby, the development of motor skills needs permanent feedback between neuronal (CNS and peripheral nerves) and muscular components (skeletal element, tendon, skeletal muscle) of the motor system. For example, a 4-year-old child is usually able to stand on one leg, whereas a 2-year-old child is not. This is due to better motor skills rather than increased muscle power. Thus, the accuracy of multi-joint movements depends markedly on the developmental stage of a child, which should tremendously influence the assessment of muscle force and power.

Children of different ages also have different co-ordinative patterns of multi-joint movements. As pointed out by Pare et al., variations in the temporal coupling of peak grip force and peak acceleration decrease with maturation[22]. Deutsch et al. provided evidence that practice-driven changes in the structure of force output, rather than a decline in the amount of white noise, largely contribute for age-related reductions in the amount of force variability[23]. In addition, Konczak et al. noted that the neural representations of limb dynamics are less precise in children and less stable in time than those of adults. Such controller instability might also contribute to the high kinematic variability observed in many motor tasks during childhood[24]. In contrast, there are literature reports that grip force can be measured reproducibly even in children just entering primary school. Groslambert et al. draw the conclusion that the neurodevelopmental level of 6-year-old children allows reliably producing moderate to intense forces during a grip force task[25].

Impairment of the central nervous system may influence the evaluation of muscle force even in the absence of muscle atrophy, because the skills of co-ordinating muscular activity are diminished. The activity of pyramidal tract neurons contributes to muscular power[26]. Generally, muscular force is related to the firing frequency of pyramidal neurons, whereas this relationship is more obvious in one-joint motor action (e.g., grip force) than in multi-joint motor movement. In summary, the paradigm of motor performance determines the pattern of muscular co-ordination, which is needed to carry out the requested motor movement. Therefore, a paradigm of motor performance should be used that is relatively stable in reliability and accuracy of performance during the ontogenetic development of the motor system.

The influence of anthropometric characteristics on muscle force and power. The relationship between body size and metabolic rate is a quite well known phenomenon and was discovered by Rubner in the 19th century. The allometric scaling law estimates the metabolic rate by the expression

$$\log\text{(metabolic rate)} = b \times \log\text{(body size parameter)}$$

Regarding the basal metabolic rate, the constant b was initially estimated to be 2/3, but later work corrected b to 3/4. Later West et al. were able to deduct the metabolic scaling law from the theory of fractals[27,28]. Thereby, the constant b is related to the smallest non-divisible unit of a system. Because muscular activity and energy turnover (metabolic rate) are closely connected to each other, it is not a surprise that data describing muscle strength are often normalized using the formula

$$\text{force}_{\text{normalized}} = \text{force}_{\text{recorded}} \times \text{(parameter of body size)}^{-b}$$

Jaric et al. tested maximal isometric force of various leg muscle groups in young athletes and suggested that the parameter b has to be differently adjusted in relation to the recorded muscle group29. Rauch et al. applied the allometric scaling law to normalize grip force to body height following previous work from Asmussen et al.30,31. Close correlations with age were found for peak force and peak power in jumping adults. The correction for muscle cross-section or body weight further increased these correlation co-efficients, particularly for peak power specific to body weight32. Thus, age influences peak power separately from parameters describing body size, which might be explained by an age-dependent change of muscular micro-structure. Studies on jumping force and power in children and adolescents emphasize the allometric relationship between muscle force body size[33]. Moreover, we could recently show that jumping force and grip force are correlated (r2 = 0.49). The influence of anthropometric characteristics on muscle function is also relevant in anaerobic cycling (e.g., Wingate test). Davies et al. demonstrated that differences in absolute power output disappeared after correction for body size. The authors concluded that absolute mechanical power output with age is mainly a function of size and the force which can be exerted at the optimal frequency of movement in children34. Furthermore, muscle force and power should be analyzed relating the data to a sex-matched reference population, because qualitative muscular factors (type II fiber, glycolytic ability, motor co-ordination and motor unit activation) are discussed to be responsible for the significantly higher body size independent peak force and power, which was shown for peak power cycling in boys and girls after correction for the lean leg volume35.

In conclusion, anthropometric characteristics, mainly body height and body mass, are important factors which influence the recording of muscle function despite co-ordination motor skills mentioned above. Therefore, the evaluation of muscle force and power needs to be related to parameters describing body size to be valid.

Two additional aspects should be mentioned generally influencing the assessment of muscle power. First, the storage and recovery of elastic strain energy by the tendons results in a considerable saving of metabolic energy[36]. Therefore, measuring muscle force is influenced by soft tissue components which are connected to the muscle (tendons and ligaments) and by soft tissue components of the muscle as it was mentioned above, as well. Recently, Ravary et al. discussed methods in the evaluation of tendon forces in animals and humans[37]. Second, the circadian rhythm influences the anaerobic performance. Souissi et al. suggest that the recording of the oral temperature will allow estimating the time of occurrence of maximal and minimal values in the circadian rhythm of anaerobic performance[38].

What should we measure for examining the developing muscle?

The choice of methods does always determine how accurate the question posed will be answered. Moreover, only validated methods deliver the guarantee that we really measure what we think to measure. The EUROFIT test battery is an evaluated method to assess physical activity in children and adolescents in general and was used to compare physical activity of children under different socioeconomic conditions[39]. Regarding functional examination of the anaerobic working muscle more precisely, methodological experience can be mainly attributed to three methods: maximal isometric grip force, maximal jumping force of a standard vertical jump (Bosco test) and power and peak power cycling (Wingate test). The relatively good correlations between jumping power and peak power cycling, and between maximal jumping force and maximal isometric grip force were mentioned above[33,34]. In contrast, Sands et al. present data indicating that the Bosco and the Wingate tests, which both measure anaerobic characteristics, appear to measure different aspects of anaerobic power[40]. Nevertheless, the discussed allometric scaling law may be one reason for the relatively high correlation between all three methods, which stand in relation to anaerobic muscle metabolism. The recently published reference values for grip force, evaluated in a large cohort ($n = 315$) under consideration of age and body height, is actually a convincing advantage, when maximal isometric grip force is assessed[31]. Studies delivering accurate and updated reference values can close this gap for the Wingate and Bosco anaerobic tests in the future. The reproducibility of the test plays an important role in the assessment of muscle function as it has been mentioned as well. Groslambert et al.[25] pointed out the good reliability of grip force in children with the beginning school age. Regarding maximal jumping power Rittweger et al. showed an acceptable reproducibility in physically competent older subjects[41]. Data describing reproducibility of maximal jumping force are recently not available in a collection of children comprising a larger range of age from infancy to adulthood. Rittweger et al. used a relatively new device for the assessment of maximal jumping power, the 'Leonardo Jumping Platform' (Novotec GmbH, Pforzheim, Germany). This device measures forces applied to the plate over time. Therefore, stationary forces (body weight) as well as the variation of forces over time (ground reaction forces) can be investigated. Measurement of force (acceleration x mass) over time (t) permits the calculation of work:

$$\text{work} = \text{force x distance}$$
$$= \text{force (t) x } [\int \int (\text{force(t)/mass})\, dt\, dt]$$
$$\text{and power} = \text{work / time}$$
$$= \text{force (t) x } [\int (\text{force(t)/mass})\, dt]$$

This platform permits the dynamic examination of muscle contraction. In contrast to devices measuring only isometric muscle contraction, the avoidance of strictly preformed patterns of motor movement displays a more realistic image of the individual motor capabilities. The measurement of forces of a counter movement jump under the advice to jump as high as possible might be a reasonable motor performance for the assessment of individual muscular characteristics in a dynamic way[41].

Despite the evaluation of muscle force and power, additional methods are available to examine muscularity in children and adolescents. The assessment of muscular cross-section is a recently used method to estimate muscle mass at the upper and lower limbs. Runge et al. investigated the cross-sectional area of the calf muscle by computed tomography. After correction for height no significant correlation was found with age (18-88 years)[32]. The assessment of cross-sectional area of the forearm was recently applied to reveal pubertal effects on muscle development and is a recommended method, when muscular parameters are referred to bone parameters (e.g., vBMD of the radius at 65% from the distal ulna)[42]. Moreover, the authors reported that MIGF and cross-sectional area are correlated[42].

A cheap and fast method to assess muscularity in children and adolescents is the estimation of the fat-free mass with 2 skinfold-thickness measurements[43]. This method is a better predictor of muscularity in anthropometry-based equations than the assessment of muscle by the midupper arm muscle area in childhood[43].

In summary, the accurate assessment of muscle force and power, respectively, muscularity, is an urgently needed method in pediatrics and adolescent medicine, because the change of lifestyle in western industry countries is followed by a dramatic increase of diseases related to impaired muscle function. Methods used to examine children should have small side effects and sufficient validity over the complete age range of musculoskeletal development. Motor skills, body size and sex are independent variables, which influence the assessment of muscle mechanics. Therefore, reference values referring to puberty, body size and sex are necessary for the accurate examination of muscle function. Under consideration of those aspects, maximal isometric grip force, maximal jumping force and power (Bosco test) and peak power cycling (Wingate test) are methods which may be recommended to examine anaerobic muscle function in children and adolescents. Nevertheless, further studies are needed to receive a sufficient evaluation, what really is described by those parameters in children and adolescents.

References

1. Strock GA, Cottrell ER, Abang AE, Buschbacher RM, Hannon TS. Childhood obesity: a simple equation with complex variables. J Long Term Eff Med Implants 2005; 15:15-32.
2. Popkin BM. The nutrition transition: an overview of world patterns of change. Nutr Rev 2004; 62(7 Pt 2):S140-143.
3. Fenn WO. Relation between work performed and energy liberated in muscular contraction. J Physiol 1924; 58:373.
4. Fenn WO, Marsh BS. Muscular force at different speeds of shortening. J Physiol 1935; 85:277.
5. Hill AV. First and last experiments in muscle mechanics. Cambridge University Press, London; 1970:23-41.
6. Hill AV. First and last experiments in muscle mechanics. Cambridge University Press, London; 1970:110-118.
7. Hill AV. Heat of shortening and heat of activation in a muscle twitch. Proc Roy Soc 1949; 136:195-211.
8. Schneck DJ. Mechanics of muscle. 2nd Ed, New York University Press, New York and London; 1992:191.
9. Huxley AF, Taylor RE. Local activation of striated muscle fibres. J Physiol 1958; 144:426-441.
10. Jewell BR, Wilkie DR. An analysis of the mechanical components in frog's striated muscle. J Physiol 1958; 143:515-540.
11. Jewell BR and Wilkie DR. The mechanical properties of the relaxing muscle. J Physiol 1960; 152:30-47.
12. Meyerhof OF. Energy conversion in muscle. Nobel Lecture, December 12; 1923.
13. Ohira Y, Tanaka T, Yoshinaga T, Kawano F, Nomura T, Nonaka I, Allen DL, Roy RR, Edgerton VR. Ontogenetic, gravity-dependent development of rat soleus muscle. Am J Physiol Cell Physiol 2001; 280:1008-1016.
14. Li X, Larsson L. Maximum shortening velocity and myosin isoforms in single muscle fibers from young and old rats. Am J Physiol 1996; 270(1 Pt 1):352-360.
15. de Vries HA. Physiology of exercise for physical education and athletics. 3rd ed. William C. Brown Company, Dubuque, Iowa; 1980:366-367.
16. Komi PV. The stretch-shortening cycle and human power output. In: Jones NL, Mc Cartney N, McComas AJ (eds) Human Muscle Power. Human Kinetics Publishers, Inc., Champaign, Illinois; 1986:27-39.
17. Crowther GJ, Gronka RK. Fiber recruitment affects oxidative recovery measurements of human muscle *in vivo* Med Sci Sports Exerc 2002; 34:1733-1737.
18. Sale DG. Influence of exercise and training on motor unit activation. Exerc Sport Sci Rev 1987; 15:95-151.
19. Sale DG. Neural adaptation to resistance training. Med Sci Sports Exerc 1988; 20:135-145.
20. Kakebeke TH, von Siebenthal K, Largo RH. Movement quality in pre-term infants prior to term. Biol Neonate 1998; 73:145-154.
21. Largo RH. Wachstum und Entwicklung. In: Lentze, Schaub, Schulte, Spranger (eds) Paediatrie: Grundlagen und Praxis. Berlin, Heidelberg, New York; 2001.
22. Pare M, Dugas C. Developmental changes in prehension during childhood. Exp Brain Res 1999; 125:239-247.
23. Deutsch KM, Newell KM. Changes in the structure of children's isometric force variability with practice. J Exp Child Psychol 2004; 88:319-333.
24. Konczak J, Jansen-Osmann P, Kalveram KT. Development of force adaptation during childhood. J Mot Behav 2003; 35:41-52.
25. Groslambert A, Nachon M, Rouillon JD. Influence of the age on self regulation of static grip forces from perceived exertion values. Neurosci Lett 2002; 325:52-56.
26. Ashe J. Force and the motor cortex. Behav Brain Res 1997; 86:1-15.
27. West GB, Brown JH, Enquist BJ. A general model for the origin of allometric scaling laws in biology. Science 1997; 276:122-126.
28. West GB, Brown JH, Enquist BJ. The fourth dimension of life: fractal geometry and allometric scaling of organisms. Science 1999; 284:1677-1679.
29. Jaric S, Urgakovich D, Kukolij M. Evaluation of methods for normalizing muscle strength in elite and young athletes. J Sports Med Phys Fitness 2002; 42:141-151.
30. Asmussen E, Heeboll-Nielsen K. A dimensional analysis of physical performance and growth in boys. J Appl Physiol 1955; 7:593-603.
31. Rauch F, Neu CM, Wassmer G, Beck B, Rieger-Wettengl G, Rietschel E, Manz F, Schoenau E. Muscle analysis by measurement of maximal isometric grip force: new reference data and clinical applications in pediatrics. Pediatr Res 2002; 51:505-510.
32. Runge M, Rittweger J, Russo CR, Schiessl H, Felsenberg D. Is muscle power output a key factor in the age-related decline in physical performance? A comparison of muscle cross-section, chair-rising test and jumping power. Clin Physiol Funct Imaging 2004; 24:335-340.
33. Fricke O, Weidler J, Tutlewski B, Schoenau E. Mechanography – A new Device for the Assessment of Muscle Function in Pediatrics. Pediatric Research in press.
34. Davies CT, Young K. Mechanical power output in children aged 11 and 14 years. Acta Paediatr Scand 1985; 74:760-764.
35. Martin RJ, Dore E, Twisk J, van Praagh E, Hautier CA, Bedu M. Longitudinal changes of maximal short-term peak power in girls and boys during growth. Med Sci Sports Exerc 2004; 36:498-503.
36. Johnston IA. Muscle action during locomotion: a comparative perspective. J Exp Biol 91; 160:167-185.
37. Ravary B, Pourcelot P, Bortolussi C, Konieczka S, Crevier-Denoix N. Strain and force transducers used in human and veterinary tendon and ligament biomechanical studies. Clin Biomech (Bristol, Avon) 2004; 19:433-447.
38. Souissi N, Gauthier A, Sesboue B, Larue J, Davenne D.

Circadian rhythmus in two types of anaerobic cycle leg exercise: force-velocity and 30-s Wingate tests. Int J Sports Med 2004; 25:14-19.

39. Ozdirenc M, Ozcan A, Akin F, Gelecek N. Physical fitness in rural children compared with urban children in Turkey. Pediatr Int 2005; 47:26-31.
40. Sands WA, McNeal JR, Ochi MT, Urbanek TL, Jemni M, Stone MH. Comparison of the Wingate and Bosco anaerobic tests. J Strength Cond Res 2004; 18;810-815.
41. Rittweger J, Schiessl H, Felsenberg D, Runge M. Reproducibility of the jumping mechanography as a test of mechanical power output in physically competent adult and elderly subjects. J Am Geriatr Soc 2004; 52:128-131.
42. Neu CM, Rauch F, Rittweger J, Manz F, Schoenau E. Influence of puberty on muscle development at the forearm. Am J Physiol Endocrinol Metab 2002; 283:103-107.
43. Boye KR, Dimitriou T, Manz F, Schoenau E, Neu C, Wudy S, Remer T. Anthropometric assessment of muscularity during growth: estimate fat-free mass with 2 skinfold-thickness measurements is superior to measuring midupper arm muscle area in healthy prepubertal children. Am J Nutr 2002; 76:628-632.