The Journal of Experimental Biology 212, 599-603
Published by The Company of Biologists 2009
doi:10.1242/jeb.020180

Muscular and non-muscular contributions to maximum power cycling in children and adults: implications for developmental motor control

Thomas Korff[1], Elaine L. Hunter[2] and James C. Martin[2,*]

[1]Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge, Middlesex UB8 3PH, UK and [2]The University of Utah, Department of Exercise and Sport Science, The Neuromuscular Function Laboratory, Salt Lake City, UT 84112, USA

*Author for correspondence (e-mail: jim.martin@utah.edu)

Accepted 2 December 2008

SUMMARY

During submaximal cycling, children demonstrate a different distribution between muscular and non-muscular (gravitational and motion-dependent) forces when compared with adults. This is partly due to anthropometric differences. In this study, we tested the hypothesis that during maximum power cycling, children would construct the task (in terms of the distribution between muscular and non-muscular pedal power) similarly to adults. Eleven children (aged 8–9 years) and 13 adults (aged 20–40 years) performed a maximal isokinetic cycling task over 3 s at 115 r.p.m. Multivariate analyses of variance revealed no significant differences in normalized maximum, minimum and average positive non-muscular pedal power between children and adults (Wilks' λ=0.755, $F_{3,20}$=2.17, P=0.124). Thus, maximum cycling is a developmental 'self-scaling' task and age-related differences in muscular power production are not confounded by differences in anthropometry. This information is useful to researchers who wish to differentiate between muscular and non-muscular power when studying developmental motor control. In addition to the similarities in the distribution between muscular and non-muscular pedal power, we found age-related differences in the relative joint power contributions to total pedal power. In children, a significantly smaller proportion of total pedal power was generated at the ankle joint (6.1±5.4% for children and 12.6±3.2% for adults), whilst relatively more power was generated at the knee and hip joints. These results suggest that intermuscular coordination may be contributing to children's limits in maximum power production during multi-joint tasks.

Key words: development, coordination, biomechanics, pedaling.

INTRODUCTION

When acquiring motor skills, children gain the ability to apply the task-appropriate forces that cause the movement. During human movement, muscular forces have to be matched to non-muscular (gravitational and motion-dependent) forces to produce a resultant force that complies with the goal of the task (Kautz and Hull, 1993). Non-muscular forces are directly related to segmental mass and inertia. As relative and absolute anthropometric characteristics change during childhood (Asmussen and Heebøll-Nielsen, 1955; Jensen, 1981; Jensen, 1986; Jensen, 1989), observed age-related differences in the application of muscular forces might not necessarily represent immature features of the neuromotor system but could be functional adjustments to account for changes in anthropometry.

Several authors have reported age-related differences in muscular force and power production during submaximal cycling (Brown and Jensen, 2003; Brown and Jensen, 2006; Korff and Jensen, 2007; Korff and Jensen, 2008). Brown and Jensen speculated that these differences were partly due to age-related differences in the anthropometry of the performer (Brown and Jensen, 2003). The reason for this is that forces as measured at the pedals are composed of muscular and non-muscular (gravitational and motion-dependent) components (Kautz and Hull, 1993), and non-muscular forces depend on the anthropometry of the performer. Thus, if the resultant (sum of muscular and non-muscular) force is the same, muscular adjustments might be necessary due to age-related anthropometry-driven differences in non-muscular forces.

Indeed, Brown and Jensen demonstrated that, during submaximal cycling, the distribution between muscular and non-muscular forces becomes more adult-like if mass is added to children's limbs (Brown and Jensen, 2006). These findings were supported by Korff and Jensen, who used a biomechanical simulation to demonstrate that relative changes in anthropometric characteristics affect muscular power production (Korff and Jensen, 2008). In related work on the development of neuromuscular power, Martin and colleagues reported that maximum cycling power of boys 8–11 years of age did not significantly differ from that of adults when power was normalized to lean thigh volume (Martin et al., 2000b). These results suggest that if the external power output is not prescribed, children construct the task in a way that accounts for their different anthropometric characteristics. Therefore, maximal cycling may serve as a developmental 'self-scaling' task during which the relative non-muscular contribution to external power is similar in children and adults. If this was the case, any differences in intermuscular coordination that emerge from such an experiment would not be confounded by differences in the anthropometry of the performer and could be attributed to features of the neuromotor system. Therefore, the first purpose of this study was to compare non-muscular pedal power between children and adults during maximal cycling. It was hypothesized that non-muscular power would not differ between children and adults when normalized to average pedal power.

The second purpose of this study was to test the assumption that, during maximal cycling, children would use similar coordination patterns in terms of average and peak joint power (normalized to average pedal power) production to those used by adults. During cycling, muscular power delivered to the pedal is composed of individual joint power contributions of the lower limb (i.e. ankle, knee and hip power) (Broker and Gregor, 1994). Previously, we have shown that during submaximal cycling at high movement speeds, children demonstrate weaker intermuscular synergies in terms of joint power production and segmental energy flow when compared with adults (Korff and Jensen, 2007). Here, we tested the hypothesis that during maximal cycling, relative average joint power contributions to total pedal power as well as relative peak powers at the lower limb joints do not differ between children and adults.

MATERIALS AND METHODS

Participants

Eleven active children (six males, five females, aged 8–9 years, 29.5±6.1 kg) and 13 adults [five males (74.6±1.6 kg), eight females (61.0±8.7 kg), aged 18–40 years] participated in the study. The adults were all recreational cyclists who regularly participated in group tour events. The children were all physically active (enrolled in physical education classes). They knew how to ride a bicycle but they did not participate in competitive cycling events. All children practiced maximal cycling on three separate days prior to experimental data collection (Martin et al., 2000a). Participants provided written consent. For children, parents also provided written assent. The procedures used in this study were approved by the Institutional Review Board of the University of Utah.

Procedure

Before the maximal cycling test, participants performed a 5 min cycling warm up at self-selected cadence and intensity. Participants then performed a 3 s maximal cycling bout on an isokinetic cycle ergometer. To ensure that motion-dependent forces would not be confounded by differences in movement speed, we set the pedaling rate to 115 r.p.m. Participants were instructed to pedal as powerfully as they could, and verbal encouragement was given during the exercise bout.

Instrumentation and data treatment

A Monark (Vansbro, Sweden) cycle ergometer frame and flywheel were used to construct an isokinetic ergometer. Seat height was set at 108.5% of leg length for all participants as used previously (Martin et al., 2000b). Several handlebar and stem combinations were used to allow each individual to have a comfortable hand position. The crank length was 170 mm for all participants. We deliberately used the same crank length for all participants as it was our goal to achieve similar non-muscular power contributions during the cycling motion. By keeping crank length the same, we achieved relatively similar linear centre of mass positions and velocities which are related to the non-muscular (i.e. gravitational and velocity-dependent) pedal power contributions. Moreover, we have previously demonstrated that maximum power production in children is independent of crank length (Martin et al., 2002). The flywheel was driven by a 3750 W direct current motor (Baldor Electric Company model CDP3605, Fort Smith, AR, USA) *via* pulleys and a belt. The motor was controlled by a speed controller equipped with regenerative braking capability (Minarik model RG5500U, Glendale, CA, USA). When a participant applied power to the ergometer, the motor acted as a generator and the generated current was dissipated by a resistor and heat sink built into the speed controller. The controller could, therefore, maintain a specified pedaling rate while resisting power outputs of up to 3750 W.

The right pedal was equipped with two 3-component piezoelectric force transducers (Kistler 9251: Kistler USA, Amherst, NY, USA), and the right pedal and crank were equipped with digital position sensors (Vishay Spectrol 601–1045: Malvern, PA, USA). Normal and tangential pedal forces and pedal and crank positions were recorded for 3 s at a frequency of 240 Hz using Bioware software (Kistler USA). The normal and tangential pedal forces were resolved into vertical and horizontal components using the pedal and crank position data.

The position of the pedal and the anterior superior iliac spine were recorded at a frame rate of 120 Hz with a 2-camera motion capture system (DMAS6, Spica Technology Corporation, Kihei, HI, USA). Motion capture data were linearly resampled to 240 Hz and synchronized with the force pedal data by matching the position of the pedal spindle, indicated by the motion capture system, with that indicated by the crank position sensor. Force and position data were filtered using a fourth-order zero phase-shift Butterworth low-pass filter with a cut-off frequency of 8 Hz.

Derivation of dependent variables

The joint powers at the hip, knee and ankle joints was derived using standard inverse dynamics techniques. The process of inverse dynamics has been described in detail by Hull and Jorge (Hull and Jorge, 1985). Briefly, the crank, foot, leg and thigh segments were modeled as rigid segments. The position of the hip joint was inferred from the position of the right anterior superior iliac spine, assuming a constant offset that was measured in a static condition (Neptune and Hull, 1995). The location of the ankle joint was determined by the angular orientation of the crank and pedal, by the length from the pedal spindle to the lateral malleolus, and by assuming the position of the lateral malleolus relative to the pedal surface was fixed throughout the pedal cycle (Hull and Jorge, 1985). Once the location of the hip and ankle joints as well as the length of the thigh and leg segments were known, the positions of the knee joint center were determined using the law of cosines. Relative angles between segments were calculated using these joint positions and the segment lengths. Linear and angular velocities and accelerations of the limb segments were determined by finite differentiation of position data with respect to time. Using these geometrically determined kinematics together with pedal forces, we determined the joint moments at the ankle, knee and hip joints. We multiplied these moments by the corresponding joint angular velocities to obtain joint powers. The hip transfer power was calculated as the dot product of hip joint reaction force and linear velocity (Broker and Gregor, 1994). Segmental mass proportions, centre of mass locations and radii of gyration were estimated from anthropometric tables in the literature. For adults, we used the regression equations presented by de Leva (de Leva, 1996). For children, we used the data provided by Jensen (Jensen, 1989), as these take developmental changes in relative anthropometric characteristics into account.

For all participants we derived power profiles which were representative of all complete revolutions within the exercise bout. Thus, some data which represented portions of the cycle before top dead center of the first revolution and after top dead center on the final revolution were not included in the calculations. We then calculated averages for each power term (pedal and joints) using 6 deg. increments of crank angle.

Pedal power was defined as the dot product of pedal force and pedal linear velocity. For each participant mean pedal power was calculated as the average pedal power over the corresponding pedal power profile. Hip, knee and ankle joint powers were averaged over the corresponding joint power profiles. Peak hip, knee and ankle power were defined as the maximum of the corresponding joint power profile.

Muscular pedal power was calculated by adding the muscular joint powers (ankle, knee, hip and hip transfer) at each point. The hip transfer power was included in this calculation to account for muscular power that resulted in linear motion of the hip (i.e. not angular motion of the joints of the lower limb). Non-muscular pedal power was calculated by subtracting the muscular pedal power from the total pedal power at each point. Joint powers as well as muscular and non-muscular pedal powers were normalized by mean pedal power to allow for meaningful comparisons between children and adults.

Statistical analysis

To test the hypothesis that relative non-muscular pedal power is similar in children and adults, we performed a multivariate analysis of variance (MANOVA) with age being the between-subject factor. Dependent variables were normalized maximum and minimum non-muscular pedal power as well as normalized mean positive non-muscular pedal power. As the non-muscular pedal power averaged over the cycle is zero, it was not necessary to consider the mean negative non-muscular pedal power, as the statistical effects are identical to those observed for positive non-muscular pedal power (see Fig. 1).

To test the hypothesis that relative mean joint power contributions are similar in children to those in adults, we performed an age×joint ANOVA with repeated measures. Here, we tested for an age×joint interaction. To test the hypothesis that relative peak joint powers would be similar in adults and children, an age×joint ANOVA was performed on relative peak joint power. We tested for a main effect for age and an age×joint interaction.

When the sphericity assumption of an ANOVA was violated (Huynh-Feldt's $\varepsilon<0.75$), the multivariate method (Wilks' lambda) was used (Schutz and Gessaroli, 1987). In the case of Huynh-Feldt's $\varepsilon>0.75$, the univariate method with adjusted degrees of freedom was used. If an age×joint interaction was significant, follow up *t*-tests (Bonferroni) were performed at each joint. Statistical significance was accepted at $P<0.05$. In addition, we used effect sizes (ES) to describe pairwise comparisons.

RESULTS

Mean power delivered to the right pedal was 139±26 and 402±148 W for children and adults, respectively (suggesting total power from both legs was approximately 278 and 804 W for children and adults, respectively).

Relative non-muscular pedal power was similar in children and adults (Figs 1 and 2). The MANOVA on relative maximum and minimum non-muscular pedal powers as well as mean positive non-muscular pedal power did not reveal any significant differences between the age groups (Wilks' $\lambda=0.755$, $F_{3,20}=2.17$, $P=0.124$). All effect sizes describing the differences between children and adults were small ($0.09<\mathrm{ES}<0.38$).

Children constructed the power delivered to the pedal differently from adults, as the age×joint interaction for relative mean joint power was significant (Wilks' $\lambda=0.661$, $F_{2,21}=5.37$, $P=0.013$). *Post-hoc t*-tests revealed that the relative power contribution of the ankle joint was significantly smaller in children than that in adults ($t_{21}=-3.61$, $P=0.002$, ES=–1.45), whereas relative power produced at the knee and hip did not differ between age groups ($t_{21}=1.21$, $P=0.241$, ES=0.49, and $t_{21}=0.05$, $P=0.964$, ES=0.02, for the knee and hip joint, respectively; see Figs 3 and 4).

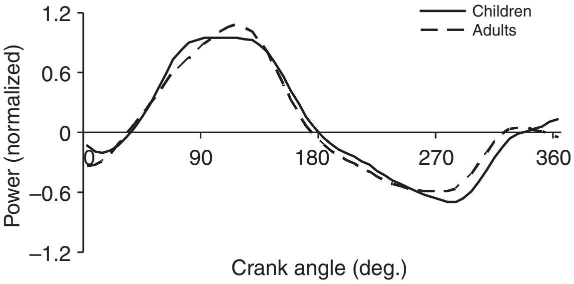

Fig. 1. Normalized non-muscular pedal power profiles for children and adults. The profiles were averaged within each age group. Zero and 360 deg. on the abscissa refer to top dead center of the crank cycle; 180 deg. refers to bottom dead center of the crank cycle.

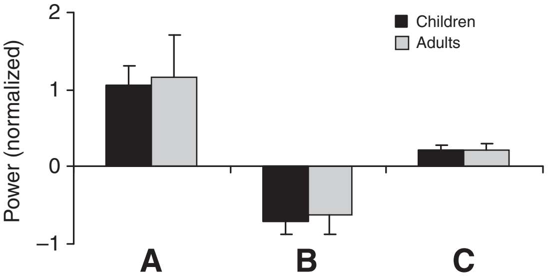

Fig. 2. Age-related differences in normalized maximum (A) and minimum (B) non-muscular pedal powers as well as mean positive non-muscular pedal power (C). The effect sizes describing the difference between children and adults for these variables were –0.22, –0.38 and 0.09, respectively.

Regarding relative peak joint power, the main effect for age was significant ($F_{21,1}=10.47$, $P=0.004$). Interestingly, children's relative peak power was greater than that of adults. Although the age×joint interaction for relative peak joint power was statistically non-significant ($F_{2,44}=1.45$, $P=0.246$), the effect sizes revealed a joint dependence of the age effect. Whilst the age group difference in relative peak power at the ankle was small (ES=–0.20), this difference was large and reversed at the knee and hip joints (knee: ES=1.07, hip: ES=0.56), indicating that children produced greater relative peak power only at the knee and hip joints (see Fig. 5).

DISCUSSION

Our first purpose for conducting this study was to compare non-muscular pedal power profiles between children and adults during maximal cycling. In conformity with our first hypothesis, we found normalized non-muscular pedal power profiles were similar in children and adults. Non-muscular pedal power is dependent on the anthropometry of the performer. Given that children possess different anthropometric characteristics from adults, non-muscular forces are different in children, and muscular adjustments are necessary to account for these changes when children pedal at a prescribed submaximal power output (Brown and Jensen, 2003; Brown and Jensen, 2006; Korff and Jensen, 2008). These results add to our knowledge by demonstrating that this is not the case during maximal cycling.

Martin and colleagues demonstrated that muscular power is similar over a wide age range when normalized by lean thigh volume (Martin et al., 2000b). Our results expand on these findings by demonstrating that, relative to average pedal power for a full

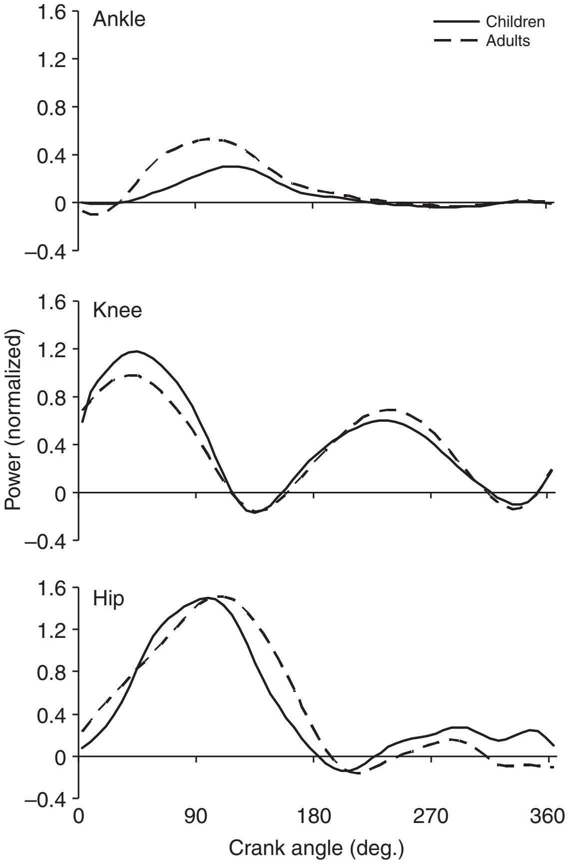

Fig. 3. Normalized joint power profiles for children and adults. The profiles were averaged within each age group. Zero and 360 deg. on the abscissa refer to top dead center of the crank cycle; 180 deg. refers to bottom dead center of the crank cycle.

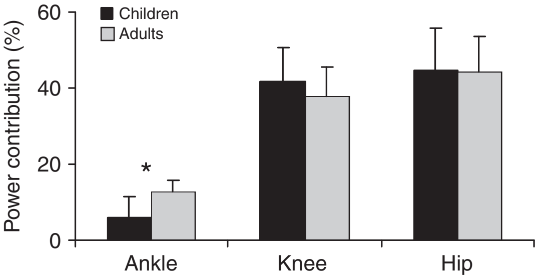

Fig. 4. Age-related differences in the relative mean joint power contributions to total pedal power. The age×joint interaction was statistically significant. The asterix indicates statistical significance for the *post-hoc* pairwise comparison. The effect sizes describing the difference between children and adults were –1.48, 0.49 and 0.02 for the ankle, knee and hip joints, respectively.

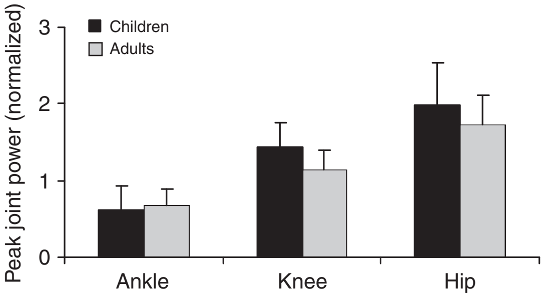

Fig. 5. Age-related differences in the relative peak joint powers. The main effect for age was significant whilst the age×joint interaction was non-significant. The effect sizes describing the difference between children and adults were –0.20, 1.07 and 0.56 for the ankle, knee and hip joints, respectively.

revolution, non-muscular pedal power during maximal isokinetic cycling is independent of the anthropometry of the performer. They thereby suggest that, when cycling at maximum power, children construct the task in a way to appropriately account for their unique anthropometric characteristics. Thus, in a developmental context, maximal cycling can be considered as a self-scaling task that is not confounded by age-related differences in the anthropometry of the performer. As a result, age-related differences in muscular power production during maximal cycling can be truly attributed to features of the neuromotor system.

The second purpose of this study was to test the assumption that, during maximum cycling, children use similar coordination patterns in terms of muscular power production to those used by adults. Contrary to our hypothesis, we found age-related differences in the relative distribution of joint powers and in relative peak joint power production. Interestingly, the relative peak joint powers were greater in children than in adults. Joint powers are related to muscle strength, which increases with increasing age (Blimkie, 1989). Therefore, one might have expected that age-related differences in overall maximum power production could be due to the children's lack of ability to produce power at the individual joints of the lower limbs. This speculation is substantiated by findings from Korff and Jensen, who showed that during submaximal cycling children's relative maximum power at the hip joint was less than that of adults (Korff and Jensen, 2007). Our findings contradict this speculation as during our maximum cycling task children produced greater relative peak joint powers at both the knee and the hip joint. They thereby suggest that factors other than increases in muscle strength contribute to age-related differences in overall maximum power production during multi-joint tasks.

Previous research has shown that during multi-joint tasks not all age-related differences in peak power can be explained by differences in muscle mass (Davies and Young, 1984; Doré et al., 2000; Ferretti et al., 1994). During cycling, the timing and magnitude of muscle activation have to be coordinated appropriately to allow an efficient energy transfer from the muscles through the segments to the pedal (Raasch et al., 1997; Neptune and Kautz, 2001). Van Praagh and Doré speculated that the ability to coordinate synergistic and antagonistic muscle groups in a timely fashion could contribute to age-related differences in maximum power production (Van Praagh and Doré, 2000). This speculation is supported the finding by Korff and Jensen that children demonstrated weaker intermuscular synergies in terms of segmental energy transfer between the synergistic muscle groups of the lower limb during submaximal cycling (Korff and Jensen, 2007).

Here we employed a maximum cycling protocol. We found age-related differences in the distribution of the individual joint power contributions to total pedal power. In children, the relative contribution of ankle power to pedal power was only half that of adults. Children compensated by producing more power mainly at the knee joint (although this difference was statistically non-significant). These results substantiate the speculation that age-related differences in maximum power production are partly due to differences in intermuscular coordination, such as muscle timings or the transfer of segmental energy between synergistic muscle groups (Fregly and Zajac, 1996; Korff and Jensen, 2007). One limitation to this speculation is that in this study we did not take individual muscle contributions into account. A second limitation to this speculation is the cross-sectional design of this study. Longitudinal and intervention studies should be designed to specifically determine the contribution of neural factors to the development of maximum power during childhood.

Our normalized joint power data indicated that relative mean and peak joint power were similar or larger at the hip compared with those at the knee and ankle (Fig. 3). These patterns contrast with patterns typically reported for submaximal cycling in which hip power is less than knee power (e.g. Ericson, 1986). However, these results agree well with data recently published by Martin and Brown (J.C.M. and N. A. Brown, 2009) who reported that hip power was the greatest contributor to maximal cycling power in trained cyclists. These differences are likely to be due to the different demands imposed on the performer during maximum cycling where (in contrast to submaximal cycling) all motor units (and thus all muscle mass) capable of propelling the pedals must be recruited. Our data support the findings of Martin and Brown (J.C.M. and N. A. Brown, 2009) and extend them to include adults and children with less cycling experience. They thereby suggest that during maximum cycling (compared with submaximal cycling) children recruit appropriate additional muscle groups, which add power to the pedal. This finding supports the notion of maximum cycling being a developmental self-scaling task.

A final consideration of this study is the employment of an isokinetic cycling task. When investigating age-related changes in maximal cycling, various methods have been used. These include the isokinetic method and the inertial load method (for a review, see van Praagh and Doré, 2000). In contrast to the inertial method, the cycling cadence is prescribed when employing the isokinetic method. The goal of the present study was to create a task that elicits similar relative non-muscular power contributions between participants with different anthropometric characteristics. As non-muscular forces are influenced by movement speed, we employed an isokinetic protocol to control the cycling cadence. When employing the isokinetic method one has to be mindful of a potential interaction between different populations, maximum power and the cadence at which maximum power is produced (optimal cadence). In a developmental context, the literature is consistent in reporting that age has little or no influence on the optimal cadence during maximum power cycling (Doré et al., 2000; Martin et al., 2000; Sargeant and Dolan, 1986). We therefore believe our methods were appropriate for the question under study and that our methods provide valid results.

In summary, our results further the understanding of the mechanisms underlying the development of maximum power production. They demonstrate that, in a developmental context, maximal cycling is a self-scaling task during which children account appropriately for their unique anthropometrics. Thus, age-related differences in muscular power production during maximum cycling are not confounded by anthropometry-driven changes in non-muscular forces. Our results let us speculate that, during multi-joint tasks, intermuscular coordination contributes to children's performance limits during maximum power cycling.

The authors would like to gratefully acknowledge the students, faculty and staff at Roland Hall-St Mark's School whose enthusiastic participation made this study possible. We also thank Ms Colleen Carroll for her help with this study.

REFERENCES

Asmussen, E. and Heebøll-Nielsen, K. (1955). A dimensional analysis of physical performance and growth in boys. *J. Appl. Physiol.* **7**, 593-603.

Blimkie, C. J. (1989). Age and sex associated variation in strength during childhood: anthropometric, morphologic, neurologic, biomechanical, endocrinological, genetic and physical activity correlates. In *Perspectives in Exercise Science and Sports Medicine* (ed. C. V. Gisolfi and D. R. Lamb), pp. 99-163. Indianapolis: Benchmark Press.

Broker, J. P. and Gregor, R. J. (1994). Mechanical energy management in cycling: source relations and energy expenditure. *Med. Sci. Sports Exerc.* **26**, 64-74.

Brown, N. A. and Jensen, J. L. (2003). The development of contact force construction in the dynamic-contact task of cycling. *J. Biomech.* **36**, 1-8.

Brown, N. A. and Jensen, J. L. (2006). The role of segmental mass and moment of inertia in dynamic-contact task construction. *J. Mot. Behav.* **38**, 313-328.

Davies, C. T. and Young, K. (1984). Effects of external loading on short term power output in children and young male adults. *Eur. J. Appl. Physiol. Occup. Physiol.* **52**, 351-354.

De Leva, P. (1996). Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J. Biomech.* **29**, 1223-1230.

Doré, E., Diallo, O., Franca, N. M., Bedu, M. and Van Praagh, E. (2000). Dimensional changes cannot account for all differences in short-term cycling power during growth. *Int. J. Sports Med.* **21**, 360-365.

Ericson, M. (1986). On the biomechanics of cycling: a study of joint and muscle load during exercise on the bicycle ergometer. *Scand. J. Rehabil. Med. Suppl.* **16**, 1-43.

Ferretti, G., Narici, M. V., Binzoni, T., Gariod, L., Le Bas, J. F., Reutenauer, H. and Cerretelli, P. (1994). Determinants of peak muscle power: effects of age and physical conditioning. *Eur. J. Appl. Physiol. Occup. Physiol.* **68**, 111-115.

Fregly, B. J. and Zajac, F. E. (1996). A state-space analysis of mechanical energy generation, absorption, and transfer during pedaling. *J. Biomech.* **29**, 81-90.

Hull, M. L. and Jorge, M. (1985). A method for biomechanical analysis of bicycle pedalling. *J. Biomech.* **18**, 631-644.

Jensen, R. K. (1981). The effect of a 12-month growth period on the body moments of inertia of children. *Med. Sci. Sports Exerc.* **13**, 238-242.

Jensen, R. K. (1986). Body segment mass, radius and radius of gyration proportions of children. *J. Biomech.* **19**, 359-368.

Jensen, R. K. (1989). Changes in segment inertia proportions between 4 and 20 years. *J. Biomech.* **22**, 529-536.

Kautz, S. A. and Hull, M. L. (1993). A theoretical basis for interpreting the force applied to the pedal in cycling. *J. Biomech.* **26**, 155-165.

Korff, T. and Jensen, J. L. (2007). Age-related differences in adaptation during childhood: the influences of muscular power production and segmental energy flow caused by muscles. *Exp. Brain Res.* **177**, 291-303.

Korff, T. and Jensen, J. L. (2008). Effect of relative changes in anthropometry during childhood on muscular power production in pedaling: a biomechanical simulation. *Pediatr. Exerc. Sci.* **20**, 292-304.

Martin, J. C. and Brown, N. A. (2009). Joint-specific power production and fatigue during maximal cycling. *J. Biomech.* doi:10.1016/j.jbiomech.2008.11.015.

Martin, J. C., Diedrich, D. and Coyle, E. F. (2000a). Time course of learning to produce maximum cycling power. *Int. J. Sports Med.* **21**, 485-487.

Martin, J. C., Farrar, R. P., Wagner, B. M. and Spirduso, W. W. (2000b). *J. Gerontol. A Biol. Sci. Med. Sci.* **55**, M311-M316.

Martin, J. C., Malina, R. M. and Spirduso, W. W. (2002). Effects of crank length on maximal cycling power and optimal pedaling rate of boys aged 8-11 years. *Eur. J. Appl. Physiol.* **86**, 215-217.

Neptune, R. R. and Hull, M. L. (1995). Accuracy assessment of methods for determining hip movement in seated cycling. *J. Biomech.* **28**, 423-437.

Neptune, R. R. and Kautz, S. A. (2001). Muscle activation and deactivation dynamics: the governing properties in fast cyclical human movement performance? *Exerc. Sport Sci. Rev.* **29**, 76-80.

Raasch, C. C., Zajac, F. E., Ma, B. and Levine, W. S. (1997). Muscle coordination of maximum-speed pedaling. *J. Biomech.* **30**, 595-602.

Sargeant, A. J. and Dolan, P. (1986). Optimal velocity of muscle contraction for short-term (anaerobic) power output in children and adults. In *Children and Exercise* (ed. J. Rutenfranz, R. Mocellin and F. Klimt), pp. 39-42. Champaign: Human Kinetics.

Schutz, R. W. and Gessaroli, M. E. (1987). The analysis of repeated measures designs involving multiple dependent variables. *Res. Q. Exerc. Sport* **75**, 132-149.

Van Praagh, E. and Doré, E. (2000). Short-term muscle power during growth and maturation. *Sports Med.* **32**, 701-728.