The Journal of Experimental Biology 212, 3737-3742
Published by The Company of Biologists 2009
doi:10.1242/jeb.033191

Development of lower limb stiffness and its contribution to maximum vertical jumping power during adolescence

Thomas Korff[1,*], Sara L. Horne[1], Sarah J. Cullen[1] and Anthony J. Blazevich[2]

[1]Centre for Sports Medicine and Human Performance, Brunel University, Uxbridge, Middlesex UB8 3PH, UK and [2]School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup Campus, 100 Joondalup Drive, Joondalup, WA, 6027, Australia

*Author for correspondence (thomas.korff@brunel.ac.uk)

Accepted 11 August 2009

SUMMARY

Maximum power production during multi-joint tasks increases as children grow older. Previous research suggests that in adults, maximum power production in jumping is related to lower limb stiffness. In a developmental context, the question arises as to whether the relationship between maximum power production and lower limb stiffness is age-dependent. The purpose of this study was to investigate the relationship between lower limb stiffness and peak power production in adolescents (AD) and pre-adolescents (PA). With institutional approval, two groups of pre-adults (pre-adolescents: 11–13 years of age, N=43; adolescents: 16–18 years of age, N=30) performed 30 two-legged hops at their preferred frequency and three maximum counter-movement jumps. AD produced significantly greater peak power during the counter-movement jump than PA (t_{71}=–5.28, P<0.001) even when body mass was accounted for. Lower limb stiffness was significantly correlated with peak power production during the counter-movement jump in AD (R=0.62, P<0.001) but not in PA (R=0.26, P=0.10). When normalised to body mass, the relationship between lower limb stiffness and peak power also differed between the two age groups (R=0.30, P=0.11 for AD and R=0.02, P=0.88 for PA). In addition, we found that during hopping, both PA and AD behaved like a simple spring-mass system. Our findings highlight the importance of lower limb stiffness in the context of muscular power production during multi-joint tasks. They let us speculate that during adolescence, children acquire the ability to take greater advantage of elastic energy storage in the musculotendinous system when performing maximum counter-movement jumps.

Key words: development, coordination, biomechanics.

INTRODUCTION

Maximum muscular power production during short-term exercise is essential for the successful performance of many motor tasks. As children grow older they improve their ability to generate muscular power as a result of both growth and maturation (Larsson et al., 1979; Martin et al., 2000). As power is a function of force and velocity, and force is well related to muscle mass (Fukunaga et al., 2001; Ikai and Fukunaga, 1968; Knuttgen, 1978), the age-related increase in muscle mass (muscle cross sectional area in particular) is a significant contributor to the age-related increase in force and power production (Kanehisa et al., 1994; Neu et al., 2002).

However, it has been consistently reported that changes in muscle mass do not fully account for changes in muscular power production (De Ste Croix et al., 2001; De Ste Croix et al., 2003). Several authors compared the peak power produced during vertical jumping in pre-adolescent children with that of adults (Davies and Young, 1984; Ferretti et al., 1994). These studies demonstrated that the large observed difference in peak power between age groups could not be solely explained by differences in muscle mass.

Previous research suggests that maximum power production in jumping is related to lower limb stiffness in adults (Arampatzis et al., 2001). Stiffness is an important parameter because we take advantage of the storage and release of elastic energy in the musculotendinous unit to improve muscle power and jump height (Bobbert, 2001). However, evidence from the literature is inconclusive. When performing a counter-movement jump, those with a stiffer musculotendinous system might benefit from a faster elastic recoil during the upward, concentric, phase of the jump (Arampatzis et al., 2001), as well as a more efficient transfer of force to the skeleton (Wilson et al., 2003). However, elastic energy storage is likely to be greater in those with more compliant muscle–tendon units, which seems important for jump success (Bobbert, 2001). Rabita et al. speculated that in skilled humans, the neuromuscular system adopts strategies to find the optimal balance between these conflicting requirements (Rabita et al., 2008).

In a developmental context then, the question arises as to whether the relationship between maximum power production and lower limb stiffness changes as a function of age. It has been reported that the stiffness of the musculotendinous unit increases with age during childhood (Lambertz et al., 2003). Moreover, Wang et al. (Wang et al., 2004) speculated that lower limb stiffness may be a contributor to developmental changes in jumping performance; however, they did not specifically quantify this relationship.

The first aim of the present investigation was to determine to which extent lower limb stiffness would contribute to maximum power production in pre-adults during a lower limb multi-joint task. First, in order to seek support for the notion that age-related differences in peak power production during maximum vertical jumping cannot solely be explained by differences in body mass, we hypothesised age-related differences in peak power production even when body mass is accounted for (aim 1A). Second, we tested the hypothesis that the relationship between lower limb stiffness and the peak power measured during a maximum vertical counter-movement jump would be age-dependent (aim 1B).

During jumping and hopping tasks, the human body can be modelled as a simple spring-mass system (Farley et al., 1991). The relationship between changes in vertical ground reaction force and vertical centre of mass (COM) displacement determines the stiffness of this system. If the relationship is linear then the body is regarded as behaving like a simple spring-mass system. Skilled humans behave like a simple spring-mass system when hopping at their preferred frequency (Farley et al., 1991; Granata et al., 2002). However, it is not intuitive to hypothesise that children would necessarily behave this way when performing hopping tasks because children demonstrate a reduced ability to control complex movements (Jensen et al., 1994). Therefore, the second aim of the present investigation was to test the assumption that pre-adults would behave like a simple spring-mass system during vertical hopping (aim 2).

Lower limb stiffness has been shown to scale relatively linearly with body mass (Farley et al., 1991; Granata et al., 2002). Granata et al. found that gender differences in whole body stiffness, as measured during a repeated hopping task, could largely be explained by differences in body mass (Granata et al., 2002). In a developmental context it is intuitive to hypothesise that, due to their smaller body size, younger children would demonstrate lower levels of body stiffness than their older peers. However, it has not been established whether their stiffness to body mass ratio differs from adults or whether younger children are able to appropriately modify their musculotendinous stiffness during jumping tasks in order to account for their smaller body mass. If the latter were the case, we would expect similar levels of lower limb stiffness between age groups if normalised by body mass. Therefore, the third aim of the present investigation was to test the hypothesis that lower limb stiffness would be similar in pre-adolescents and adolescents, when normalised by body mass (aim 3).

METHODS

Participants

Seventy-three volunteers participated in this study. Participants were divided into two groups: pre-adolescents (‘PA’, 11–13 years of age, N=43) and adolescents (‘AD’ 16–18 years of age, N=30) (Table 1). All procedures complied with the Declaration of Helsinki and were approved by the Institutional Ethics Committee. The procedures were explained in detail to all participants, and they were made aware of their right to withdraw from the study at any time without penalty. All participants provided written informed consent and written assent was given by the parent or guardian.

Procedure

Participants were instructed to perform 30 two-legged hops without shoes on a force platform (Kistler Instruments, Winterthur, Switzerland). They were instructed to hop at their preferred frequency and to complete the hops in place with their hands on their iliac crests. After completion of the hopping task, the participants performed three maximal vertical counter-movement jumps. The instructions for each participant were standardised. They included a detailed verbal explanation, a demonstration by the experimenter and two to three practice trials by the participant. During the verbal instructions, the importance of jumping as high as possible was emphasised. All jumps were initiated from an upright posture with the participants’ hands remaining on their iliac crests. Force data were sampled at 1000 Hz.

Vertical COM velocity was obtained by numerically integrating the vertical acceleration, which was calculated by dividing the vertical ground reaction force by the participant’s body mass. The initial condition for COM velocity was set to zero. Vertical COM displacement was derived by numerically integrating the vertical COM velocity. The initial condition for COM displacement was set to zero. Total vertical jump height was derived as the maximum vertical COM displacement relative to the COM displacement before the initiation of the counter-movement. For further analysis only the highest counter-movement jump was analysed.

Absolute and relative peak power production (aim 1A)

Power during the counter-movement jump was calculated as the product of vertical COM velocity and vertical force. To test the hypothesis that peak power production differs between age groups even when body mass is accounted for, independent t-tests were employed. Relative peak power was expressed as the ratio of peak power and body mass (Schepens et al., 1998) as well as the ratio of peak power and body mass to the exponent of 0.66 (Folland et al., 2008).

Stiffness and peak power production (aim 1B)

Lower limb stiffness was calculated using two separate methods (hopping stiffness and jumping stiffness). We derived hopping stiffness from the force data during the hopping task according to following equation (Farley et al., 1991), where k is the lower limb stiffness, M_b is the participant’s body mass and ω is the resonant frequency:

$$k = M_b \omega^2 .$$

Vertical COM displacement during the counter-movement jump was obtained by double integration of the vertical COM acceleration. Initial conditions for COM velocity and displacement were set to zero. For the ground contact phase of each hop, the Pearson’s correlation coefficient was computed between vertical force and vertical COM displacement. Stiffness values were averaged across 10 hops. These 10 hops were chosen according to two criteria, as described by Granata et al. (Granata et al., 2002): first, the stiffness value had to be within 5% of the mean across the 30 hops and second, the correlation between vertical force and vertical COM displacement had to be greater than 0.8.

Table 1. Descriptive characteristics of participants

	Pre-adolescents (PA)	Adolescents (AD)
N	43	30
Age (yrs)	12.3±0.6	16.8±0.8
Height (m)	1.53±0.09	1.73±0.09
Body mass (kg)	48.3±11.5	65.08±13.5
Maximum vertical jumping power (W)	931±305	1504±611
Total vertical jump height (m)	0.39±0.09	0.45±0.08
Maximum vertical force during counter-movement (BW)	1.28±0.30	1.50±0.35
Resonant frequency (rad s^{-1})	0.64±0.09	0.66±0.07

To derive lower limb stiffness during the counter-movement jump (jumping stiffness), we divided the vertical ground reaction force at the lowest point of the COM during the ground contact phase by the lowest vertical position of the COM (derived from numerical double integration as described above) (Wang et al., 2004).

To eliminate the potentially confounding relationship between body mass and peak power production, both hopping stiffness and jumping stiffness were normalised to body mass (Schepens et al., 1998) and body mass to the exponent of 0.66 (Folland et al., 2008). The Pearson's correlation coefficient was computed between lower limb stiffness (both absolute and normalised) and peak power during the counter-movement jump within each of the age groups.

Spring-mass system (aim 2)

To determine whether pre-adults behaved like a simple spring-mass system during hopping, the Pearson's correlation coefficients were computed between vertical force and vertical COM displacement during the ground contact phase of each hop. For each participant, this correlation coefficient was averaged across the 30 hops. The correlation coefficients were then averaged within each age group. Independent *t*-tests were performed to determine any differences between the two age groups.

Lower limb stiffness adjustment (aim 3)

To determine if pre-adults adjusted their lower limb stiffness appropriately to account for their lower mean body mass, independent *t*-tests were performed on the absolute and relative (normalised by body mass) lower limb stiffness values. Alpha level was set at 0.05 for all statistical tests.

RESULTS

Absolute and relative peak power production (aim 1A)

Absolute peak power was greater in AD (16–18 years old) when compared with PA (11–13 years old) (t_{71}=–5.28, P<0.001, Fig. 1A). More interestingly, even when normalised to body mass (Fig. 1B) or body mass to the power of 0.66 (Fig. 1C), peak power was significantly greater in AD than in PA (t_{71}=–3.33, P=0.001 and t_{71}=–4.43, P<0.001, respectively).

Lower limb stiffness and peak power production (aim 1B)

In AD, hopping stiffness was positively correlated with peak power (R=0.70, P<0.001) whereas it was not correlated for PA (R=0.07, P=0.66). When normalised to body mass, hopping stiffness and peak power were positively correlated (R=0.37, P=0.046) in AD and negatively correlated in PA (R=–0.36, P=0.018) (Fig. 2).

In AD, jumping stiffness and peak power were positively correlated (R=0.62, P<0.001) whereas this relationship was non-significant in PA (R=0.26, P=0.10). The correlation coefficient between normalised jumping stiffness was greater in AD than in PA but the relationship was non-significant in both groups (R=0.30, P=0.11 for AD and R=0.02, P=0.88 for PA) (Fig. 3).

Spring-mass system (aim 2)

Both PA and AD behaved like a simple mass-spring system, as the change in vertical force during hopping was highly correlated with the COM displacement (R=0.95±0.04 for PA and R=0.97±0.01 for AD). In spite of these strong correlations the correlation coefficient was significantly smaller for PA compared with AD (t_{71}=–2.06, P=0.04). Figs 4A,B show representative traces illustrating the

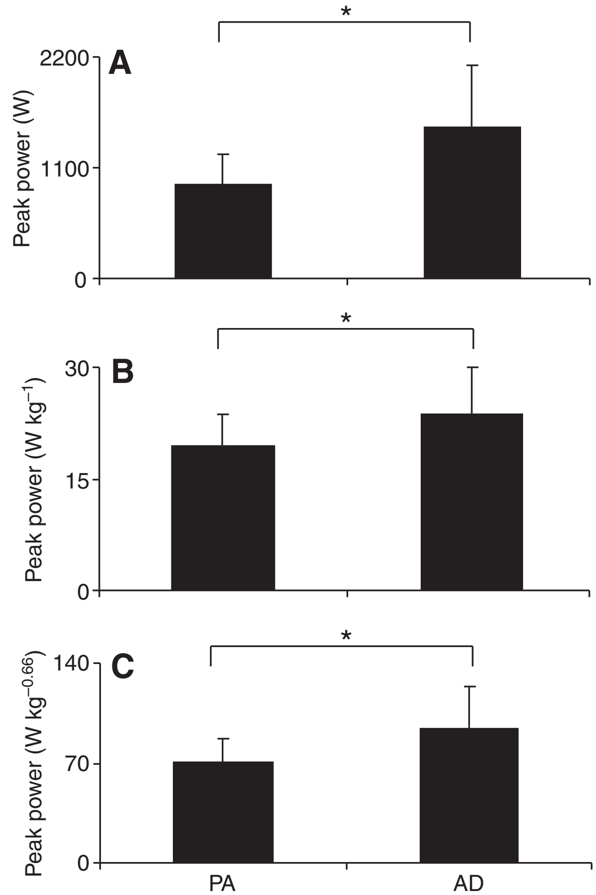

Fig. 1. Age group differences in absolute peak power (A), peak power normalised to body mass (B) and peak power normalised to body mass to the exponent of 0.66. PA: pre-adolescents; AD: adolescents. Absolute and relative peak powers were greater in AD compared with PA. The asterisks indicate statistical significance.

relationship between the vertical COM displacement and the vertical ground reaction force for a pre-adolescent and an adolescent, respectively.

Hopping stiffness adjustment (Aim 3)

Hopping stiffness was greater in AD than PA (t_{71}=–4.72, P<0.001). However, when normalised to body mass, there were no differences in stiffness between the age groups (t_{71}=–0.89, P=0.374) (Fig. 5).

DISCUSSION

The first aim of this study was to determine to which extent lower limb stiffness would contribute to maximum power production in pre-adults during lower limb multi-joint tasks. In conformity with our hypothesis, our results demonstrate that AD produce greater peak power than PA, even when body mass is accounted for. Our results are robust across two different methods of normalising peak power. Thus, they confirm previous findings (Davies and Young, 1984; De Ste Croix et al., 2003; Ferretti et al., 1994; Martin et al., 2000) that age-related differences in peak power production during lower limb multi-joint tasks cannot solely be explained by differences in body size.

This finding raises the question of potential contributors to age-related differences in peak power production other than muscle mass. Accordingly, we asked whether age-related differences in lower limb

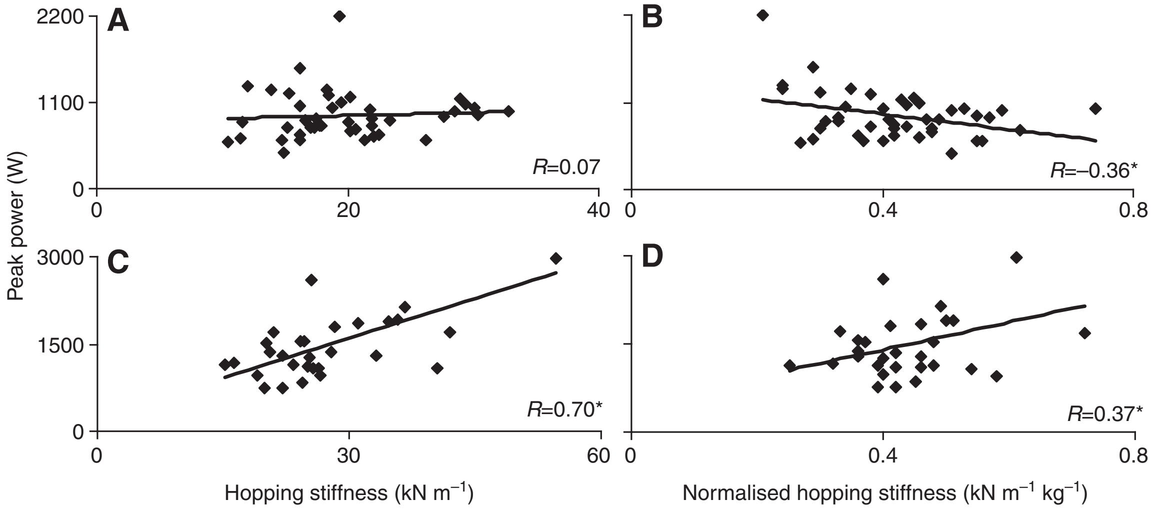

Fig. 2. Relationship between absolute and relative hopping stiffness and peak power during the counter-movement jump for pre-adolescents (PA – graphs A and B) and adolescents (AD – graphs C and D). Relative hopping stiffness was normalised by body mass. The asterisks indicate statistical significance.

stiffness could be a potential contributor to age-related differences in peak power production. In AD we found a positive relationship between lower limb stiffness (hopping and jumping stiffness) and peak power measured during a maximal counter-movement jump.

Thus, those AD who demonstrated greater leg stiffness produced greater peak power. In PA, lower limb stiffness and peak power were unrelated. Because stiffness and body mass are well related (Farley et al., 1991; Granata et al., 2002) the possibility exists that this relationship reflects an influence of body mass on jumping performance. After normalising to body mass, the relationships were changed somewhat. Both normalised hopping and jumping stiffness were positively related to peak power production in AD but this relationship was weaker. These results suggest that leg stiffness (independent of body mass) may enhance power production during vertical jumping in AD. In PA, there was no relationship between normalised jumping stiffness and peak power whilst the relationship between normalised hopping stiffness and peak power was negative. These findings suggest that in PA, the ability to produce mechanical power during vertical jumping is not related to the mechanical stiffness of the system. Together these findings let us speculate that AD are able to take advantage of using elastic energy stored in the muscle–tendon complex to enhance power production during vertical jumping, and that this ability is acquired during the period between 12 and 16 years of age.

We have used a two-legged repeated hopping task to measure lower limb stiffness. This method allows the estimation of the total muscle–tendon stiffness of the lower limb without the need to test each muscle–tendon unit individually. It is based on the assumption that humans choose to operate at or near their natural, most efficient frequency (Ferretti et al., 1994). However, there is a requirement to meet the assumption that the hopping is performed with a pattern consistent with a simple spring-mass system. Adults have been shown to clearly behave like a simple spring-mass system, as vertical COM displacement and vertical ground reaction forces are highly correlated (Farley et al., 1991; Granata et al., 2002). Given that this has not previously been examined in a developmental context, our second aim was to test whether pre-adults would perform the hopping test with a pattern consistent with a simple spring-mass system. Given that we found very high correlations between vertical ground reaction

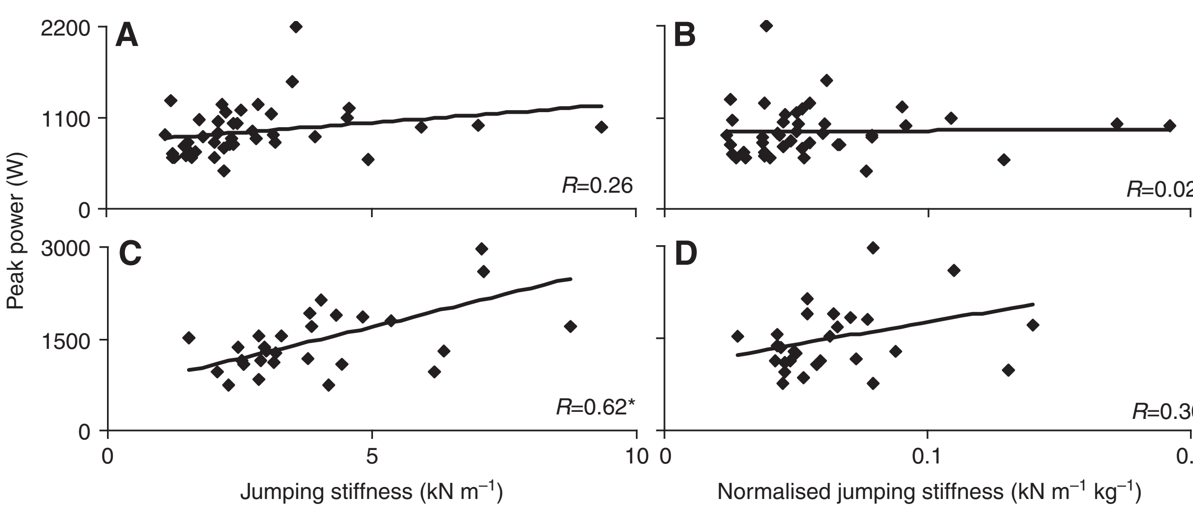

Fig. 3. Relationship between absolute and relative jumping stiffness and peak power during the counter-movement jump for pre-adolescents (PA – graphs A and B) and adolescents (AD – graphs C and D). Relative jumping stiffness was normalised by body mass.The asterisk indicate statistical significance.

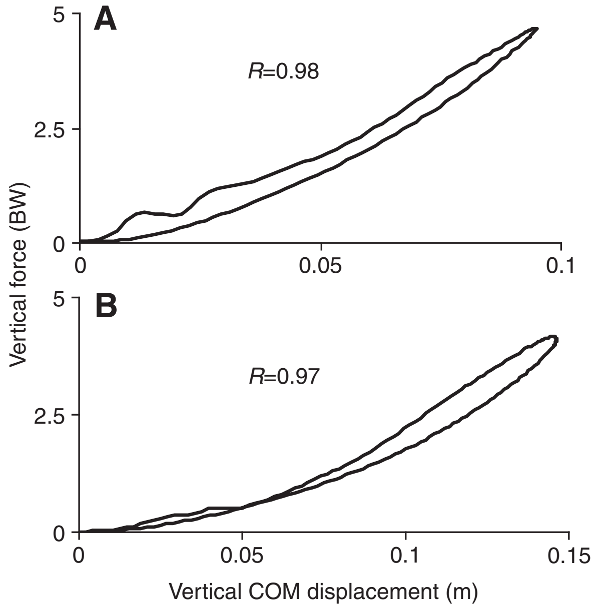

Fig. 4. Representative traces illustrating the relationship between vertical force and vertical centre of mass (COM) displacement in a pre-adolescent (A) and an adolescent (B) during hopping. The vertical ground reaction force was normalised by body weight.

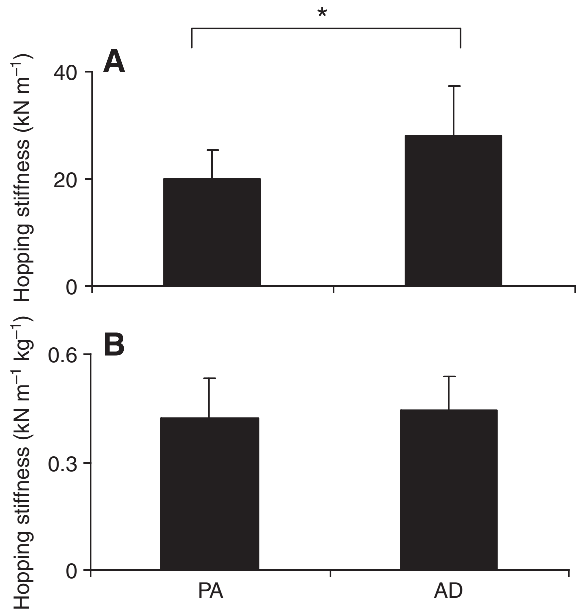

Fig. 5. Age group differences in absolute (A) and normalised (B) hopping stiffness. Hopping stiffness was normalised by body mass. PA: pre-adolescents; AD: adolescents. Absolute lower limb stiffness was greater in AD than in PA. This difference was non-significant for normalised lower leg stiffness. The asterisks indicate statistical significance.

forces and COM displacements in both AD and PA (R>0.95), we conclude that, already at the age of 12 years, PA coordinate their limbs appropriately in order to behave like a simple spring-mass system during hopping. This result is somewhat surprising as children tend to show a lack of control during vertical jumping (Jensen et al., 1994). Nonetheless, our results validate the assumption that a linear relationship exists between vertical ground reaction forces and COM displacement, and thus the appropriateness of the derivation of lower limb stiffness in PA using the methods described by Farley et al. (Farley et al., 1991) and Granata et al. (Granata et al., 2002). They let us speculate that PA utilise the elastic properties of their musculo-skeletal system during hopping (although possibly not during maximum vertical jumping) as appropriately as AD. This speculation is substantiated by the fact that lower limb stiffness measured during hopping was not different between AD and PA when normalised by body mass (aim 3). Thus, our results extend those from Schepens et al. who found that during running, mass-specific stiffness stays relatively constant beyond 12 years of age (Schepens et al., 1998). Our results also extend those by Granata et al. who demonstrated that gender differences in lower limb stiffness during hopping could largely be explained by differences in body mass (Granata et al., 2002).

Our findings are an important step toward fully understanding the determinants of the development of maximum power production during childhood. The literature is consistent in demonstrating that age-related changes in peak power production during maximum lower limb motor tasks cannot be fully explained by differences in body size (Davies and Young, 1984; De Ste Croix et al., 2003; De Ste Croix et al., 2001; Ferretti et al., 1994). It has been speculated that age-related differences in neural drive could partially explain these results (Ferretti et al., 1994). Expanding on this speculation, we propose that changes in the mechanical stiffness of the system could be a contributor to age-related changes in peak power production.

Lower limb stiffness is influenced by the passive elastic structures of the musculo-skeletal system (passive stiffness) (Farley et al., 1991) and the ability to actively stiffen the joints of the lower limb through antagonistic co-activation (Hortobagyi and DeVita, 2000). Accordingly, there could be two explanations for the observed differences. First, a greater compliance in passive elastic structures in the younger participants (Asai and Aoki, 1996; Lambertz et al., 2003) could potentially contribute to the weak relationship between limb stiffness and peak power in PA. Alternatively, a lesser ability to actively stiffen their joints through antagonistic co-activation (Hortobagyi and DeVita, 2000) might have resulted in a lesser ability of intersegmental control (Jensen et al., 1994). The fact that both passive (Bobbert, 2001) and active (Arampatzis et al., 2001) stiffness components affect jumping performance, lets us speculate that PA are limited in their ability to actively stiffen their joints in order to enhance maximum power production. This challenge might be amplified by the greater compliance of the passive elastic structures in these participants (Lambertz et al., 2003). A limitation to this speculation is the fact that our analysis of correlations between lower limb stiffness and peak power during the counter-movement jump does not allow us to make conclusive inferences about the causality between these two variables. Furthermore, in the present study we did not distinguish between the stiffness of the passive elastic structures and active stiffness caused by co-activation of antagonistic muscles. Future research should therefore focus on distinguishing between the effects of passive and active components of muscle–tendon stiffness on muscular power production.

In summary, results from the present investigation demonstrate the importance of the role of the development of the musculo-skeletal system being a partial contributor to age-related changes in muscular force and power production (Brown and Jensen, 2003; Brown and Jensen, 2006; Korff and Jensen, 2008). By highlighting the role of lower limb stiffness they further our understanding about potential contributors to developmental changes in maximum muscular power production during multi-joint lower limb motor tasks.

This research was supported by the Engineering and Physical Sciences Research Council (EPSRC) under grant EP/E013007/1.

REFERENCES

Arampatzis, A., Schade, F., Walsh, M. and Bruggemann, G. P. (2001). Influence of leg stiffness and its effect on myodynamic jumping performance. *J. Electromyogr. Kinesiol.* **11**, 355-364.

Asai, H. and Aoki, J. (1996). Force development of dynamic and static contractions in children and adults. *Int. J. Sports Med.* **17**, 170-174.

Bobbert, M. F. (2001). Dependence of human squat jump performance on the series elastic compliance of the triceps surae: a simulation study. *J. Exp. Biol.* **204**, 533-542.

Brown, N. A. and Jensen, J. L. (2003). The development of contact force construction in the dynamic-contact task of cycling [corrected]. *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 Ste Croix, M. B., Armstrong, N., Chia, M. Y., Welsman, J. R., Parsons, G. and Sharpe, P. (2001). Changes in short-term power output in 10- to 12-year-olds. *J. Sports Sci.* **19**, 141-148.

De Ste Croix, M., Deighan, M. and Armstrong, N. (2003). Assessment and interpretation of isokinetic muscle strength during growth and maturation. *Sports Med.* **33**, 727-743.

Farley, C. T., Blickhan, R., Saito, J. and Taylor, C. R. (1991). Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. *J. Appl. Physiol.* **71**, 2127-2132.

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.

Folland, J. P., Mc Cauley, T. M. and Williams, A. G. (2008). Allometric scaling of strength measurements to body size. *Eur. J. Appl. Physiol.* **102**, 739-745.

Fukunaga, T., Miyatani, M., Tachi, M., Kouzaki, M., Kawakami, Y. and Kanehisa, H. (2001). Muscle volume is a major determinant of joint torque in humans. *Acta Physiol. Scand.* **172**, 249-255.

Granata, K. P., Padua, D. A. and Wilson, S. E. (2002). Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *J. Electromyogr. Kinesiol.* **12**, 127-135.

Hortobagyi, T. and DeVita, P. (2000). Muscle pre- and coactivity during downward stepping are associated with leg stiffness in aging. *J. Electromyogr. Kinesiol.* **10**, 117-126.

Ikai, M. and Fukunaga, T. (1968). Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Int. Z. Angew. Physiol.* **26**, 26-32.

Jensen, J. L., Phillips, S. J. and Clark, J. E. (1994). For young jumpers, differences are in the movement's control, not its coordination. *Res. Q. Exerc. Sport* **65**, 258-268.

Kanehisa, H., Ikegawa, S., Tsunoda, N. and Fukunaga, T. (1994). Strength and cross-sectional area of knee extensor muscles in children. *Eur. J. Appl. Physiol. Occup. Physiol.* **68**, 402-405.

Knuttgen, H. G. (1978). Force, work, power, and exercise. *Med. Sci. Sports.* **10**, 227-228.

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.

Lambertz, D., Mora, I., Grosset, J. F. and Perot, C. (2003). Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *J. Appl. Physiol.* **95**, 64-72.

Larsson, L., Grimby, G. and Karlsson, J. (1979). Muscle strength and speed of movement in relation to age and muscle morphology. *J. Appl. Physiol.* **46**, 451-456.

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

Neu, C. M., Rauch, F., Rittweger, J., Manz, F. and Schoenau, E. (2002). Influence of puberty on muscle development at the forearm. *Am. J. Physiol. Endocrinol. Metab.* **283**, E103-E107.

Rabita, G., Couturier, A. and Lambertz, D. (2008). Influence of training background on the relationships between plantarflexor intrinsic stiffness and overall musculoskeletal stiffness during hopping. *Eur. J. Appl. Physiol.* **103**, 163-171.

Schepens, B., Willems, P. A. and Cavagna, G. A. (1998). The mechanics of running in children. *J. Physiol.* **509 (Pt 3)**, 927-940.

Wang, L. I., Lin, D. C. and Huang, C. (2004). Age effect on jumping techniques and lower limb stiffness during vertical jump. *Res. Sports Med.* **12**, 209-219.

Wilson, A. M., Watson, J. C. and Lichtwark, G. A. (2003). Biomechanics: a catapult action for rapid limb protraction. *Nature* **421**, 35-36.