Rapid Force Production in Children and Adults: Mechanical and Neural Contributions

CHARLIE M. WAUGH[1,2], THOMAS KORFF[1], FLORIAN FATH[1], and ANTHONY J. BLAZEVICH[1,3]

[1]Centre for Sports Medicine and Human Performance, Brunel University, Middlesex, UNITED KINGDOM; [2]Centre for Sports and Exercise Medicine, Queen Mary, University of London, London, UNITED KINGDOM; and [3]Centre for Exercise and Sports Science Research (CESSR) Edith Cowan University, Joondalup, AUSTRALIA

ABSTRACT

WAUGH, C. M., T. KORFF, F. FATH, and A. J. BLAZEVICH. Rapid Force Production in Children and Adults: Mechanical and Neural Contributions. *Med. Sci. Sports Exerc.*, Vol. 45, No. 4, pp. 762–771, 2013. **Purpose**: Children demonstrate lower force production capacities compared with adults, which has often been attributed to "neuromuscular immaturity." However, tendon stiffness, which influences both the electromechanical delay (EMD) and rate of force development (RFD) in adults, is lower in children and may influence rapid force production. The aims of this study were 1) to document EMD and RFD variation as a function of age, 2) to determine the relationships between tendon stiffness and parameters relating to rapid force production in children and adults, and 3) to estimate the relative neural and mechanical contributions to age-related changes in force production by examining the effects of tendon stiffness and muscle activation rate (rate of EMG increase [REI]) on RFD. **Methods**: Achilles tendon stiffness, EMD, RFD, and REI were measured during plantarflexion contractions in 47 prepubertal children (5–12 yr) and 19 adults. Relationships were determined between 1) stiffness and EMD, 2) stiffness and RFD, and 3) REI and RFD. The relative contributions of age, stiffness, and REI on RFD were determined using a multiple regression analysis. Age-related differences in tendon stiffness, EMD, RFD, and REI were also examined according to chronological age (5–6, 7–8, and 9–10 yr) and compared with adults. **Results**: Increases in tendon stiffness with age were correlated with decreases in EMD ($r < -0.83$). Stiffness and REI could account for up to 35% and 30% of RFD variability in children, respectively, which increased to 58% when these variables were combined. **Conclusions**: Both neural and mechanical factors influence rapid force production in prepubertal children. Children's longer EMD and slower RFD indicate a less effective development and transfer of muscular forces, which may have implications for complex movement performance.

Key Words: ELECTROMECHANICAL DELAY, RFD, ULTRASOUND, ACHILLES, CHILDREN

Children often adopt different neuromuscular coordination patterns than adults when performing complex motor tasks (29,49), a feature that is commonly attributed to having an "immature" neuromotor system (29). Although the maturation of the nervous system undoubtedly contributes to age-related improvements in the intermuscular coordination and maturity of movement kinematics (47,48), researchers have recently considered the possibility that changes in nonneuromotor factors such as changing anthropometry (26) and the mechanical properties of the musculoskeletal system (25) may influence movement production during child development.

The mechanical properties of the muscle–tendon complex are important factors influencing muscular force production and movement performance in adults. For example, tendons play an integral role in movement by transferring muscular forces across joints to the bones, the rate and efficiency of which is influenced by their stiffness (8,36). This notion is consistent with the laws of wave propagation, which state that the rate of force transmission through a viscoelastic material is partly governed by the material's stiffness (wave propagation $v = \sqrt{kx/\mu}$, where v is the wave velocity, μ is the mass per unit length of the material, x is the elongation of the material from its resting length, and k is the material's stiffness). Thus, changes in tendon stiffness could have a notable effect on the force production rate. Indeed, tendon stiffness is thought to influence rapid force production by affecting the time lag between muscle activation and muscle force production. In particular, it has been shown that electromechanical delay (EMD) is negatively correlated with tendon stiffness in adults (e.g., [10,36]), whereas the maximum rate of force development (RFD) exhibits a positive correlation with stiffness (e.g., [8,42]). It is also well documented that EMD is longer and RFD is slower in children than in adults (2,15,22). Given the association between tendon stiffness and force production characteristics in adults, and the fact that tendon stiffness is lower in children (38,52), it is reasonable to hypothesize that previously observed differences in the RFD between children and adults are partly

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Address for correspondence: Anthony Blazevich, Ph.D., Centre for Exercise and Sports Science Research, School of Exercise and Health Sciences, Edith Cowan University, 270 Joondalup Drive, Joondalup 6027, Australia; E-mail: a.blazevich@ecu.edu.au.

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dependent on tendon stiffness. Nonetheless, it is not known whether differences in tendon stiffness between children and adults are sufficient for it to be a factor contributing to differences in RFD and EMD.

Force production parameters such as RFD also depend on the rate of muscle activation (1). Neuromuscular capacity is important in the context of force production in children (23,41), and the lower RFD found in children has been linked to a lower rate of muscle activation (15). The ability to rapidly produce muscular force may be a prerequisite for successful movement outcomes, as a delay in transferring rapidly generated forces may negatively affect balance and stability (20,40), movement reaction times (24,42), and complex movement performance (30). Thus, examining age-related differences in force production parameters in relation to the tendon's mechanical properties and muscle's activation capacity may provide an insight into the mechanisms underpinning previously observed age-related differences in intermuscular coordination during complex motor tasks (50). Therefore, the purpose of this study was to partition the neural and mechanical contributions to the developmental changes in force production capacity in prepubescent children. The specific aims of this study were 1) to document age-related changes in tendon stiffness, EMD, and RFD in the plantar flexor muscle–tendon unit, 2) to determine whether these variables are interrelated in typically developing prepubescent children and adults, and 3) to determine the relative contributions of tendon stiffness and rate of muscle activation (as mechanical and neural factors, respectively) on plantar flexor RFD in children and adults. The Achilles tendon was chosen for investigation due to its importance in daily activities such as quiet standing and locomotion.

METHODS

Ethics and participant information. Forty-seven prepubertal children age 5–12 yr (24 boys, 23 girls; age = 8.3 ± 1.6 yr; mean ± SD), 10 men (27.0 ± 1.9 yr), and 9 women (25.3 ± 3.4 yr) participated in the current study. Table 1 provides each group's descriptive characteristics. Peak height velocity, as an indicator of maturational offset, was estimated in children older than 8 yr to confirm their prepubertal status (32). All participants were free from known neuromuscular and musculoskeletal disorders and did not partake in competitive sports. In addition, none of the adults had previously embarked on a structured resistance training program or the performance of specific plantarflexion resistance training. Children provided written assent for participation in the study, and parents/guardians and adult participants provided written consent. The study was granted institutional research ethics approval, and testing conformed to the guidelines set out in the Declaration of Helsinki.

TABLE 1. Participant characteristics for age groups (mean ± SD).

Group	*n*	Age (yr)	Height (m)	Mass (kg)
$CG_{5–6}$	13	6.2 ± 0.6	1.20 ± 0.04	21.3 ± 2.5
$CG_{7–8}$	17	8.4 ± 0.6	1.35 ± 0.05	29.5 ± 6.7
$CG_{9–10}$	15	9.6 ± 0.7	1.39 ± 0.06	32.7 ± 5.6
Men	10	26.8 ± 1.8	1.80 ± 0.06	78.6 ± 11.7
Women	9	24.8 ± 3.2	1.68 ± 0.06	64.3 ± 7.8

$CG_{5–6}$, $CG_{7–8}$, and $CG_{8–10}$ represent children age 5–6, 7–8, and 9–10 yr, respectively.

Familiarization. Standing height, sitting height, and body mass were measured for determining PHV. Participants then performed five to eight submaximal isometric plantarflexion contractions followed by three to five maximal contractions to ensure that 1) the correct technique was used in developing an ankle joint moment (contractions were performed under the instruction to "rotate the foot away from the body using the ball of the foot") and 2) the maximum plantar flexor moment was identified. This protocol also provided a task-specific warm-up and tendon preconditioning exercise (46). All consecutive contractions were separated by a 30-s rest period. A compulsory 5-min rest separated the familiarization and testing protocols to minimize the likelihood of muscular fatigue.

Measurement of tendon stiffness. The present data were captured from a subset of participants whose tendon stiffness data have been published previously (52). Mean ankle joint moment was obtained from two (for children <8 yr) or three (for children >8 yr and adults) maximal voluntary isometric contractions (MVC) performed with a straight knee (180°) and 0° ankle angle (neutral) on a dynamometer (Biodex 3; Medical Systems, Shirley, NY). Antagonist muscle activity was accounted for by quantifying the EMG–moment relationship of the tibialis anterior muscle obtained during a dorsiflexion contraction. The dorsiflexion moment associated with a specific level of EMG present in each plantarflexion contraction was added to the net ankle joint moment recorded (45). Achilles tendon force was obtained by dividing the coactivation-adjusted ankle joint moment by the Achilles tendon moment arm. Achilles moment arm length was estimated using the tendon travel method (16) by measuring the tendon's excursion at its junction with the gastrocnemius medialis (GM) muscle using ultrasonography (Megas GPX, Esaote, Italy; 10-MHz transducer scanning, 45-mm linear scanning interface) as the ankle was passively rotated from 20° dorsiflexion to 20° plantarflexion. Tendon elongation, resulting from muscular loading during each MVC, was captured using ultrasound imaging of the GM muscle–tendon junction. Distal tendon movements resulting from small changes in ankle angle and heel movement during the MVC were corrected for using motion capture (27). Tendon stiffness was calculated as the slope of the Achilles force–tendon elongation relationship between 10% and 90% of the maximum tendon force.

Many of the younger children found it difficult to perform plantarflexion MVC slowly and to produce a unimodal moment–time profile (where no fall in moment was greater than 10% of the maximum moment achieved in that trial). Therefore, to minimize the effect of contraction history on the tendon's force–elongation relationship (44), the children were instructed to produce their MVC with a maximum RFD. Although the children's time to peak moment (2.3 ± 0.7 s) was statistically shorter than that of adults (3.0 ± 0.8 s, $P = 0.003$), we have previously demonstrated that this difference in tendon-loading rate does not significantly affect the calculation of tendon stiffness (52).

Measurement of RFD. In children, the maximum RFD was calculated from the same plantarflexion MVC used for calculating tendon stiffness. Adults performed an additional three MVCs under the instruction to rotate the foot away from the body "as hard and as fast as possible." Participants were reminded not to dorsiflex the foot immediately before plantarflexion and were given a 3-s countdown in addition to verbal encouragement for all contraction efforts. Ankle moment and joint angle data were sampled at 1000 Hz using a 12-bit A/D card (NI PCI-6071E; National Instruments, Austin, TX) and low-pass filtered with a fourth-order, zero-lag Butterworth filter with a 14-Hz cutoff frequency.

The calculation of absolute RFD to different time intervals is of functional importance as the capacity of a muscle to develop forces within a minimal time frame may be an important determinant of successful movement performance, and RFD measured to these intervals provides an insight into the underlying physiological mechanisms that influence rapid force production at different stages of a muscular contraction. RFD was calculated as the change in force (from force onset) per time interval (i.e., Δforce/Δtime) to 50, 200, and 400 ms using a custom written program (Matlab Version 7.14; MathWorks, Cambridge, UK). The mean coefficients of variation (CV) calculated for three individuals across three independent measurements for these time intervals were 9.8%, 6.6%, and 2.1%, respectively. To remove strength as a factor influencing the slope of the force–time curve (1), RFD was also normalized to peak force (RFDnorm) and calculated to 30%, 50%, and 70% of each individual's peak force (subsequently called $\text{RFD}_{30\%}$, $\text{RFD}_{50\%}$, and $\text{RFD}_{70\%}$) to approximate early, mid, and late force development, respectively (mean CV of 11.2%, 8.2%, and 6.4%, respectively). RFD and RFD_{norm} are reported in kilonewtons per second ($\text{kN}\cdot\text{s}^{-1}$) and percentage of MVC per second ($\%\text{MVC}\cdot\text{s}^{-1}$), respectively.

Electromyographic measurement of muscle activity. In adults, the GM muscle belly was prepared for electrode placement by shaving and lightly abrading the skin before cleansing with an antiseptic pad. In children, the skin was rubbed vigorously with an alcohol-based antiseptic pad. Adhesive hydrogel electrodes (Kendall H59P' Covidien plc., Dublin, Ireland) were placed approximately in parallel with the orientation of the underlying fascicles using a bipolar arrangement at an interelectrode distance of 20 mm. A reference electrode was positioned on the tibial plateau to account for background electrical noise. Wireless EMG signals were received remotely (1000 Hz; Telemyo 2400R; NorAxon Inc., Scottsdale, Arizona) and synchronized with the dynamometry data using the same 12-bit A/D card. GM EMG data were digitally filtered using a 10- to 500-Hz band-pass filter (Spike2 Version 5.12a software, Cambridge Electronic Design, UK).

Measurement of EMD. EMD was measured in GM because it was assumed to be influenced by Achilles tendon stiffness to a greater extent (as opposed to the soleus) due to a substantially greater length through which forces are transferred and contributes significantly to plantar flexor force production at a fully extended knee angle (11). In addition, tendon slack is reported to be fully absorbed when the ankle is at 10° of plantarflexion (with a fully extended knee); thus, the use of a neutral ankle angle here would have minimized the influence of tendon slack on EMD (36). For the determination of EMD, GM EMG data were corrected for digital conversion offsets and full-wave rectified. The mean ± SD joint moment and GM EMG baseline activity were calculated at rest during a 200-ms window. The threshold for signal onset was set at ±3 SD from the baseline mean, for a minimum of 10 ms (12). Trials displaying a moment decrease greater than 0.5 N·m from baseline were discarded, as the moment onset could not be identified confidently. GM EMD was calculated as the mean time lag between the onset of EMG activity and onset of joint moment for the MVC trials. The mean CV for EMD was 7.3%.

Calculation of the rate of increase of EMG amplitude. For the determination of rate of EMG increase (REI), the root mean square of the band-pass filtered GM EMG data was calculated for a 50-ms time window (6). REI was calculated from GM EMG onset to 25, 75, and 150 ms (mean CV of 12.1%, 8.7%, and 6.1%, respectively). Normalized REI (REI_{norm}) was calculated to 30%, 50%, and 70% of peak EMG amplitude (subsequently called $\text{REI}_{30\%}$, $\text{REI}_{50\%}$, and $\text{REI}_{70\%}$) to represent early, mid, and late EMG increase, respectively (mean CV of 10.0%, 8.3%, and 6.7%, respectively). To enable comparison between individuals, all REI variables are reported as percentage of peak EMG per second.

Statistical analysis. All data were analyzed using the Statistical Package for the Social Sciences (Version 16.0; SPSS Inc., Chicago, IL). Children were grouped according to age (5–6, 7–8, and 9–10 yr, subsequently called $\text{CG}_{5\text{–}6}$, $\text{CG}_{7\text{–}8}$, and $\text{CG}_{9\text{–}10}$, respectively). This age grouping resulted in the exclusion of two children (>10 yr) from the age group-related analyses. A two-way MANOVA was used to test all dependent variables (DV; stiffness, EMD, RFD and REI) for a main effect for age group and age group-by-sex interactions. For this analysis only, RFD and REI data measured by time interval were log-transformed to satisfy the assumptions of homogeneity of variance. In case of significance, a one-way ANOVA was performed for each DV, followed by Gabriel *post hoc* tests to identify significant differences between age groups. Statistical significance was accepted at $P < 0.05$.

To determine the relationships between 1) tendon stiffness and EMD, 2) tendon stiffness and RFD, and 3) REI and RFD, polynomial functions were fitted to the data for children, adults, and all ages combined (i.e., children plus adults). The order of the polynomial chosen to represent each relationship was determined according to the following criteria: the coefficient of determination (R^2) was initially quantified using a first-order polynomial, the order of which was increased until the coefficient of determination did not improve by more than 2%.

Finally, separate stepwise multiple regression analyses were performed to determine the contributions of age, tendon stiffness, and $\mathrm{REI}_{\mathrm{norm}}$ to $\mathrm{RFD}_{\mathrm{norm}}$ for children, adults, and all ages combined. For inclusion of an independent variable into the model, the level of significance was set to $P < 0.05$. Age was also included in the regression as a separate independent variable to assess its suitability as a predictor of RFD.

RESULTS

The MANOVA revealed a main effect of age ($F_{3,62}$ = 6.338, $P < 0.05$) but not sex ($F_{3,62}$ = 1.009, $P > 0.05$). Furthermore, no age group-by-sex interactions were found ($F_{3,62}$ = 0.847, $P > 0.05$); therefore, sex-related data for subsequent analyses were pooled. Follow-up ANOVAs were significant for all DV except REI to 25 ms. Specific ANOVA and *post hoc* test results are presented in the section relevant to each DV.

Achilles tendon stiffness. The main effect of age on tendon stiffness was significant ($F_{3,62}$ = 46.24, $P < 0.05$). Achilles tendon stiffness was significantly lower in $\mathrm{CG}_{5–6}$ (85.7 ± 29.8 $\mathrm{N{\cdot}mm^{-1}}$) than for all other age groups. Furthermore, stiffness was significantly greater ($P < 0.05$) in adults (259.3 ± 41.9 $\mathrm{N{\cdot}mm^{-1}}$) than in $\mathrm{CG}_{7–8}$ (146.1 ± 42.1 $\mathrm{N{\cdot}mm^{-1}}$) and $\mathrm{CG}_{9–10}$ (165.4 ± 39.9 $\mathrm{N{\cdot}mm^{-1}}$).

Electromechanical delay. The main effect of age on EMD was significant ($F_{3,62}$ = 22.37, $P < 0.05$). EMD in $\mathrm{CG}_{5–6}$ (96.0 ± 14.0 ms) was significantly longer ($P < 0.05$) than in $\mathrm{CG}_{7–8}$ (77.4 ± 17.7 ms), $\mathrm{CG}_{9–10}$ (74.5 ± 13.7 ms), and adults (50.4 ± 12.2 ms). No difference in EMD was observed between $\mathrm{CG}_{7–8}$ and $\mathrm{CG}_{9–10}$, but both groups had a significantly longer EMD than adults ($P < 0.05$). Between $\mathrm{CG}_{5–6}$ and adulthood, EMD decreased by ~48% (mean group data).

The relationship between EMD and tendon stiffness was best approximated by a first-order (linear) polynomial function for all groups. EMD was strongly and negatively correlated with tendon stiffness in children, adults, and for all ages combined ($r = -0.66$, -0.61, and -0.83, respectively, $P < 0.05$; see Fig. 1). Thus, EMD was found to decrease as tendon stiffness increased from childhood through to adulthood.

Rate of force development. There was a significant main effect of age on RFD ($F_{3,62}$ = 26.48–92.21, $P < 0.05$). RFD (50, 200, and 400 ms) and $\mathrm{RFD}_{\mathrm{norm}}$ ($\mathrm{RFD}_{30\%}$, $\mathrm{RFD}_{50\%}$, and $\mathrm{RFD}_{70\%}$) were significantly lower in all children than those in adults ($P < 0.05$). $\mathrm{CG}_{9–10}$ also had a significantly greater RFD to 50, 200, and 400 ms than $\mathrm{CG}_{5–6}$. No other differences in RFD or $\mathrm{RFD}_{\mathrm{norm}}$ were observed between age groups (Figs. 2A and 2B). RFD and $\mathrm{RFD}_{\mathrm{norm}}$ were found to increase from $\mathrm{CG}_{5–6}$ to adulthood by an average of 76% and 9%, respectively, across all age intervals.

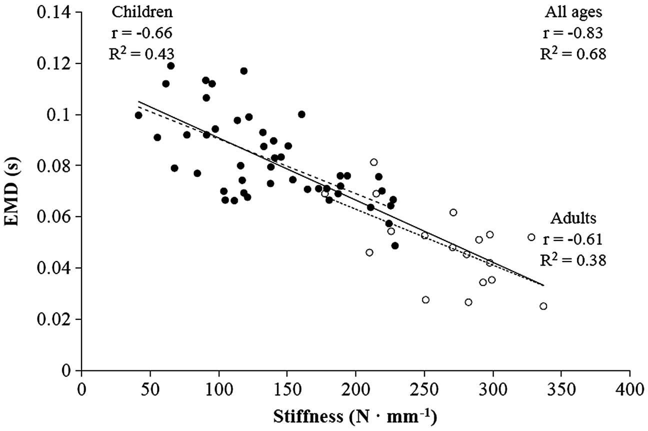

FIGURE 1—Relationship between EMD and Achilles tendon stiffness. *Filled* and *open circles* represent child and adult participants, respectively. Regression lines for children (*solid line*), adults (*dotted line*), and all ages combined (*dashed line*) are shown.

The relationship between RFD and Achilles tendon stiffness for children and adults was best described by a first-order polynomial, whereas a second-order polynomial best approximated this relationship when all ages were combined. A first-order polynomial best approximated the relationship between $\mathrm{RFD}_{\mathrm{norm}}$ and tendon stiffness for all groups. RFD was positively correlated with tendon stiffness in children, adults, and all ages combined (Fig. 3). The highest coefficients of determination (R^2) quantifying the strength of the relationship between tendon stiffness and RFD and tendon stiffness and $\mathrm{RFD}_{\mathrm{norm}}$ for children, adults, and all ages combined were 0.35, 0.22, and 0.69, and 0.21, 0.26, and 0.58, respectively. Most relationships were significant ($P < 0.05$).

Rate of EMG increase. There was a significant main effect of age on all measures of REI ($F_{3,62}$ = 6.14–38.89, $P < 0.05$) except REI to 25 ms ($F_{3,62}$ = 1.74, $P > 0.05$). REI was significantly greater in adults compared with $\mathrm{CG}_{5–6}$ and $\mathrm{CG}_{7–8}$ when calculated to 75 ms after EMG onset ($P < 0.05$) and all child age groups when calculated to 150 ms. REI at 75 and 150 ms was greater in $\mathrm{CG}_{9–10}$ than in $\mathrm{CG}_{5–6}$ and $\mathrm{CG}_{7–8}$ ($P < 0.05$). $\mathrm{REI}_{30\%}$, $\mathrm{REI}_{50\%}$, and $\mathrm{REI}_{70\%}$ were significantly greater in adults than those in all child age groups ($P < 0.05$). No other differences in REI or $\mathrm{REI}_{\mathrm{norm}}$ were found between age groups (Figs. 2C and 2D). REI and $\mathrm{REI}_{\mathrm{norm}}$ increased from $\mathrm{CG}_{5–6}$ to adulthood by an average of 10% and 15%, respectively.

According to the criteria that were defined, the relationships between REI and RFD were best approximated by a linear regression line. Most relationships were significant ($P < 0.05$); all but one nonsignificant relationship were found in adults (Table 2). The highest coefficients of determination quantifying the strength of the relationship between REI and RFD for children, adults, and all ages combined were 0.21, 0.25, and 0.53, respectively, whereas those for $\mathrm{REI}_{\mathrm{norm}}$ and $\mathrm{RFD}_{\mathrm{norm}}$ were 0.30, 0.26, and 0.59.

Predictability of RFD from tendon stiffness, age, and REI. The stepwise multiple regression revealed that both tendon stiffness and $\mathrm{REI}_{\mathrm{norm}}$ were significant predictors of $\mathrm{RFD}_{\mathrm{norm}}$. Together, these variables accounted for 31%–58% of RFD variance in children and 44%–45% of

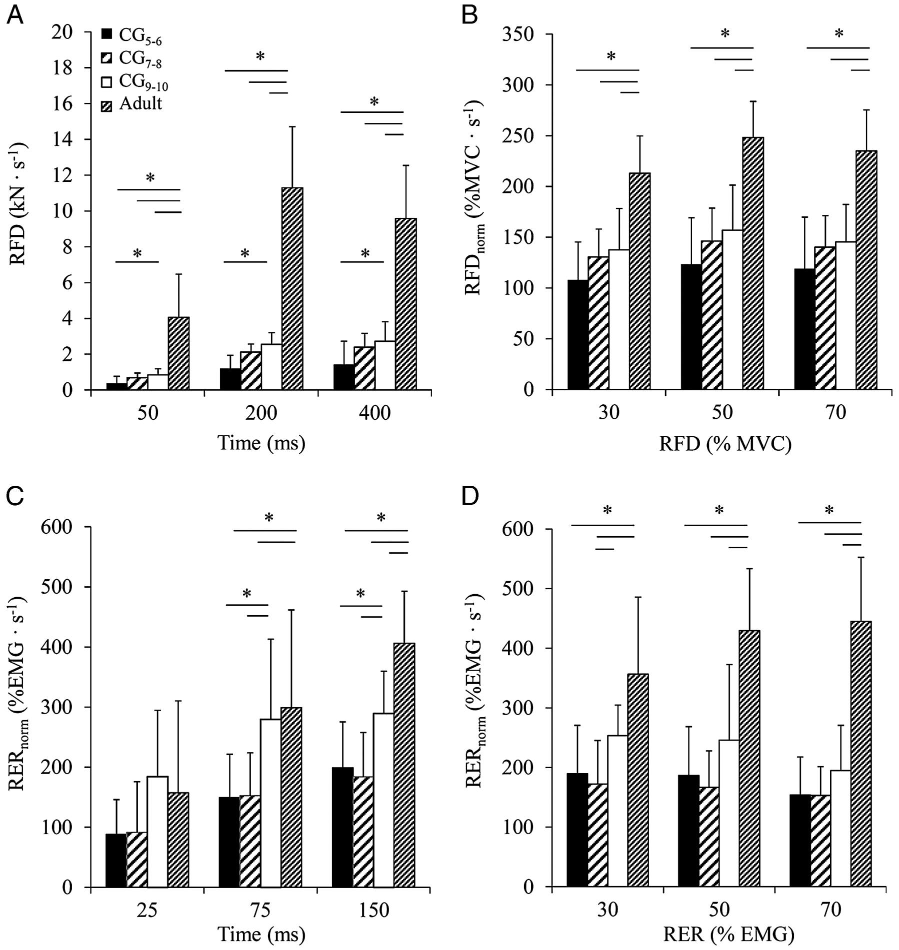

FIGURE 2—Differences in the RFD from onset of force to 50, 200, and 400 ms (A); normalized RFD (RFD_{norm}) to 30%, 50%, and 70% of peak force (B); REI from onset of EMG activity to 25, 75, and 150 ms (C) and to 30%, 50%, and 70% of peak EMG amplitude between different age groups and adults (D). Results shown are for group means. Vertical bars represent SD. Asterisks indicate statistical significance between two groups ($P < 0.05$).

RFD variance in adults. This proportion increased to between 66% and 74% when both children and adults were combined. No significant predictors of $\text{RFD}_{70\%}$ were found for adults. Age accounted for a significant proportion of $\text{RFD}_{30\%}$ variability in children and for RFD to 30%, 50%, and 70% in all ages combined. Predictive regression equations for all populations are presented in Table 3.

DISCUSSION

The main findings of the present study were as follows: 1) EMD, RFD, and REI in the plantar flexor muscle group changed substantially between 5 yr of age and adulthood; 2) EMD was negatively correlated with Achilles tendon stiffness whereas RFD was positively correlated with Achilles tendon stiffness in children; and 3) Achilles tendon stiffness and muscle activation rate of the GM have a cumulative effect on the prediction of plantarflexion RFD in children. These results extend previous findings in adults by demonstrating that rapid force production, which is influenced by both EMD and RFD, depends on both increased rates of muscle recruitment and changes in tendon mechanical properties in children. In addition, these findings significantly add to our understanding of the mechanisms underpinning age-related improvements in muscular force production and have implications for the interpretation of age-related differences in the performance of complex motor tasks.

Age-related changes in factors relating to rapid force production. EMD is influenced by several factors, including mechanisms associated with the excitation–contraction coupling process (37). However, the time taken to stretch the tendon during a muscle contraction, which is a function of its stiffness, is thought to account for most EMD (10,36). In the present study, GM EMD values were comparable with those published previously for voluntary contractions in adult men and prepubertal boys (48 vs 76 ms, respectively [15]). Assuming that voluntary muscle contraction results in EMD values approximately four times longer than those produced with electrical stimulation (36), our results are also consistent with those reported by Grosset et al. (22) in children (17–11 ms). EMD was found to decrease with age, in agreement with that previously shown for the elbow flexor (2) and triceps surae muscle groups (22). Tendon stiffness was also found to increase with age, a finding

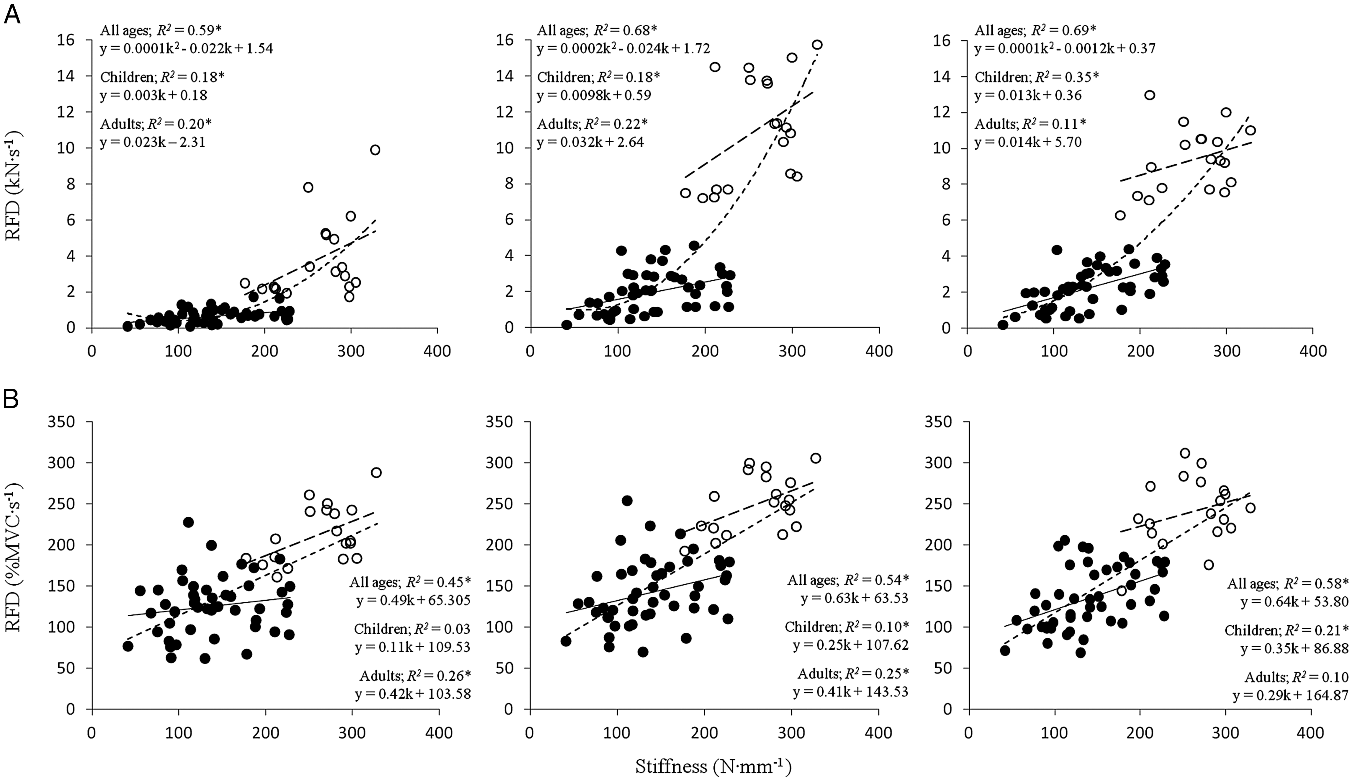

FIGURE 3—Relationship between Achilles tendon stiffness and RFD to 50, 200, and 400 ms (A) and 30%, 50%, and 70% of peak force (L-R) (B). Filled and open circles represent children and adults, respectively. Regression lines for children (solid line), adults (dotted line), and all ages combined (dashed line) are shown.

which has been previously attributed to both the tendon growth and maturation associated with age-related increases in body mass and muscle peak force (52). It was not surprising, therefore, to find that EMD was strongly and negatively correlated with age-related increases in tendon stiffness in children. These relationships suggest that the changes in tendon stiffness with childhood development are sufficient to have a noticeable effect on EMD. Our findings also support those of Muraoka et al. (36), who found a significant relationship between tendon slack length and EMD. Combined, these data allow for the speculation that previously documented age-related changes in EMD are at least partially due to changes in tendon stiffness, and that changes in tendon stiffness are an important factor influencing the decrease in EMD during childhood development.

In addition to EMD, RFD is also an important variable influencing rapid force production. In the present study, RFD was found to be significantly slower in children than in adults for all time intervals, which is in agreement with previous findings (2,15,22). However, the lack of difference in RFD found between children of different age groups (aside from RFD to 400 ms between CG_{5-6} and CG_{9-10}) contrasts with the results of Grosset et al. (22), who found that plantar flexor RFD increased significantly per year of age between 7 and 11 yr. Methodological differences between the studies could account for these discrepant findings. First, Grosset et al. (22) calculated RFD from force rises elicited by supramaximal electrical stimulation, which has been shown to recruit muscle differently to voluntary contractions in adults (for a review, see [21]). Second, these authors calculated

TABLE 2. Coefficients of determination describing the relationship between RFD and REI for children, adults, and all ages combined.

	Children			Adults			All Ages		
	RFD_{T50}	RFD_{T200}	RFD_{T400}	RFD_{T50}	RFD_{T200}	RFD_{T400}	RFD_{T50}	RFD_{T200}	RFD_{T400}
REI_{T25}	0.13*	0.15*	0.07*	0.10*	0.20*	0.10*	0.15*	0.20*	0.32*
REI_{T75}	0.16*	0.21*	0.09*	0.07*	0.25*	0.08*	0.22*	0.35*	0.53*
REI_{T150}	0.14*	0.20*	0.12*	0.10*	0.07*	0.00*	0.32*	0.26*	0.45*
	$RFD_{30\%}$	$RFD_{50\%}$	$RFD_{70\%}$	$RFD_{30\%}$	$RFD_{50\%}$	$RFD_{70\%}$	$RFD_{30\%}$	$RFD_{50\%}$	$RFD_{70\%}$
$REI_{30\%}$	0.23*	0.29*	0.09*	0.19*	0.21*	0.03*	0.43*	0.44*	0.40*
$REI_{50\%}$	0.29*	0.30*	0.12*	0.26*	0.21*	0.05*	0.57*	0.59*	0.53*
$REI_{70\%}$	0.11*	0.23*	0.14*	0.20*	0.08*	0.03*	0.45*	0.50*	0.51*

RFD_{T50}, RFD_{T200}, and RFD_{T400} is RFD calculated to 50, 200, and 400 ms, respectively; $RFD_{30\%}$, $RFD_{50\%}$, and $RFD_{70\%}$ is RFD calculated to 30%, 50%, and 70% of peak force, respectively; REI_{T25}, REI_{T75}, and REI_{T150} is REI calculated to 25, 50, and 150 ms, respectively; $REI_{30\%}$, $REI_{50\%}$, and $REI_{70\%}$ is REI calculated to 30%, 50%, and 70% of peak EMG amplitude, respectively.
* $P < 0.05$.

TABLE 3. Regression equations for predicting RFD to 30%, 50%, and 70% MVC from tendon stiffness and REI in children, adults, and all ages combined.

Group	Variable	$REI_{30\%}$, *a*	$REI_{50\%}$, *b*	$REI_{70\%}$, *c*	*k*, *e*	Age	Constant *Z*	Adjusted R^2
Children	$RFD_{30\%}$	—	−0.27	0.14	—	7.94	73.16	0.31
	$RFD_{50\%}$	—	0.39	−0.30	0.32	—	71.72	0.41
	$RFD_{70\%}$	−0.20	0.52	0.24	0.43	—	57.90	0.58
Adults	$RFD_{30\%}$	—	−0.50	—	0.48	—	146.65	0.45
	$RFD_{50\%}$	−0.61	—	—	0.45	—	186.45	0.44
	$RFD_{70\%}$	—	—	—	—	—	—	—
All Ages	$RFD_{30\%}$	—	−0.31	0.15	0.21	2.64	98.19	0.66
	$RFD_{50\%}$	—	−0.33	0.16	0.29	3.15	100.27	0.74
	$RFD_{70\%}$	—	−0.21	0.09	0.30	3.19	85.478	0.72

Equation constants in the form of $Y = a(REI_{30\%}) + b(REI_{50\%}) + c(REI_{70\%}) + d(k) + e(\text{age}) + Z$. *k*, stiffness.

maximal RFD from two points identified manually on the linear portion of the ascending force curve, as a consequence, calculating RFD over different intervals for each individual. These differences in methodology are likely to have a substantial effect on the outcome of RFD measures, and thus the studies are not directly comparable. Once normalized to peak force, RFD_{norm} was still found to be significantly greater in adults than in children, although differences between age groups were reduced. This finding demonstrates that only part of the difference found between RFD for children and adults was associated with the adults' greater peak force generating capacity.

Normalizing RFD to peak force provides information as to the muscle's physiological properties as well as the mechanical properties of the tendon (1). One factor that influences RFD is the muscle's maximal shortening velocity. Contractile velocity is significantly slower in children than that in adults (2,4), so the time taken to reach their peak force will also be longer for children. Muscle fascicle length is an important determinant of maximum shortening velocity because it is thought to be representative of the number of in-series sarcomeres (5). As children are likely to have fewer in-series sarcomeres than adults (due to their shorter GM muscle fibers [34]), it could be theorized that whole-muscle shortening velocity will be slower, which in turn would limit maximal RFD. However, there is evidence that longer fascicle or muscle lengths may actually slow RFD due to an association with increased compliance (14), thus highlighting the need for further research to quantify this relationship. Moreover, ATPase activity, also a major determinant of contractile speed (3), has been shown to be lower in infant than adult rats (13) and might be expected to affect contractile speed in humans (43). Although somewhat speculative, these factors potentially contribute to the slower RFD_{norm} observed in children and consequently the greater the time required to stretch the tendon and transfer forces to the bone.

The rate at which the muscle can be activated has also been shown to influence RFD (1). The REI calculated to 75 and 150 ms in the present study was greater in adults than in children (except REI to 75 ms in $CG_{9–10}$) and greater in older ($CG_{9–10}$) than in younger ($CG_{5–6}$ and $CG_{7–8}$) children. It is assumed that the temporal increase in EMG amplitude reflects both an increase in motor unit firing frequency and recruitment of larger, high threshold motor units, the capacity of which has been postulated to be lesser in children than in adults (4,7). As the depolarizing potentials are greater in amplitude for larger motor units (31), individuals who are able to recruit these motor units earlier during fast force production should display a steeper EMG–time relation (i.e., greater REI). The greater muscle activation rates exhibited by older compared with younger children here suggests that aspects of neural maturation may occur between 7 and 10 yr and continue through to adulthood. Support for this latter speculation comes from the literature. Through the use of transcranial magnetic stimulation, previous studies have demonstrated that the latency of motor-evoked potentials decreases with age, plateauing at approximately 10 yr of age (9,35). As much of the peripheral nervous system appears to mature around the age of 3 yr (18), these findings suggest that aspects of the central nervous system mature at this age. Age-related increases in motor unit synchronization also plateau at a similar age (19) and may also contribute to improvements in the coordination of force development. Such changes may be of functional importance. For example, the requirement for fast force production, initiated by rapid muscle activation, may be warranted for appropriate control of the rapidly increasing segmental masses that are observed during pubertal growth (28).

REI, normalized to the peak EMG amplitude (REI_{norm}), was also greater in adults than children, indicating that the ability to reach one's own peak activation limit is faster in adults. This finding is consistent with that shown previously for the elbow flexors (15). There is a growing body of literature postulating that large motor units may be more rapidly recruited when faced with a task requiring rapid force production, under certain circumstances (17). For children who are unable to fully activate their fast muscle fibers, rapid muscle activation would be impaired. In addition, children may have slower motor neuron conduction velocities, longer residual latencies (delay in transmission at the neuromuscular junction), and a lower frequency of neuron firing than adults (39,51). These mechanisms may also help explain our observed the differences in REI_{norm} between children and adults.

Factors influencing RFD. Tendon stiffness has been positively correlated with RFD in adults. For example, Bojsen-Moller et al. (8) found a greater knee extensor RFD in individuals with stiffer vastus lateralis tendons. The significant relationship found presently between Achilles tendon stiffness and plantar flexor RFD_{norm} for adults ($R^2 = 0.29$)

is consistent with these findings and adds to the data suggesting that a greater stiffness of elastic structures enhances the rate of force transmission (53). The significant relationship between tendon stiffness and RFD_{norm} in children found presently ($R^2 = 0.21$) extends this concept to the prepubescent population. It is also clear that increases in tendon stiffness of the magnitude found between children and adults are sufficient to affect RFD. These findings significantly improve our understanding of the effects of tendon stiffness on muscular force production and have important consequences for movement performance in children (30).

Falk et al. (15) found that RFD_{norm} was moderately correlated with REI_{norm} ($r = 0.40$) for the elbow flexors in prepubertal boys. In the present study, REI_{norm} was positively correlated with RFD_{norm} in children (best R^2 of 0.33 for $\text{REI}_{50\%}$ and $\text{RFD}_{50\%}$), suggesting that neural drive substantially influences the RFD, especially in the early ($\text{RFD}_{30\%}$) to mid ($\text{RFD}_{50\%}$) stages of a muscle contraction. The relationship between REI_{norm} and RFD_{norm} in adults was not as strong (best R^2 of 0.22 found for $\text{REI}_{30\%}$ and $\text{RFD}_{50\%}$), indicating that the adults' abilities to produce explosive force were not as heavily reliant on the ability to rapidly increase neural drive. Nonetheless, our findings suggest that the ability to recruit motor units for fast force production is influenced by the maturational status of the neuromuscular system.

Relative influences of tendon stiffness and neural drive on RFD. One specific aim of the present study was to gain a clearer understanding of the mechanisms underpinning age-related differences in RFD. According to the results of the regression analysis, both muscle activation rate and tendon stiffness play an important and cumulative role in predicting RFD in children and adults. The additive effects of tendon stiffness and REI_{norm} significantly improved the predictability of RFD_{norm} from a maximum of 28% to 61% for $\text{RFD}_{70\%}$ in children and from 29% to 45% in adults. Despite their combined influence however, a significant proportion of the variance in RFD_{norm} remained unaccounted for, suggesting that factors not examined in the present study must play a central role in rapid force production. For example, Edman and Josephson (14) found that 60% of the force rise time in frog muscle fibers was attributable to the processes underlying muscle activation (e.g., calcium kinetics, cross-bridge cycling rate), whereas the remaining 40% represented the time taken to stretch the series elastic structures for force transfer. It is likely therefore that other physiological processes affect rapid force production and that the significance of these processes differs between children and adults.

Despite the results of the regression analysis highlighting a contribution of both tendon stiffness and rate of muscle activation, each variable was best correlated with RFD at markedly different stages of the force development process in children and adults. For example, tendon stiffness appeared to have a greater effect on the later rise in force in children but the early rise of force in adults. This suggests that there are age-related differences in the dominant mechanisms that influence early, mid, and late RFD. It is possible that the low stiffness associated with the uncrimping of collagen fibrils during the early stages of force production (i.e., toe region of the force–elongation relationship [44]), in addition to an overall greater compliance (52), causes slow and inefficient transfer of muscular forces in children, and thus they may be more dependent on fast muscle activation. Practically, this indicates that improvements in RFD in children may require specific training modalities. For example, rates of muscle activation appear to be greater for children involved in sports where muscle forces must be developed rapidly, such as gymnastics (33), indicating that basic strength or plyometric training may be beneficial for improving muscle activation in this population.

Conclusion. To our knowledge, this is the first study to identify significant relationships between tendon-specific stiffness and parameters relating to rapid force production (EMD and RFD) in prepubertal children. EMD (negatively) and RFD (positively) were well related to tendon stiffness in both children and adults and REI was also positively related to RFD in both groups. Interestingly, muscle activation rate appeared more important than tendon stiffness in the early stages of development of force in children, whereas the opposite was true for adults. Nonetheless, the combined influences of REI and tendon stiffness were able to account for a significant proportion of RFD variability in both children (<61%) and adults (<45%), highlighting the role of both neural and mechanical factors in rapid force production in these populations. On the basis of the relationships found in the present study, it can be concluded that the significant differences in tendon stiffness and muscle activation rates found between children and adults partly explain differences in rapid force production characteristics. The relative effects of these differences on complex movement require further study.

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