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Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity

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Lambertz, Daniel, Isabelle Mora, Jean-Francois Grosset, and Chantal Pérot. Evaluation of musculotendinous stiffness in prepubertal children and adults, taking into account muscle activity. *J Appl Physiol* 95: 64–72, 2003. First published March 14, 2003; 10.1152/japplphysiol.00885.2002.—Musculotendinous (MT) stiffness of the triceps surae (TS) muscle group was quantified in 28 prepubertal children (7–10 yr) by using quick-release movements at different levels of submaximal contractions. Surface electromyograms (EMG) of each part of the TS and of the tibialis anterior were also recorded. A stiffness index, defined as the slope of the angular stiffness-torque relationship ($SI_{MT\text{-}Torque}$), was used to quantify changes in MT stiffness with age. Results showed a significant decrease in $SI_{MT\text{-}Torque}$ with age, ranging from 4.02 ± 0.29 to 2.88 ± 0.31 rad^{-1} for the youngest to the oldest children. Because an increase in stiffness with age was expected due to the maturation of elastic tissues, overactivation of the TS was suspected to contribute to the higher $SI_{MT\text{-}Torque}$ values found in the youngest children. TS EMG-torque analyses confirmed that neuromuscular efficiency was significantly lower for the 7- or 8-yr-old children compared with 10-yr-old children, notably due to a higher degree of tibialis anterior coactivation found in the youngest children. Thus the stiffness index originally defined as the slope of the angular stiffness-EMG relationship increased significantly with age toward adult values. The results underlined the necessity to take into account the capacities of muscle activation to quantify changes in elastic properties of muscles, when those capacities are suspected to be altered.

triceps surae; muscle activation; electromyogram

PUBERTY CAN BE DESCRIBED AS a period of transition from childhood to adulthood within a context of sexual maturation and statural growth. During and after puberty, human skeletal muscles undergo both structural and functional changes due to muscular, neuronal, hormonal, and biomechanical factors (6), leading to an increase in physical performance.

Because strength is one of the basic determinants of physical performance, studies are often focused on changes in maximal voluntary isometric strength (4, 10, 18, 29) or on the relationship between muscle strength and muscle size of the plantar flexors (10, 18). Changes in electrically evoked twitch contractile properties during puberty have also been well studied in the plantar flexors (4, 10, 25, 29) to assess force independently of volition. It has been shown that the twitch force increases with age (4, 10, 25, 29) and that this increase was related to the increase in muscle size (10). Furthermore, no significant differences in the time course of the twitch (contraction time and half relaxation time) were reported between pre- and postpubescent children (4, 10, 25, 29), which suggests that the fiber-type composition of the muscles was already adultlike. As reported by Elder and Kakulas (12), the soleus (Sol) muscle acquires its slow-type properties at the latest at 3 yr of age.

With regard to elastic properties, data in the literature concerning children remained scarce. For instance, increases in passive muscle and joint stiffness with age and stature were reported by Lin et al. (23) and Lebiedowska and Fisk (22), by rotating the ankle joint or by using a free oscillation technique applied to the knee joint, respectively. Recently, by using ultrasonic images, Kubo et al. (20) reported an increase in the tendon elastic properties of the vastus lateralis with growth. To assess the elastic properties of the series elastic component (SEC), i.e., musculotendinous stiffness, Cornu et al. (9) and Cornu and Goubel (8) used the quick-release technique. In these studies, stiffness indexes of the knee extensors of children showed a tendency to decrease with age (9), whereas the elbow flexors exhibited identical stiffness indexes for children and adults (8). These differences in the evolution of the stiffness index between muscle groups of the upper and the lower limbs might also be due to differences in the development of neuromuscular activation in these muscle groups. Differences in strength development of reciprocal muscle groups of children were already supposed to be influenced by muscle activation capacities (4, 17).

In the present study, musculotendinous stiffness was quantified for the ankle plantar flexors of prepubertal children, aged 7–10 yr. For that, a specific motor-driven ankle ergometer has been developed (30) to analyze the elastic properties of the musculotendinous complex by using quick-release movements. Thanks to

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this technique, a stiffness index, defined as the slope of the linear angular stiffness-torque relationship, was previously proposed to quantify changes in musculotendinous stiffness after spaceflight (21). It is hypothesized that *1*) if normalized muscle force and normalized muscle activation grow in the same proportions, stiffness indexes should increase with age, due to the maturation of tendinous structures, and *2*) if such a result fails to be found, alteration in the activation capacities can be suspected to influence musculotendinous quantification. In such a case, another stiffness index can be proposed, which corresponds to the slope of the angular stiffness-electromyogram (EMG) relationship. This new index should allow one approach more the intrinsic elastic properties of the musculotendinous complex.

MATERIALS AND METHODS

Testing machine. The technical support of the present ankle ergometer has been derived from an ankle ergometer already used in adult subjects (35). Briefly, the ankle ergometer consisted of *1*) a platform supporting a power unit, which contained the actuator, its power supply unit, position and torque transducers, and its associated electronics; and *2*) a driving unit composed of a personal computer equipped with a 12-bit analog-to-digital converter and a timer board.

Angular displacement of the actuator was measured with an optical digital sensor, and angular torque was obtained by using a strain-gauge torque transducer. Specific menu-driven software controlled all procedures and recorded mechanical variables and EMGs (1-kHz sampling frequency) for later analysis. A dual-beam oscilloscope gave the child visual feedback about the procedure in progress.

Subjects. Twenty-eight 7- to 10-yr-old prepubertal children (16 girls and 12 boys) were tested at the Centre Hospitalier Universitaire in Amiens. The medical staff determined the pubertal status of each child. Based on pubic hair, breast development, and no apparent changes in the voice and skin, all children were classified as prepubescent. Anthropometric measurements included calf circumference, height, foot length (calculated from the shoe size), and body mass. Additional experiments were done on six college students (6 men aged 20.8 ± 1.6 yr), who constituted an adult target group for the same parameters. Anthropometric characteristics are given in Table 1.

Written, informed consent was given by the college students, and for the children by the legal guardians, who were always present during testing, fully advised of the procedures, and free to withdraw their child from the experiment at any time. The experimental protocol was approved by the local committee of hygiene, safety, and ethics at the University of Compiègne.

Experimental protocol. The subject was comfortably placed on an adjustable seat without back support to limit the contribution of the trunk to the requested effort. The left foot was attached rigidly to an adjustable footplate, so that the horizontal bimalleolar axis coincided with the axis of rotation of the actuator of the ankle ergometer. The knee was extended to 120°, and the ankle was placed to 90° of dorsiflex-

Table 1. *Anthropometric characteristics of prepubertal children and adults*

Anthropometric Data	Age, yr 7	8	9	10	Adult
n	5	7	5	11	6
Female/male	2/3	4/3	4/1	6/5	0/6
Calf circumference, cm	26.2 ± 0.3	28.2 ± 1.2	28.7 ± 1.2	31.1 ± 1.1	39.0 ± 1.3†
Height, cm	129.5 ± 0.7	130.9 ± 2.7	135.4 ± 1.1	145.2 ± 2.5	175 ± 2.4†
Foot length, cm	20.8 ± 0.3	21.3 ± 0.5	21.4 ± 0.3	23.2 ± 0.4	26.7 ± 0.5†
Body mass, kg	28.4 ± 0.9	32.0 ± 3.4	31.6 ± 3.5	41.2 ± 3.1	63 ± 3.5†

Values are means ± SE; *n,* no. of subjects. Significant differences between *the prepubertal children and †the adult subjects and the 4 prepubertal child groups from ANOVA: $P < 0.05$.

ion, i.e., neutral position. The thigh was maintained by a restraint system to keep it immobilized.

Surface EMGs were detected on each part of the triceps surae (TS), i.e., the Sol and the gastrocnemius lateralis (GL) and medialis (GM) muscles, by using Ag-AgCl surface electrodes (2 mm in diameter). In addition, EMG signals of the tibialis anterior (TA) were recorded to evaluate antagonist EMG activity. To reduce the electrode impedance to <5 kΩ, the skin areas over the electrode application sites were gently rubbed with an abrasive skin cleaning paste and cleaned with an alcohol pad. Electrode gel was used with all surface electrodes for good electroconductive coupling. The electrodes were placed over the belly of each gastrocnemius muscle and, for the Sol, 2 cm below the insertion of the gastrocnemii muscles on the Achilles tendon. The ground electrode was placed over the tibia. EMGs were recorded differentially, amplified, and band-pass filtered (1–1,000 Hz).

The maximal motor direct response (M_{max}) was elicited by applying a supramaximal electrical stimulus to the posterior tibial nerve with the cathode located in the poplitea fossa and the anode placed on the thigh, proximal to the patella. The stimulus intensity was adjusted so as to obtain the maximal M wave on each part of the TS. Most children did not experience any unpleasant effects of the stimulation, but, for four children (one 7-, one 9-, and two 10-yr-old children) who appeared to be sensitive to the stimulation, this part of the experimental protocol was stopped. The M_{max} was used to normalize the EMG signals and thus to account for different conditions of skin and surface electrode impedance.

Then the absolute torque from a maximal voluntary contraction (MVC) was determined in plantarflexion under isometric conditions while the subject was asked to develop a maximal contraction against the actuator. The MVC of the day was defined as the highest torque of three attempts to generate the maximal voluntary effort. Maximal relative torque values were also considered with regard to dimensions that change with growth, i.e., expressed as the ratio between maximal absolute torque and foot length ($Torque_{rel\text{-}FL}$), as foot length may be related to the length of the tendon moment arm, and body mass ($Torque_{rel\text{-}BM}$). As reported by Seger and Thorstensson (32), a difference in strength per body mass would indicate a change in "muscle quality" (e.g., fiber-type composition of a muscle or packing of contractile elements).

Finally, the elastic properties of the musculotendinous complex were assessed by means of a quick-release technique adapted for in vivo experiments (13). As in isolated muscles, the aim was to determine the stiffness of the so-called SEC. Because the quick-release technique characterizes SEC stiffness of Hill's muscle model (14), a major proportion of the series elasticity resides in the tendon (passive component of the SEC) (34), whereas cross bridges constitute the active component of the SEC (16). This heterogeneity of the SEC leads to nonlinear tension-extension relationships, and SEC stiffness is classically linearly related to force.

Quick-release movements from the neutral position were achieved by a sudden releasing of the footplate while the subject maintained a submaximal voluntary isometric torque in plantarflexion. Three trials were performed at 25, 50, and 75% of MVC. From each trial, the plateau values in torque and EMG before the release were used to construct EMG-torque relationships and to calculate TA coactivation.

A full test session, including rest periods, lasted ~1 h and comprised *1*) explanation of the test, *2*) preparation of the subject, *3*) familiarization to the test, and *4*) the actual test, which was presented once to each child. Rest periods were standardized in terms of intratest (1 min) and intertest (3–5 min).

Data processing. The M_{max} response was obtained by averaging five M-wave records. Then Sol, GL, and GM EMG signals were rectified and summed up to get TS M_{max}. A mean amplitude of the TS M_{max} response ($\overline{M}_{max}$) was calculated as the ratio between TS M_{max} area and TS M_{max} duration. Computing the mean amplitude of the TS M_{max} instead of the amplitude takes into account the polyphasic response in some of the recorded M waves of GL and GM muscles.

To construct EMG-torque relationships for the TS, the EMG signals of Sol, GL, and GM were rectified and summed up to get TS activity. TS activity was expressed as a mean amplitude ($\overline{EMG}$), calculated as the ratio between the TS EMG area and duration over the 200-ms isometric torque just before the quick-release movement. For subject-to-subject comparisons, TS $\overline{EMG}$ was normalized with respect to TS $\overline{M}_{max}$ (TS $\overline{EMG}/\overline{M}_{max}$) and expressed as a percentage. Similar to the method proposed by Moritani and de Vries (26), TS $\overline{EMG}/\overline{M}_{max}$-torque relationships were constructed to attest possible changes in the muscle activation capacities of the children. Then, to express force output per electrical input, the inverse of the slope of these relationships gave the index of neuromuscular efficiency (NME). In the same way, TA EMG was quantified over the same duration. An index of coactivation was calculated between TA EMG at 25% MVC-to-TS EMG at 25% MVC and TA EMG at 75% MVC-to-TS EMG at 75% MVC ratios.

Musculotendinous stiffness (S) was calculated as the ratio between variations in angular acceleration $\ddot{\Theta}$ (as the second derivative of angular displacement Θ) and angular displacement, multiplied by the corresponding inertia (I) value as expressed by the formula

$$S = (\Delta\ddot{\Theta}/\Delta\Theta)\cdot I \qquad (1)$$

SEC characteristics were measured at the very beginning of the quick-release movement, i.e., when the elastic elements are supposed to recoil and before any reflex changes in muscle activation (e.g., unloading reflex) (1, 13), were possible. Thus stiffness calculation was conducted over the first 20 ms (21). Moreover, maximal angular velocity of the release (as the first derivative of angular displacement) at lowest torque (25% of MVC) was 16.0 rad/s, which is higher than the maximal shortening velocity of the adult plantar flexors found in the literature (6.0–7.0 rad/s) (38). This high-release velocity should minimize the influence of a shortening of the contractile component, which could lead to an underestimation of musculotendinous stiffness. Maximal shortening velocity of the plantar flexors has never been quantified in children, but, for the elbow flexors, Asai and Aoki (2) reported lower maximal shortening velocity values in children than in adults.

Then musculotendinous stiffness values were related to the corresponding isometric torque, calculated over the 200 ms preceding the quick-release movement. The slope of the linear stiffness-torque relationship so obtained was defined as a stiffness index of the musculotendinous complex ($SI_{MT\text{-}Torque}$) and was proposed to attest changes in musculotendinous stiffness. Taking a stiffness index has the advantage of being independent of the required torque level and avoiding the use of MVC or cross-sectional area measurements for normalizing musculotendinous stiffness (21).

Musculotendinous stiffness was also related to TS activation to give an activation stiffness index ($SI_{MT\text{-}EMG}$), defined by the slope of the stiffness-TS $\overline{EMG}/\overline{M}_{max}$ relationships.

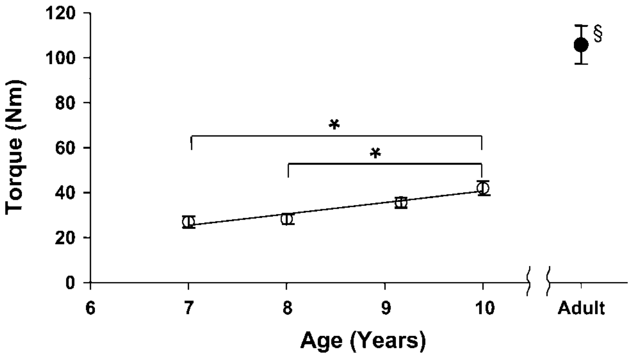

Fig. 1. The increase in torque from maximal voluntary contraction of prepubertal children (○) was significantly correlated with age (r = 0.97, n = 4, $P < 0.05$) and was higher for the adult target group (●). Values are means ± SE. Significant differences between *the prepubertal child groups and §the adult subjects and the 4 prepubertal child groups from ANOVA: $P < 0.05$.

Comment. Data in the literature often indicated no differences in anthropometric data, maximal isometric force, and twitch characteristics of the plantar flexors between prepubertal girls and boys (10, 18). Furthermore, pennation angles have been reported to differ between adult men and women (7); gender-related differences were not demonstrated in children (5). In the present study, preliminary analyses of anthropometric data, maximal isometric torque, and stiffness index of the plantar flexors between girls and boys showed no significant influence of gender on these parameters. Therefore, girls and boys were grouped together on the basis of their chronological age, and further analyses were conducted across the four age groups (7–10 yr).

Statistics. Statistical analyses included linear regression analyses to test TS $\overline{\text{EMG}}/\overline{\text{M}}_{\text{max}}$-torque, stiffness-torque, and stiffness-TS $\overline{\text{EMG}}/\overline{\text{M}}_{\text{max}}$ relationships, as well as relationships between the different parameters and age. A one-way ANOVA was carried out to analyze the effect of prepubertal age on the parameters. Furthermore, a one-way ANOVA was also used to attest differences in the parameters between the four age groups of prepubertal children and the adult target group. When the ANOVA indicated significant differences, a multiple-comparison procedure was applied to determine which means are significantly different from which others. For both tests, a post hoc Fisher's least significant difference procedure was used to discriminate among the means. A level of $P < 0.05$ was selected to indicate statistical significance. Values are represented as means ± SE.

RESULTS

Anthropometric data. Anthropometric data of the prepubertal children were significantly different among the age groups [calf circumference: $F(3,24) = 5.1$, $P = 0.009$; height: $F(3,24) = 10.49$, $P = 0.002$; foot length: $F(3,24) = 8.37$, $P = 0.003$; body mass: $F(3,24) = 5.06$, $P = 0.008$]. More precisely, calf circumference was significantly different between the 7- or 8-yr-old children compared with the 10-yr-old children. Body mass, height, and foot length were significantly different between the 7-, 8-, or 9-yr-old children compared with the 10-yr-old children. Obviously, calf circumference, body mass, height, and foot length were significantly higher for the adult subjects compared with each prepubertal child group. A summary is given in Table 1.

Maximal force production capacities. As expected, absolute torque from a MVC of the adult target group (105.7 ± 8.6 N·m) was significantly higher with respect to all four age groups of children (see Fig. 1). Figure 1 also indicates that the increase in absolute torque of the prepubertal children was significantly related to age. Significant differences in torque were found between the 7-yr-old children (26.9 ± 2.6 N·m) or the 8-yr-old children (28.2 ± 2.2 N·m) compared with the 10-yr-old children (41.9 ± 3.2 N·m) [$F(3,24) = 5.42$, $P = 0.006$].

When relative torque values were considered, no significant differences among ages were found with regard to body mass [$F(3,24) = 0.94$, $P = 0.44$]. Furthermore, the regression analysis indicated no age-related changes in Torque$_{\text{rel-BM}}$ ($r = 0.47$, $n = 4$, $P > 0.05$). When Torque$_{\text{rel-BM}}$ values were compared between the adult target group and the prepubertal children, mean Torque$_{\text{rel-BM}}$ of the adults was significantly higher with respect to all four age groups of the children. When relative torque values were considered with regard to foot length, significant differences were found between the 7- or 8-yr-old children compared with the 10-yr-old children [$F(3,24) = 3.06$, $P = 0.048$]. The regression analysis indicated significant age-related increases in Torque$_{\text{rel-FL}}$ values ($r = 0.97$, $n = 4$, $P < 0.05$). Mean Torque$_{\text{rel-FL}}$ of the adult target group

Table 2. *Maximal relative torque values of prepubertal children and adults*

	Age, yr				
	7	8	9	10	Adult
n	5	7	5	11	6
Female/male	2/3	4/3	4/1	6/5	0/6
Torque$_{\text{rel-BM}}$, N·m·kg^{-1}	1.01 ± 0.01	0.92 ± 0.09	1.18 ± 0.07	1.05 ± 0.08	1.54 ± 0.1†
Torque$_{\text{rel-FL}}$, N·m·cm^{-1}	1.37 ± 0.13	1.42 ± 0.13	1.66 ± 0.15	1.81 ± 0.14	3.96 ± 0.32†

*

*

Values are means ± SE; n, no. of subjects. Torque$_{\text{rel-BM}}$, maximal torque per body mass; Torque$_{\text{rel-FL}}$, maximal torque per foot length. Significant differences between *the prepubertal children and †the adult subjects and the 4 prepubertal child groups from ANOVA: $P < 0.05$.

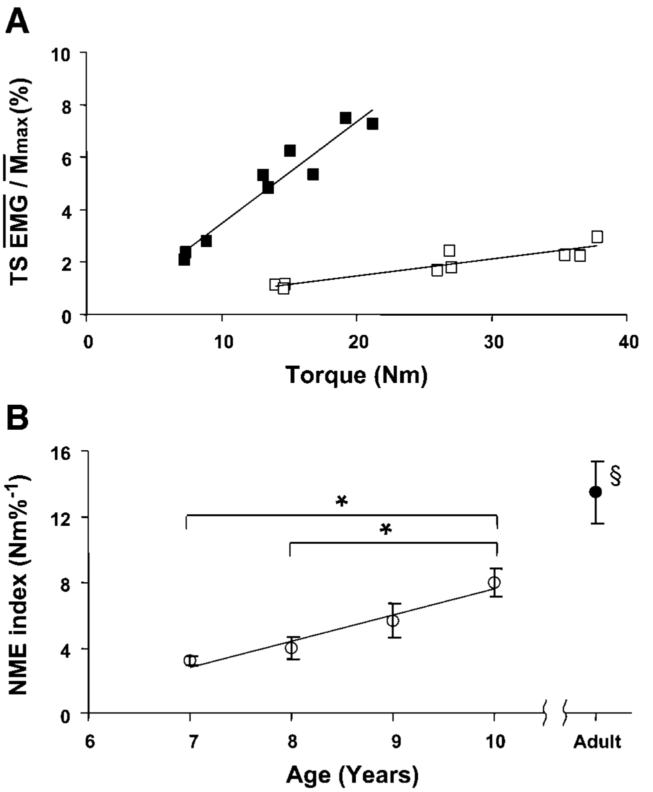

Fig. 2. *A*: typical relationships between normalized electromyogram (EMG) of triceps surae (TS) and torque for a 7-yr-old child (■) and a 10-yr-old child (□); the slopes are 0.39 and 0.16 $\% \cdot N^{-1} \cdot m^{-1}$, respectively. $\overline{EMG}$, mean amplitude EMG; $\overline{M}_{max}$, mean maximal motor direct response; TS $\overline{EMG}/\overline{M}_{max}$, TS $\overline{EMG}$ normalized with respect to TS $\overline{M}_{max}$. *B*: the increase in neuromuscular efficiency (NME) index (inverse of the slope) was significantly correlated with age ($r = 0.98$, $n = 4$, $P < 0.05$) for the children (○) and was still higher for the adult target group (●). Values are means ± SE. Significant differences between *prepubertal child groups and §the adult subjects and the 4 prepubertal child groups from ANOVA: $P < 0.05$.

was significantly higher with respect to all four age groups of the children. A summary is given in Table 2.

Maximal M wave. TS $\overline{M}_{max}$ showed no changes among age [$F(3,20) = 0.89$, $P = 0.47$]. Furthermore, no significant differences in TS $\overline{M}_{max}$ were found among the prepubertal children and the adult target group. Mean TS $\overline{M}_{max}$ of the prepubertal children was 3.25 ± 0.43 mV, and that of the adult subjects was 4.16 ± 0.51 mV.

EMG-torque relationships. Figure 2*A* illustrates typical EMG-torque relationships for a young child and for an older one. As one can see, both children exhibited good relationships when a linear regression analysis was used. This was also true for the population. It is also noteworthy that TS EMG, at each level of torque, was always higher for the younger child compared with the older child. This should lead to lower NME indexes, expressed by the inverse of the slope of the relationships. Indeed, when NME indexes were related to age (Fig. 2*B*), for the 24 children for whom normalized EMG-torque relationships were available, the increase in NME index was significantly correlated with age. Significant differences in NME index were found between the 7- (3.25 ± 0.28 $N \cdot m \cdot \%^{-1}$) or 8-yr-old children (4.03 ± 0.68 $N \cdot m \cdot \%^{-1}$) compared with the 10-yr-old children (7.98 ± 0.85 $N \cdot m \cdot \%^{-1}$) [$F(3,20) = 7.03$, $P = 0.002$]. As shown in Fig. 2*B*, the NME index of the adult subjects (13.49 ± 1.88 $N \cdot m \cdot \%^{-1}$) was significantly different with respect to the four age groups of the children.

Figure 3 shows that the index of coactivation was the highest for the youngest children and then decreased with age and was still lower for the adult target group compared with the four child groups. The linear regression analysis indicated a trend of an age-related decrease in the index of coactivation. However, no statistically significant differences were found among the prepubertal children [$F(3,24) = 0.89$, $P = 0.46$], as well as among the adult group and the four child groups.

Stiffness-torque relationships. Figure 4*A* illustrates typical stiffness-torque relationships for a young child and his or her older counterpart. For both children, musculotendinous stiffness increased gradually when the instruction torque was increased, and best fit was always a linear regression, whatever the age of the child. The $SI_{MT\text{-}Torque}$ was higher for the young child. Figure 4*B* shows that the decrease in $SI_{MT\text{-}Torque}$ was significantly correlated with age. Significant differences in $SI_{MT\text{-}Torque}$ were found between the 7- (4.02 ± 0.29 rad^{-1}) or 8-yr-old children (3.71 ± 0.23 rad^{-1}) compared with the 10-yr-old children (2.88 ± 0.31 rad^{-1}), as well as the 7-yr-old children compared with the 9-yr-old children (2.94 ± 0.16 rad^{-1}) [$F(3,24) = 3.48$, $P = 0.032$]. As shown in Fig. 4*B*, $SI_{MT\text{-}Torque}$ of the adult subjects (3.90 ± 0.50 rad^{-1}) was only significantly different with regard to the 10-yr-old children.

Stiffness-EMG relationships. Typical stiffness-activation relationships are shown in Fig. 5*A* for a 7- and a 10-yr-old child. For both children, the linear regression analysis showed significant relationships between stiffness and normalized TS $\overline{EMG}$. This was also true for the population. In Fig. 5*B*, $SI_{MT\text{-}EMG}$ values of the 24 children, for whom stiffness-$\overline{EMG}/\overline{M}_{max}$ relationships were available, were related to age. The correla-

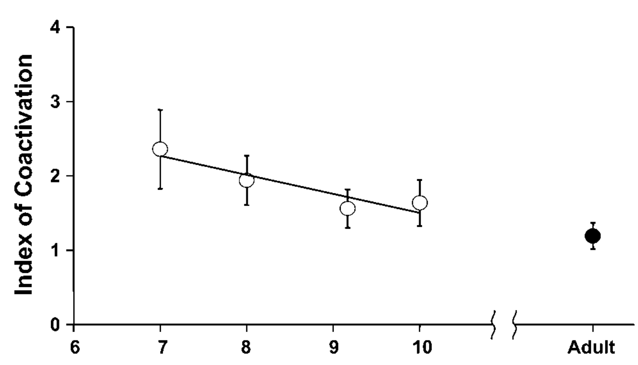

Fig. 3. The index of coactivation showed a trend of an age-related decrease ($r = 0.92$, $n = 4$, $P > 0.05$) for prepubertal children (○) and was lower for the adult target group (●). Values are means ± SE. ANOVA indicated no statistical differences between the prepubertal children and between the adult subjects and the 4 prepubertal child groups.

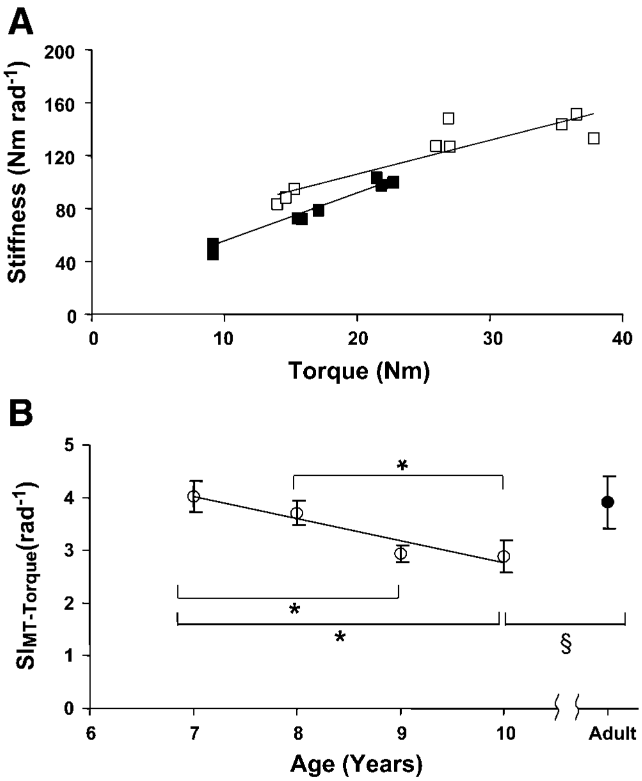

Fig. 4. *A*: typical relationships between musculotendinous stiffness and torque for a 7-yr-old child (■) and a 10-yr-old child (□). The slopes define the stiffness index ($SI_{MT\text{-}Torque}$) and are 3.63 and 2.56 rad^{-1}, respectively. *B*: the decrease in $SI_{MT\text{-}Torque}$ was significantly correlated with age ($r = 0.96$, $n = 4$, $P < 0.05$) for the children (○), but was increased thereafter for the adult target group (●). Values are means ± SE. Significant differences between *the prepubertal child groups and §the adult subjects and the 10-yr-old child group from ANOVA: $P < 0.05$.

tion coefficient of the regression analysis indicated that the increase in $SI_{MT\text{-}EMG}$ was significantly correlated with age. Significant differences in $SI_{MT\text{-}EMG}$ were found between the 7- (12.66 ± 1.62 $N \cdot m \cdot rad^{-1} \cdot \%^{-1}$) or the 8-yr-old children (14.18 ± 1.56 $N \cdot m \cdot rad^{-1} \cdot \%^{-1}$) compared with the 10-yr-old children (24.77 ± 3.66 $N \cdot m \cdot rad^{-1} \cdot \%^{-1}$) [$F(3,20) = 3.85$, $P = 0.026$]. Interestingly, $SI_{MT\text{-}EMG}$ of the adult target group (38.46 ± 7.42 $N \cdot m \cdot rad^{-1} \cdot \%^{-1}$) was significantly different with respect to the four age groups of the children (see Fig. 5*B*).

DISCUSSION

Muscle characteristics depend not only on their force production capacities but also on their elastic properties. In general, large muscle stiffness has important functional consequences in terms of movement control, because, for a given variation in displacement, the stiffer muscle will develop higher levels of force during a controlled movement. Knowledge of the muscle elastic properties can then be useful in understanding the underlying mechanisms in neuromuscular diseases or rehabilitation and of the muscular maturation processes.

However, little is known about these maturation processes on the muscle elastic properties in children. The present study dealt with the quantification of a possible maturation process of the elastic structures of the musculotendinous complex, taking into account age and activation capacities of children.

Anthropometric data. The anthropometric data reported in the present study were in agreement with those reported by others for European school children (10, 29, 32), but were slightly higher with regard to Japanese school children (17, 18). Obviously, anthropometric data of prepubertal children increased with age, so that significant differences were found between the youngest and the oldest children. Such age-related increases in body mass or calf circumferences with statural growth were already reported (17, 31). It seemed also that the increase in body mass appeared to be the most important parameter during young childhood (32, 37). The present results indicated that the body mass of the oldest children was 1.5 times that of the youngest child group, whereas calf circumference, height, and foot length were only ~1.1 times greater. These relative increases were in good agreement with those reported by Raudsepp and Jürimäe (31) in prepubertal girls of the same age span. Altogether, the

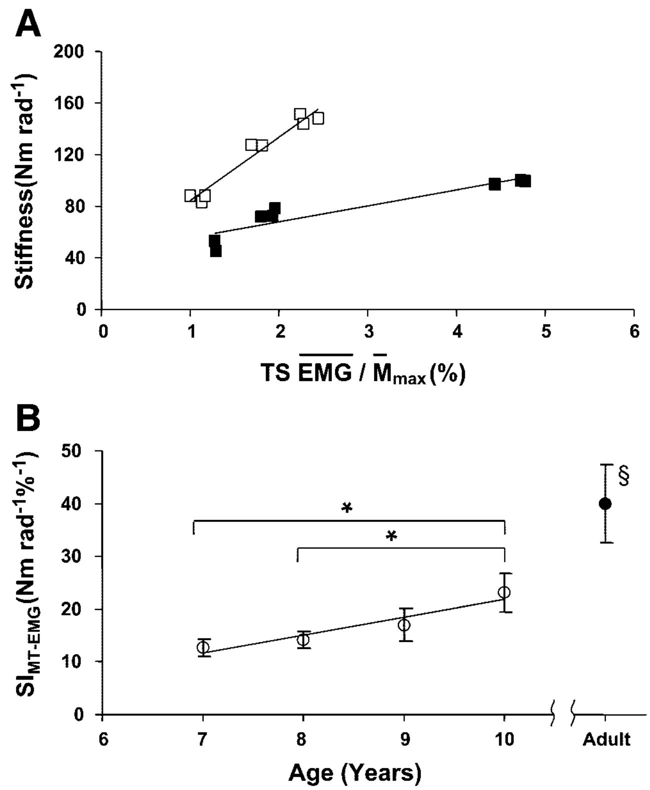

Fig. 5. *A*: typical relationships between musculotendinous stiffness and normalized EMG of TS for a 7-yr-old child (■) and a 10-yr-old child (□); the slopes ($SI_{MT\text{-}EMG}$) are 12.3 and 34.7 $N \cdot m \cdot rad^{-1} \cdot \%^{-1}$, respectively. *B*: the increase in $SI_{MT\text{-}EMG}$ was significantly correlated with age ($r = 0.96$, $n = 4$; $P < 0.05$) for the children (○) and was even higher for the adult target group (●). Values are means ± SE. Significant differences between *prepubertal child groups and §the adult subjects and the 4 prepubertal child groups from ANOVA: $P < 0.05$.

analyses of the anthropometric data showed that the present group of prepubertal children appeared to be representative of European children of the same age.

Maximal force production capacities. Maximal isometric torque of prepubertal children increased with age. Others have already reported increases in maximal voluntary muscle strength under isometric conditions with age for the knee extensors (9), elbow flexors (8), and ankle dorsi and plantar flexors (4, 10, 18, 29). However, most of the cited studies often focused on changes in maximal force between late prepubescent (~11 yr) and pubescent (~14–16 yr) children. In the present study, a limited age span of 7–10 yr was considered, but the results confirmed that, even in this narrow age span, muscle strength of prepubertal children significantly increased from the youngest (7–8 yr) to the oldest children (10 yr).

When absolute muscle strength was normalized with regard to anatomic cross-sectional area (10, 17, 18) or body mass (29, 32), differences in strength with age between children often disappeared but increased through adolescence and early adulthood (17, 18). Most of the cited studies assumed, as one of the reasons for the increase in relative force, an increase in the ability to activate the muscle optimally during maximal motor tasks. Similarly, no significant differences in relative maximal torque values (with regard to body mass) between prepubertal children were found in the present study, whereas significantly higher relative torque values were reported for the adult target group. When relative torque was calculated with regard to foot length, significant differences were found between the youngest and the oldest child groups. Because torque is the product between tendon force and tendon moment arm length, the variations in maximal $\text{Torque}_{\text{rel-FL}}$ with age can reflect the importance of the leverage. Moreover, changes in pennation angle also contribute to changes in tendon force. Recently, it has been reported that the pennation angle of the GM increased during growth (5).

Musculotendinous stiffness and age. The present study reported, for the first time, age-related changes in the elastic properties of the musculotendinous complex of the ankle plantar flexors in prepubertal children, by means of a quick-release technique. Similar to that in adult subjects (11, 15, 21), musculotendinous stiffness increased with torque for each subject. This relation was found to be linear, illustrating the nonlinear tension-extension relationship of the SEC.

As in other studies (8, 11, 15, 21), musculotendinous stiffness was expressed in angular terms, which should simplify the comparison between different groups of subjects, because no assumption about the geometry of the musculotendinous system is required. Furthermore, the use of a stiffness index should also avoid the influences of further anatomic and physiological data (i.e., tendon moment arm, pennation angle, MVC) for normalizing musculotendinous stiffness, making the stiffness index a reliable parameter to quantify changes in musculotendinous stiffness. Thus the stiffness indexes of this study can be easily compared with those already reported in the literature: they were within the range of those found by others for the ankle plantar flexors in adults (ranges from 3.4 ± 0.5 to $5.9 \pm 3.0\ \text{rad}^{-1}$) (11, 15, 21) and for the elbow flexors in children ($5.4 \pm 2.4\ \text{rad}^{-1}$) (8).

In children, age-related changes in musculotendinous stiffness were already reported for the knee extensors (9) but not for the elbow flexors (8). Because musculotendinous stiffness characterizes the elastic properties of the active and the passive fraction of the SEC, different processes of maturation between lower and upper limbs may well exist in the elastic properties of both fractions.

Knowing that slow- and fast-type fibers may well have different elastic properties (36), with slow fibers being stiffer than fast fibers, the differences in musculotendinous stiffness might be attributed to an age-dependent fiber-type distribution in the ankle plantar flexor muscles of the children. However, it has been reported that the differentiation of the ankle plantar flexors in slow and fast muscles is accomplished at the age of 3–4 yr (12). Thus differences in the fiber-type distribution cannot explain the differences in $\text{SI}_{\text{MT-Torque}}$. With regard to the passive elastic properties, animal studies have shown that tendons became stiffer during growth and maturation (27, 33). This should be mainly attributed to changes in the ultrastructure between immature and mature tendons, because differences in the morphological characteristics of collagen were reported by Nakagawa et al. (28). In humans, Kubo et al. (20) reported age-related increases in tendon stiffness of the vastus lateralis. Lin et al. (23) reported a strong increase in passive stiffness of the calf during the first two decades of life. Increases in passive stiffness were also reported by Lebiedowska and Fisk (22), when stiffness was related to statural growth. The maturation of passive elastic structures was already put forward by Cornu and Goubel (8) to explain the adultlike pattern of the elbow flexor stiffness index of children. Taking these results into consideration, it is unlikely that $\text{SI}_{\text{MT-Torque}}$ decreased with age in prepubertal children to increase afterwards.

One element to explain the decrease in $\text{SI}_{\text{MT-Torque}}$ of the prepubertal children could be the influence of the activation capacities of the muscles to generate strength. In another study, it was hypothesized that changes in the recruitment patterns of voluntary activated muscles after spaceflight could influence stiffness quantification (21).

As shown in Fig. 2*A*, TS activation, required to maintain a level of torque, was higher in the 7-yr-old children compared with the 10-yr-old children. It remains to be determined whether the higher level of the detected EMG in the youngest children corresponded to neural mechanisms or to EMG detection, e.g., the influence of changes in pennation angle with the level of contraction (24) and growth (5). Changes in pennation angle should led to changes in the conduction volume of the EMG detection site, because more or less contractile material will be placed in parallel. However, maximal M waves recorded during submaximal voluntary contractions for another study in progress did not change, either with the level of contraction or with the age of the children. Thus it might be concluded that the higher level of TS EMG detected in the 7-yr-old children corresponds to neural mechanisms, an hypothesis also supported by the higher index of coactivation in the 7-yr-old children. In other studies, the degree of maturation of the nervous system and the development of the neuromuscular coordination have also been hypothesized as a reason for differences in muscle strength development (3, 19). Indeed, most of the related studies reported that differences in the activation capacities between prepubertal children and young adults should influence the maximal force production capacities (4, 18, 29). The present study demonstrated that this less ability to activate the muscles optimally is also present under submaximal conditions. This overactivation was explained by the higher index of coactivation found in the 7-yr-old children. Coactivation was recently proposed to explain increased SEC stiffness of the ankle dorsi flexors during voluntary contractions in adult subjects (11a). Then, because SEC release occurs against the resistance of the agonist and antagonistic muscles, SEC stiffness should be increased.

This should influence stiffness quantification, and it can be hypothesized that $SI_{MT\text{-}Torque}$ was overestimated for the youngest of the prepubertal children, due to the relatively higher level of agonist activation. Consequently, a possible effect of maturation of the musculotendinous complex could not be revealed, because it was masked by this influence of agonist-antagonist overactivation. Therefore, musculotendinous stiffness was related to normalized TS EMG, to overcome the influence of the muscle activation capacities. By using such an approach, $SI_{MT\text{-}EMG}$ revealed the expected increase in the elastic properties of the musculotendinous complex with age. As mentioned above, the involved structures should be notably the passive fraction of the SEC. In contrast to what happened in the elbow flexors of children (8), the hypothesis that increase in elastic tissue during growth would parallel with the increase in force production cannot be put forward for the present results. Otherwise, as hypothesized by Cornu and Goubel (8), stiffness indexes should be constant during growth up to adulthood, because stiffness is a ratio between changes in force and length. The present study revealed an increase in elastic properties of the musculotendinous complex of the ankle plantar flexor in prepubertal children. This result was obtained when the stiffness index was quantified with regard to muscle activation.

In conclusion, anthropometric data, as well as maximal torque under isometric conditions, of prepubertal children showed the expected age-related increases. The quantification of the index of NME was useful to indicate the maturation of muscular coordination. The most unexpected and interesting point to emerge from this study was that musculotendinous stiffness index decreased when expressed by torque but increased when muscle activation was taken into consideration. This demonstrated that the quantification of the intrinsic elastic properties of the musculotendinous complex was affected by changes in the muscle activation capacities of prepubertal children. Therefore, it is necessary to quantify musculotendinous stiffness by using a stiffness index, independent of the level of activation, to reveal the intrinsic elastic properties during maturation. This method is recommended when muscle activation is suspected to change, as is often the case, in neuromuscular diseases and rehabilitation.

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