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A cross-sectional study of the size and strength of the lower leg muscles during growth

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Abstract The influences of age and sex on the cross-sectional area (CSA) and isometric strength of the ankle dorsiflexors and plantarflexors (PF) were investigated in four age groups of 121 boys and 121 girls aged: 7–9, 10–12, 13–15, and 16–18 years. A single anatomical cross-section was determined at 30% of the distance from the articular cleft between the femur and tibiacondyles by using an ultrasonic apparatus. In both sexes, the increase in age was associated with significant increases in the CSA and strength (ST) of these opposing muscle groups. The sex differences became apparent in the 13–15 year group for CSA and in the 16–18 year group for ST but the differences reduced considerably when CSA and ST were expressed per unit of the second power of the lower leg length ($CSA \cdot LL^{-2}$) and the product of CSA and the lower leg length ($ST \cdot CSA^{-1} \cdot LL^{-1}$), respectively. However, $CSA \cdot LL^{-2}$ of both muscles had a tendency to be increased at and over the age of 10–12 years, and was the highest at 16–18 years, and $ST \cdot CSA^{-1} \cdot LL^{-1}$ of PF showed higher values in the older boys than in the younger. Thus, it appeared that, at least in the reciprocal muscle groups of the ankle joint, the sex differences in muscle CSA and ST during growth could be accounted for by differences in LL and muscle mass, respectively. However, other factors must also be involved to explain completely the age differences in these variables.

Key words Plantarflexor · Dorsiflexor · Isometric strength · Muscle cross-sectional area

Introduction

Muscle groups in the posterior and anterior aspects of limbs have a reciprocal function to each joint such as flexion and extension. Among agonist-antagonistic muscle groups, dorsiflexors (DF) and plantarflexors (PF) for the ankle joint have been found to show quite striking physiological differences (Belanger et al. 1983). For infants aged 6–12 months, twitch contraction times of PF have been reported to become markedly longer with growth, while those of DF remain unchanged (Elder and Kakulus 1993). However, in adult populations, it has been reported that as a result of aging the twitch contraction times and half-relaxation times are prolonged in both PF and DF (Vandervoort and McComas 1986). While growth trends in the strength capability of these opposing muscles during development has been previously studied (Belanger and McComas 1989; McComas et al. 1973; Tabin et al. 1985), its relationship to muscle cross-sectional area (CSA) has yet to be determined.

Belanger and McComas (1989) have suggested that the strength capability of reciprocal muscle groups for the ankle joint, assessed by torque measurements in both twitch and maximal voluntary contractions, was too large in adolescents compared to pre-adolescents to be accounted for on the basis of changes in leverage. On the other hand, a few previous studies which have used an anthropometric technique (Davies et al. 1983) or ultrasonic apparatus (Ikai and Fukunaga 1968) have reported that isometric strength expressed per unit of muscle CSA of triceps surae or elbow flexor muscles would appear to remain unchanged throughout adolescence and early adulthood. For knee extensor muscles, however, the ability to produce dynamic

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strength proportional to muscle CSA for knee extensor muscles has been shown to be lower in children than in young adults (Kanehisa et al. 1994a, 1995). According to a dimensional analysis (Asmussen and Heebøll-Nielsen 1954, 1955), it has been reported that isometric strength increases more than would be expected from the assumption of geometrical similarity, and the extent of extra increments is different among muscle groups and/or movement patterns. It should be re-examined, therefore, as to the relationship between isometric strength and CSA in the period of development including prepuberty.

In the present study, muscle CSA and isometric strength of DF and PF were measured in male and female subjects aged from 7 to 18 years. The purpose of this study was primarily to investigate the influence of age and sex on the muscle strength and CSA in the agonist-antagonistic muscles of the ankle joint during growth.

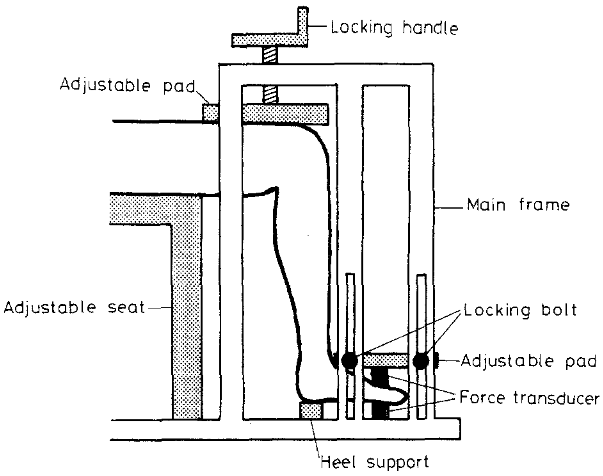

Fig. 1 Apparatus for measuring ankle dorsiflexor and plantarflexor strength

Methods

Subjects

The subjects consisted of 121 Japanese boys and 121 girls. The subjects were divided into four groups according to their ages; 7–9 year group, 10–12 year group, 13–15 year group, 16–18 year group. The physical characteristics of the subjects in each age group are given in Table 1. Each subject and the parents were informed of the procedures to be used as well as the purpose of the study, and their informed written consent was obtained.

Measurement of muscle CSA

The cross-sectional image of the right lower leg was measured using ultrasonic apparatus (SSD-120 Echo-Vision, Aloka, Japan). The accuracy and validity of these ultrasound measurements were certified in a prior study (Kanehisa et al. 1994b). The subjects set their right lower legs perpendicularly along the central axis of a water tank. The scanner, oscillating in a range of 60°, circulated around the tank for 30 s. An image of a cross-section of the lower leg was displayed on a specially designed oscilloscope, and was photographed with a 35-mm camera. The site measured in the lower leg was at 70% of the distance from the malleolus lateralis to the articular cleft between the femur- and tibiachondyles. From the photograph of the cross-section, the boundary between DF and PF and other tissues was traced and planimetric values were obtained. They were then converted into the actual CSA by a calibration equation. The CSA of DF ($\mathrm{CSA}_{\mathrm{DF}}$) and PF ($\mathrm{CSA}_{\mathrm{PF}}$) analysed were as follows: PF included medial and lateral gastrocnemius, soleus, flexor digitorum longus, flexor hallucis, tibialis posterior, peroneus longus and peroneus brevis muscles; DF, tibialis anterior and extensor digitorum longus muscles. The repeatability for CSA measurements was assessed on 2 separate days in a pilot study with 29 young adults (aged 20–25 years). The test-retest correlation coefficient (*r*) was 0.980 for PF and 0.922 for DF. The SEE in the regression were 3.0 cm^2 for PF and 0.7 cm^2 for DF.

Measurement of strength

The maximal voluntary isometric strength of DF ($\mathrm{ST}_{\mathrm{DF}}$) or PF ($\mathrm{ST}_{\mathrm{PF}}$) for the right ankle joint was measured with a specially designed dynamometer. The general arrangement of the dynamometer-subject system is shown in Fig. 1. To standardize the measurement and localize the action to the appropriate muscle groups, the subjects were seated in an adjustable chair with support for the back and hips. The subject's kneecap and front side of the thigh were held down by an adjustable pad with the knee and ankle joints fixed at a right angle. The subject's right foot was placed inside a strength-measuring device in which strain-gauges were equipped on both the upper and lower sides. The subjects made maximal voluntary isometric contraction to the transducer with articulation regions between metatarsus and ossa digitorum pedis as the point of application while the ankle joint was either planterflexed by 10° for dorsiflexor experiments, or dorsiflexed by 20° for planterflexor experiments. The subjects performed more than three trials with a 1-min rest period at each dorsiflexion and plantarflexion. The highest among these trials was accepted as the strength score. The repeatability for strength measurements was investigated on 2 separate days in a preliminary study with 34 young men and women (aged 17–25 years). The test-retest correlation coefficient (*r*) for strength measurement was 0.982 for DF and 0.989 for PF. The SEE in the regression were 13.9 N for DF and 49.9 N for PF.

Calculation of ratio of ST to muscle size

The CSA obtained in the present study was a single anatomical one at right angles to the muscle's long axis, not the physiological CSA. If the strength (ST) of a muscle is to be properly related to its CSA, the cross-section should be measured at a right angle to the muscle fibres (Maughan et al. 1983). The physiological CSA can be estimated from muscle volume divided by the length of muscle fibres (see Wickiewicz et al. 1983), and is linearly correlated to the muscle volume (see Fukunaga et al. 1992). During development, because there is a increase in limb length with each stage of growth, it is likely that the ratio of ST to anatomical CSA for the older children will be overestimated due to their larger muscle volumes (i.e. larger physiological CSA). Therefore, for approximating the CSA measured in the present study to the physiological one, it was multiplied by the length of the lower leg (LL), the distance between the articular cleft between the femur and tibiachondyles and malleolus lateralis, as an index or muscle volume. The ratio of ST to the product of CSA and LL ($ST \cdot CSA^{-1} \cdot LL^{-1}$) was calculated, and it was used as an index of growth changes in ST capability taking account of the differences in muscle size.

Statistics

A two-way analysis of variance was used to assess the effects of sex or age on the measurements. When significant effects of age and/or sex were found, differences among groups were assessed by a Scheffé method. The probability level accepted for statistical significance was set at $P < 0.05$.

Results

Muscle CSA

Increasing age was found to cause a significant increase in CSA of two muscle groups in both sexes (Fig. 2). While there was no significant difference in CSA of either muscle groups between sexes in 7–9 year and 10–12 year groups, the boys showed significantly larger CSA than the girls in 13–15 year and 16–18 year groups.

The CSA is a function of the second power of length (Asmussen and Heebøll-Nielsen 1954). In the present results, regression analyses of the data for both the boys and girls showed significant positive correlations between the second power of the lower leg length (LL^2) and CSA of each PF ($r = 0.872$, $P < 0.01$) and DF ($r = 0.884$, $P < 0.01$). Therefore, the CSA was divided by LL^2 to reduce the influence of the dimensional relationship on the comparisons among group differences in CSA (Fig. 3). Significant age effects were found in the ratios of CSA to LL^2 ($CSA \cdot LL^{-2}$) of PF ($F = 12.025$, $P < 0.01$) and DF ($F = 8.720$, $P < 0.01$). Regardless of sex and muscle groups, the average value in the ratio was the lowest in the 10–12 year group and the highest in the 16–18 year group. The $CSA_{PF} \cdot LL^{-2}$ of the 16–18 year group for both sexes were significantly higher than those of other age groups. For the boys the 16–18 year group had significantly higher $CSA_{DF} \cdot LL^{-2}$ than the 10–12 and 13–15 year groups, for the girls the 16–18 year than 10–12 and 13–15 and 7–9 than 10–12 year groups. While the sex effect was not significant in $CSA_{PF} \cdot LL^{-2}$ ($F = 0.347$, $P > 0.05$), it was significant in $CSA_{DF} \cdot LL^{-2}$ ($F = 10.112$, $P < 0.01$). The boys showed a significantly higher value in the ratio than the girls in the 10–12 year group.

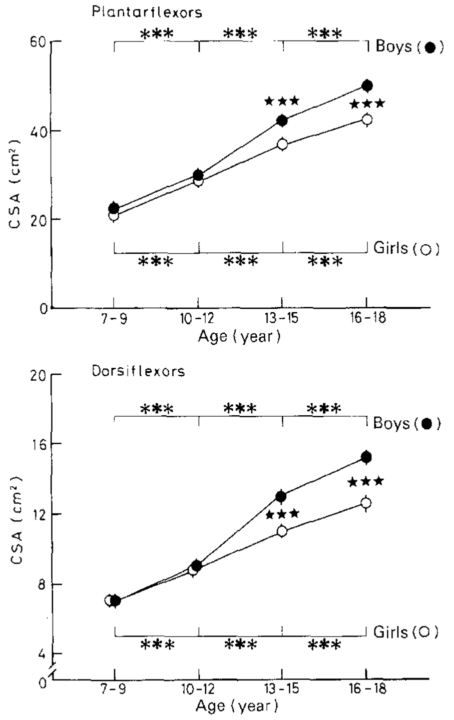

Fig. 2 Changes in muscle cross-sectional area (*CSA*) with age. *Each data point* indicates the mean and standard error of the mean.
*** Significant difference between adjacent age groups at $P < 0.001$.
★★★ Significant difference between boys and girls within the same generation at $P < 0.001$

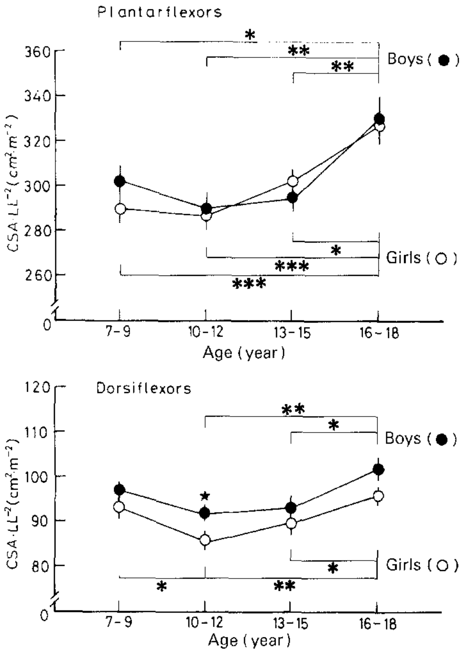

Fig. 3 Changes with age in muscle cross-sectional area (*CSA*) per unit of the second power of the lower leg length ($CSA \cdot LL^{-2}$). *Each data point* indicates the mean and standard error of the mean.
***, **, * Significant difference among age groups at $P < 0.001$, $P < 0.01$ and $P < 0.05$, respectively.
★ Significant difference between boys and girls within the same generation at $P < 0.05$

Muscle ST

The ST of each muscle group increased significantly with increasing age except between the 13–15 and 16–18 year groups in the girls for ST_{DF} (Fig. 4). Significant sex differences were observed in the 13–15 and 16–18 year groups for ST_{PF}, and in 7–9, 13–15 and 16–18 year groups for ST_{DF}.

The correlation between $CSA \cdot LL$ and ST in each age group was significant in both sexes, $r = 0.515$–0.915 ($P < 0.05$) for PF and $r = 0.409$–0.761 ($P < 0.05$) for DF. In the $ST_{DF} \cdot CSA^{-1} \cdot LL^{-1}$ (Fig. 5), although the girls

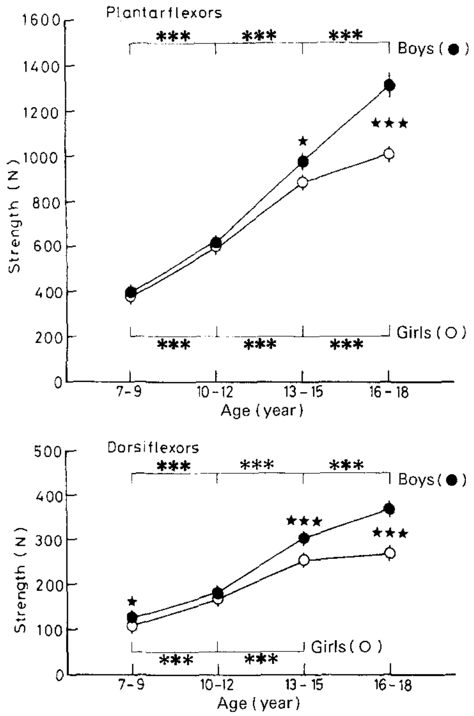

Fig. 4 Changes with age in muscle strength. *Each data point* indicates the mean and standard error of the mean. * * * Significant difference between adjacent age groups at P <0.001. ★★★, ★ Significant difference between boys and girls within the same generation at P <0.001 and P <0.05, respectively

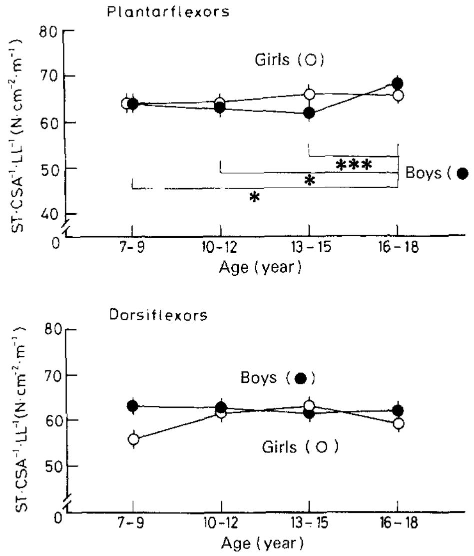

Fig. 5 Changes with age in strength (*ST*) per unit of the product of muscle cross-sectional area (CSA) and lower leg length ($ST\cdot CSA^{-1}\cdot LL^{-1}$). *Each data point* indicates the mean and standard error of the mean. * * *, * Significant difference among age groups at P < 0.001 and P < 0.05, respectively

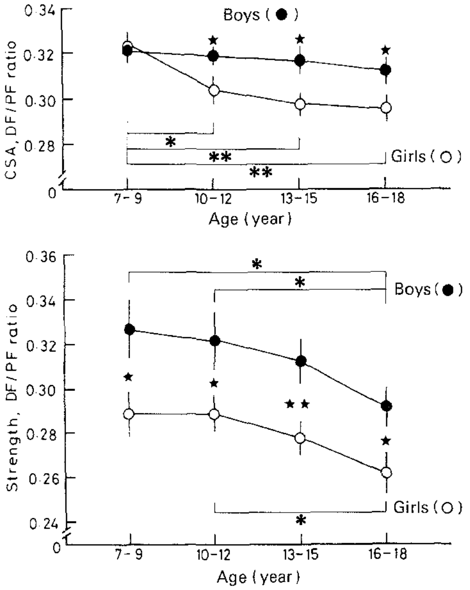

Fig. 6 Changes with age in ratio of dorsiflexors to plantarflexors (DF/PF ratio) in muscle cross-sectional area (CSA) and strength. *Each data point* indicate the mean and standard error of the mean. * * *, * Significant difference among age groups at P <0.01 and P <0.05, respectively. ★★★, ★ Significant difference between boys and girls within the same generation at P <0.01 and P <0.05, respectively

had a tendency to increase with growth, there was no significant influence of sex (F =0.751, P >0.05) and age (F =2.487, P >0.05). While the influence of sex on $ST_{\mathrm{PF}}\cdot CSA^{-1}\cdot LL^{-1}$ was not significant (F =0.020, P >0.05), the age effect was significant (F =2.839, P < 0.05). For the boys the 16–18 year group showed a significantly higher ratio than other age groups.

Ratios of DF to PF in CSA and ST

The ratio of DF to PF in CSA ($\mathrm{CSA}_{\mathrm{DF/PF}}$, Fig. 6) had significant age (F =4.136, P <0.01) and sex (F =9.692, P <0.01) effects. For the girls the 7–9 year group showed a significantly higher value than other age groups. The boys showed significantly higher ratios than the girls in all age groups except for the 7–9 year group.

The ratio of DF to PF in ST ($\mathrm{ST}_{\mathrm{DF/PF}}$) was also significantly influenced by age (F =3.972, P <0.01) and sex (F =22.203, P <0.01). For the boys the 7–9 and 10–12 year groups had significantly higher $\mathrm{ST}_{\mathrm{DF/PF}}$ than the 16–18 year group and for the girls the 10–12 than the 16–18 year groups. The boys showed significantly higher ratios than the girls in all age groups.

Discussion

It is important to bear in mind, before interpreting the present results, that muscle CSA measured in this study involved fat and other non-muscle tissue located within a muscle compartment, and not *pure* muscle tissue. Therefore, it seems that, especially after puberty, the

Table 1 Phyaical characteristics of subject. *M* male, *F* female, *LL* lower leg length

Group (years)	Sex	*n*	Age (years)		Body height (m)		Body mass (kg)		LL (m)	
			Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
7–9	M	29	7.75	0.18	1.229	0.011	24.07	0.50	0.273	0.003
	F	29	7.81	0.18	1.220	0.009	23.80	0.53	0.276	0.003
10–12	M	30	10.67	0.14	1.390	0.010	33.75	1.04	0.321	0.004
	F	29	10.76	0.17	1.400	0.015	33.02	1.17	0.319	0.004
13–15	M	31	13.81	0.15	1.606	0.006	48.79	0.72	0.379	0.002
	F	34	13.93	0.14	1.546	0.004	47.26	0.54	0.354	0.002
16–18	M	31	17.03	0.18	1.688	0.008	60.95	1.71	0.389	0.003
	F	29	17.07	0.17	1.583	0.008	51.40	0.65	0.362	0.003

content of fat tissue located within a muscle compartment can alter the extent of the sex and/or age differences in muscle CSA and $ST \cdot CSA^{-1} \cdot LL^{-1}$ observed in this study. However, Maughan et al. (1983) have reported that the variation in muscle density was small among subjects involving both sexes aged 20–38 years and correction of measured CSA for the area occupied by fat, as estimated from the mean Hounsfield number for the muscle area, had no significant effect on the results for a strength per unit muscle CSA.

In the present study, no assessment for the stage of puberty was made. Considering the differences in body height between each age group (Table 1), however, it is likely that the 10–12 year group for the girls and the 13–15 year group for the boys were at the peak of puberty. In both sexes, CSA of two muscle groups showed significant increments with increasing age. For the girls, however, the extent of the increment in CSA between the 13–15 and 16–18 year groups was lower compared to that of the boys, so that the sex differences in CSA became apparent on and after 13–15 years. These growth trends in CSA for both sexes agree with those of calf muscle width that have been determined by roentgenograms (see Malina and Johnston 1967; Maresh 1963, 1966; Tanner et al. 1981).

On the other hand, there was also no significant sex difference in $CSA \cdot LL^{-2}$ in either muscle groups except for DF in the 10–12 year group. These results seem to imply that, at least in the lower leg muscle, the sex difference in muscle CSA within the same generation can be referred to body dimension. However, $CSA \cdot LL^{-2}$ was significantly influenced by age. The ratio had a tendency to decrease between the 7–9 and 10–12 year groups, and was the highest in the 16–18 year group. From a previous longitudinal finding (Tanner et al. 1981), peak growth velocity of muscle width in limbs has been shown to coincide closely with that of the sitting height in boys and were some six months later than the sitting height peak in girls. Because present results are based on cross-sectional data, a definitive conclusion cannot be demonstrated. However, it is tempting to speculate that muscle CSA might be slow to change with growth compared with limb length in the early stages of puberty. And the growth rate of muscle CSA might surpass that of limb length during the later stages of puberty.

According to a prior finding based on the anthropometric data (Davies et al. 1983), isometric strength per unit CSA of PF remained unchanged through adolescence and early adulthood. In the present results, while the effect of age on $ST_{\mathrm{DF}} \cdot CSA^{-1} \cdot LL^{-1}$ was not significant, it was significant in the case of the ratio of PF; for the 16–18 year group of boys showed a significantly higher value than the other age groups. Dimensional analyses have shown that muscle strength during growth increased more than would be expected from the assumption of geometical similarity (Asmussen and Heeøbll-Nielsen 1954, 1955). As a reason for the extra increase in muscle strength, a qualitative change in the muscle and/or an increase in the ability to recruit motor units under maximal voluntary muscle action has been assumed (Asmussen and Heeøbll-Nielsen 1954). Moritani et al. (1989) have suggested that, based on the rather limited information available on development of muscle fibre characteristics (Colling-Saltin 1980; Saltin and Gollnick 1983), the adult patterns of muscle fibre composition in soleus and medial gastrocnemius muscle is established at an age earlier than 9 years. Motor unit activation is complete in the DF during maximal voluntary contraction even in the prepubetal boys, but this has not always been found to be true of PF (Belanger and McComas 1989). Since this deficiency in PF has been noted for an adult population (Belanger and McComas 1989), it is not a phenomenon peculiar to children.

From a prior finding as to the electromyogram activities of soleus and medial gastrocnemius muscles during a variety of motor tasks, however, major differences between boys and adults have been observed in neural control in postural tasks and maximal height hopping (Moritani et al. 1989). Moritani et al. (1989) have suggested that prepuberty had a lesser ability to potentiate the activation of particularly the fast medial gastrocnemius muscles in the eccentric phase following ground contact during maximal hopping. Taking account of this finding, it might be assumed that there is a certain development with growth in the neural control of the triceps surae muscle complex when maximal motor tasks are performed. If so, a lower $ST_{PF} \cdot CSA^{-1} \cdot LL^{-1}$ in the younger boys might be referred to their inferior ability to recruit available motor units during maximal plantar flexions.

Leaving this consideration aside, an interesting observation was that $ST \cdot CSA^{-1} \cdot LL^{-1}$ of PF and DF was not much different despite large differences in CSA and ST between both muscles. Making comparisons of the ratios of ST to muscle CSA among various muscle groups, it is necessary to determine not only their physiological CSA but also absolute ST exerted by the muscles through their tendons. Calculation of the absolute ST demands information as to the dimension of the lever system involved during muscle activity. In relation to the influence of growth or sex, there is insufficient data about the difference in the lever system between PF and PF. According to a previous finding obtained from cadavers, however, there are few differences in the moment arm between PF and DF, i.e. 2.6 cm for PF and 2.4 cm for DF (Wickiewicz et al. 1984). Although there are these limitations and assumptions, the present results of $ST \cdot CSA^{-1} \cdot LL^{-1}$ support a hypothesis that PF and DF have a similar intrinsic strength in terms of per unit physiological CSA.

Dorsiflexor values represented about one-third of CSA and ST of PF in the entire age range studied. The influences of age on the ratios were small but significant – lower in the older than in the younger children. This result might imply that the growth rate of CSA and strength in PF is greater than that of DF. Dorsiflexor and plantarflexors have an antagonistic effects at the ankle joint. The PF always acts for body mass bearing in physical activities. The load against PF will become larger as a child increases his capacity for physical exertion, so that may be a factor in accelerating the growth in morphological and/or functional aspects of PF.

Moreover, DF/PF ratios in CSA and ST were significantly higher in the boys than in the girls. With advancing growth, boys generally become more aggressive than girls. It has been shown that co-activation of the agonist-antagonist muscles is necessary to aid the ligaments in maintaining joint stability, equalizing the distribution of articular surface pressure, and regulating the joint's mechanical impedance (Baratta et al. 1988). Many studies have shown that asymmetric development of muscle strength in reciprocal muscle groups may be a predisposing factor of muscle and/or joint impingement syndrome resulting from performing various sports (Burkett 1970; Burnham et al. 1993; Goldfuss et al. 1973; Hagood et al. 1990; Hinton 1988; McMaster et al. 1991; Stafford and Grana 1984). Therefore, the reason for the higher DF/PF ratios of CSA and ST in the boys might be to activate fully the other's functions between DF and PF and/or to reduce exposure to the risk of ligament injury during physical activities.

In summary, the effect of age caused significant increments in CSA and ST of the ankle DF and PF during growth, and sex differences became apparent in the 13–15 year age group for CSA and in the 16–18 year age group for ST. These differences were reduced when CSA and ST were expressed per unit of the second power of LL and the product of CSA and LL, respectively. Even when limb length and muscle dimension were allowed for however, significant age effects of CSA and ST still remained. The age differences in $CSA \cdot LL^{-2}$ seemed to be attributable to an extra increase in muscle CSA depending on the adolescent spurt, and in $ST \cdot CSA^{-1} \cdot LL^{-1}$ to a change in the neural drive during maximal voluntary contractions.

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