Human *gastrocnemius medialis* Pennation Angle as a Function of Age: From Newborn to the Elderly

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Abstract The aim of the present study was to quantify changes in human skeletal muscle pennation angle (F_θ) values during growth and adult life. The human *gastrocnemius medialis* muscle of 162 subjects (96 males and 66 females) in the age range 0–70 years was scanned with ultrasonography. The subjects were laying prone, at rest, with the ankle maintained at 90° with all muscles relaxed. F_θ increased monotonically starting from birth (0 years) and reached a stable value after the adolescent growth spurt. There was a significant ($p < 0.05$) linear relationship between F_θ and muscle thickness (TK). $F_\theta = 0.84 (\pm 0.09) * TK + 3.15 (\pm 1.13)$. Human *gastrocnemius medialis* F_θ and TK data found in the literature seem to fit the F_θ -TK plot in a coherent manner, independent of the physiological or anatomical characteristics of the subject. The present findings indicate that F_θ is not a constant parameter but evolves, as is the case for bone length and height, as a function of age. *J Physiol Anthropol* 20 (5): 293-298, 2001 <http://www.jstage.jst.go.jp/en/>

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Introduction

Human skeletal muscle architecture, i.e. the macroscopic arrangement of the muscle fibres, closely correlates with its function. The most important architectural parameters are pennation angle (F_θ), muscle physiological cross sectional area and muscle fibre length (Lieber and Fridén, 2000). F_θ and muscle physiological cross sectional area are important determinants of the maximum force of contraction. Muscle fibre length is positively related to the speed of

contraction. The first quantitative studies on muscle architecture have been pioneered by Gans & Bock (1965) and Gans & De Vree (1987). Until recent years, studies on humans have been performed on cadavers (Lieber and Fridén, 2000). With the introduction of sonography, non invasive studies of the human muscle architecture have become possible (Henriksson-Larsen et al., 1992; Rutherford & Jones, 1992) and, in particular, studies of muscular dynamics (Narici et al., 1994; Herbert & Gandevia, 1995; Kuno & Fukunaga, 1995). It has been demonstrated in humans that F_θ , physiological cross sectional area and fibre length may vary as a function of joint position and force of muscle contraction (Narici et al., 1996; Herbert & Gandevia, 1995, Kawakami et al., 1998; Maganaris et al., 1998 Maganaris & Baltzopoulos, 1999), of the type of physical training (Kawakami et al., 1993; Abe et al., 2000; Kearns et al., 2000; Kumagai et al., 2000) and of gender (Chow et al., 2000).

The above observations highlight the fact that muscle architecture is subjected to a certain degree of plasticity. From a general point of view, in mammals, environmental pressure also seems to have contributed to architectural phylogenetic adaptations. For example, the monkey *Cynomolgus* has the capacity to develop a considerable isometric force in its upper limbs (Roy, 1984), therewith facilitating the evolution in its natural environment. It happens that the *Cynomolgus* has a pennated *biceps brachii* while humans have not (Roy, 1984). Architectural differences of muscle may also be found within the same species. The *Lemur catta* and the *Lemur fulvus* show a different structure of their *biceps femoris* (Ward & Sussman, 1979), the latter having a higher F_θ value. This may be related to the fact that *Lemur catta* travels by ground over 65% of the time whereas the *Lemur fulvus* uses the upper level of the

Fig. 1 Subjects height as a function of age. ○ males; ● females.

Fig. 2 Subjects weight as a function of age. ○ males; ● females.

canopy forest and is on the ground less than 2% of its time (Ward & Sussman, 1979). Pennation angle seems to increase with higher demands on muscle tasks.

We were interested on knowing whether some kind of adaptation, physiological or ancestral phylogenic change, also occur during human growth. In a newborn, one might expect to find small F_0 values in the lower limb muscles compared to an adult. Large F_0 allow to develop greater mechanical forces (Woittiez, 1984). One might speculate, that such a development is completely “useless” for a newborn who has not yet used his legs for weight bearing and locomotion. To test this hypothesis, the present study was undertaken to investigate, by ultrasonography, whether the human *gastrocnemius medialis* F_0 increases during subject growth.

Methods

Subjects

The present investigation was conducted on 134 subjects (87 males and 47 females) in the age range of 0–70 years. Height and weight values of each subject are reported in Figs. 1 and 2. The subjects gave their informed consent to participate in the study and the protocol was approved by the local Ethical Committee. For underaged subjects, informed consent was obtained from a parent. None had any clinical evidence of musculoskeletal disease, orthopaedic abnormality nor was involved in competitive physical activity.

Ultrasound scanning

Sonograms of the *medial gastrocnemius* muscle Images were obtained using a Sequoia (ACUSON, Mountain View, CA, USA) real time ultrasound scanner and a multifrequency (7.5–13 MHz) linear array

transducer. Muscle thickness (TK) was measured on hard copy images as the distance between the superficial and the deep aponeurosis (Narici et al., 1994; Ichinose et al., 1995; Narici et al., 1996; Fukunaga et al., 1997). The angle between the fascicles echo and the superficial aponeurosis was defined as the muscle F_0 (Rutherford & Johnes, 1992; Narici et al., 1994; Ichinose et al., 1995; Narici et al., 1996; Fukunaga et al., 1997). The fibre bundle length (F_L) was estimated using the equation:

$$F_L = TK * \sin(\pi * F_0 * 180^{-1})^{-1}. \quad (1)$$

Protocol

For the sonographic study of the right *gastrocnemius medialis* the subject was laying prone on the examining table. The lower limbs were extended, muscles relaxed and the feet rested over the edge of the table at an angle of 90° to the leg. The linear array transducer was coated with transmission gel to obtain acoustic coupling and oriented along the mid-sagittal axis of the muscle. The probe was positioned on the midline of the right *gastrocnemius medialis* centred at the level of the maximum diameter of the transverse muscle section (Narici et al., 1994; Narici et al., 1996). Lower leg length (TL) was measured with a ruler between the medial malleolus and the upper articular surface of the tibia, spotted by palpation.

Statistics

Statistical comparison between two regression lines, corresponding in the present study to male and female groups, and the calculation of relatives slopes and intercepts was performed by one-way analysis of covariance. Calculated confidence bounds corresponds to nonsimultaneous bounds for a new observation. Errors on the estimated parameters are expressed as standard deviation (SD). The a priori level of statistical significance

Fig. 3 Human *gastrocnemius medialis* pennation angle (F_θ) as a function of age. $\circ$ males; $\bullet$ females.

Fig. 4 Human *gastrocnemius medialis* muscle thickness (TK) as a function of age. $\circ$ males; $\bullet$ females.

Fig. 5 Human tibia length (TL) as a function of age, corresponding to the distance between the medial malleolus and medial joint space of the knee. $\circ$ males; $\bullet$ females.

Fig. 6 Human tibia length (TL) as a function of *gastrocnemius medialis* muscle thickness (TK). The continuous line represents the linear fitting of the experimental data. Dashed lines define the 95% confidence bounds. $\circ$ males; $\bullet$ females.

was set at $p < 0.05$. Our results are compared to data reported for adults in some key papers in the literature (see RESULTS and DISCUSSION; Abe et al., 1997; Abe et al., 1998; Maganaris et al., 1998; Abe et al., 1999; Chow et al., 2000; Kearns et al., 2000; Kumagai et al., 2000).

Results

F_θ increases monotonically starting from birth (0 years) and reaches a stable value after the adolescent growth spurt. Fig. 3 shows the F_θ values as a function of age for males and females.

Figs. 4 and 5 report the TK and T_L values as a function of age. T_L follows the typical age dependent pattern reported in the literature (Hensiger, 1986).

Fig. 6 shows the T_L values as a function of TK. T_L is linearly related to TK ($p < 0.05$): $T_L = 1.82 (\pm 0.26) * TK + 5.92 (\pm 2.84)$. T_L values for males ($p < 0.05$) and females ($p < 0.05$) are both linearly related to TK. The two regression lines for males and females are not statistically different.

Fig. 7 shows the F_θ values as a function of TK. F_θ is linearly related to TK ($p < 0.05$): $F_\theta = 0.84 (\pm 0.09) * TK +$

Fig. 7 Human *gastrocnemius medialis* pennation angle (F_{θ}) as a function of muscle thickness (TK). The continuous line represents the linear fitting of the experimental data. Dashed lines define the 95% confidence bounds. $\circ$ males; $\bullet$ females.

$3.15 (\pm 1.13)$. F_{θ} values for males ($p < 0.05$) and females ($p < 0.05$) are both linearly related to TK. The two regression lines for males and females are not statistically different.

Fig. 8 illustrates a series of human *gastrocnemius medialis* F_{θ} and TK values reported in the literature (Abe et al., 1997; Abe et al., 1998; Maganaris et al., 1998; Abe et al., 1999; Chow et al., 2000; Kearns et al., 2000; Kumagai et al., 2000). The values are plotted simultaneously with the regression line and confidence intervals calculated in the present study (see Fig. 3). The ultrasound probe position used for the measurements and the position of subjects were comparable to those of our work. For adult subjects, our data were similar to those reported in the literature.

Fig. 9 shows the fibre bundle length (F_L) as a function of TK. TK and F_{θ} values utilized for the F_L calculation (see equation 1) were taken from the linear regression illustrated in Fig. 3. The TK and F_{θ} values are also reported above in the present RESULTS section. A series of F_L and TK values obtained from the literature (Abe et al., 1998; Maganaris et al., 1998; Abe et al., 1999; Chow et al., 2000; Kearns et al., 2000; Kumagai et al., 2000; same as in Fig. 8) and calculated with equation (1), are included in the same figure. Figs. 8 and 9 report data obtained from the same experiments, with the exception of Abe et al. (1997) because the authors did not calculate F_L (data not presented in Fig 9).

Discussion

To our knowledge, no previous data for development of F_{θ} during infancy and childhood have been published.

Fig. 8 Human *gastrocnemius medialis* pennation angle (F_{θ}) as a function of muscle thickness (TK). The continuous line represents the linear fitting of our experimental data (same as in Fig. 7). Dashed lines define the 95% confidence bounds. The data points illustrate human *gastrocnemius medialis* F_{θ} and TK measurements found in the literature. $\circ$ Before (high TK value) and after (low TK value) 20 days bed rest (Abe et al., 1997); $\square$ Normal subjects (Maganaris et al., 1998); $\triangle$ Difference between males (high TK value) and females (low TK value), (Abe et al., 1998); $\diamond$ Difference between black (high TK value) and white (low TK value) football players (Abe et al., 1999); $\times$ Difference between males (high TK value) and females (low TK value), (Chow et al., 2000); $\star$ Difference between normal (low TK value) subjects and sumo (high TK value) wrestlers (Kearns et al., 2000); ∇ Relation between F_{θ} and 100 m sprint high (low TK value) and low (high TK value) performance (Kumagai et al., 2000). Horizontal and vertical bars represent the standard deviation.

Fig. 1 illustrates that F_{θ} monotonically increases as a function of age, reaching a stable value by adolescence. There is a large spread of F_{θ} values for a given age, which is probably due to physiological differences. The linear relationship between T_L and TK (Fig. 6) and between TK and F_{θ} (Fig. 7) lets one think that F_{θ} probably follows the same trend of growth observed for bones (Hensinger, 1986). Just as body weight increases by growth spurts, F_{θ} might increase at different speeds as a function of age and reach maturity at a different chronological age in males than in females. At maturity, F_{θ} values have been demonstrated to differ between males and females (Chow et al., 2000). The training status of the subjects probably also modulates F_{θ} (Kawakami et al., 1993; Abe et al., 2000; Kearns et al., 2000; Kumagai et al., 2000). Considering that F_{θ} is one of the determinants of muscle force, the present findings might in part explain the low values of mechanical muscle peak power observed in children compared to adults (Ferretti et al., 1994).

It appears from the above discussion, that it is extremely

Fig. 9 Human *gastrocnemius medialis* fiber bundle length (F_L) as a function of muscle thickness (TK). F_L was estimated from the results of Fig. 7 (see METHODS) and reported as a continuous line. The data points were collected from human *gastrocnemius medialis* F_θ and TK measurements found in the literature (as in Fig. 8). $\circ$ Normal subjects (Maganaris et al., 1998); $\square$ Difference between males (high TK value) and females (low TK value), (Abe et al., 1998); $\triangle$ Difference between black (high TK value) and white (low TK value) football players (Abe et al., 1999); $\diamond$ Difference between males (high TK value) and females (low TK value), (Chow et al., 2000); $\circ$ Difference between normal (low TK value) subjects and sumo (high TK value) wrestlers (Kearns et al., 2000); $\square$ Relation between F_θ and 100 m sprint high (low TK value) and low (high TK value) performance (Kumagai et al., 2000). Horizontal and vertical bars represent the standard deviation.

difficult to find a mathematical model allowing to describe the data illustrated in Fig. 3. For this reason, in the present study we have opted for a graphical representation of F_θ which does not depend on age, sex, etc. The representation in Fig. 3 seems to be a possible solution. In fact, F_θ increases linearly as a function of TK and seems, as a first approximation, not to be influenced by age, sex, etc. Similar observations in adults were also reported for example by Kawakami et al. (1993) for *triceps brachii* and Abe et al. (1998; 1999) for the long head of the *triceps*. These authors found a linear relationship between F_θ and TK over a limited range of TK values.

F_θ is often represented as a function of TK normalized by the bone length (in the present study: TK/T_L) of the studied muscle (Kawakami et al., 1993; Abe et al., 1999; Kearns, 2000). Data are then fitted using a linear model (usually significantly correlated). However, our findings demonstrate that both F_θ (Fig. 7) and T_L (Fig. 6) are linearly correlated to TK. In such a case, F_θ cannot mathematically be linearly related to TK/T_L , as found by Kawakami et al. (1993), Abe et al. (1999) and Kearns

(2000). Probably, this apparently contradictory conclusion is due to the large range of variation of F_θ , TK and T_L measurements (the TK/T_L ratio further increases the error). In fact, the observed scattered data “fit” a linear model in both F_θ -TK and F_θ -(TK/T_L) data representations. There is no doubt that more work is necessary to solve this problem.

The linear F_θ -TK relationship holds when the subject foot is positioned at 90° to the leg. It is well known that F_θ changes as a function of ankle position and of the force issued by muscle contraction (Narici et al., 1996; Herbert & Gandevia, 1995, Kawakami et al., 1998; Maganaris et al., 1998 Maganaris & Baltzopoulos, 1999). As this aspect was not addressed in our study we cannot say how the F_θ -TK relationship will change with different ankle positions or muscle contraction.

To facilitate the comparison between the present results and the data taken from the literature we summarize a series of F_θ and TK values obtained by different research groups in Fig. 8. It is interesting to notice that all the values fit into the confidence intervals. This representation depicts F_θ values in a logical way even if they seem very different one of each other. Small variations on F_θ values, related to different methods of measurement by different laboratories, must be taken into account. For the sake of completeness, Fig. 9 illustrates the F_L values of our study together with the F_L data calculated by the same groups depicted in Fig. 8. It shows that F_L in our study is far from linearity for small TK values. These small TK values are representative of young subjects not examined by previous researchers.

It remains to be proven whether the observed age dependence of F_θ has any physiological aim e.g., in children, small F_θ values (i.e. low maximum isometric force) might protect tendons, or tendon insertions from high mechanical stress.

Conclusions

In conclusion, we demonstrated that the human *gastrocnemius medialis* pennation angle (F_θ) value is not constant during growth but increases as a function of age from the newborn period to the adulthood. F_θ seems to reach a stable value after adolescence, as is also observed for bone length, height, etc. The plot of F_θ as a function of muscle thickness (TK) allows one to show, in a single simplified coherent way, data values that are usually influenced in a complex manner by other variables such as training status, age, sex, etc.

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