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ORIGINAL ARTICLE

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Allometric scaling of isokinetic peak torque: the Nebraska Wrestling Study

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Abstract Allometric scaling has been used increasingly in the exercise sciences to control statistically for body size differences in physical performance variables. The purpose of this study was to use multivariate allometric scaling to examine the influence of fat-free mass (FFM) on age-related differences in strength in young club (8–13 years) and high-school (14–18 years) wrestlers. The dependent variables were log-transformed values of isokinetic peak torque for leg extension and flexion at 0.52, 3.14, and 5.24 rad · s^{-1} (30, 180, and 300 · s^{-1}). The independent variables used in the multiple regression analyses were log-transformed values for FFM, age, and the FFM versus age interaction. The resulting regression equations were of the form: $\log Y = \log a + b_1 \log X_1 + b_2 \log X_2 + b_n \log X_n$. The initial multiple regression analyses showed significant interaction effects ($P < 0.05$) for all dependent variables, therefore separate regression analyses were performed for the younger and older groups of wrestlers. The results indicate that for the younger wrestlers there were increases in isokinetic peak torque at all velocities across age after controlling for FFM. The FFM scaling exponents ranged from 0.94 to 1.31. All exponents included 1.0 in the 95% confidence interval, except for extension at 3.14 rad · s^{-1}. For the high-school wrestlers, both FFM and age were significant for the extension data, but only FFM was significant for the flexion data. All FFM exponents included 1.0 in the 95% confidence interval. These results indicate that the relationship between FFM and peak torque differed across age. In addition, with the exception of the flexion data for the high-school wrestlers, within each group increases in isokinetic peak torque occurred across age, independent of increases in FFM. The causes of the age effect for strength are speculative, but it may be due to developmental changes in neuromuscular function, alterations in the distribution of muscle mass as a percentage of FFM and/or the distribution of FFM across body segments.

Key words Growth · Development · Age · Fat-free mass

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Introduction

Studies in which muscle strength is examined at various ages in children and adolescents have generally shown an "age effect" in which strength differences between older and younger subjects are greater than can be accounted for by differences in body size (Housh et al. 1989, 1990; Weir et al. 1992). In general, the age effect has been examined by utilizing analysis of covariance (ANCOVA) in which the body size variable is the covariate, or by creating ratio scores in which strength is divided by the body size variable. Recently, however, increased attention has been focused on the use of allometric scaling as an approach to examine physiological and performance variables that are affected by differences in body size (Nevill et al. 1992). In a number of studies allometric scaling has been used to examine body size relationships with maximal oxygen uptake (Armstrong et al. 1995; Rogers et al. 1995a, b; Vanderburgh and Katch 1996; Welsman et al. 1996), anaerobic performance (Batterham and Birch 1996), left ventricular mass (Batterham et al. 1997a), and indoor rowing performance (Vanderburgh et al. 1996). Less research has utilized allometric scaling to examine strength testing (Davies and Dalsky 1997; Vanderburgh et al. 1995).

The mechanics of allometric scaling have been explained in detail elsewhere (Nevill and Holder 1995; Nevill et al. 1992; Vanderburgh et al. 1996) and will be described only briefly here. The data are analyzed using standard regression procedures in which the dependent variable is the logarithm of the raw performance variable, and the independent variable is the logarithm of the raw size variable. A regression model is created as follows:

$$\log Y = \log a + b \log X$$

where b and $\log a$ are the slope and y-intercept, respectively. Antilog conversion to non-log units results in the power function of the form

$$Y = a \cdot X^b$$

where the constant multiplier (a) and the allometric exponent (b) define the relationship between the scaling variable (X) and the performance variable (Y). When including another variable (e.g., age or gender), multiple regression (or equivalently ANCOVA) is employed, resulting in a log-linear regression model

$$\log Y = \log a + b_1 \log X_1 + b_2 \log X_2$$

which can be similarly transformed to

$$Y = a \cdot X_1^{b1} \cdot X_2^{b2}$$

In addition, the size of the b coefficients can have physiological significance. For example, dimensionality theory suggests that an exponent of 0.67 should be appropriate for scaling oxygen consumption to body mass (Astrand and Rodahl 1986; Nevill 1994), however an exponent of 0.75 has also been found (Bergh et al. 1991; Welsman et al. 1996). Similarly, since muscle torque (T) is the product of muscle force (F) and the moment arm (d), and F should be proportional to height (h) squared (i.e., $F \propto h^2$), while d should be proportional to h, then $T \propto h^2 \cdot h^1 \propto h^3$. Since mass ($m$) should also be proportional to h^3, then $T \propto m$ (Astrand and Rodahl 1996). That is, the mass exponent for T should be 1.0.

The advantages of allometric scaling over other procedures for examining size-independent performance scores have been detailed elsewhere (Nevill et al. 1992; Welsman et al. 1996). For example, ratio scaling adequately removes the effect of body size in very limited statistical situations, which are rarely met (Tanner 1949). Traditional regression and ANCOVA procedures often result in non-zero y-intercepts, which is physiologically impossible, indicating that extrapolation beyond the data is not recommended in these models. In contrast, allometric analyses result in y-intercepts that pass through the origin. In addition, allometric scaling allows for a non-linear function, which may result in a superior fit to the data versus linear modeling. Statistically, heteroscedasticity is often present when linear modeling with body Size, while the logarithmic transformations in allometric scaling tend to correct for the heteroscedastic nature of the data (Nevill 1994). Because of these advantages, we chose to use allometric scaling to re-examine age, fat-free mass (FFM), and strength relationships in participants from the on-going Nebraska Wrestling Study. Specifically, isokinetic leg extension and flexion peak torque across young club wrestlers (8–13 years) and older (high-school) wrestlers (14–18 years) were examined, with the effects of differences in FFM and age examined via allometric scaling. Because differences in body composition can alter the scaling exponents when using body mass as the scaling variable (Batterham et al. 1997a, b), FFM was selected as the scaling variable in this investigation. The data in this investigation represent the combined sample from two previous studies in which age-related increases in isokinetic peak torque were examined using ratio scaling (Housh et al. 1996) and first-order partial correlations (Housh et al. 1997).

Methods

Subjects

A total of 258 young club (n = 108) and high-school (n = 150) wrestlers volunteered to participate in this investigation. Their descriptive characteristics are presented in the Table 1. The older wrestlers were recruited from area high schools and ranged in the age from 14.3 to 18.6 years. The younger wrestlers were recruited from local wrestling clubs and ranged in the age from 8.1 to 13.9 years. Both groups of wrestlers were tested 1–2 weeks prior to the start of their respective competitive seasons. The testing was approved by the Institutional Review Board, and written informed consent was obtained from the wrestlers and their parent or guardian prior to study.

Isokinetic testing

All subjects were tested for isokinetic peak torque for extension and flexion of the dominant leg (based on kicking preference) on a

Table 1 Descriptive statistics [mean (SD)] of young club wrestlers and high-school wrestlers

Parameter	Young club	High school
Age (years)	11.3 (1.5)	16.6 (1.0)
Percent fat	12.8 (6.7)	10.1 (4.2)
Height (cm)	145.9 (11.7)	172.4 (6.7)
Fat-free mass (kg)	35.3 (9.3)	58.2 (8.8)
Leg extension (0.52 rad $\cdot$ s^{-1}) Peak torque (Nm)	68.6 (26.0)	155.8 (31.9)
Leg extension (3.14 rad $\cdot$ s^{-1}) Peak torque (Nm)	40.5 (16.8)	88.6 (17.3)
Leg extension (5.24 rad $\cdot$ s^{-1}) Peak torque (Nm)	26.4 (11.6)	56.3 (12.4)
Leg flexion (0.52 rad $\cdot$ s^{-1}) Peak torque (Nm)	40.2 (15.4)	85.3 (21.2)
Leg flexion (3.14 rad $\cdot$ s^{-1}) Peak torque (Nm)	28.5 (11.0)	57.0 (13.3)
Leg flexion (5.24 rad $\cdot$ s^{-1}) Peak torque (Nm)	20.9 (8.2)	42.5 (10.3)

calibrated Cybex II isokinetic dynamometer with a damping setting of 2. Positioning and stabilization was accomplished with the procedures described by the manufacturer. The subjects were tested at angular velocities of 0.52, 3.14, and 5.24 rad $\cdot$ s^{-1} (30, 180, and 300° $\cdot$ s^{-1}). At each velocity, the subjects were given three to four practice trials followed by three maximal extension and flexion contractions while receiving verbal encouragement to push and pull as hard as possible. At each velocity, the highest peak torque values for extension and flexion were used in the analyses described below.

Body composition testing

Body composition was determined from underwater weighing, as described by Thorland et al. (1981), and corrections for residual lung volume were made using the oxygen dilution technique of Wilmore (1969). Calculation of relative fat from body density was accomplished using the conversion constants of Brozek et al. (1963) for the older wrestlers, while the age-specific conversion constants of Lohman (1986) were used for the younger wrestlers. FFM was derived from the resulting relative fat values. The Brozek (1963) conversion constants were used to calculate relative fat from body density for the older wrestlers because Thorland et al. (1991) have shown that, for high-school wrestlers, the Brozek conversion constants resulted in lower total error values than did the age-specific constants of Lohman (1986). However, comparable data for the young wrestlers have not been reported and therefore the age-specific constants of Lohman (1986) were used.

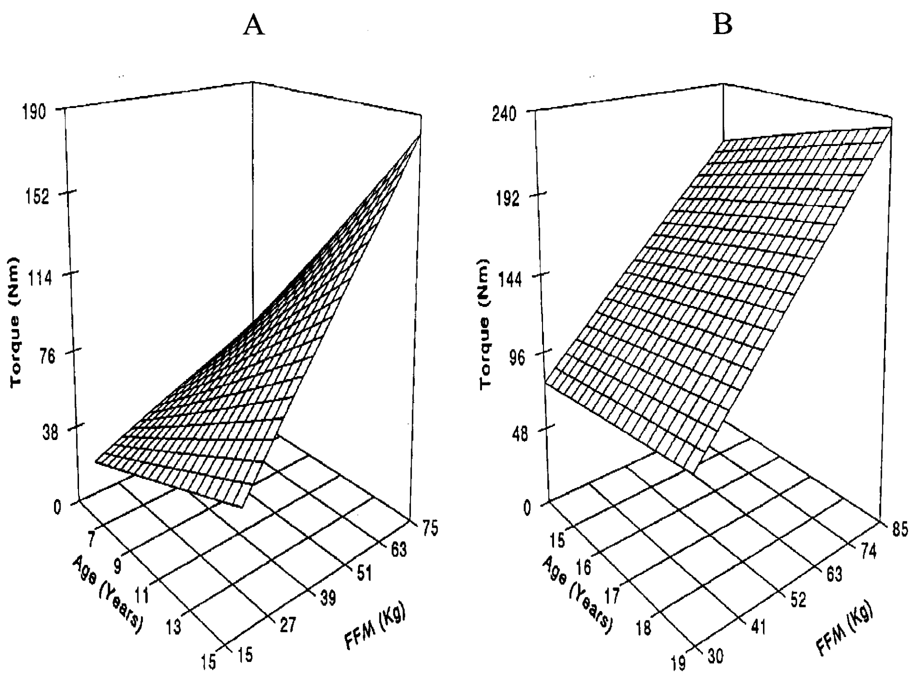
Data analysis

The data were analyzed with multiple regression analyses in which the log of peak torque (log TRQ; separate analyses for extension and flexion at each speed) was the dependent variable and the log transformations of FFM (log FFM) and age (log AGE), as well as the log FFM × log AGE interaction (INTERACT) were entered as independent variables. The inclusion of the interaction term allowed for examination of whether the relationship between FFM and isokinetic peak torque varies as the function of age in these subjects. Significant interaction effects are analogous to violations of the homogeneity of the regression assumption in ANCOVA and indicate that a common scaling exponent for FFM should not be used across all ages in the study. The multiple regression analyses were performed using BMDP2R statistical software. An alpha level of 0.05 was employed for all analyses.

Results

The descriptive characteristics of the subjects are presented in Table 1. For each of the initial regression analyses, the log FFM, log AGE, and INTERACT effects were all statistically significant ($P < 0.05$). Because of the significant INTERACT effects, follow-up procedures involved performing separate multiple regression analyses for the younger and older wrestlers. For the younger wrestlers, both log FFM and log AGE were statistically significant factors in the regression analyses for both extension and flexion at all contraction velocities. However, none of the INTERACT effects were significant (see Figs. 1–6). The significant log AGE ef-

Fig. 1A, B Relationships between age fat free mass (FFM), and extension torque at 0.52 rad $\cdot$ s^{-1}. **A** Young club wrestlers. The curve was plotted from torque (TRQ) = $0.18 \cdot AGE^{1.06} \cdot FFM^{0.94}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −0.74 + 1.06(log AGE) + 0.94 (log FFM); $R^2 = 0.82$, $F_{2,105} = 234.9$, $P < 0.0001$. Both log AGE ($F_{1,105} = 43.0$, $P < 0.0001$) and log FFM ($F_{1,105} = 110.2$, $P < 0.0001$) were statistically significant, however the interaction effect was not significant ($F_{1,104} = 1.60$, $P = 0.21$). The 95% confidence interval for the FFM slope coefficient (0.94) was [0.76, 1.12]. **B** High-school wrestlers. The curve was plotted from TRQ = $0.89 \cdot AGE^{0.50} \cdot FFM^{0.92}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −0.05 + 0.50(log AGE) + 0.92(log FFM); $R^2 = 0.54$, $F_{2,147} = 87.3$, $P < 0.0001$. Both log AGE ($F_{1,147} = 6.8$, $P < 0.01$) and log FFM ($F_{1,147} = 143.9$, $P < 0.0001$) were statistically significant, however the interaction effect was not significant ($F_{1,146} = 0.01$, $P = 0.92$). The 95% confidence interval for the FFM slope coefficient (0.92) was [0.77, 1.08]



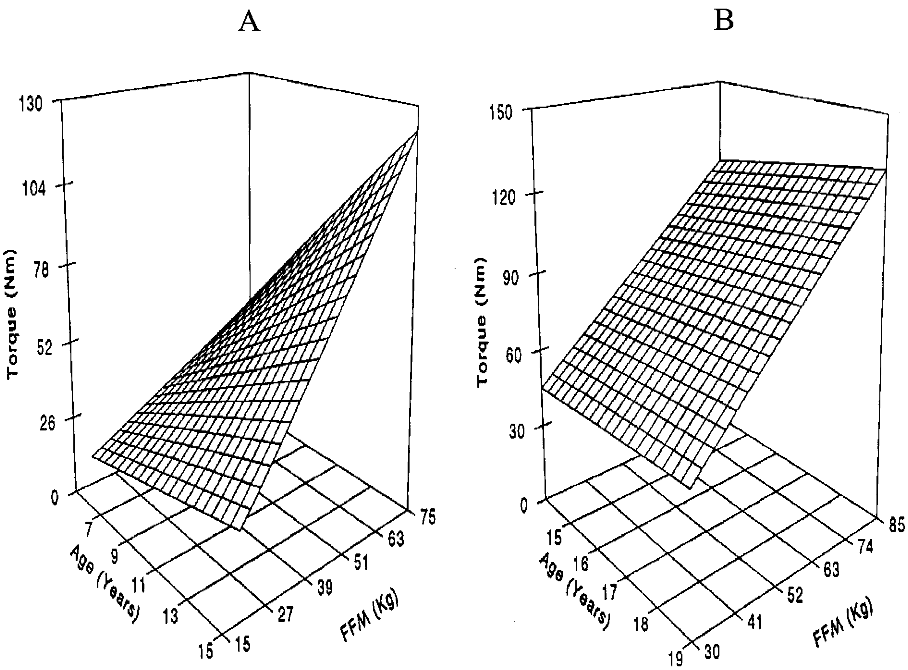
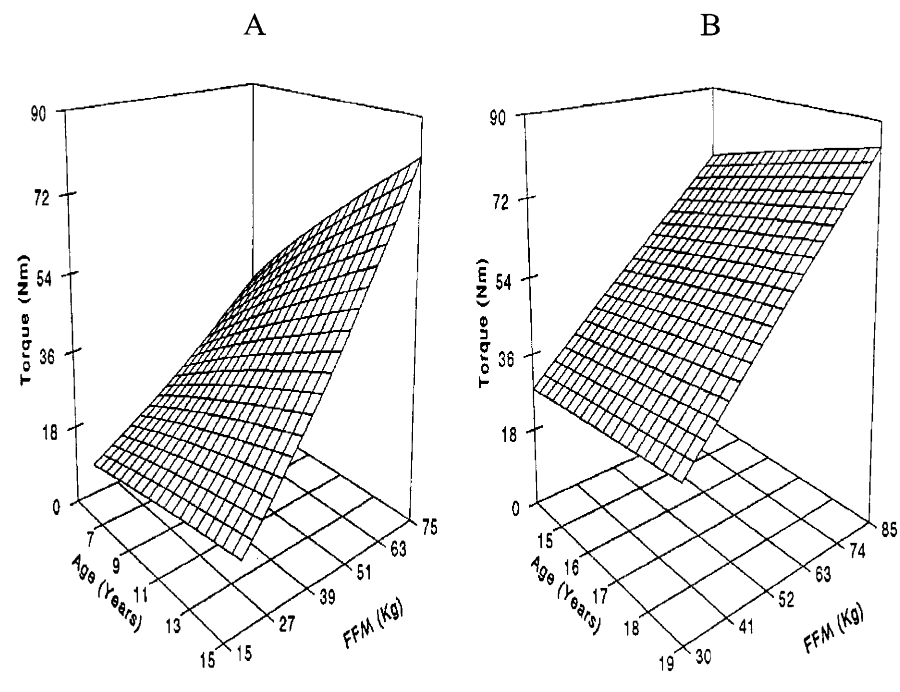


Fig. 2A, B Relationships between age, FFM, and extension torque at 3.14 rad $\cdot$ s^{-1}. **A** Young club wrestlers. The curve was plotted from TRQ = 0.07 $\cdot$ $AGE^{0.93}$ $\cdot$ $FFM^{1.16}$, which was based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −1.17 + 0.93(log AGE) + 1.16(log FFM); R^2 = 0.87, $F_{2,105}$ = 338.0, P < 0.0001. Both log AGE ($F_{1,105}$ = 38.6, P < 0.0001) and log FFM ($F_{1,105}$ = 197.8, P < 0.0001) were statistically significant, however the interaction effect was not significant ($F_{1,104}$ = 1.91, P = 0.17). The 95% confidence interval for the FFM slope coefficient (1.16) was [0.99, 1.32]. **B** High-school wrestlers. The curve was plotted from TRQ = 0.75 $\cdot$ $AGE^{0.37}$ $\cdot$ $FFM^{0.92}$, which is based on the antilog conversion of the following log-linear regression equation: log TRQ = −0.13 + 0.37(log AGE) + 0.92(log FFM); R^2 = 0.55, $F_{2,147}$ = 90.8, P < 0.0001.Both log AGE ($F_{1,147}$ = 4.11, P < 0.05) and log FFM ($F_{1,147}$ = 156.0, P < 0.0001) were statistically significant, however the interaction effect was not significant ($F_{1,146}$ = 0.09, P = 0.76). The 95% confidence interval for the FFM slope coefficient (0.92) was [0.77, 1.07]



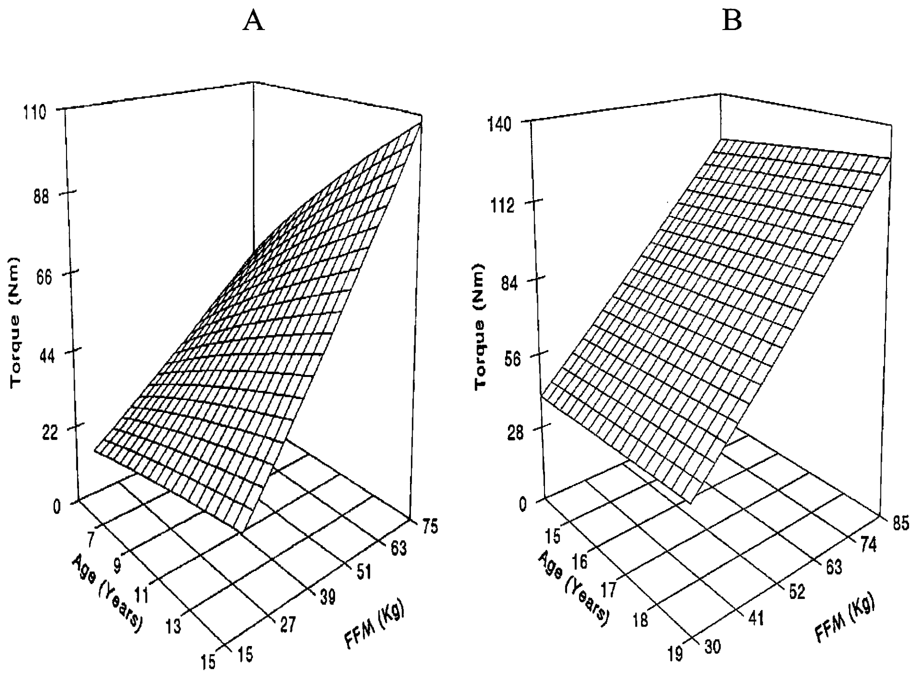


Fig. 4A, B Relationships between age, FFM, and flexion torque at 0.52 and rad · s^{-1}. **A** Young club wrestlers. The curve was plotted from $TRQ = 0.16 \cdot AGE^{0.60} \cdot FFM^{1.13}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −0.78 + 0.60(log AGE) + 1.13(log FFM); $R^2 = 0.79$, $F_{2,105} = 193.6$, $P < 0.0001$. Both log AGE ($F_{1,105} = 11.6$, $P < 0.0001$) and log FFM ($F_{1,105} = 137.8$, $P < 0.0001$) were statistically significant, however the interaction effect was not significant ($F_{1,104} = 1.32$, $P = 0.25$). The 95% confidence interval for the FFM slope coefficient (1.13) was [0.94, 1.32]. **B** High-school wrestlers. The curve was plotted from $TRQ = 0.62 \cdot AGE^{0.19} \cdot FFM^{1.07}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −0.21 + 0.19(log AGE) + 1.07(log FFM); $R^2 = 0.42$, $F_{2,147} = 53.4$, $P < 0.0001$. The factor log FFM was significant ($F_{1,147} = 97.2$, $P < 0.0001$), but log AGE ($F_{1,147} = 0.5$, $P = 0.48$) and the interaction effect ($F_{1,146} = 0.72$, $P = 0.40$) were not. The 95% confidence interval for the FFM slope coefficient in the two-factor model (1.07) was [0.86, 1.29], while in the model with FFM only, the slope coefficient (1.09) was [0.88, 1.30]

fects indicate that, within the younger wrestlers, isokinetic peak torque increased across age after controlling for the influence of FFM. The size of the FFM scaling exponents in the two-factor models for the younger wrestlers ranged from 0.94 (extension at 0.52 rad · s^{-1}) to 1.31 (extension at 3.14 rad · s^{-1}). All exponents, except that at 3.14 rad · s^{-1} for extension, included 1.0 within the 95% confidence interval.

For the high-school wrestlers, analyses of the leg extension data showed statistically significant effect for both log FFM and log AGE with non-significant effects for INTERACT (see Figs. 1–3). Therefore, similar to the younger wrestlers, isokinetic peak torque for leg extension increased with age even after controlling for FFM. For the analyses of the leg flexion data, however, only the log FFM effects were statistically significant (see Figs. 4–6), indicating that differences in flexion peak torque were associated with differences in FFM and were not associated with an age effect. As with the data from the younger wrestlers, all FFM exponents included 1.0 within the 95% confidence interval.

Because of recent concerns regarding lack of regression diagnostic evaluations in allometric analyses, the separate multiple regression analyses were examined for colinearity, heteroscedasticity, and appropriateness of model specification (Batterham and George 1997; Batterham et al. 1997b). The tolerance between age and FFM was 0.53 (variance inflation factor = 1.90) and 0.95 (variance inflation factor = 1.06) for the younger and older wrestlers, respectively, indicating relatively low colinearity. Examination of plots of predicted values versus residuals (Judd and McClelland 1989) indicated no discernible pattern (e.g., funnel) and thus no heteroscedasticity. As recommended by Batterham and George (1997), model specification was evaluated by examining plots of log FFM versus the raw residuals.

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Fig. 3A, B Relationships between age, FFM, and extension torque at 5.24 rad · s^{-1}. **A** Young club wrestlers. The curve was plotted from $TRQ = 0.05 \cdot AGE^{0.66} \cdot FFM^{1.31}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −1.32 + 0.66(log AGE) + 1.31(log FFM); $R^2 = 0.83$, $F_{2,105} = 261.8$, $P < 0.0001$. Both log AGE ($F_{1,105} = 14.6$, $P < 0.0001$) and log FFM ($F_{1,105} = 189.4$, $P < 0.0001$) were statistically significant, however the interaction effect was not significant ($F_{1,104} = 1.01$, $P = 0.32$). The 95% confidence interval for the FFM slope coefficient (1.31) was [1.12, 1.50]. **B** High-school wrestlers. The curve was plotted from $TRQ = 0.33 \cdot AGE^{0.48} \cdot FFM^{0.93}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = −0.48 + 0.48(log AGE) + 0.93(log FFM); $R^2 = 0.45$, $F_{2,147} = 61.0$, $P < 0.0001$. Both log AGE ($F_{1,147} = 4.5$, $P = 0.04$) and log FFM ($F_{1,147} = 101.2$, $P < 0.0001$) were statistically significant, however the interaction effect was not significant ($F_{1,146} = 0.02$, $P = 0.19$). The 95% confidence interval for the FFM slope coefficient (0.93) was [0.74, 1.11]

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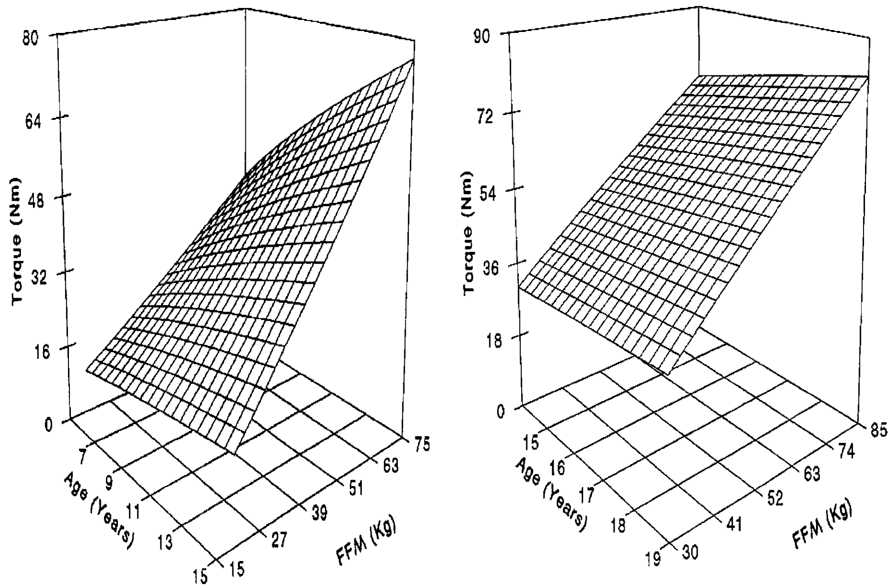

Fig. 5A, B Relationships between age, FFM, and flexion torque at 3.14 and rad · s^{-1}. **A** Young club wrestlers. The curve was plotted from TRQ = 0.12 · $AGE^{0.57}$ · $FFM^{1.14}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = –0.92 + 0.57 (log AGE) + 1.14(log FFM); R^2 = 0.79, $F_{2,105}$ = 203.0, P < 0.0001. Both log AGE ($F_{1,105}$ = 11.1, P < 0.0001) and log FFM ($F_{1,105}$ = 147.6, P < 0.0001) were statistically significant, however the interaction effect was not significant ($F_{1,104}$ = 0.73, P = 0.39). The 95% confidence interval for the FFM slope coefficient (1.14) was [0.94, 1.32]. **B** High-school wrestlers. The curve was plotted from TRQ = 0.57 · $AGE^{0.43}$ · $FFM^{0.83}$, which is based on the antilog conversion of the following log-linear multiple regression equation: log TRQ = –0.24 + 0.43(log AGE) + 0.83(log FFM); R^2 = 0.36, $F_{2,147}$ = 41.2, P < 0.0001. The factor log FFM was significant ($F_{1,147}$ = 68.6, P < 0.0001), but log AGE ($F_{1,147}$ = 2.92, P = 0.09) and the interaction effect ($F_{1,146}$ = 1.05, P = 0.31) were not. The 95% confidence interval for the FFM slope coefficient in the two-factor model (0.83) was [0.63, 1.04], while in the model with FFM only, the slope coefficient (0.87) was [0.68, 1.07]

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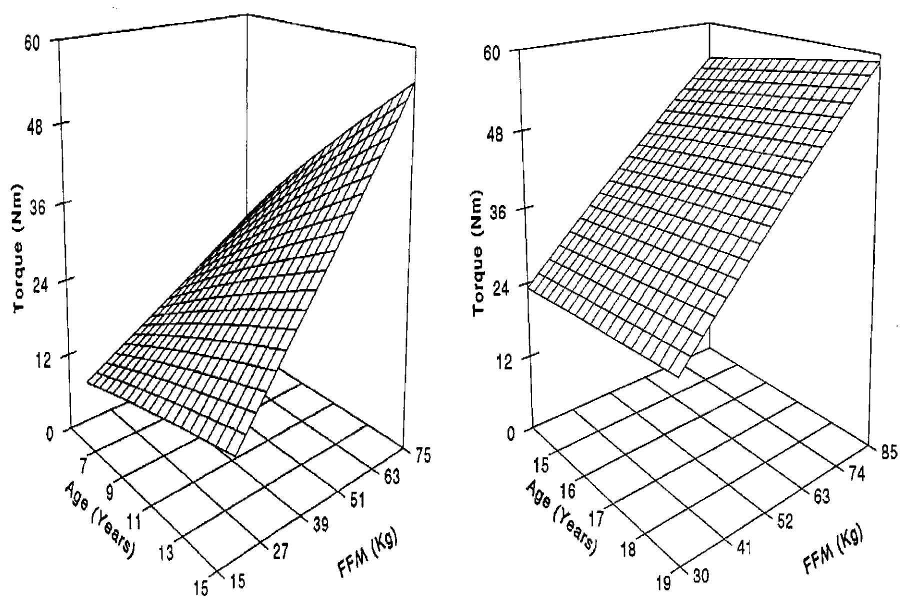

No systematic variations were apparent in the plots, and the correlations ranged from −0.004 to 0.006. In addition, the correlations between FFM and $[T/(\text{age}^{b1} \cdot \text{FFM}^{b2})]$ ranged from −0.04 to 0.02 and between age and $[T/(\text{age}^{b1} \cdot \text{FFM}^{b2})]$ ranged from −0.04 to 0.02, indicating the allometric models effectively removed the influence of age and FFM from the torque data.

Discussion

The results of the initial analyses show significant interaction effects between log AGE and log FFM. These effects were found at all contraction velocities for both extension and flexion. The significant interactions indicated that the relationship between FFM and isokinetic peak torque differed across age. That is, the effect of body size on strength varies across age. The nature of the interactions can be seen in the differences in the shape of the curves between age groups presented in Figs. 1–6. To further examine these interaction effects, separate regression analyses were performed for the younger and older wrestlers. Within each group, the interaction effects between log AGE and log FFM were not significant, while all log FFM main effects were significant. In the younger wrestlers, after accounting for the variance due to log FFM, log AGE was a significant factor in the multiple regression analyses. This effect was found at all contraction velocities for both extension and flexion. The positive exponents for age indicate that within the younger wrestlers, increases in age were associated with increases in peak torque, even after accounting for the age-associated increase in FFM. For the high-school wrestlers, age was a significant factor for the extension peak torque data, but not for flexion.

Based on these follow-up procedures, the interaction effects in the initial analyses indicate the following. For the leg extension data, the age exponents were larger for the younger than for the high-school wrestlers (see Figs. 1–3), indicating that at a given level of FFM, differences in age have a larger effect on isokinetic peak torque for the younger wrestlers than the older wrestlers. For the leg flexion data, the age exponents were statistically significant for the younger, but not the older wrestlers (see Figs. 4–6), indicating that for high-school wrestlers, FFM was the primary determinant of differences in isokinetic peak torque, while age had no effect. However, in the younger wrestlers, both age and FFM were significant factors. Differences in strength development across age between muscle groups have been reported by Kanehisa et al. (1995). Specifically, plantarflexion strength, ratio-scaled for differences in cross-sectional area and limb length, was greater in teenage boys than in younger boys. However, similar effects were not found for the dorsiflexors. Muscle-group-specific differences in strength development across age require further study.

Examination of FFM exponents across velocities and movements (flexion and extension) between the two groups indicates a trend for lower values in the older wrestlers, suggesting a smaller influence of FFM in the older versus younger subjects. It should be noted, however, that the 95% confidence intervals for these exponents overlapped for the two groups, with the exception of extension peak torque at 5.24 rad · s^{-1}. In addition, with the exception of the extension data for the younger wrestlers at 3.14 rad · s^{-1}, all of the values included 1.0 in the 95% confidence interval. While the size of the scaling exponents should be interpreted with caution (Batterham et al. 1997b), it is interesting to note that 1.0 is consistent with the predicted value for torque based on dimensionality theory (Astrand and Rodahl 1986).

The R^2 values for the older wrestlers were lower (0.29–0.55) than those of the younger wrestlers (0.79–0.87), indicating that most of the variance in isokinetic peak torque in the younger wrestlers was accounted for by age and FFM, while unknown factors play a larger role in peak torque differences in the older subjects. Differences in physical activity may be one of these factors, however the nature of high-school wrestling participation presumes high levels of physical activity, and we do not have additional data quantifying activity level in these subjects.

We have previously reported an age effect for isokinetic strength, in which increases in age, independent of differences in FFM or body mass, are associated with higher levels of peak torque. These results extend those findings, and indicate that the magnitude of the age effect varies across age groups. Specifically, the effect is larger for younger wrestlers. In addition, the effect does not appear to be consistent across muscle groups, since the knee flexion peak torque was not associated with age in the high-school wrestlers. From a practical standpoint, these results suggest that matching of competitors for fair competition requires tight matching for age as well as body size in young wrestlers.

The significant main effects for age in the extension data for each age group and in the flexion data for younger wrestlers is consistent with previous studies that

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Fig. 6A, B Relationships between age, FFM, and flexion torque at 5.24 rad · s^{-1}. **A** Young club wrestlers. The curve was plotted from $\text{TRQ} = 0.09 \cdot \text{AGE}^{0.73} \cdot \text{FFM}^{1.04}$, which is based on the antilog conversion of the following log-linear multiple regression equation: $\log \text{TRQ} = -1.07 + 0.72(\log \text{AGE}) + 1.04(\log \text{FFM})$; $R^2 = 0.81$, $F_{2,105} = 218.2$, $P < 0.0001$. Both log AGE ($F_{1,105} = 20.1$, $P < 0.0001$) and log FFM ($F_{1,105} = 137.9$, $P < 0.0001$) were statistically significant, however the interaction effect was not significant ($F_{1,104} = 0.05$, $P = 0.82$). The 95% confidence interval for the FFM slope coefficient (1.04) was [0.87, 1.22]. **B** High-school wrestlers. The curve was plotted from $\text{TRQ} = 0.68 \cdot \text{AGE}^{0.29} \cdot \text{FFM}^{0.81}$, which is based on the antilog conversion of the following log-linear multiple regression equation: $\log \text{TRQ} = -0.17 + 0.29 (\log \text{AGE}) + 0.81 (\log \text{FFM})$; $R^2 = 0.29$, $F_{2,147} = 30.4$, $P < 0.0001$. The factor log FFM was significant ($F_{1,147} = 52.9$, $P < 0.0001$) but log AGE ($F_{1,147} = 1.14$, $P = 0.29$) and the interaction effect ($F_{1,146} = 0.04$, $P = 0.84$) were not. The 95% confidence interval for FFM slope coefficient in the two-factor model (0.81) was [0.59, 1.03], while in the model with FFM only, the slope coefficient (0.84) was [0.62, 1.05] show an age effect for isokinetic peak torque. The age effect, in which increases in strength across age are larger than can be attributed to concomitant increases in body size (e.g., FFM) have also been reported for young male (Thorland et al. 1990) and female (Thorland et al. 1987) distance runners. At present, we do not know to what extent strength increases across age are affected by supporting activities versus normal growth and development. However, several hypotheses can be put forward to explain these effects. First, neuromuscular development occurs across the age groups represented in this investigation. For example, myelination of motor neurons is not complete until sexual maturity is achieved (Brooks and Fahey 1985). In addition, muscle fiber conduction velocity has been shown to increase across age in children (Malmstrom and Lindstrom 1997). How developmental changes such as these affect the expression of strength is unclear, however Blimkie (1989), based on data using the interpolated twitch technique, has reported an ability to activate a higher percentage of available motor units in 16- vs 11-year-old boys. These results suggest that strength differences across age may be at least partially due to an enhanced ability of older children to activate muscle mass.

Second, a change in the proportion of FFM that is composed of skeletal muscle has been suggested to contribute to the age effect (Housh et al. 1996). We have reported previously that anthropometric estimates of total skeletal muscle mass (Housh et al. 1995) and muscle cross-sectional area (Housh et al. 1997) do not completely account for age-related increases in strength. However, to date there are no published studies in which the development of muscle mass and the physiological cross-sectional area have been examined using direct measures in children and adolescents. Such studies would require a combined assessment of FFM and measures of skeletal muscle such as that obtained with multi-slice magnetic resonance imaging. Furthermore, the proportion of muscle mass that is distributed at different sites varies during growth and development. Malina (1969) reported that at birth, approximately 40% of total muscle mass is located in the lower extremities, but this value increases to about 55% at sexual maturity. Thus, of the FFM determined in this study, a larger percentage is likely to be lower-extremity muscle mass in older subjects, resulting in higher FFM-adjusted strength in older subjects.

In addition, there may be developmental changes occurring in the muscle tissue itself. Welsman et al. (1996) and Cooper et al. (1984) have shown increases in peak oxygen uptake in older children after allometrically controlling for differences in body mass. An age effect for peak oxygen uptake may be due to age-related improvements in oxygen delivery capability and/or oxygen utilization. The latter effect suggests modifications in the muscle tissue, and Cooper et al. (1984) have suggested that differences in force production per unit of cross-sectional area of muscle may explain their results. Similar changes in the muscle-specific tension could at least partially account for the age effect in isokinetic peak torque reported both here and elsewhere (Thorland et al. 1987, 1990).

In summary, the results of this investigation indicate that, in general, increases in the isokinetic peak torque across age exceed those that could be explained by increases in FFM. In addition, the significant interaction effects shown in the combined data from both age groups indicate that the relationship between FFM and isokinetic peak torque for leg extension and flexion differ across age. Notably, the age effects were greater in the younger than the older wrestlers. These effects may be due to age-associated developments in the neuromuscular system, alterations in the distribution of muscle mass (both within the FFM fraction of the body as well as across body segments), changes in muscle contractile function, or some combination of these factors.

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