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Normalizing Lower Extremity Strength Data for Children, Adolescents, and Young Adults With Cerebral Palsy

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The traditional method for normalizing quantitative strength data is to divide force or torque by body mass. We have previously shown that this method is not appropriate for able-bodied children and young adults and that normalization using allometric scaling is more effective. The purpose of the current study was to evaluate the effectiveness of applying existing normalization equations for lower extremity strength to children, adolescents, and young adults with cerebral palsy (CP) and, if appropriate, to develop CP-specific normalization equations using allometric scaling. We measured the maximum torque generated during hip abduction/adduction, knee extension/flexion, and ankle dorsiflexion/plantar flexion in 96 subjects with spastic diplegia CP ages 4–23 years. Traditional mass normalization (Torque/Mass$^{1.0}$) and allometric scaling equations from children without disability (Torque/Mass$^{1.6}$ for hip and knee; Torque/Mass$^{1.4}$ for ankle) were not effective in eliminating the influence of body mass. Normalization using CP-specific allometric scaling equations was effective using both muscle-specific and common (Torque/Mass$^{0.8}$ for ankle plantar flexors; Torque/Mass$^{1.4}$ for all others) scaling relationships. For the first time, normalization equations have been presented with demonstrated effectiveness in adjusting strength measures for body size in a group of children, adolescents, and young adults with CP.

Keywords: growth, body size, torque, muscle development

A major impairment in individuals with cerebral palsy (CP) is weakness or lack of strength (Damiano et al., 1995; Engsberg et al., 1998a, 2000a, 2000b; Kramer & MacPhail, 1994a). When quantifying strength in patients with CP, the most common method of normalization is to divide force or torque by body mass (in kilograms) (Damiano et al., 1995; Engsberg et al., 1998a, 2000a; 2000b; Kramer & MacPhail, 1994a). This normalization is performed to account for differences in body size and to permit equitable comparisons among individuals or groups, over time, or as a consequence of an intervention. However, the effectiveness of this commonly used normalization procedure has not been evaluated in young patients with CP.

We previously investigated different methods of normalizing lower extremity strength measurements in pediatric subjects without disability and found that traditional mass normalization was not effective (Wren & Engsberg, 2007). Normalization by mass × height was better, but still failed to appropriately adjust for body size in many muscle groups. The most effective normalization involved allometric scaling, an approach based on a power law equation that is widely used to normalize physiological variables in other fields (Jaric, 2002; Nevill et al., 2005). In this approach, the variable of interest, e.g., muscle strength (S), is modeled as a function of a confounding variable, e.g., body mass (m), by the equation $S_n = S/m^b$ (Eq. 1), where S_n is the normalized strength and b is the allometric scaling parameter (Jaric, 2002). The exponent (b) can be determined either through theoretical analysis or through empirical fitting of experimental data. For the theoretical method, geometric similarity is usually assumed (area $\propto$ length^2, mass $\propto$ volume $\propto$ length^3). Under this assumption, the scaling parameter would be $b = 1.0$ for muscle torque (torque $\propto$ area $\times$ length $\propto$ length^3) and $b = 0.67$ for muscle force (force $\propto$ area $\propto$ length^2) (Jaric, 2002). A value of $b = 1.0$ for muscle torque represents the typical normalization procedure.

In subjects without disability, we found that a single allometric scaling equation could be used to normalize torques at the hip and knee (Torque/Mass$^{1.6}$) and that a different equation was required for the ankle (Torque/

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$\text{Mass}^{1.4}$) (Wren & Engsberg, 2007). Since CP affects muscle anatomy and physiology (Castle et al., 1979; Friden & Lieber, 2003; Tardieu et al., 1982a; Tardieu et al., 1982b), it is unclear whether these equations will also provide appropriate normalization for patients with CP. The purposes of this investigation were therefore (1) to evaluate the effectiveness of existing normalization equations for lower extremity strength in children, adolescents, and young adults with spastic diplegia CP and (2) if appropriate, to develop separate normalization equations for these subjects using allometric scaling.

Methods

This study retrospectively examined strength data from 96 subjects (48 male, 48 female) with spastic diplegia CP, ages 4–23 years (Ross & Engsberg, 2007). The participants were at least 1 year post orthopedic surgery, 6 months post Botox, and had no history of spasticity altering surgeries (Baclofen pump, selective dorsal rhizotomy) before testing. The majority of the participants (66%) were independent ambulators with a relatively equal distribution between Gross Motor Function Classification System (GMFCS) Levels I–III (N = 33, 37, 26 for GMFCS Levels I, II, III, respectively; Palisano et al., 1997). Since preliminary analyses indicated no significant differences in the relationship between body mass and peak torques between males and females, the data from both sexes were pooled. All participants or parents (when appropriate) signed an informed consent approved by the Washington University Internal Review Board.

All subjects underwent testing on an isokinetic dynamometer (KinCom, Chattanooga Group, Hixson, TN) to determine the maximum torque they could produce for the ankle plantar flexors/dorsiflexors, knee flexors/extensors, and hip adductors/abductors (Engsberg et al., 1998a, 1998b, 1999, 2000a, 2000b, 2002, 2006). Previous investigations have indicated acceptable reliability ($r > .81$) for dynamometer strength testing in children with able bodies, mild retardation, and spastic diplegia (Kramer & MacPhail, 1994b; Molnar et al., 1979). For the ankle, subjects sat on the dynamometer's seat and had their ankle joint axis aligned with the center of rotation of the KinCom lever arm (Engsberg et al., 1999, 2000a). The pelvis and thigh were secured with Velcro straps. A custom footplate including Velcro straps was made to securely hold small feet on the plate. The hip was placed in about a 90° angle, while the knee was in about 25° of flexion. Wedges and other support structures were used to permit children of all sizes to achieve these positions. The testing was performed in a barefoot condition.

A physical therapist established the range-of-motion limits for ankle dorsiflexion and plantar flexion. Each subject actively moved his or her ankle at 10°/s from end-range ankle dorsiflexion to end-range plantar flexion, and vice versa, to obtain maximum concentric contractions of the ankle plantar flexors and dorsiflexors, respectively. A movement speed of 10°/s in the passive mode was selected since previous experimentation indicated that some children could not produce enough torque to initiate movement of the KinCom's support arm and others could not "keep up" with the arm at faster speeds. Isometric contractions were not used because they did not quantify torque over an entire range of motion, thereby potentially missing the joint angle where the greatest torque could be produced (Engsberg et al., 1998a). Thus, 10°/s was a slow enough speed to be close to an isometric contraction, but strength was assessed over the entire range of joint motion.

For the knee, each subject was seated in a similar position as with the ankle testing, which included thigh and pelvis straps (Engsberg et al., 1998a). The knee joint axis was aligned with the center of rotation of the KinCom lever arm. The leg of the subject was attached to the KinCom support arm with Velcro straps. The range was from full knee extension to about 60° below the horizontal, and the movement speed was again 10°/s.

For the hip, each subject lay supine on the KinCom dynamometer bench and had their hip joint abduction/adduction axis aligned with the center of the KinCom lever arm (Engsberg et al., 2000b). The pelvis was stabilized with a belt and with the aid of a research assistant. End-range hip abduction/adduction limits were established by the physical therapist with a slight amount of hip flexion to permit the heel to clear the bench during the movement. Range of motion limits were set at the point where further movement in a direction resulted in lateral pelvic tilt. Caution was taken to maintain the lower extremity in resting knee extension and neutral rotation within the participant's bony alignment limits. The movement speed was 10°/s.

Three to 5 repetitions of each movement were performed to permit the subjects to achieve their best performance; however, only the test results indicating the greatest amount of torque produced were used in the analysis. Determining the best performance was relatively simple since the dynamometer automatically overlaid the data on the monitor for consecutive tests. The maximum torque values were recorded for each movement.

The strategy to investigate the normalization of the CP strength data followed a similar path as our previous work on children without disability (Wren & Engsberg, 2007). First, the traditional normalization method of simply dividing the strength value by subject mass ($\text{Torque}/\text{Mass}^{1.0}$) was examined using linear regression versus body mass. Similar analysis was performed for normalization by subject mass and height ($\text{Torque}/\text{Mass} \times \text{Height}$). An effective normalization scheme would produce regressions with a slope not significantly different from zero. Two-tailed t tests with $\alpha = .05$ were used to determine if the slopes differed significantly from zero.

Next, we examined whether the normalization procedure that was effective for subjects without disability

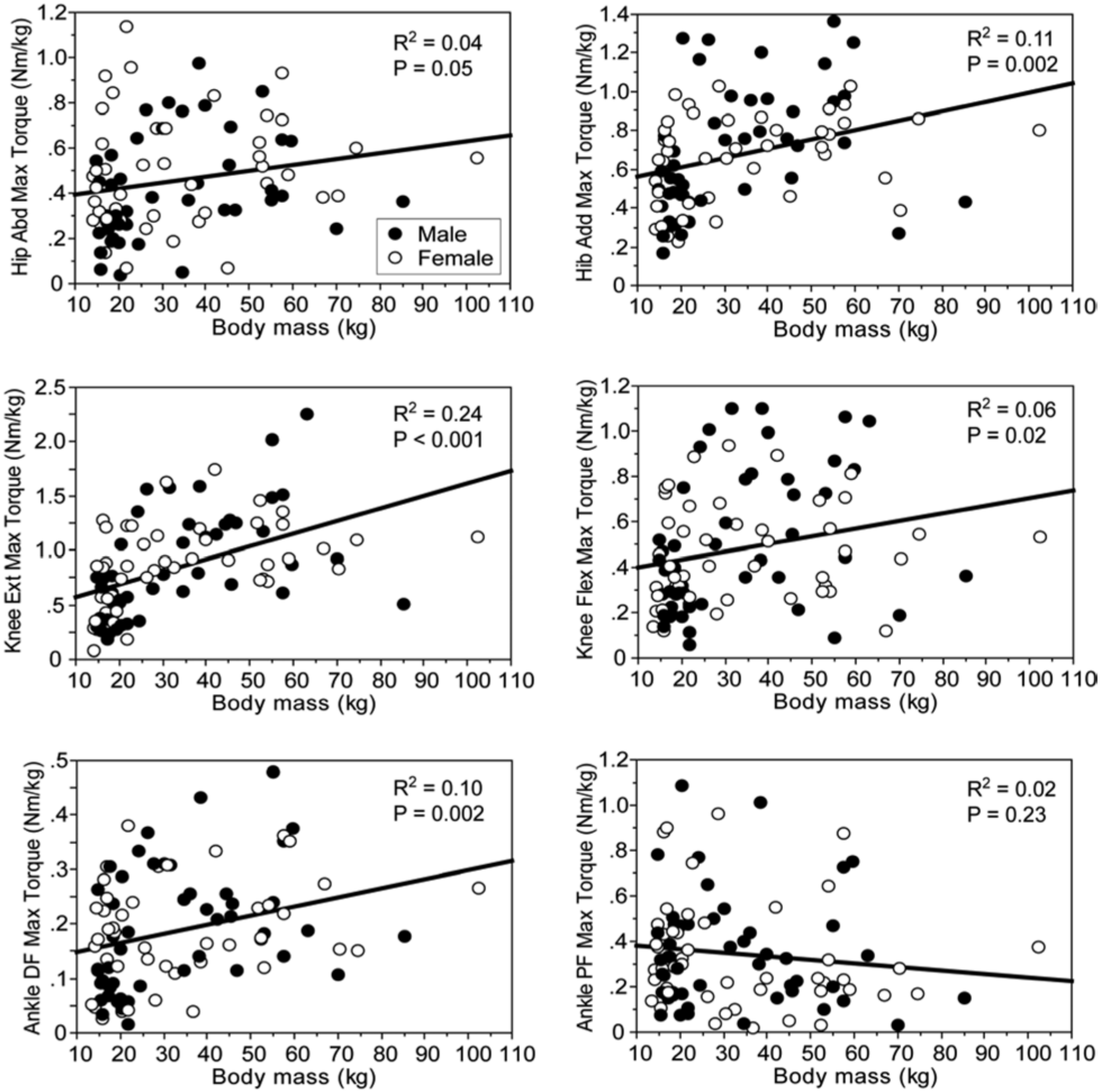

Figure 1 — Regression results for traditional mass normalization. Dependence on body mass remains after normalization except for ankle plantar flexors and possibly hip abductors.

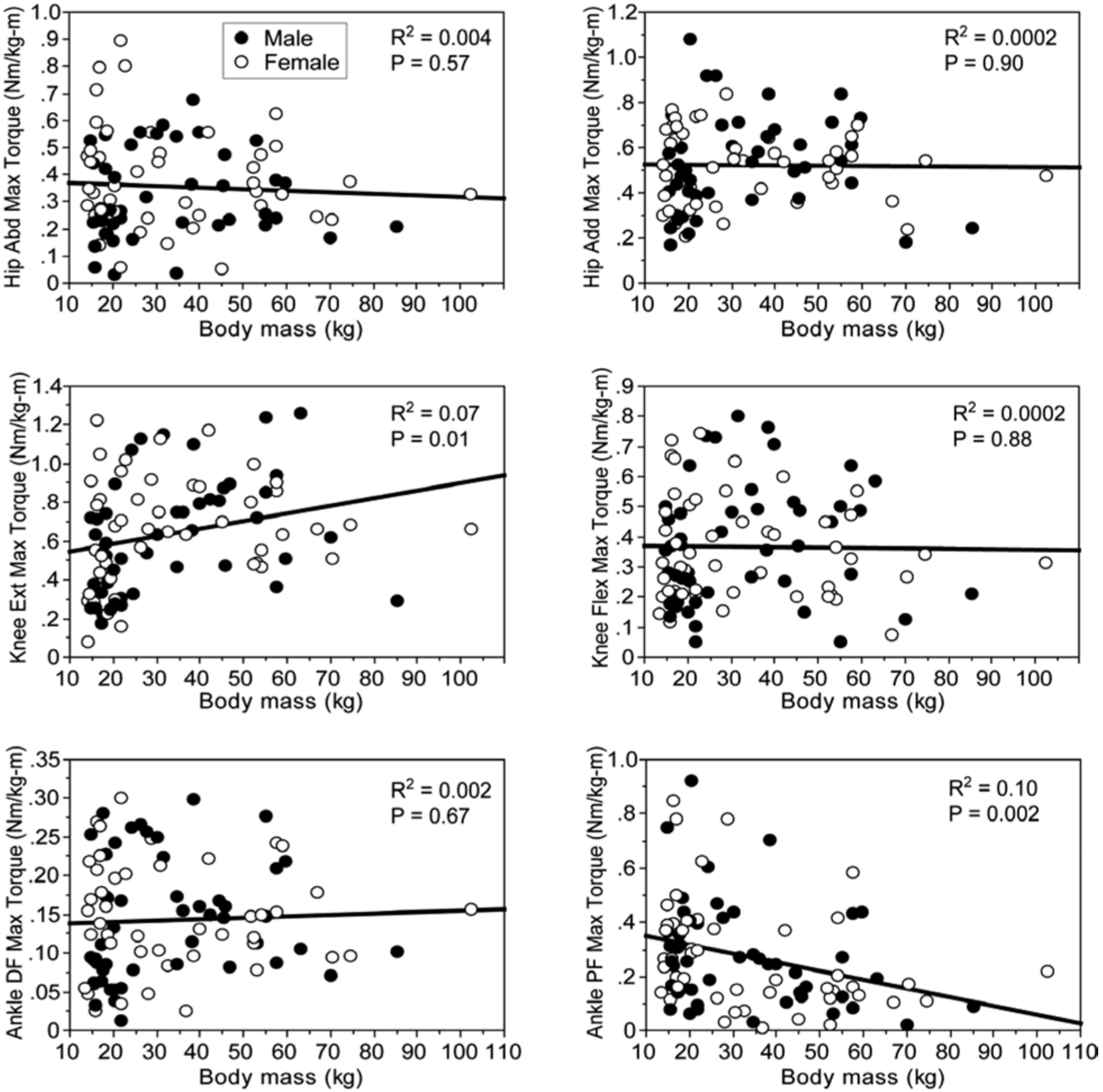

Figure 2 — Regression results for normalization by Mass × Height. Dependence on body mass remains after normalization for knee extensors and ankle plantar flexors.

(Wren & Engsberg, 2007) would be equally effective for subjects with CP. This normalization procedure involved dividing the hip and knee torques by body mass to the 1.6 power (i.e., $b = 1.6$ in Eq. 1) and dividing ankle torques by body mass to the 1.4 power (i.e., $b = 1.4$ in Eq. 1). If this were an effective normalization scheme, then the regressions versus body mass would produce slopes not significantly different from zero. Two-tailed t tests with $\alpha = .05$ were used to determine if the slopes differed significantly from zero.

If the previous steps failed to establish an effective normalization procedure for the children with CP, the next step was to use the allometric scaling equation ($S_n = S/m^b$; Eq. 1) to determine $b = b_{\mathrm{musc}}$ for each muscle group. This was done by fitting a best-fit power curve ($S = S_n \times m^b$) to the experimental data for the participants with CP, where S is the measured torque, m is body mass, and S_n and b_{musc} are the empirically determined curve fit parameters. Ninety-five percent confidence intervals (CI) for b_{musc} were used to determine whether the exponents differed significantly from the theoretical value of 1.0. As with the previous steps, each allometric normalization equation was applied to the data and tested to determine if its slope from linear regression versus body mass was different from zero.

Finally, in an attempt to establish a single exponent (b_{avg}) that could be used to normalize the strength data for the major muscles of the lower extremity (i.e., hip, knee, and ankle) for children with CP, an average value b_{avg} was calculated from the different values obtained from each of the six muscle groups. The torques from each muscle group were normalized using this average exponent, and the results were again tested to determine if the slopes from linear regression differed significantly from zero.

Results

The initial linear regressions with Torque/Mass$^{1.0}$ (simple mass normalization having $b = 1$) indicated that the slopes for the hip adductor, knee flexor and extensor, and ankle dorsiflexor muscles differed significantly from zero ($p \leq .02$; Figure 1). The slope for the ankle plantar flexors did not differ significantly from zero ($p = .23$), and the slope for the hip abductors bordered on statistical significance ($p = .05$).

Normalization by Mass × Height performed better than the simple mass normalization. Slopes for the hip abductors and adductors, knee flexors, and ankle plantar flexors did not differ significantly from zero ($p > .57$; Figure 2). However, slopes for the knee extensors and ankle plantar flexors did differ from zero ($p \leq .01$).

Using normalization equations derived from children without disability also did not fully eliminate the mass dependence of the muscle torques. While the knee extensors and ankle dorsiflexors produced slopes that did not differ significantly from zero after this normalization ($p > .60$), the slopes still differed from zero for the hip abductors and adductors, knee flexors, and ankle plantar flexors ($p \leq .01$).

The results for determining CP-specific allometric scaling exponents indicated different values of b_{musc} for each muscle group (Table 1). The exponents differed significantly from the theoretical value of 1.0 for all measures except ankle plantar flexion (Table 1). The slopes from the linear regressions with different values of b_{musc} for each muscle group indicated no significant difference from zero ($p \geq .17$).

An average value of the scaling exponent ($b_{\mathrm{avg}} = 1.4$) was calculated from the values for the individual muscle groups excluding the ankle plantar flexors, which clearly differed from the others. The slopes from the linear regressions using b_{avg} for all muscle groups except the ankle plantar flexors indicated no significant differences from zero ($p \geq .15$; Figure 3). The separate value of $b_{\mathrm{PF}} = 0.8$ was retained for the ankle plantar flexors.

Discussion

The influence of growth and size on muscle strength is well recognized. However, there has been no systematic approach to adjusting for size when assessing strength. Most studies use either simple mass normalization or no normalization (Damiano et al., 1995; Engsberg et al., 1998a, 2000a, 2000b; Jaric, 2002; Kramer & MacPhail, 1994a) although other approaches such as normalization by weight × height (Buckon et al., 2002) and allometric

Table 1 Allometric scaling parameters (*b*) for maximum torque versus body mass

	Scaling parameter (95% CI)	
	Children with Cerebral Palsy (current study)	**Children without Disability (Wren & Engsberg, 2007)**
Hip abduction	1.32* (1.06–1.58)	1.66* (1.35–1.98)
Hip adduction	1.35* (1.19–1.52)	1.68* (1.36–2.00)
Knee extension	1.69* (1.50–1.88)	1.87* (1.54–2.21)
Knee flexion	1.33* (1.10–1.56)	1.59* (1.35–1.84)
Ankle dorsiflexion	1.49* (1.24–1.74)	1.47* (1.27–1.68)
Ankle plantar flexion	0.75 (0.43–1.06)	1.32 (0.98–1.67)

*Indicates significant difference from 1.0.

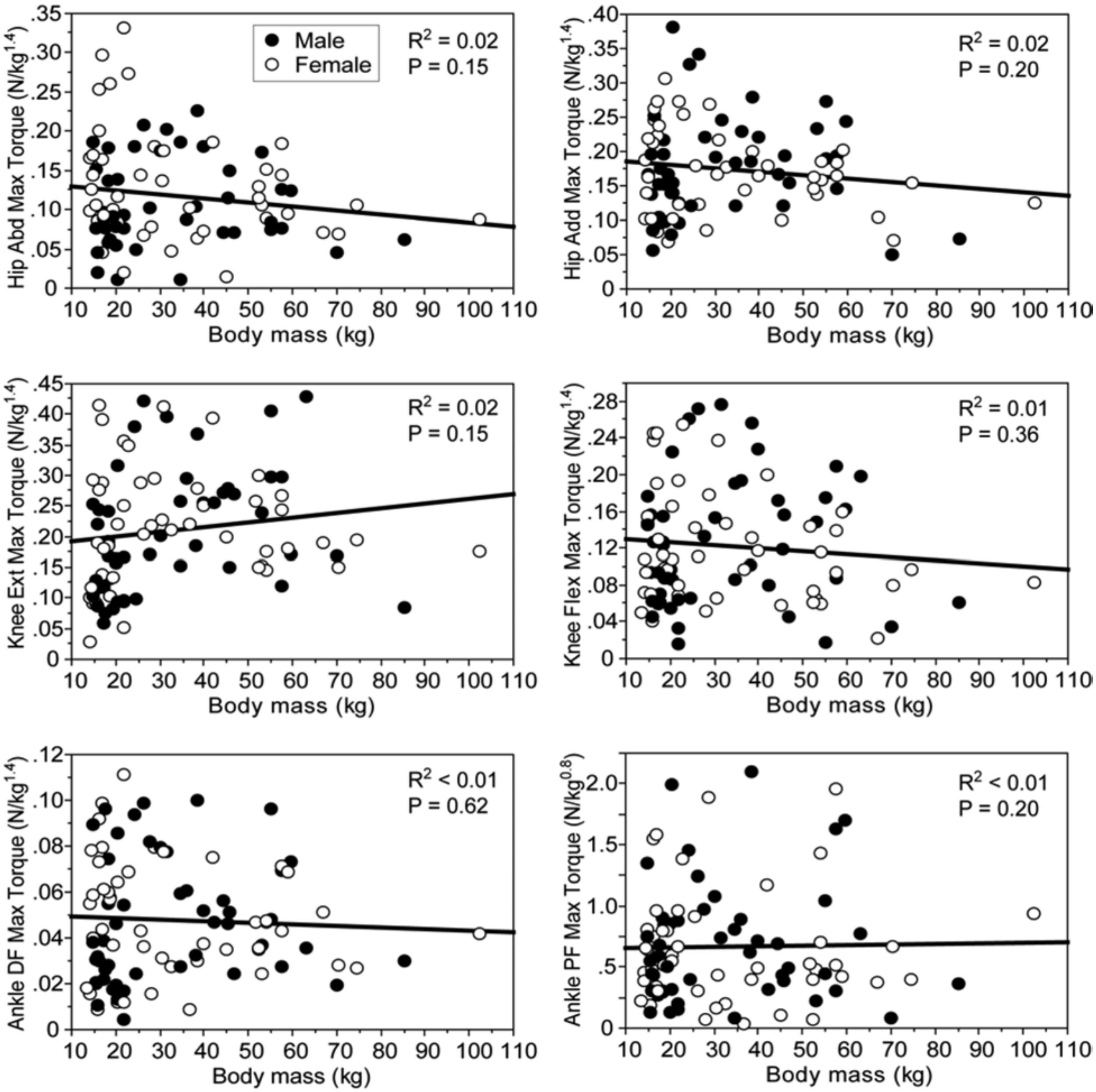

Figure 3 — Regression results using allometric scaling with a common exponent ($b_{\text{avg}} = 1.4$) for all muscle groups except the ankle plantar flexors ($b_{\text{PF}} = 0.8$). Mass dependence of the peak torques is eliminated for all muscle groups.

scaling (Wren & Engsberg, 2007) have also been applied. The present investigation is the first to examine the effectiveness of these normalization procedures in children, adolescents, and young adults with CP. We found that the existing normalization equations do not always work for these subjects and therefore derived separate normalization equations for this population. This is the first study to offer specific scaling factors that would effectively normalize strength data of all muscle groups from young subjects with CP of varying size.

The results of this study are similar to our investigation of subjects without disability in that simple mass normalization of lower extremity torques does not effectively adjust for size in children with CP. Joint torques (except for ankle plantar flexors) continue to increase with body mass after simple mass normalization (Figure 1). Furthermore, it appears that the allometric scaling equations from children without disability also do not effectively adjust for size in children with CP. Using these scaling factors, normalized joint torques decrease as body mass increases, perhaps indicating that throughout development individuals with CP tend to fall further and further behind relative to their peers without disability. This interpretation is supported by the fact that the scaling exponents were generally lower for the subjects with CP. These exponents indicate the degree to which strength increases as a function of size, with lower exponents reflecting lesser gains in strength. For both groups of subjects, the highest exponent was for knee extension. This would be expected since the knee extensors are the strongest muscle group and therefore experience the greatest increases in torque generation during growth. The different patterns of strength development in different muscle groups reinforce the need for a general normalization approach that can be adapted to each muscle group, rather than a fixed approach for all muscles (such as division by body mass).

There are several limitations of the present investigation. These are primarily related to the limited size of the sample available for analysis and the variability among subjects, which results in large confidence intervals for the scaling parameters. In this sample, we did not observe any differences in strength between genders. However, such differences may appear as the children pass through puberty (Ahmad et al., 2006; Jones et al., 2000; Kanehisa et al., 2006; Ramos et al., 1998; Sinaki et al., 1996), raising the possibility that different allometric scaling exponents would be required for boys and girls after a certain age or maturity level. In addition, there may be differences between GMFCS levels that we were not able to detect in the current investigation. For the subjects in this study, we observed that children in GMFCS Level III tended to have lower strength values than children in GMFCS Level I, but there were no noticeable differences in the *relationship* between strength and body mass (e.g., the regressions were shifted in magnitude but had a similar slope). Finally, due to the large confidence intervals of the CP-specific allometric scaling parameters derived in this study, the proposed normalization equations should be considered preliminary. These equations need to be tested on additional subjects and may need to be refined through analysis of a much larger group of subjects than is available at this time.

The scaling equations presented in this study are only appropriate for ambulatory subjects with CP. They should not be used for other patients with CP or for persons without CP. This reflects the fact that the method used to adjust for body size should be selected, at least in part, based on the application. If the intent is to compare subjects with CP versus subjects without disability, then CP-specific scaling equations are not appropriate. In this case, the normalization from children without disability could be used, and children with CP would be expected to show decreased strength values as age and body mass increase. If, however, only subjects with CP are being examined, the CP-specific scaling is preferable. This scaling would reveal deviations from the expected strength development for patients with CP and should be applicable at all time points in longitudinal or cross-sectional studies. An alternative to scaling equations is to develop reference curves (similar to growth charts) that would allow a child's strength to be expressed as a percentile or z score. While a large amount of data must be collected to develop such references, they could enable simultaneous comparisons to normal development, patients with CP in general, or patients with CP in a specific GMFCS level.

In summary, because maximum torques at the hip, knee, and ankle do not scale geometrically with body mass, simple mass normalization may not be an appropriate measure for cross-sectional or longitudinal comparisons of strength in children, adolescents, and young adults with CP. Furthermore, the allometric scaling equations determined for individuals without disability are not effective for patients with CP. CP-specific allometric scaling equations such as those derived in this study may provide more effective normalization.

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