Journal of Sport Rehabilitation, 2011, 20, 311-320
© 2011 Human Kinetics, Inc.

The Effects of Anthropometric Scaling Parameters on Normalized Muscle Strength in Uninjured Baseball Pitchers

Wendy J. Hurd, Bernard F. Morrey, and Kenton R. Kaufman

Context: Muscle force must be normalized for between-subjects comparisons of strength to be valid. The most effective method for normalizing muscle strength has not, however, been systematically evaluated. ***Objective:*** To evaluate the effects of normalizing muscle strength using a spectrum of anthropometric parameters. ***Design:*** Cross-sectional. ***Setting:*** Laboratory. ***Participants:*** 50 uninjured high-school-age baseball pitchers. ***Interventions:*** Shoulder-rotation strength was tested at 0° and 90° abduction with a handheld dynamometer. Muscle force was normalized to parameters including subject height, weight, height × weight, body-mass index (BMI), forearm length, and forearm length × height. ***Outcome Measures:*** Statistical analysis included evaluating the coefficient of variation, skewness, and kurtosis of the nonnormalized and normalized muscle force. The most effective normalization method was determined based on the scaling factor that yielded the lowest variability for the data set and promoted the most normal distribution of the data set. ***Results:*** Using body weight to scale muscle force was the most effective anthropometric parameter for normalizing strength values based on the group of statistical measures of variability. BMI, height × weight, and forearm length × weight as scaling factors also yielded less variable values for muscle strength compared with nonnormalized strength, but less consistently than body weight. Height and forearm length were least effective in reducing the variability of the data set relative to nonnormalized muscle force. ***Conclusion:*** This study provides objective support for scaling muscle strength to subject body weight. This approach to normalizing muscle strength uses methods readily accessible to clinicians and researchers and may facilitate the identification of differences in strength between individuals with diverse physical characteristics.

Keywords: force normalization, shoulder, internal rotation, external rotation, glenohumeral

Muscle strength is one of the key physical parameters assessed by rehabilitation specialists. Muscle strength, defined as the maximum force (in N) or torque (in Nm) developed during a maximal voluntary contraction,[1,2] can provide insight

Hurd and Kaufman are with the Div of Orthopedic Research, and Morrey, the Dept of Orthopedic Surgery, Mayo Clinic, Rochester, MN.

into the effects of an injury, progress made subsequent to treatment intervention, and readiness for return to preinjury activities. When an individual has sustained an arm or leg injury, a bilateral comparison of muscle strength is often performed to determine the presence or magnitude of muscle weakness. A side-to-side strength comparison is not, however, appropriate in all instances. There may be a history of injury to the contralateral limb that continues to affect muscle strength, or an individual may have sustained bilateral injuries. Alternatively, participation in a work or sporting activity may require the individual to reach a strength criterion. In these instances it is more appropriate to compare and interpret an individual's muscle strength relative to normative group data.

The baseball pitcher is an excellent model for illustrating challenges in muscle-strength interpretation. The rotator-cuff complex has been identified as playing a key role in dynamically stabilizing the glenohumeral joint during pitching.[3] Furthermore, weakness of this musculature has been suggested to increase a baseball athlete's risk of injury.[4–6] Nonetheless, repetitive overhead pitching can induce adaptations in muscle strength of shoulder internal rotators (IR)[6–10] and external rotators (ER)[10,11] of the throwing limb compared with the nonthrowing limb in an uninjured athlete. Consequently, a rehabilitation goal of restoring symmetrical shoulder strength for the injured baseball pitcher may not adequately prepare the athlete for the sport's demands.

Evaluating a pitcher's strength relative to his uninjured peers would complement side-to-side comparisons and calculation of strength ratios, thus facilitating identification of any strength deficits that may be present. Currently, one of the most common clinical techniques for evaluating shoulder strength in baseball pitchers is calculating the ratio of peak isometric external- to internal-rotation muscle force or torque. Ellenbecker and Davies[6] suggested that an ER:IR ratio of 66% be considered normal for uninjured subjects on both the dominant and nondominant limbs. In baseball pitchers, deviation from this ratio may occur secondary to selective muscle development of the internal rotators without a concomitant increase in external-rotator strength. Although this technique for evaluating muscle strength provides valuable insight to shoulder-muscle performance, an accurate assessment of strength with this calculation method is not possible because multiple numeric combinations may yield the same ratio.

Valid comparisons of muscle strength between individuals necessitate data normalization. Body size is a well-recognized factor affecting strength[12,13]; muscle mass and lever-arm length positively affect the ability to generate a force or torque. Simply, a taller or heavier individual is usually stronger than a shorter and lighter person.[1] Consequently, muscle strength may be scaled to anthropometric characteristics including weight, height, body-mass index (BMI), limb length, or a combination of these parameters to permit between-subjects comparisons. There is no agreement, however, regarding which parameter to use for scaling muscle strength.[14] Ideally a scaling factor would promote a normal distribution, and reduce the variability, of a data set. This would facilitate clinicians' and clinical researchers' ability to identify differences in strength that may otherwise be masked by heterogeneous or nonuniform data.

The purpose of this study was to evaluate the effects of normalizing muscle strength using a spectrum of anthropometric parameters including height, weight, height × weight, BMI, forearm length, and forearm length × height. The most effective normalization method was determined based on the scaling factor that yielded the lowest variability for the data set and promoted the most normal distribution of the data set.

Methods

Participants

Fifty male high school baseball pitchers participated in the study. The average age for the group was 16 years (range 14–18), with an average of 7 years (range 2–11) experience as a pitcher. Anthropometric characteristic including height, weight, and forearm length were recorded for data normalization (Table 1). Subjects were not excluded from study participation if they had a history of upper extremity injury. However, all subjects were required to be uninjured and participating in unrestricted baseball activities at the time of testing and for a minimum of 2 years before study participation. The absence of upper extremity injury was confirmed by a musculoskeletal examination conducted by either an orthopedic surgeon or a board-certified sports physical therapist. Subject consent and parental assent were obtained before testing was initiated. The research protocol was approved by the Mayo Clinic institutional review board.

Procedures

Testing was performed onsite at the players' respective baseball fields. This was to accommodate their academic and athletic schedules and facilitate study participation of a large sample. All subjects performed a 5- to10-minute warm-up consisting of stretching, jogging, and short-toss activities before strength testing was initiated. Forearm length was measured from the lateral epicondyle to the most distal aspect of the ulnar styloid process using a tape measure.[15] The measurement was performed with the arm by the side, elbow flexed to 90°, and forearm in neutral rotation. Isometric muscle force of the dominant limb, defined as the subject's throwing arm, was assessed with a handheld dynamometer (MicroFet2, Hoggan Health Industries, West Jordan, UT).[16] The validity and reliability of upper extremity strength assessment with handheld dynamometers have been established.[17–19] The measurement range of the unit was 0 to 660 N, with a manufacturer-reported mechanical accuracy of 99%.

Testing order was standardized and included internal and external rotation at 0° and 90° abduction. Two maximum-effort practice trials were performed for each

Table 1 Subject Anthropometric Characteristics

Measure	Mean (SD)
Height, m	1.8 (0.1)
Weight, kg	76.1 (10.1)
Body-mass index	22.9 (2.8)
Forearm length, m	0.7 (0.1)

arm position before testing was initiated, which consisted of 2 “break” tests with a 30-second rest between trials. Trials were limited to 5 seconds in length when the subject’s strength could not be “broken.” All strength tests were conducted by a single examiner. Between-days intrarater reliability (3,2) testing yielded ICC values ranging from .889 to .975. Trial-to-trial variability for measures obtained during the study was <7 N. During testing subjects were seated with their hips, knees, and ankles in 90° flexion and trunk unsupported. They were free to stabilize themselves by grasping the table with the nontesting arm. A variety of shoulder and trunk positions have been described for isometric strength testing.[20,21] We elected to place subjects in the seated position because we believed this would be a better reflection of functional muscle performance than a supine or prone testing position. The humerus was stabilized against the trunk during strength tests conducted at 0° abduction. An assistant supported the humerus during testing at 90° abduction. The arm was in a modified neutral position (45° of internal rotation) for shoulder rotation and the elbow flexed to 90° during all tests. These arm positions were chosen based on previous studies that have evaluated muscle activity and variability during strength testing.[20,22] During testing the dynamometer was positioned just proximal to the ulnar styloid process. During external-rotation strength testing placement was on the dorsal surface of the arm, and it was on the volar surface of the arm during internal-rotation testing.

Statistical Analysis

The peak values for the 2 trials were averaged and the average was used for analysis.[21] Descriptive statistics and measures of variability were calculated for the variables of interest. The coefficient of variation was calculated to evaluate the variability of muscle force for each normalization method. The D’Agostino-Pearson value, which is based on skewness and kurtosis, was also calculated to assess the impact of scaling factors on the distribution (ie, a more normal distribution is equated with lower variability) of the data set.

Results

Body weight and BMI were the most consistent normalization methods for reducing the variability of strength values. In 3 out of the 4 strength tests the effect on the coefficient of variation was much less when strength was scaled to weight rather than BMI. For external rotation at 0° abduction the coefficient of variation was lowest when muscle force was normalized to height × weight, followed by weight and BMI. At 90° abduction the coefficient of variation was lowest when external-rotation muscle force was normalized to forearm length × weight, followed by BMI and weight (Table 2). For internal rotation at both 0° and 90° abduction the coefficient of variation was lowest when muscle force was normalized to weight. After weight, the coefficient of variation was lowest when muscle force was normalized to forearm length × weight, height × weight, and BMI at 0° and BMI and forearm length when the arm was in 90° abduction (Table 2).

No scaling factor consistently improved the normality of the data set for all strength tests. For external rotation at 0° abduction, normality was greatest when weight was used as a scaling factor, followed by height × weight and forearm length

Table 2 Statistical Descriptive and Distribution Results

	Mean (SD)	Coefficient of variation	D'Agostino-Pearson value
External Rotation at 0°			
Muscle force, N, nonnormalized	122.7 (22.3)	18.17	.388
Muscle force, N, normalized to			
height, m	67.3 (12.4)	18.42	.386
weight, kg	1.6 (0.2)	12.50	.867
height × weight	0.9 (0.1)	11.11	.853
body-mass index	5.4 (0.8)	14.81	.862
forearm length, m	168.8 (30.8)	18.25	.363
forearm length × weight	2.2 (0.4)	18.18	.804
External Rotation at 90°			
Muscle force, N, nonnormalized	125.4 (25.9)	20.65	.008*
Muscle force, N, normalized to			
height, m	68.7 (14.2)	20.67	.003*
weight, kg	1.6 (0.3)	18.75	<.001*
height × weight	0.9 (0.2)	22.22	<.001*
body-mass index	5.5 (1.0)	18.18	.001*
forearm length, m	172.4 (35.7)	20.71	.003*
forearm length × weight	2.3 (0.4)	17.39	<.001*
Internal Rotation at 0°			
Muscle force, N, nonnormalized	181.2 (35.6)	19.65	.840
Muscle force, N, normalized to			
height, m	99.2 (18.8)	18.95	.831
weight, kg	2.4 (0.3)	12.50	.762
height × weight	1.3 (0.2)	15.38	.680
body-mass index	7.9 (1.3)	16.46	.743
forearm length, m	248.6 (45.7)	18.38	.945
forearm length × weight	3.3 (0.5)	15.15	.633
Internal Rotation at 90°			
Muscle force, N, nonnormalized	137.4 (26.1)	19.00	.245
Muscle force, N, normalized to			
height, m	75.4 (14.6)	19.36	.220
weight, kg	1.8 (0.3)	16.67	.321
height × weight	1.0 (0.2)	20.00	.360
body-mass index	6.0 (1.1)	18.33	.431
forearm length, m	188.9 (35.7)	18.90	.226
forearm length × weight	2.5 (0.5)	20.00	.387

* Normality rejected; higher values represent greater normality.

(Table 2). For external-rotation strength tested at 90° abduction, none of the scaling factors resulted in a normal distribution of the data set—all D'Agostino-Pearson values were ≤.003 (Table 2). Forearm length was the most effective scaling factor for internal rotation tested at 0° abduction, followed by height, weight, and BMI.

Height × weight and forearm length × weight were the least effective scaling factors for promoting normality in distribution in this position (Table 2). When internal rotation was tested at 90° abduction, normality was greatest when strength was normalized to BMI, followed by forearm length × weight, height × weight, and weight. Forearm length and height were the least effective scaling factors for promoting normal distribution for internal rotation tested in this arm position (Table 2).

Discussion

A spectrum of anthropometric parameters was evaluated for their effect on normalizing muscle strength. Using body weight to scale muscle force was the most effective anthropometric parameter for normalizing strength values based on a collective group of statistical measures of variability. It should be noted that using subjects' weight as a scaling factor did not yield the greatest reduction in variability for all statistical measures, nor for all strength tests. BMI, height × weight, and forearm length × weight as scaling factors also yielded less variable values for muscle strength compared with nonnormalized strength. The effects of these scaling factors, however, were less consistent and had less impact on reducing data variability than weight. The scaling factors that were least effective in reducing the variability of the data set were those that included only length measurements (ie, height and forearm length).

Strength is strongly related to lean-muscle physiological cross-sectional area.[23] A common misconception is that individuals with relatively greater weight have more muscle mass and are capable of generating greater muscle force than individuals who weigh less.[1,14,24] This is one rationale to explain why previous investigators have elected to normalize muscle strength relative to weight.[24] An increase in weight, however, does not necessarily directly correlate with an increase in fat-free muscle mass.[24] Furthermore, muscle strength measured with a dynamometer at a fixed distance from the joint center is the result of both lean-muscle cross-sectional area and lever-arm length.[12] The limited effectiveness of height and forearm length in reducing data variability was not surprising, because no proxy of muscle mass was included with these scaling factors. It was unexpected, however, that scaling factors that captured both weight and length were not more effective than weight alone in reducing data variability. It is possible that our methods of measuring functional forearm length (tape measure) and height (stadiometer) were not precise enough to capture the true effect of segment lengths on strength normalization. Measurement of the point of application of the dynamometer on the forearm is another potential source of error. These measurement techniques are, however, likely to be employed by both clinicians and researchers. Consequently, the results from this study have applicability in real-world conditions.

We distinguished the effects of anthropometric scaling factors using the coefficient of variation and the D'Agostino-Pearson value. The most effective scaling factor was the one that produced the lowest variability and most normal distribution of the data. This is critical to investigators performing statistical analysis of mean strength for different subject groups. Reducing the variability in muscle strength is equally important to clinicians. Ballistic movements in sports, such as the pitching motion, may result in injury in the presence of muscle weakness as a consequence of inadequate dynamic joint stability.[25] Comparing a baseball pitcher's shoulder strength with that of a group of his uninjured peers would provide valuable information regarding potential injury risk and preparedness for return to play after an injury. The coefficient of variation is a measure of relative variation of a measurement and is independent of measurement units.[26] A data set with a low coefficient of variation can therefore help identify subtle differences in strength. The D'Agostino-Pearson value was evaluated secondary to the impact of data distribution on measures of central tendency. Although the mean is the most stable measure of central tendency, a data set that is not normally distributed will affect this value. The quantitative value of each data point affects the mean and can be biased by extreme values. Thus, a data set with normal skewness and kurtosis, as indicated with the D'Agostino-Pearson value, will produce a mean value that is a more accurate reflection of the group.[26]

Our sample consisted of uninjured, high-school-age baseball pitchers. This resulted in a homogeneous group of subjects relative to age and activity level. In addition, all subjects were male. The intention was not to identify the most effective scaling factor for normalizing strength within a narrow percentage of the population. Rather, the characteristics of our study sample allowed us to emphasize the relationship between body size and strength while eliminating or minimizing gender, age, and activity level as confounding factors. It has been suggested, though, that as the range of size for individuals increases, the relationship between strength and body size is likely to increase.[12,27] A study sample consisting of individuals with similar body dimensions, therefore, is a potential limitation. The range of heights (1.6–2.0 m, or 62.9–78.7 in) and weights (59.0–95.3 kg, or 130–210 lb) for subjects in this study was, however, reasonably large. Future studies that confirm the effects of different scaling factors on normalized muscle strength among different populations are necessary. Until then, the results of this study may serve as rationale for normalizing strength to subject body weight regardless of subject characteristics.

This investigation evaluated the effect of normalizing muscle strength with an array of anthropometric characteristics using a linear-ratio calculation method. Defined as the measurement of the size and proportions of the human body, anthropometric measurements are easily obtained in the clinical setting. Modeling normalized muscle strength as a linear relationship to a given anthropometric parameter, however, has been criticized as being used merely as a consequence of its simplicity and the lack of alternative normalization methods.[28] Jaric et al[12] advised against modeling strength linearly to body dimensions, stating that muscle-force production should not be a consequence of body dimensions but rather muscle cross-sectional area. Consistent with this proposal, Klein et al[29] stated that calculating strength relative to muscle cross-sectional area was the gold standard for normalization of fusiform muscle groups. To obtain individualized muscle cross-sectional area, however, would require diagnostic imaging (eg, MRI, ultrasound, CT) for each muscle group of interest. Consequently, reporting strength relative to muscle cross-sectional area is not a viable option for the overwhelming majority of health care and research professionals.

An alternative approach for normalizing strength is allometric scaling. This technique is based on the concept of geometric similarity, which assumes that all humans have the same shape and differ only in size.[13,30] Strength normalization with allometric scaling uses the following equation: $\text{Strength}_{\text{normalized}} = \text{strength}_{\text{raw}}/$

body parameter$_{\text{allometric scaling factor}}$. This equation models strength as proportionally, not linearly, related to body dimensions. Dividing strength by the body parameter raised to an appropriate power has been proposed as an effective technique to negate the effects of body-size variability.[24,31] Wren and Engsberg[28] evaluated lower extremity muscle strength when peak torque was normalized relative to mass, height, and BMI using both linear and allometric scaling equations. Based on the results of linear-regression analyses, they reported that traditional mass normalization (ie, a linear-ratio model) did not effectively adjust for the influence of body mass. Rather, allometric scaling performed using torque/mass raised to the power 1.6 for the hip and knee, and to the power 1.4 for the ankle, yielded the most appropriate strength normalization. The primary limitation associated with allometric normalization is selecting the value of the scaling exponent, which depends on many factors including the body parameter (eg, height, weight),[1] whether strength was recorded as a force or torque,[1] and the amount of the subject's adipose tissue.[24] Given the range of scaling factors, values, and variables influencing the value of the scaling factor, allometric scaling has not been integrated into clinical settings as an accepted strength-normalization technique.

A major study limitation was the use of a handheld dynamometer and a "break" test to assess maximum muscle force. Not all subjects "broke" during testing. In these instances maximum muscle force was not precise. There are additional factors that may have contributed to the inconsistency in the effects of scaling factors on normalized muscle strength. We made every effort to ensure that subjects were performing a maximum-effort contraction, including the performance of multiple warm-up trials and providing adequate rest between test trials. In addition, trial-to-trial variability (<7 N) was low, suggesting that subjects were consistent in their muscle-force production. If subjects had not been performing a maximum voluntary isometric contraction or were not fully activating the muscle group of interest, that may have affected the relationship between strength and body dimension. As previously addressed, imprecise measurement of segment length or body height or dynamometer placement may have also been a contributing factor to the inconsistent effectiveness of scaling factors. We did, however, use methods that are readily available in the clinic and could not perform more precise measurements because our testing was done at the playing fields. Finally, arm positioning may have affected the lever-arm (or moment-arm) length and subjects' force production. The magnitude of a moment is equal to the magnitude of the force times perpendicular distance to the point of interest (in this case the shoulder joint) and the line of action of the force. When testing shoulder-rotation strength with the elbow flexed to 90°, the lever arm is the horizontal distance from point-of-force application on the distal forearm to the center of the shoulder joint. When testing shoulder rotational strength at 0° of abduction, the assumption is that the humerus is aligned vertically with the shoulder joint, resulting in a lever-arm length equal to forearm length. However, this is not true if the arm is in slight flexion or extension. The same is true when testing rotational strength at 90° abduction. If the humerus is not in alignment with the center of the shoulder joint, the lever arm is no longer equal to the length of the forearm. Thus, it is possible that errors in arm positioning may have been alleviated by positioning and stabilizing subjects using a mechanical dynamometer in a laboratory setting.

Conclusions

This study provides objective support for scaling muscle strength to subject body weight. Compared with other anthropometric variables that captured a spectrum of subject height and weight parameters, body weight was the most effective scaling factor in terms of reducing variability and normalizing the distribution of normalized muscle strength. This approach to normalizing muscle strength uses methods readily accessible to clinicians and researchers and may facilitate the identification of differences in strength between individuals with diverse physical characteristics.

References

1. Jaric S. Muscle strength testing: use of normalisation for body size. *Sports Med*. 2002;32(10):615–631.
2. Sale DG. Testing strength and power. In: MacDougal JD, Wenger HA, Green HJ, eds. *Physiological Testing of the High-Performance Athlete*. Champaign, IL: Human Kinetics; 1991:21–75.
3. Wilk KE, Andrews JR, Arrigo CA, Keirns MA, Erber DJ. The strength characteristics of internal and external rotator muscles in professional baseball pitchers. *Am J Sports Med*. 1993;21(1):61–66.
4. Jobe FW, Moynes DR, Tibone JE, Perry J. An EMG analysis of the shoulder in pitching: a second report. *Am J Sports Med*. 1984;12(3):218–220.
5. Jobe FW, Tibone JE, Perry J, Moynes D. An EMG analysis of the shoulder in throwing and pitching: a preliminary report. *Am J Sports Med*. 1983;11(1):3–5.
6. Ellenbecker TS, Davies GJ. The application of isokinetics in testing and rehabilitation of the shoulder complex. *J Athl Train*. 2000;35(3):338–350.
7. Ellenbecker TS, Mattalino AJ. Concentric isokinetic shoulder internal and external rotation strength in professional baseball pitchers. *J Orthop Sports Phys Ther*. 1997;25(5):323–328.
8. Brown LP, Niehues SL, Harrah A, Yavorsky P, Hirshman HP. Upper extremity range of motion and isokinetic strength of the internal and external shoulder rotators in Major League Baseball players. *Am J Sports Med*. 1988;16(6):577–585.
9. Hinton RY. Isokinetic evaluation of shoulder rotational strength in high school baseball pitchers. *Am J Sports Med*. 1988;16(3):274–279.
10. Donatelli R, Ellenbecker TS, Ekedahl SR, Wilkes JS, Kocher K, Adam J. Assessment of shoulder strength in professional baseball pitchers. *J Orthop Sports Phys Ther*. 2000;30(9):544–551.
11. Magnusson SP, Gleim GW, Nicholas JA. Shoulder weakness in professional baseball pitchers. *Med Sci Sports Exerc*. 1994;26(1):5–9.
12. Jaric S, Ugarkovic D, Kukolj M. Evaluation of methods for normalizing muscle strength in elite and young athletes. *J Sports Med Phys Fitness*. 2002;42(2):141–151.
13. Jaric S, Mirkov D, Markovic G. Normalizing physical performance tests for body size: a proposal for standardization. *J Strength Cond Res*. 2005;19(2):467–474.
14. Nevill AM, Bate S, Holder RL. Modeling physiological and anthropometric variables known to vary with body size and other confounding variables. *Am J Phys Anthropol*. 2005;Suppl 41:141–153.
15. Tyler TF, Nahow RC, Nicholas SJ, McHugh MP. Quantifying shoulder rotation weakness in patients with shoulder impingement. *Journal Shoulder Elbow Surg*. 2005;14(6):570–574.

16. Wadsworth CT, Krishnan R, Sear M, Harrold J, Nielsen DH. Intrarater reliability of manual muscle testing and hand-held dynametric muscle testing. *Phys Ther*. 1987;67(9):1342–1347.
17. Byl NN, Richards S, Asturias J. Intrarater and interrater reliability of strength measurements of the biceps and deltoid using a hand held dynamometer. *J Orthop Sports Phys Ther*. 1988;9(12):395–398.
18. Sullivan SJ, Chesley A, Hebert G, McFaull S, Scullion D. The validity and reliability of hand-held dynamometry in assessing isometric external rotator performance. *J Orthop Sports Phys Ther*. 1988;10(6):213–217.
19. Magnusson SP, Gleim GW, Nicholas JA. Subject variability of shoulder abduction strength testing. *Am J Sports Med*. 1990;18(4):349–353.
20. Kuhlman JR, Iannotti JP, Kelly MJ, Riegler FX, Gevaert ML, Ergin TM. Isokinetic and isometric measurement of strength of external rotation and abduction of the shoulder. *J Bone Joint Surg Am*. 1992;74(9):1320–1333.
21. Roy JS, MacDermid JC, Orton B, et al. The concurrent validity of a hand-held versus a stationary dynamometer in testing isometric shoulder strength. *J Hand Ther*. 2009;22(4):320–326, quiz 327.
22. Kelly BT, Kadrmas WR, Speer KP. The manual muscle examination for rotator cuff strength: an electromyographic investigation. *Am J Sports Med*. 1996;24(5):581–588.
23. Maughan RJ, Watson JS, Weir J. Strength and cross-sectional area of human skeletal muscle. *J Physiol*. 1983;338:37–49.
24. Folland JP, Mc Cauley TM, Williams AG. Allometric scaling of strength measurements to body size. *Eur J Appl Physiol*. 2008;102(6):739–745.
25. Wilk KE, Meister K, Andrews JR. Current concepts in the rehabilitation of the overhead throwing athlete. *Am J Sports Med*. 2002;30(1):136–151.
26. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. Upper Saddle River, NJ: Prentice Hall Health; 2000.
27. Hortobagyi T, Katch FI, Katch VL, LaChance PF, Behnke AR. Relationships of body size, segmental dimensions, and ponderal equivalents to muscular strength in high-strength and low-strength subjects. *Int J Sports Med*. 1990;11(5):349–356.
28. Wren TA, Engsberg JR. Normalizing lower-extremity strength data for children without disability using allometric scaling. *Arch Phys Med Rehabil*. 2007;88(11):1446–1451.
29. Klein CS, Rice CL, Marsh GD. Normalized force, activation, and coactivation in the arm muscles of young and old men. *J Appl Physiol*. 2001;91(3):1341–1349.
30. Zoeller RF, Ryan ED, Gordish-Dressman H, et al. Allometric scaling of isometric biceps strength in adult females and the effect of body mass index. *Eur J Appl Physiol*. 2008;104(4):701–710.
31. Sholl D. The quantitative investigation on the vertebrate brain and the applicability of allometric formula to its study. *Proc R Soc Lond B Biol Sci*. 1948;(135):243–258.