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Journal of Sport and Health Science 1 (2012) 107−113

www.jshs.org.cn

Original article

Anthropometrics and electromyography as predictors for maximal voluntary isometric arm strength

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Received 25 April 2012; revised 25 May 2012; accepted 28 May 2012

Abstract

Background: Muscular strength can be conceptually determined by two components: muscle activation and size. Muscle activation by the central nervous system can be measured by surface electromyography (sEMG). Muscular size reflects the amount of contractile protein within a skeletal muscle and can be estimated by anthropometric measurements. The purpose of this study was to determine the relative contributions of size parameters and muscle activation to the prediction of maximal voluntary isometric elbow flexion strength.

Methods: A series of anthropometric measurements were taken from 96 participants. Torque and root-mean-square (RMS) of the sEMG from the biceps brachii were averaged across three maximal voluntary isometric contractions. A multiple linear regression analysis was performed based on a Pearson's correlation matrix.

Results: Body weight (BW) accounted for 39.1% and 27.3% in males and females, respectively, and was the strongest predictor of strength for males. Forearm length (L3) was the strongest predictor of strength in females (partial $R^2 = 0.391$). Elbow circumference (ELB) accounted for a significant ($p < 0.05$) amount of variance in males but not females. The addition of sEMG RMS as a third variable accounted for an average of 10.1% of the variance excluding the equation of BW and L3 in females. The strongest prediction equation included BW, L3, and ELB accounting for 55.6% and 58.5% of the variance in males and females, respectively.

Conclusion: Anthropometrics provide a strong prediction equation for the estimation of isometric elbow flexion strength. Muscle activation, as measured by sEMG activity, accounted for a significant ($p < 0.05$) amount of variance in most prediction equations, however, its contribution was comparable to an additional anthropometric variable.

Keywords: Biceps brachii; Biomechanics; Gender differences; Multiple linear regression; Muscle force

1. Introduction

Muscular strength can be determined by two components: muscle activation and muscle size. The first of these two components, muscle activation, is the result of efferent output from the central nervous system (CNS).[1] This includes the control of motor unit recruitment (the number of active motor units) and motor unit firing rate (the rate at which they fire). Motor unit recruitment and firing rate are reflected in the amplitude of the interference pattern of the summated action potentials recorded by surface electromyography (sEMG).[2] The second component of strength is based on the amount of contractile proteins within skeletal muscle.[3−5] The amount of contractile tissue can be measured by cross-sectional area (CSA) and anthropometric measures used to infer muscle size.[4,6]

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Peer review under responsibility of Shanghai University of Sport

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jshs.2012.05.004

It is widely known that CSA is at least moderately correlated ($r = 0.5-0.7$) with voluntary strength regardless of gender, age and training status.[5,7] The relationship between muscle size and force is of sufficient magnitude that the "specific tension" of a muscle is commonly used in musculoskeletal modeling studies to predict force.[8] The specific tension of a muscle is the force normalized with respect to its CSA.

Kroll and colleagues[9] extended the research in this field by developing strength prediction equations using non-invasive, simple measures of body weight (BW), body volume, segmental limb lengths and volumes of the upper limb for both males and females. Multiple regression analysis revealed that the best predictor of elbow flexion strength was BW for males ($R = 0.69$), and total upper limb volume for females ($R = 0.72$). Kroll and colleagues[9] also determined that limb girths and lengths predict elbow flexion strength as well as, or better than, segmental limb volumes thereby simplifying the methodology in this area.

Given the relationship between muscle activation (sEMG) and force[10,11] it would seem logical to add this variable to a multiple regression equation that predicts force. An equation that incorporates both anthropometric data and sEMG measurement should theoretically capture the two components of muscle strength (size and muscle activation) and decrease the standard error of estimate. The present study will therefore determine the relative contributions of body size and muscle activation in a strength prediction equation. The hypothesis of this study is that adding muscle activation (sEMG) to anthropometrics will improve the strength prediction equation.

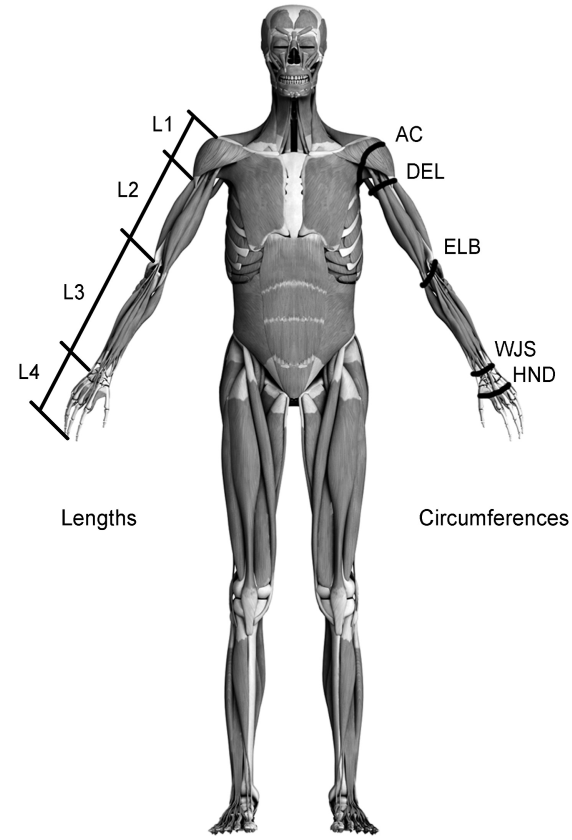

Fig. 1. Illustration of anthropometric length and circumference measurements collected. L1, acromion process to deltoid tubercle; L2, deltoid tubercle to olecranon process; L3, olecranon process to ulnar styloid; L4, ulnar styloid to tip of third finger; AC, girth at acromion process; DEL, girth at deltoid tubercle; ELB, girth at olecranon process; WJS, girth at styloid process (wrist joint space); HND, girth at base of hand.

2. Materials and methods

Ninety-six (46 males and 50 females), right-handed college age participants took part in the present study. Each subject was verbally acquainted with the experimental design and provided written, informed consent (REB #02-284).

2.1. Anthropometrics

Since this paper attempted to extend the work of Kroll and colleagues[9] by adding muscle activation (sEMG), we collected the same anthropometric measurements used in that paper. Anthropometric data (Fig. 1) were collected prior to the testing procedure by an experienced person who took the average of three measurements using a tape measure and the following landmarks:

Lengths

L1: acromion process to deltoid tubercle
L2: deltoid tubercle to olecranon process
L3: olecranon process to styloid process of the ulna
L4: styloid process of the ulna to tip of the third finger

Circumferences

AC: circumference at acromion process
DEL: circumference at deltoid tubercle
ELB: circumference at olecranon process
WJS: circumference at distal space to styloid process of the ulna
HND: thickness of the base of the hand, cross-sectional height of thenar and hypothenar eminence.

2.2. Set up and procedure

Testing took place within a Faraday cage, and was completed in one session. Participants were seated in an adjustable chair and fastened with Velcro® straps to reduce movement. The right arm of the participant was positioned in the sagittal plane, with the shoulder and elbow flexed to 90° within a jig designed to isolate the upper limb. With the wrist in neutral position, a cuff was fastened proximal to the styloid process and attached to a load cell (JR3 Inc., Woodland, CA, USA) to record force. Participants were asked to perform three 5-s MVCs separated by 3-min rest intervals. An oscilloscope (VC-6525; Hitachi, Woodbury, NY, USA) displaying the participant's force trace was placed in front of the participant for visual feedback. Surface EMG was recorded while participants performed the contractions.

Each participant's arm was shaved, abraded and cleansed with alcohol to reduce signal impedance to below 10 kΩ

(Grass EZM5; Astro-Med Inc., West Warwick, RI, USA). Motor points were determined using low level surface stimulation to elicit a visible twitch. Silver−silver chloride electrodes (Grass F-E9; Astro-Med Inc.) were then placed on the skin surface in line with the biceps brachii muscle fibers, 2 cm away from the motor point toward the distal tendon. The electrode configuration was bipolar with an inter-electrode distance of 2 cm. A 5-cm ground electrode (CF5000; Axelgaard Manufacturing Company Ltd., Fallbrook, CA, USA) was placed on the participant's clavicle. Surface EMG activity was amplified 1000 times before being band-passed filtered between 3 and 1000 Hz (Grass P511, Astro-Med Inc.).

All signals were sampled at 2048 Hz using a 16-bit analog-to-digital converter (NI PCI-6052E; National Instruments, Austin, TX, USA) controlled by a computer-based data acquisition system DASYLab (DASYTEC, National Instruments, Amherst, NH, USA). The data were collected and stored for off-line processing on a desktop computer (Seanix Technology Inc., Blaine, WA, USA). A one-second window centered at the middle of each contraction was used to extract the mean force and root-mean-square (RMS) amplitude of the sEMG signal. The data used for analysis was the mean of three trials.

2.3. Statistics

The correlational approach followed was that described by Kroll and colleagues.[9] All statistical analysis was performed using SYSTAT (Systat Inc., Evanston, IL, USA). First, a correlation (Pearson) matrix was constructed to determine which anthropometric measurements correlated highly with torque. A stepwise multiple linear regression analysis was performed based on the correlation matrix. In the first stage, the variable with the highest correlation, BW, was entered as the only predictor of strength. In the second stage, a second anthropometric variable was added. To avoid multicolinearity, only one of each length and circumference were chosen to be included in the primary equations. Forearm length (L3) was selected because it was highly correlated with torque for both males and females, and it is a measure of the lever length during elbow flexion. Elbow circumference (ELB) was selected because it was highly correlated with torque for both males and females, and includes the size of the elbow flexor muscles at the joint crossing. Once the equation for BW and L3 or ELB was determined, sEMG RMS was added to the equation to determine the contribution of muscle activation. The predictive value of three anthropometric variables was also assessed. As well, prediction equations were performed using the four length measurements with the addition of sEMG RMS, and the five circumference measurements with the addition of sEMG RMS, to determine the contribution of sEMG to each group of variables.

For each equation, the R^2 and partial R^2 were calculated to determine the strength of the equation and the relative contribution of the added variable, respectively. The standard error of the estimate (SEE) was calculated to help determine the benefit of adding another variable versus the cost of decreasing the degrees of freedom associated with the specific equation. Finally, an F-ratio was calculated to determine if there was a significant ($p < 0.05$) increase in the variance accounted-for by an additional variable, relative to the benchmark equation.[12]

3. Results

The mean ± SD values for torque, sEMG RMS and anthropometric measurements are presented in Table 1. The results of the correlation matrix are presented in Table 2 and multiple linear regression analyses are presented in Table 3, for males and females, respectively.

3.1. Contribution of anthropometrics

The initial prediction equation with only BW accounted for 39.1% and 27.3% of variance in elbow flexion strength in males and females, respectively (Fig. 2). BW was the strongest strength predictor for males. The addition of L3 to the equation improved strength prediction for both males and females. Based on the partial R^2, L3 was the strongest strength predictor for females accounting for 39.1% of the variance. The addition of ELB to the initial equation with BW improved the strength prediction for males with a significant ($p < 0.05$) partial R^2 of 12.5%; however, it had little effect on the equation for females. The best prediction equation for both males and females consisted of three anthropometric measures (BW, L3, and ELB), accounting for 55.6% and 58.5% of the total variance in strength, respectively (Fig. 3). To compare lengths versus circumferences, overall prediction equations of all four lengths and all five circumferences were performed. In males, the circumferences were much stronger predictors compared to the lengths ($R^2 = 0.545$ and 0.293, respectively). This was

Table 1
Mean ± SD values for subject physical characteristics, anthropometric measurements and sEMG root-mean-square (RMS).

	Male ($n = 46$)	Female ($n = 50$)
Age (year)	23.28 ± 3.30	22.98 ± 1.90
Height* (cm)	180.29 ± 7.21	167.33 ± 7.07
Weight* (N)	800.50 ± 131.85	627.45 ± 85.84
Torque* (Nm)	93.08 ± 18.39	47.30 ± 8.23
sEMG RMS* (mV)	1.63 ± 0.64	1.08 ± 0.50
L1* (cm)	17.72 ± 1.82	16.13 ± 1.40
L2* (cm)	19.12 ± 2.05	17.72 ± 1.85
L3* (cm)	27.69 ± 2.44	24.66 ± 2.42
L4* (cm)	20.62 ± 1.24	18.94 ± 0.97
AC* (cm)	44.47 ± 4.80	37.12 ± 3.00
DEL* (cm)	33.79 ± 3.48	28.66 ± 2.71
ELB* (cm)	27.81 ± 3.13	23.84 ± 1.46
WJS* (cm)	17.54 ± 1.09	15.40 ± 0.76
HND* (cm)	25.11 ± 2.11	21.71 ± 1.16

Anthropometric length measurements include: acromion process to deltoid tubercle (L1), deltoid tubercle to olecranon process (L2), olecranon process to ulnar styloid process (L3), and ulnar styloid to tip of third finger (L4). Anthropometric circumference measurements include: girth at acromion process (AC), girth at deltoid tubercle (DEL), girth at olecranon process (ELB), girth at styloid process (WJS), and girth at base of hand (HND).
*$p < 0.05$, t test grouped by gender.

Table 2
Correlation matrix of anthropometric variables including body weight (BW), biceps brachii root-mean-square (RMS) and elbow flexion force.

	Force	BW	RMS	L1	L2	L3	L4	AC	DEL	ELB	WJS	HND
Force	–	0.522*	0.224	0.196	0.080	0.555**	0.266	0.334	0.312	0.479*	0.344	0.527**
BW	0.625**	–	−0.103	0.297	0.163	0.042	0.272	0.565**	0.649**	0.809**	0.535**	0.386
RMS	0.079	−0.217	–	0.006	0.099	0.302	0.030	−0.006	−0.205	−0.089	0.008	0.204
L1	0.319	0.215	0.012	–	0.054	−0.057	0.197	−0.004	0.098	0.260	0.349	0.105
L2	0.281	0.407	−0.110	0.215	–	−0.003	0.206	0.142	0.246	0.247	0.148	−0.095
L3	0.457	0.360	−0.035	0.324	0.150	–	0.106	0.169	−0.061	−0.042	−0.051	0.211
L4	0.487*	0.508*	0.048	0.531**	0.373	0.661	–	0.043	−0.025	0.374	0.508*	0.346
AC	0.588**	0.644**	0.030	0.151	0.350	0.016	0.156	–	0.359	0.433	0.241	0.155
DEL	0.522*	0.779**	−0.061	−0.040	0.183	−0.094	0.073	0.754**	–	0.542**	0.188	0.119
ELB	0.576**	0.556**	−0.199	0.092	0.400	0.069	0.316	0.481*	0.564**	–	0.577**	0.441
WJS	0.576**	0.703**	−0.084	0.387	0.254	0.423	0.635**	0.424	0.531**	0.436	–	0.525**
HND	0.408	0.577**	0.019	0.233	−0.093	0.348	0.448	0.322	0.439	0.207	0.643**	–

Anthropometric length measurements include: acromion process to deltoid tubercle (L1), deltoid tubercle to olecranon process (L2), olecranon process to ulnar styloid process (L3), and ulnar styloid to tip of third finger (L4). Anthropometric circumference measurements include: girth at acromion process (AC), girth at deltoid tubercle (DEL), girth at olecranon process (ELB), girth at styloid process (WJS), and girth at base of hand (HND). Values below diagonal for males, values above diagonal for females.
*$p < 0.05$, **$p < 0.01$.

Table 3
Multiple regression analysis for maximal voluntary isometric force prediction in male and female.

	Male					Female				
	R	SEE (%)	R^2	Partial R^2, %	F-ratio	R	SEE (%)	R^2	Partial R^2, %	F-ratio
BW	0.625	140.52 (15.6)	0.391	39.1	–	0.522	70.09 (15.0)	0.273	27.3	–
BW + L3	0.673	13.92 (15.0)	0.452	10.1	4.86*	0.746	50.59 (11.8)	0.557	39.1	30.21#
BW + L3 + RMS	0.704	13.52 (14.5)	0.496	7.9	3.71	0.756	50.56 (11.8)	0.572	3.3	1.58
BW + ELB	0.683	13.74 (14.8)	0.467	12.5	6.12*	0.531	70.12 (15.1)	0.282	1.3	0.62
BW + ELB + RMS	0.727	13.08 (14.1)	0.528	11.5	5.60*	0.600	60.79 (14.4)	0.360	10.9	5.75#
BW + L3 + ELB	0.746	12.69 (13.6)	0.556	18.9	10.04*	0.765	50.47 (11.6)	0.585	6.3	3.17
Lengths	0.542	16.20 (17.4)	0.293	29.3	–	0.623	60.17 (13.0)	0.388	38.8	–
Lengths + RMS	0.550	16.30 (17.5)	0.302	10.3	0.55	0.625	60.78 (14.3)	0.391	0.4	0.19
Circumferences	0.738	13.16 (14.1)	0.545	54.5	–	0.624	60.79 (14.4)	0.389	38.9	–
Circ + RMS	0.754	12.99 (14.0)	0.568	5.0	2.26	0.651	60.67 (14.1)	0.424	5.7	2.67

Anthropometric measurements include body weight (BW); length measurements: acromion process to deltoid tubercle (L1), deltoid tubercle to olecranon process (L2), olecranon process to ulnar styloid process (L3), and ulnar styloid to tip of third finger (L4); circumference measurements: girth at acromion process (AC), girth at deltoid tubercle (DEL), girth at olecranon process (ELB), girth at styloid process (WJS), and girth at base of hand (HND). Biceps brachii activation measured by surface EMG root-mean-square (RMS). SEE, standard error of estimate.
*$p < 0.05$: $F_{(1,42)} = 40.073$; $F_{(1,43)} = 40.067$; $F_{(1,40)} = 40.09$; $F_{(1,41)} = 40.08$.
#$p < 0.05$: $F_{(1,46)} = 40.052$; $F_{(1,47)} = 40.047$; $F_{(1,44)} = 40.06$; $F_{(1,45)} = 40.06$.

not the case in females where the lengths and circumferences equations were equal ($R^2 = 0.389$).

3.2. Contribution of muscle activation (sEMG)

Muscle activation, as measured by sEMG RMS, was added to each of the equations containing two anthropometric variables (Fig. 3). The addition of sEMG RMS to a prediction equation with BW and L3 resulted in a non-significant ($p > 0.05$) increase in variance-accounted-for in elbow flexion strength. The partial R^2 for males was 7.9% while it was only 3.3% for females. The addition of sEMG RMS to a prediction equation with BW and ELB resulted in a significant ($p < 0.05$) increase in the variance-accounted-for in elbow flexion strength, with a partial R^2 of 11.5% for males and 10.9% for females (Fig. 2). The addition of sEMG RMS to the four lengths and to the five circumferences was found to be statistically non-significant ($p > 0.05$) for both equations. The prediction equations and their results are detailed further in Table 3.

4. Discussion

4.1. Contribution of anthropometrics

In agreement with Kroll et al.,[9] BW alone was a moderate predictor of strength. BW is the most common anthropometric measure used in strength prediction[3] and was used as the basis of this regression analysis. The inclusion of a second anthropometric measure was determined based on both the correlation with strength and its biomechanical significance to elbow flexion. L3 was selected because it functioned as the biomechanical lever during the task. Forearm length was calculated from the olecranon process (joint) to the styloid process (location of load cell). Since the elbow was fixed at 90° of flexion the

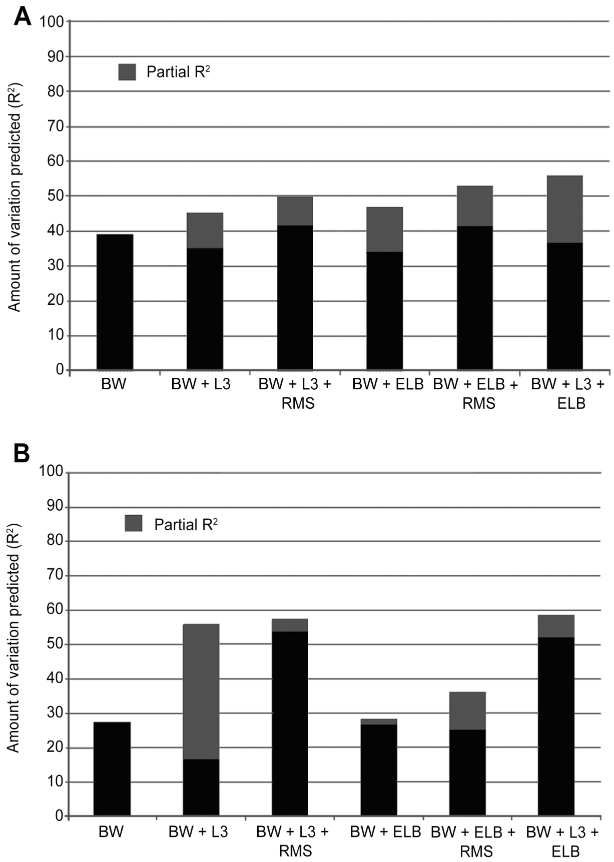

Fig. 2. Graphical results of the multiple linear regression analysis to predict maximal voluntary isometric elbow flexion force in males (A) and females (B). The total of each bar displays the total amount of variation predicted by the equation. The gray portion of each bar displays the additional amount of partial variation predicted with the inclusion of the last variable in the equation. Variables in the prediction equations include: body weight (BW), length from olecranon process to styloid process (L3), circumference at olecranon process (ELB), and biceps brachii activity (RMS).

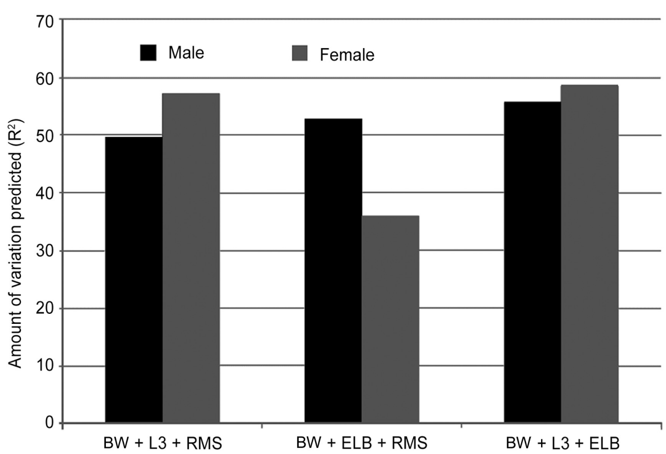

Fig. 3. Graphical results of the total variance accounted for by prediction equations including three variables for males (black) and females (gray). Variables in the prediction equations include: body weight (BW), length from olecranon process to styloid process (L3), circumference at olecranon process (ELB), and biceps brachii activity (RMS).

distance from the joint to the load cell represents the lever arm, or resistance arm of the movement.[13] The other anthropometric variable included in the second stage of the regression was elbow circumference. ELB represents regional muscle mass due to its widely accepted high, positive correlation with force.[5,7,14,15]

Upper arm circumference is a popular measure used in force prediction equations for upper body exercises due to its high correlation ($r = 0.65-0.77$) with force.[7,14,16] Likewise, in the present study, ELB accounted for an additional 12.5% and 18.9% of the variance in male elbow flexion strength, when added to equations of one and two variables, respectively (Table 3). The elbow circumference measure was, however, not statistically significant ($p > 0.05$) when added to either equation in females. Gender differences in strength and CSA are well-known and are more apparent for the upper versus lower limbs.[17] Although the amount of force produced per unit CSA has been found to be equal between males and females, it cannot necessarily be applied to circumference measurements. Miller et al.[18] and Kanehisa et al.[19] have found that females have an increased proportion of fat mass compared to lean tissue mass (muscle and bone). Therefore, circumference measurements may not be as representative of force per CSA in females as in males, and it ultimately was not as good of a strength predictor for females.

Scanlan and colleagues[20] performed a factor analysis on anthropometric variables used in a bench press prediction equation and was able to account for 68.4% of the total variance in force. The first factor consisted of body mass, muscle circumferences, and skinfolds accounting for 47.8% of the variance in force. In contrast, the third factor included height and limb lengths and accounted for only 7% of the total variance in force. The regression analysis for males in the present study is consistent with the findings of Scanlan et al.[20] because a circumference measure (ELB) had a greater impact on the equation for predicting elbow flexion strength than a length measure (L3). In contrast, the inclusion of L3 to a prediction equation with BW had a greater impact for females than it did for males, in terms of accounting for additional variance in elbow flexion strength.

The large contribution of limb length to the strength prediction equation for females may be explained by the relationship between the length of a muscle and the number of sarcomeres in series.[21,22] The number of sarcomeres in parallel (physiological cross-sectional area) is proportional to the amount of tension that is produced whereas the number of sarcomeres in series (muscle fiber length) is proportional to the velocity at which tension is.[23,24] While the dependent measure in this study was mean torque, not velocity of shortening, it has been suggested that the number of sarcomeres in series, and therefore the length of a muscle, has a relationship with the amount of force being produced.[22,25] This relationship was demonstrated for sprint performance and leg characteristics in female sprinters. Abe and colleagues[26] found that increased fascicle length was highly correlated with increased shortening velocity and concurrently, sprint performance. These physiological characteristics combined with females' decreased proportion of lean tissue mass may explain the large contribution of limb length compared to weight and circumference measurements.

4.2. Contribution of muscle activation

The contribution of muscle activation in addition to muscle size to the prediction of strength was assessed by incorporating RMS sEMG amplitude to equations consisting of BW and a second anthropometric variable. The addition of sEMG RMS resulted in a significant ($p < 0.05$) increase in the variance-accounted-for by each equation, except when the second variable was L3 for females. The minimal contribution may have been due to the immense contribution of L3 alone (partial $R^2 = 39.1\%$). Excluding this particular case, on average, sEMG RMS accounted for an additional 10.1% of the variance in strength. Surprisingly, the addition of a third anthropometric variable instead of sEMG RMS resulted in superior prediction equations for both males and females.

The majority of the literature on force and sEMG is focused on the linear versus non-linear nature of the relationship, to create a calibrating equation throughout the range of muscle forces (0−100% maximal voluntary contraction). Musculoskeletal modeling focuses mainly on individual muscle forces, not maximum force prediction at the joint as accomplished in this study.[27−29] The impact of adding sEMG to a prediction equation for muscle force that already includes a measure of muscle size was less than expected. Hahn[30] used sEMG to predict isokinetic knee torque using a multiple linear regression. An equation containing limb position, height, body mass and sEMG produced R^2 values of 0.67−0.71. Similarly, Youn and Kim[31] used sEMG from the biceps brachii and brachioradialis for elbow flexion prediction and found correlations of 0.90 and above between observed and predicted forces.

One possible reason that sEMG had a greater contribution to the prediction of muscle strength in the aforementioned studies may be the inclusion of activity from multiple muscles, including antagonistic co-activation. Joint torque is the product of a multiple muscle system and we only included sEMG activity from the primary agonist. Praagman and colleagues[32] observed sEMG of elbow flexors and extensors during static contractions at varying joint angles and pronation−supination positions. They found that joint angle, moment arm, and muscle length influenced the EMG amplitude. Similarly, Brookham and colleagues[33] found that these same variables, and the load applied to the joint, influenced the amount of co-activation present during isometric contractions. The inclusion of sEMG from multiple muscles at different joint angles may be beneficial for the prediction of muscle strength. However, in agreement with the current findings, Hahn[30] reported that the primary force predictors for knee torque were the position of the limb, body mass and body height, followed secondarily by sEMG.

5. Conclusion

Anthropometrics provides a strong prediction equation for the estimation of isometric elbow flexion strength using multiple linear regression. While muscle activation, as measured by RMS sEMG activity, accounted for a significant ($p < 0.05$) amount of variance in most prediction equations, its contribution was comparable to the use of an additional anthropometric variable. Therefore, the hypothesis that muscle activation would improve the prediction equation more than anthropometrics alone cannot be entirely accepted. It was found that the strongest prediction equation for both males and females included BW, forearm length, and elbow circumference.

Acknowledgments

This study was supported by the Natural Sciences and Engineering Research Council of Canada. This work is dedicated to the memory of Dr. Walter Kroll.

References

1. Gabriel D, Kamen G, Frost G. Neural adaptations to resistive exercise: mechanisms and recommendations for training practices. *Sports Med* 2006;**36**:133−49.
2. Staudenmann D, Poeleveld K, Stegeman D, van Dieen J. Methodological aspects of SEMG recordings for force estimation: a tutorial and review. *J Electromyogr Kinesiol* 2010;**20**:375−87.
3. Kroll W. Motor learning/control. In: *Proceedings: NAPEHE, National Association for Physical Education in Higher Education: Theory into Practice: Annual Conference, Indianapolis, Indiana, January 6-9, 1983*. Champaign, IL: Human Kinetics Publishers; 1983.
4. Ikai M, Fukunaga T. Calculation of muscle strength per unit cross-sectional area of human muscle by means of ultrasonic measurement. *Eur J Appl Physiol Occup Physiol* 1968;**26**:26−32.
5. Sale D, MacDougall J, Always S, Sutton J. Voluntary strength and muscle characteristics in untrained men and women and male bodybuilders. *J Appl Physiol* 1987;**62**:1786−93.
6. Bamman M, Newcomer B, Larson-Meyer D, Weinsier R, Hunter G. Evaluation of the strength-size relationship *in vivo* using various muscle size indices. *Med Sci Sports Exerc* 2000;**32**:1307−13.
7. Mayhew J, Ball T, Ward T, Hart C, Arnold M. Relationships of structural dimensions to bench press strength in college males. *J Sports Med Phys Fitness* 1991;**31**:135−41.
8. Maganaris C, Baltzopoulos V, Ball D, Sargeant A. *In vivo* specific tension of human skeletal muscle. *J Appl Physiol* 2001;**90**:865−72.
9. Kroll W, Bultman L, Kilmer W, Boucher J. Anthropometric predictors of isometric arm strength in males and females. *Clin Kinesiol* 1990;**44**:5−10.
10. Lippold OCJ. The relation between integrated action potentials in a human muscle and its isometric tension. *J Physiol* 1952;**117**:492−9.
11. Bigland B, Lippold OCJ. The relation between force, velocity and integrated electrical activity in human muscles. *J Physiol* 1954;**123**:214−24.
12. Kleinbaum DG, Kupper LL, Nizam A, Muller KE. *Applied regression analysis and other multivariable methods*. 4th ed. Boston: Duxbury Pr.; 2007.
13. DiCarlo S, Sipe E, Layshock P, Varyani S. Experiment demonstrating skeletal muscle biomechanics. *Am J Physiol* 1998;**275**:59−71.
14. Mayhew J, Piper F, Ware J. Anthropometric correlates with strength performance among resistance trained athletes. *J Sports Med Phys Fitness* 1993;**33**:159−65.
15. Hetzler R, Schroeder B, Wages J, Stickley C, Kimura I. Anthropometry increases 1 repetition maximum predictive ability of NFL-225 test for division 1A college football players. *J Strength Cond Res* 2010;**24**:1429−39.
16. Mayhew J, Jacques J, Ware J, Chapman P, Bemben M, Ward T, et al. Anthropometric dimensions do not enhance one repetition maximum

predictions from the NFL-225 test in college football players. *J Strength Cond Res* 2004;**18**:572−8.
17. Bishop P, Cureton K, Collins M. Sex difference in muscular strength in equally-trained men and women. *Ergonomics* 1987;**30**:675−87.
18. Miller AEJ, MacDougall JD, Tarnopolsky MA, Sale DG. Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol* 1992;**66**:254−62.
19. Kanehisa H, Ikegawa S, Fukunaga T. Comparison of muscle cross-sectional area and strength between untrained women and men. *Eur J Appl Physiol* 1994;**68**:148−54.
20. Scanlan J, Ballmann K, Mayhew J, Lantz C. Anthropometric dimensions to predict 1-RM bench press in untrained females. *J Sports Med Phys Fitness* 1999;**39**:54−60.
21. Lindsey C, Makarov M, Shoemaker S, Birch J, Buschang P, Cherkashin A, et al. The effect of the amount of limb lengthening on skeletal muscle. *Clin Orthop Relat Res* 2002;**402**:278−87.
22. Rassier D, MacIntosh B, Herzog W. Length dependence of active force production in skeletal muscle. *J Appl Physiol* 1999;**86**:1445−57.
23. Narici M. Human skeletal muscle architecture studied *in vivo* by non-invasive imaging techniques: functional significance and applications. *J Electromyogr Kinesiol* 1999;**9**:97−103.
24. Wickiewicz T, Roy R, Powell P, Edgerton V. Muscle architecture of the human lower limb. *Clin Orthop Relat Res* 1983;**179**:275−83.
25. Burkholder T, Fingado B, Baron S, Lieber R. Relationship between muscle fibre type and sizes and muscle architectural properties in the mouse hindlimb. *J Morphol* 1994;**221**:177−90.
26. Abe T, Fukashiro S, Harada Y, Kawamoto K. Relationship between sprint performance and muscle fascicle length in female sprinters. *J Physiol Anthropol* 2001;**20**:141−7.
27. Challis J, Kerwin D. Determining individual muscle forces during maximal activity: model development, parameter determination and validation. *Hum Mov Sci* 1994;**13**:29−61.
28. Crowninshield R, Brand R. A physiologically based criterion of muscle force prediction in locomotion. *J Biomech* 1981;**14**:793−801.
29. Herzog W. Individual muscle force estimations using a non-linear optimal design. *J Neurosci Methods* 1987;**21**:167−79.
30. Hahn M. Feasibility of estimating isokinetic knee torque using a neural network model. *J Biomech* 2007;**40**:1107−14.
31. Youn W, Kim J. Estimation of elbow flexion force during isometric muscle contraction from mechanomyography and electromyography. *Med Biol Eng Comput* 2010;**48**:1149−57.
32. Praagman M, Chadwick E, van der Helm F, Veeger H. The effect of elbow angle and external moment on load sharing of elbow muscles. *J Electromyogr Kinesiol* 2010;**20**:912−22.
33. Brookham R, Middlebrook E, Grewal T, Dickerson C. The utility of an empirically derived co-activation ratio for muscle force prediction through optimization. *J Biomech* 2011;**44**:1582−7.