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Interrelationships among various measures of upper body strength assessed by different contraction modes

Evidence for a general strength component

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Summary. Two studies were conducted in 83 college men to determine the degree of generality of individual differences in upper body muscular strength assessed by different testing modes. In study 1 ($N=43$), correlations were computed between four measures of upper body strength using the bench press movement, maximal isokinetic (0.09 $rad \cdot s^{-1}$), maximal fast (0.126 $m \cdot s^{-1}$) and slow (0.037 $m \cdot s^{-1}$) hydraulic, and one repetition maximum (1-RM) free weight bench press (BP). Compared to free weight BP, maximal strength during isokinetic and slow hydraulic BP was ~29% and ~8% larger, and fast hydraulic BP strength was ~63% lower ($p<0.05$). Simple linear regression of isokinetic BP on 1-RM BP yielded $r=0.79$, error of prediction (SE) = 12%, and generality = 81%. The corresponding averaged values for the regression of slow and fast hydraulic BP on free weight 1-RM BP were $r=0.77$, SE = 13.5%, and generality = 84%. In Study 2 ($N=40$), testing included maximal isokinetic concentric and eccentric arm flexion and extension at 0.524, 1.570, and 2.094 $rad \cdot s^{-1}$. The ratio of concentric to eccentric torque at the 3 speeds averaged 0.68 (flexion) and 0.70 (extension), and eccentric torques were 32% and 30% greater than concentric torques ($p<0.05$). The linear regression between concentric vs. eccentric flexion and extension torques at the three velocities yielded an average $r=0.80$, SE = 13.7%, and generality = 73%. The findings from both studies provide evidence for generality of concentric muscle forces obtained during isokinetic, hydraulic, and 1-RM BP movement, and concentric and eccentric torque measured at 3 velocities for simple arm flexion and extension. Thus, individuals who performed well (or poorly) on one type of upper body strength test were able to achieve the same relative level of performance when tested by different contraction modes.

Key words: Muscular strength — Isokinetic — Concentric — Eccentric — Free weight — Dynamometry

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Introduction

The new generation of computerized dynamometers is a valuable adjunct in the assessment of human muscular strength. Computer interfaced isokinetic and hydraulic resistive exercise testing is now routinely used for evaluation of muscular strength in ergonomics (Aghazadeh and Ayoub 1985), pediatrics (Weltman et al. 1986), sports physiology (Hortobagyi et al. 1988; LaChance et al. 1987), and sports medicine (Cooney and Walker 1986). There is little information, however, concerning how maximal muscle performance evaluated by isometric, isokinetic, and isotonic contractions compares to the more conventional methods of assessing strength using free weights. Despite clear-cut differences in physiological and mechanical properties for shortening (concentric) and lengthening (eccentric) muscle actions (Åstrand and Rodahl 1986, p. 44), it is unclear how these two forces produced by the same muscle(s) correlate at discrete testing velocities and strength levels. Prior reports have focused primarily on comparisons between isometric and some dynamic measure of muscular strength with little concern for issues of generality or specificity (Highenboten et al. 1988; Rasch and Pierson 1960). If there is a general muscular strength component across various contraction modes, then individual's who performed well (or poorly) would achieve the same relative level of performance independent of test mode or type of strength being evaluated. Generality would not imply numeric equivalency between the force output scores for the same individual across the various contraction modes because of differences due to neurophysiological (Rothwell 1987, p. 31), biomechanical (Cavagna et al. 1968), and metabolic (Abbott et al. 1952) factors. The crucial statistical test for a general strength component is to determine the extent of relation between various measures of strength performed by essentially the same muscle groups using different contraction modes. Intercorrelations that exceed $r = 0.71$ would indicate a greater proportion of generality than specificity between modes, velocities, and types of movements ($r^2 \times 100 = 50\%$ or greater common variance). In such analyses, reliability of the various strength measurements must be considered in order to remove the error variance (unreliability) using the correction for attenuation. This permits evaluation of the true magnitude of generality or specificity.

Two studies have been conducted to establish the extent of generality of individual differences in upper body muscular strength. In Study 1, only concentric muscle actions were employed during isokinetic, hydraulic, and free weight bench press movements. In Study 2, torques were assessed for both concentric and eccentric contractions during arm flexion and extension exercise.

Methods

Study 1. Study 1 included measurements of age, stature, body mass, isokinetic, and hydraulic tests for bench press on Day 1, and one repetition maximum (1-RM) free weight bench press test on Day 2. A balanced order protocol was used for administering the two dynamometer tests.

Subjects. The subjects were 43 college men from University physical education weight-lifting classes. The mean (±SD) for age, stature, and body mass was 22.1 years (2.82), 1.76 m (0.768), and 72.2 kg (9.06). Subjects had 0.5 to 3.0 years of experience and knowledge with weight lifting exercise, but none had participated in competitive weight-lifting. Informed written consent was obtained prior to testing.

Day 1. Dynamometer tests

Isokinetic. Maximal isokinetic force during supine bench press (BP) was measured with the Ariel dynamometer (Ariel Dynamics Inc., Trabuco Canyon, CA, USA); in this device, fluid is forced through an adjustable valve opening in response to movement of an exercise bar. The valve size is controlled with a fast-response stepper motor. The dynamometer includes a potentiometer and force transducer with an analog-to-digital interface to a microcomputer for on-line data acquisition at a sampling rate of 16,000 Hz. Force was calibrated by hanging weights of known mass on the handles of the exercise bar. The constant error of measurement for 15 repeated trials over several days was 1.5% of the mean force value. This confirms the validation data for this dynamometer reported by Jacobs and Pope (1986).

Prior to testing, subjects performed a standardized warm-up of 10 push-ups followed by 5 movements with the unresisted exercise bar to set the range of motion. Testing velocity was $0.08 \ rad \cdot s^{-1}$ ($0.013 \ m \cdot s^{-1}$) because this speed of movement allowed subjects to achieve a high force output (Wilkie 1950), and subjects were able to mimic the movement speed of the free weight BP (Lander et al. 1985). Multiple sets and trials were used to establish a baseline of performance. Subjects performed 3 sets of 2 trials with a 1 min rest period between sets and with 3 s pause between trials. There was no eccentric resistance while lowering the exercise bar. The criterion score used in the subsequent data analysis was the peak score of the 6 trials. Reliability was $r = 0.96$ for peak isokinetic BP force over multiple days in an independent sample of 24 male subjects tested prior to Study 1.

Hydraulic. The second strength assessment on Day 1 was performed with the Omnitron hydraulic dynamometer (Hydra-Fitness Industries, Belton, TX, USA). This computer-interfaced apparatus provides concentric resistance by use of hydraulic cylinders. Unlike isokinetic dynamometry, the Omnitron does not control the speed of movement or the resistive load. Instead, the resistance to movement is designated by selecting 1 of 12 valve diameter openings through which hydraulic fluid (Gulf 30AW at 12 lbs) is acted on by a Class III lever arm system. The subsequent force output is "effort-dependent", i.e. a greater rate and amount of force application to the lever arm results in greater force output and faster movement. The Omnitron has one potentiometer and a pair of pressure transducers in series with the BP lever arm. Integration of force and displacement data enable analysis of several variables including peak torque. Calibration of the dynamometer-recording system was performed prior to each testing session according to the manufacturer's instructions. The validity of the force scores for the Omnitron was determined by comparing the observed forces at different speeds and resistances with the corresponding forces measured by independent strain gauges. The correlations were $r = 0.97$ to 0.99 between the force scores from the dynamometer and the strain-gauges (standard errors of measurement ranged from 10.5 *N* to 13.7 *N*).

There was a warm-up for the seated bench press. This included 6 consecutive trials of submaximal and progressively more intensive efforts at slower and faster movement speeds. There was a 1 min rest interval between the warm-up and the start of testing. The order of testing was balanced for the two speeds. Subjects performed 2 sets of 5 trials of unidirectional exercise with a pause of 1–2 s between each trial, and a 1 min rest between sets. The average linear movement velocity was $37 cm \cdot s^{-1}$ (SD ± 2.71, slow) and $126 \ cm \cdot s^{-1}$ (SD ± 8.38, fast). The criterion score was the peak score of the 10 trials. Test-retest reliability of the peak scores was $r = 0.89$ (slow) and $r = 0.93$ (fast) assessed on two separate days with 16 males.

Day 2. Free weight tests

Subjects were tested with free weights for one repetition maximum (1-RM) concentric supine BP. There was no eccentric contraction during the 1-RM test because the experimenters lowered the barbell to the subject's chest to eliminate prestretch and store of elastic energy. The arm extension movement was performed after a 1–2 s pause to mimic the isokinetic and hydraulic exercises. Eight to 12 trials were used to achieve the 1-RM. They were performed at successively higher percentages of the estimated 1-RM, starting at 3 repetitions at 70% of the estimated 1-RM, progressing to 2 at 80% 1-RM, and finally 1 at 90% 1-RM. No more than 2 trials were allowed at the 1-RM loads, and the rest pause averaged three min between the maximal lifts. Subject used their normal grip width spacing during the different BP tests. Test-retest reliability for 1-RM was $r = 0.92$ assessed on two separate days with 9 men.

Study 2. Subjects. A different group of 40 college men participated in Study 2. Their mean (±SD) age, stature, and body mass was 22.9 years (4.15), 1.78 m (0.810), and 83.8 kg (14.12). They also signed an informed consent document as in Study 1.

Arm strength tests. Subjects were tested for arm flexion and extension strength using the Biodex dynamometer (Shirley, NY, USA) in which a 3/4 HP DC servomotor is interfaced with four strain gauges located at the output shafts of the powerhead. Three A/D channels provide simultaneous conversion of real-time data signals for torque, velocity, and position. The 3 parallel A/D input channels have the capacity of 10-bit A/D conversion in 35 µs. After signal conditioning and data transfer to a microcomputer, the data were stored on floppy disks for subsequent analysis.

Prior to testing, subjects were seated and straps were secured around the upper arm, waist, and shoulders. The dominant upper arm was positioned on a padded support. The axis of the elbow joint was aligned with the axis of the measuring shaft, and the seat and lever arm settings were set to conform to the individuals' body size. During the arm flexion and extension movements, subjects grasped a plastic handle situated in a neutral anatomical position.

A balanced order test protocol was used to assess isokinetic concentric and eccentric torque for arm flexion and extension. During concentric actions, subjects performed maximum arm flexion and extension at a preset velocity. For eccentric actions, the lever arm moved at the preset velocity when an initial resistance was applied to the exercise bar. For example, eccentric tests for the biceps were initiated with the arm in a fully flexed position. Subsequently, the motor driven lever arm was cued by the subject to begin flexion against the resistance of the volitionally contracting but lengthening biceps. Prior to testing, subjects performed 2 submaximal and 1 maximal contraction for each mode of testing. The tests included 2 maximal flexion/extension cycles at each testing velocity of 0.52, 1.57, and 2.09 $rad \cdot s^{-1}$. There was a 1 min rest between the speed conditions. The criterion score was peak torque. Reliability was estimated in 20 of the 40 subjects on 2 separate days. Reliabilities for peak torque measured at the 3 testing speeds for concentric and eccentric flexion and extension ranged from $r = 0.85$ to 0.97; there were no significant differences between days for peak torque ($p < 0.05$).

Statistics. Because variables with skewness may produce artificially inflated or deflated correlations (Tabachnik and Fidell 1983, p. 67), measures of stature, body mass, and the 16 criterion scores for force were tested for skewness (range from −0.98 to 1.01; $p > 0.05$).

Analysis of variance with repeated measures (followed by Scheffe's post hoc contrast) was used to compare means of the criterion measures in Studies 1 and 2. Pearson product-moment correlations were used to examine the relationships between the variables, and the various intercorrelations were compared by z-transformation (Ferguson 1976, p. 184). The partial correlation technique was used to determine the net relationship between measures of strength without the confounding effect of such variables as body mass and stature. In Study 1, simple linear regression was employed to predict the criterion 1-RM bench press using the other strength measures as independent variables. The slope coefficients for the linear regressions were compared by the technique of small sample t-test for parallelism (Kleinbaum and Kupper 1978, p. 100).

It was necessary to correct the intercorrelations among the strength measures for attenuation due to test unreliability to determine the magnitude of generality vs. specificity (Ferguson 1976, p. 431). With this procedure, generality and specificity can be expressed as $r^2 \times 100\%$ (generality) and $k^2 = (1 - r^2) \times 100\%$ (specificity). There is a large amount of generality if the r^2 is greater than the k^2; thus, the division between generality and specificity is $r = 0.71$ (Clarke and Clarke 1970, p. 316).

Table 1. Descriptive data for the 4 bench press exercises in Study 1 (N=43). Values are expressed in Newtons

Variable	Mean	SD
Free weight	809.4[a]	188.97
Isokinetic	1146.5	285.13
Slow hydraulic	882.5	146.16
Fast hydraulic	302.5	53.61

[a] All means are significantly different from one another ($p < 0.05$)

Results

Study 1. Table 1 presents the descriptive data for the 4 measures of BP force. One-way ANOVA with repeated measures followed by Scheffe's post hoc contrast revealed that the 4 test measures were all significantly different from each other ($F_{3,126} = 399.1$; $p < 0.05$). Isokinetic and slow hydraulic BP forces were 29.4% and 8.3% larger than free weight BP, whereas fast hydraulic BP was 62.6% lower than free weight BP.

Table 2. Correlations among stature, body mass, and the 4 BP measures of strength in Study 1 (N=43). The 6 correlation coefficients (bold upper right) show the single order partial correlations among the 4 test measures without the influence of body mass

Variable	ST	BM	FW	IK	HS	HF
Stature (ST)						
Body mass (BM)	0.56					
Free weight (FW)	0.18	0.56		**0.79**	**0.75**	**0.79**
Isokinetic (IK)	0.30	0.52	0.85		**0.77**	**0.76**
Slow hydraulic (HS)	0.29	0.59	0.83	0.84		**0.82**
Fast hydraulic (HF)	0.26	0.54	0.80	0.83	0.87	

$r = 0.29$ is required for $p < 0.05$

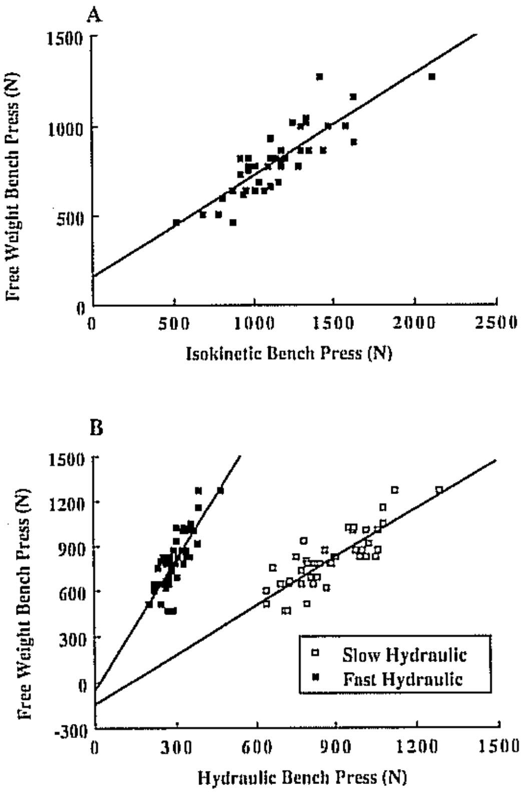

Fig. 1. Linear regression of isokinetic **A** and slow and fast hydraulic bench press **B** on 1-RM free weight bench press. A: $y = 0.564x + 162.963$, SEE = 100.5 *N*, $r = 0.85$, $N = 43$. **B**: Fast: $y = 2.833x - 47.456$, SEE = 113.8 *N*, $r = 0.80$, $N = 40$. Slow: $y = 1.074x - 137.957$, SEE = 106.6 *N*, $r = 0.83$, $N = 40$

The average correlation between the 4 BP tests was $r = 0.84$ ($p < 0.05$), and there were no significant differences among the correlations ($p > 0.05$). Because body mass correlated $r \geq 0.55$ with the 4 BP tests ($p < 0.05$), partial correlations were used to determine the net relationship among the 4 expressions of muscular strength (effects of body mass removed). The average $r = 0.84$ was reduced to $r_p = 0.78$ (Table 2 upper right). The double-order partial correlation technique was also used to remove the combined effects of body mass and stature ($r_p = 0.77$).

Figure 1 illustrates the regression of isokinetic BP (1A) and hydraulic BP (1B) as the independent variables versus free weight BP as the dependent variable. The error of prediction for isokinetic BP was 100.5 *N* (12%), and 106.6 *N* (13%) for slow hydraulic and 113.8 *N* (14%) for fast hydraulic BP. As expected, there were significant differences between the slopes for slow and fast hydraulic BP evaluated by the *t*-test for parallelism ($t_{36} = 14.0$; $p < 0.05$).

Study 2. Table 3 compares the data for eccentric and concentric arm flexion and extension torque. The percentage differences between eccentric and concentric torque averaged 32% for flexion and 30% for extension. There was a significant interaction between eccentric and concentric torque for both flexion ($F_{2,78} = 6.78$; $p < 0.05$) and extension ($F_{2,78} = 23.23$; $p < 0.05$). Thus, a 4-fold increase in testing velocity from 0.524 to 2.094 rad·s^{-1} decreased concentric torque ~10.1% ($p < 0.05$) and increased eccentric torque only ~6.6% ($p > 0.05$, Table 3). The concentric to eccentric torque ratios averaged 0.68 (flexion) and 0.70 (extension).

Table 4 lists the intercorrelations between eccentric and concentric torque evaluated at the same velocity. The correlations averaged $r = 0.83$ ($p < 0.05$) and the partial correlations (holding body mass statistically constant) averaged slightly less ($r_p = 0.80$; $p < 0.05$). The correlations between concentric and eccentric torque for flexion and extension at each of the 3 speeds averaged $r = 0.07$ with age ($p > 0.05$), $r = 0.16$ with stature ($p < 0.05$), and $r = 0.46$ with body mass ($p < 0.05$). There also were no significant differences between the correlations or slope coefficients for the linear regression of eccentric torque on concentric torque at the 3 testing speeds for flexion and extension. The average error of prediction of concentric torque from eccentric torque at the 3 testing speeds was

Table 3. Arm flexion and extension torque (Nm) and concentric to eccentric ratios in Study 2 ($N = 40$)

Speed (rad·s^{-1})	Flexion					Extension				
	Eccentric		Concentric		Ratio	Eccentric		Concentric		Ratio
	Mean	±SD	Mean	±SD		Mean	±SD	Mean	±SD	
0.524	90.2	23.16	65.1	17.30	0.72	96.1	29.02	74.6	21.51[a]	0.77
1.570	92.3	23.56	62.5	14.91	0.68	98.1	28.75	67.3	15.74[b]	0.68
2.094	94.0	23.56	61.1	13.94	0.65	100.2	28.21	64.1	15.09	0.64

[a] Significant difference between torques at 0.524 vs. 2.094 rad·s^{-1}
[b] Significant difference between torques at 1.570 vs. 2.094 rad·s^{-1}

Table 4. Correlation (r) and partial correlation (r_p; body mass held constant) between eccentric and concentric torque for arm flexion and extension (Study 2, $N=40$)

	Eccentric versus concentric torque			
	Flexion		Extension	
Test Velocity, rad·s⁻¹	r	r_p	r	r_p
0.524	0.81	0.80	0.80	0.79
1.570	0.85	0.83	0.86	0.84
2.094	0.84	0.83	0.84	0.82

$r=0.31$ is required for $p<0.05$

13.3 N (13.5% for flexion) and 16.1 N (13.9% for extension).

Discussion

A basic tenet of the generality hypothesis of strength is that if strength is measured by different contraction modes and velocities, the same relative ranking of an individual's performance would be obtained on the different tests. The statistical evidence for generality would be high intercorrelations among the different expressions of measuring strength. One group of physiologists, for example, have reported correlations of $r=0.74$ to $r=0.99$ between various measures of strength, thus supporting the concept of generality (Rasch 1957; Rasch and Pierson 1960; Asmussen 1965; Carlson 1970; Otis 1976; Knapik and Ramos 1980). In contrast, others have reported correlations less than $r=0.71$ between performance and different strength tests (Clarke and Henry 1961; Olson et al. 1972; Osternig et al. 1977). Similarly conflicting findings have been reported about the generality vs. specificity issue in the occupational physiology and ergonomics literature where a major concern is the predictability of lifting capacity. For example, Kamon et al. (1980) reported an average correlation of only $r=0.54$ for 3 comparisons of dynamic lifting strength, whereas a single isokinetic lift proved to be an excellent predictor of operational lifting ability (Jacobs et al. 1988). Most of these studies compared muscle forces for isometric and dynamic contractions. The prediction of muscular force in one mode from a different testing mode has been rarely studied using dynamic measures of strength. Knapik et al. (1983a) compared torques measured at 3 isokinetic speeds with knee and arm extension/flexion measured isotonically. In their study with 16 males generality averaged 48%. In contrast, Jacobs et al. (1988) reported high correlations ($r>0.96$) between isoinertial, isokinetic, and operational lifting tasks in 28 females and 22 males.

Table 5. Generality vs. specificity between the various measures of bench press strength (Study 1), and concentric vs. eccentric torque during arm flexion and extension at 3 testing velocities (Study 2)

	N	r[a]	Generality, %	Specificity, %
Study 1				
IK[b] vs. FW[c]	43	0.90	81.0	19.0
HS[d] vs. FW	43	0.92	84.0	16.0
HF[e] vs. FW	43	0.86	74.8	25.2
IK vs. HS	43	0.91	82.6	17.4
IK vs. HF	43	0.94	88.3	11.7
Study 2				
Arm flexion				
0.524 rad·s⁻¹	40	0.84	70.2	29.8
1.570 rad·s⁻¹	40	0.86	73.2	26.8
2.094 rad·s⁻¹	40	0.91	83.6	16.4
Arm extension				
0.524 rad·s⁻¹	40	0.80	64.3	35.7
1.570 rad·s⁻¹	40	0.86	74.2	25.8
2.094 rad·s⁻¹	40	0.85	71.5	28.5

[a] Pearson product-moment correlation coefficients corrected for attenuation from unreliability
[b] Isokinetic bench press
[c] Free weight bench press
[d] Slow hydraulic bench press
[e] Fast hydraulic bench press

Table 5 summarizes the major findings of the present study for the comparison of isokinetic, hydraulic, and free weight 1-RM BP. Generality averaged 82% for the 3 measures of BP after the influence of body mass was accounted for statistically by use of partial correlations. Clearly, a "general strength component" was present for the 3 modes of BP exercise. These results support prior data by Pytel and Kamon (1981), Mital et al. (1986), and Jacobs et al. (1988). The high degree of generality in Study 1 suggests an intrinsic similarity of muscular function during the 3 modes of BP exercise. Indeed, examination of the position-peak force curves showed that peak force occurred at a similar limb position of ~107° elbow angle during both hydraulic and isokinetic BP in the 6 subjects for whom such data were available. Unfortunately, position-force data were not collected during the free weight exercise and such comparisons with the other modes cannot be made. Lander et al. (1985), however, reported that peak force occurred at 0.295 m to 0.341 m into the range of motion with no significant differences between isokinetic and free weight BP exercises. Further, Lander et al. (1985) observed significant differences in the forces generated during free weight and isokinetic BP. In the current study, significantly different yet highly correlated muscle forces were obtained at the same muscle length for 3 different contraction modes. Such generality of muscular strength appears to be substantiated by the similarities in the direction of force application (Lander et al. 1985), or angle of peak force in the range of motion (Knapik et al. 1983b), and motor skill components (Sage 1984). Further evidence for the generality concept would be enhanced by ascertaining whether motor unit recruitment patterns are also scaled in proportion to the absolute strength differences across the 3 test conditions.

A second purpose of the current study was to examine the relationship between differences in muscular torque production during concentric and eccentric arm flexion and extension exercise. The differences between concentric and eccentric torques are well established in terms of physiological (Abbott et al. 1952), mechanical (Cavagna et al. 1968), and electrophysiological (Moritani et al. 1988) characteristics. In addition, there seems to be a proportionally in the torque produced concentrically and eccentrically. Observations from numerous studies have reported virtually parallel torque-angle curves for concentric and eccentric contractions. When concentric and eccentric torque measured at identical muscle length and contraction velocities is expressed as a ratio, the average ratio is approximately 0.7 for forearm flexion (Singh and Karpovich 1966), arm flexion/extension (Doss and Karpovich 1965; Griffin 1987), knee extension/flexion (Bennett and Stauber 1986; Highgenboten et al. 1988; Tredinnick and Duncan 1988) and hip abduction (Olson et al. 1972). The data in Tables 4, 5, and 6 support the existence of such a proportionality between concentric and eccentric torque during arm flexion/extension movements. The ratios for concentric vs. eccentric torque averaged 0.69 (Table 4), the intercorrelations averaged $r = 0.82$ (with the influence of body mass removed; Table 5), and generality averaged 73.8% (Table 6). Such results reveal that individuals with a high torque output for a concentric action will have a ~ 1.3 times greater torque output during an eccentric action. This degree of proportionality does not change significantly with contraction velocity and strength level. Thus, an individual who is able to produce high concentric forces can be also expected to perform at a correspondingly high level of eccentric force production.

In summary, the results from Studies 1 and 2 provide evidence for a "general strength component" that encompasses concentric muscle forces for isokinetic, hydraulic, and free weight BP, and concentric and eccentric torques measured during arm flexion and extension movements. Within the framework of generality, individuals will perform at the same relative level of proficiency on different tests of upper body muscular strength, independent of testing mode or velocity of contraction.

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