A Trend Analysis of the In Vivo Quadriceps Femoris Angle-Specific Torque-Velocity Relationship

By: Brent L. Arnold, PhD, ATC[*], David H. Perrin, PhD, ATC[†], David M. Kahler, MD[‡]
Bruce M. Gansneder, PhD[§], Joe H. Gieck, EdD, PT, ATC[**]

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Abstract:
To adequately assess isokinetic human muscle performance, it is important for clinicians to understand how the muscle functions across a range of velocities. Thus, the purpose of this study was to re-examine the in vivo quadriceps torque-velocity relationship using trend analysis. Twelve uninjured university-age females performed three concentric and eccentric contractions at velocities of 0, 25, 50, 75, 100, 125, 150, 175, and 200°/sec on the Kin-Corn isokinetic dynamometer. A trend analysis was performed on the angle-specific torques at 30, 60, and 75° of knee flexion. The results indicated that the concentric and eccentric relationships at 30° and the concentric relationship at 60° were represented by a third-order polynomial, and a linear relationship was found for concentric contractions at 75°. There were no significant trends for the eccentric relationship at 60 and 75°, suggesting that they were best described by the grand mean. These results suggest that muscular torque production varies across velocities and contraction modes and that this relationship varies depending on the joint angle of torque measurement.

Article:
Clinicians are often asked to assess the function of muscle. Frequently, this is partially achieved by performing isokinetic strength assessment. One of the difficulties in performing an isokinetic evaluation is selecting an appropriate velocity or velocities. One possible alternative to assessing strength at specific velocities is to assess strength at multiple velocities and evaluate the torque-velocity relationship. If this type of evaluation of muscle is to be useful, the clinician needs to know the normal shape of the torque-velocity relationship.

While earlier investigators (13, 18) have studied the concentric *in vivo* human quadriceps torque-velocity relationship, Perrine and Edgerton (15) were one of the first to attempt to describe the shape of the relationship. Using the Cybex II isokinetic dynamometer, they tested 10 males and five females at velocities ranging from 0 to 288°/sec. Based on the normalized torque at 30° of knee flexion, they concluded that the *in vivo* torque-velocity relationship increased linearly from high velocities to lower velocities but then plateaued and declined at approximately 96°/sec. Similarly, Wickiewicz et al (23), using 12 males and four females and the same protocol as Perrine and Edgerton, produced very similar curves.

In contrast to the above studies, several investigators have graphically depicted data which suggest that concentric torque production continues to increase in a linear fashion as velocity decreases. Thorstensson et al (18) had 25 males perform maximal knee extensions at 0-180°/sec on the Cybex II. Using both peak torque and torques at 15, 30, 45, 60, and 75° of knee flexion, their data plots suggest that torque increased linearly as

[*] Assistant Professor/Associate Director, Sports Medicine/Athletic Training Research Laboratory, Curry School of Education, University of Virginia, Charlottesville, VA. Address for correspondence: Memorial Gymnasium, University of Virginia, Charlottesville, VA 22903.
[†] Professor/Director, Sports Medicine/Athletic Training Research Laboratory, Curry School of Education, University of Virginia, Charlottesville, VA
[‡] Associate Professor, Department of Orthopaedics, University of Virginia Health Sciences Center, University of Virginia, Charlottesville, VA
[§] Professor, Department of Educational Studies, Curry School of Education, University of Virginia, Charlottesville, VA
[**] Professor, Department of Human Services, Curry School of Education, University of Virginia, Charlottesville, VA

velocity decreased, with a marked increase in torque for isometric contractions. These results are supported by a series of studies conducted by Westing et al (20-22). Using a dynamometer constructed in their lab and velocities ranging from 0 to 360°/sec, they demonstrated that the concentric peak torque and angle-specific torque increased as velocity decreased. Furthermore, their results did not demonstrate a plateau similar to Perrine and Edgerton's (15). Finally, Cress et al (6) used linear regression to characterize the quadriceps torque-velocity relationship. Their results demonstrated a significant linear trend for the concentric torque-velocity relationship.

Subject	Velocity (°/sec)							
501	25	50	75	100	125	150	175	200
502	200	25	50	75	100	125	150	175
503	175	200	25	50	75	100	125	150
504	150	175	200	25	50	75	100	125
505	125	150	175	200	25	50	75	100
506	100	125	150	175	200	25	50	75
507	75	100	125	150	175	200	25	50
508	50	75	100	125	150	175	200	25
509	200	25	50	75	100	125	150	175
510	150	175	200	25	50	75	100	125
511	100	125	150	175	200	25	50	75
S12	50	75	100	125	150	175	200	25

TABLE 1. *Velocity rotation (°/sec).*

In addition to examining the concentric torque-velocity relationship, Westing et al (20-22) also examined the eccentric torque-velocity relationship. Their results indicated that quadriceps torque production remained constant across all tested velocities. Similarly, Cress et al (6) reported there was no significant linear trend of the eccentric torque- velocity relationship when analyzed with linear regression.

One of the weaknesses of the previous *in vivo* studies has been the methods of data analysis utilized. Perrine and Edgerton (15), Wickiewicz et al (23), and Thorstensson et al (18) all based their conclusions on a visual analysis of the results. This type of analysis is naturally susceptible to the bias of the investigator and data presentation. In contrast to visual analysis, Westing et al (20-22) based their conclusion on post hoc tests of the means of each velocity. While this type of statistical analysis can detect differences among means, it cannot characterize the shape of the relationship. Cress et al's (6) use of linear regression permits testing for a linear relationship; however, it does not permit the analysis of more complex relationships. Thus, it is the purpose of this study to examine the *in vivo* torque-velocity relationship of the quadriceps femoris using a trend analysis.

METHODS

Subjects

Twelve females (age = 21 ± 1.4 years, height = 162.0 ± 6.1 cm, and weight = 60.8 ± 6.2 kg) with no training experience or history of knee pathology gave informed consent to participate in the study.

Dynamometer Set-Up

Each subject sat on the Kin-Com II isokinetic dynamometer (Chattecx Corp., Hixson, TN) with the lateral epicondyle of the knee aligned with the axis of the dynamometer and the inferior edge of the force pad aligned directly superior to the medial malleolus. Velcro® straps were placed across the hips, thigh, and ankle of each subject for stabilization.

Test Protocol

To prevent testing of dominant and nondominant legs, subjects were asked to kick a tennis ball, and the preferred stance leg was used for testing. Concentric and eccentric isokinetic tests of the quadriceps femoris were performed at 25, 50, 75, 100, 125, 150, 175, and 200°/sec, with the maximum velocity determined by the limitations of the dynamometer. Isokinetic velocities were rotated (Table 1) to reduce the effect of fatigue. Prior to isokinetic testing, 5-second isometric tests were performed at 30, 60, and 75° of knee flexion.

Prior to testing, each subject performed a 5-minute warm-up on a cycle ergometer at a comfortable pace with 1 Kp of resistance. Additionally, each subject performed two submaximal familiarization contractions followed by one maximal familiarization contraction at each test velocity prior to performing the test contractions. The stability of measures produced by this protocol has been previously documented (2). To reduce fatigue, a 1-minute rest was given between the warm-up contractions and test contractions and between the test contractions and the next velocity's warm-up contractions. The efficacy of this procedure has been reported elsewhere (1). For testing, each subject performed three eccentric and three concentric contractions at each velocity through a range of 10-100° of flexion. The eccentric test contraction at a given velocity followed the concentric test contraction at the same velocity without any rest between the contractions. Gravity correction was performed according to the manufacturer's protocol with the knee at 0° of flexion. The dynamometer's preload and minimal force values were set at 50 and 20 N, respectively.

Data Extraction and Analysis

Data analysis was performed on concentric, eccentric, and isometric angle-specific torques at 30, 60, and 75° of knee flexion. To reduce measurement error, concentric and eccentric angle-specific torque values

	$F(1,11)$	$R2$ (%)
30°		
Linear	101.9*	21.0
Quadratic	17.9*	3.6
Cubic	24.89*	5.1
60°		
Linear	22.79*	6.3
Quadratic	0.38	
Cubic	6.03*	1.7
75°		
Linear	77.34*	14.8
Quadratic	1.6	
Cubic	0.62	

*$p < .05$.

TABLE 2. *Concentric trend analysis F and R^2 values.*

were extracted from the torque curve produced as the mean of the three contractions completed at each velocity. A specialized analysis of variance (ie., a trend analysis) was performed to determine the shape of the relationship across the velocities. Based on the recommendations of Myers and Well (14), curves beyond the cubic trend (ie., curves with more than two "bends") were not analyzed. The alpha level was set at .05 for all statistical tests. Additionally, R^2 values, or the percent of variance explained, were calculated to provide an additional basis for trend selection.

RESULTS

Concentric Contractions

For concentric contractions at 30°, there were significant linear, quadratic, and cubic components. The trend analysis for concentric contractions at 60 and 75° produced significant linear trends, with the angle-specific torque at 60° also demonstrating a significant cubic trend. The F values and the R^2 values for significant trends are presented in Table 2.

Eccentric Contractions

For eccentric contractions, the trend analysis of the torque at 30° produced significant linear, quadratic, and cubic trends. There were no significant trends for the angle-specific torques at 60 and 75°. The *F* values and the R^2 values for significant trends are presented in Table 3.

DISCUSSION

When performing an isokinetic muscle assessment using multiple velocities, it is possible for scores obtained later in the velocity sequence to be affected by fatigue. In a group design study, this can be controlled by either randomly assigning the velocities or systematically rotating the velocities. Rotation was chosen to avoid the "random bias" that can result from randomization. For example, a coin has a 50% chance of landing heads with each toss. However, if the coin is tossed 10 times, it is possible for heads to be the result seven of 10 times. This is not a common event but a possible one. If this were to happen in a study such as this, fatigue would potentially produce lower mean torque scores for the velocities that occurred late in the sequence. Thus, we chose to rotate the velocities to better control for this possibility. It should also be noted that the isometric velocity was not included in the velocity rotation. Due to the design of the Kin-Com's operating software, it was necessary to reestablish the dynamometer's set-up each time the isometric contraction was performed. Thus, if the isometric velocity occurred in this middle of the velocity sequence, it would have been necessary to re-establish the set-up three times, eg., once for the initial velocities, once for the isometric contraction, and once for the remaining velocities. By not including the isometric velocity as part of the rotation, one less dynamometer set-up was required, potentially resulting in greater procedural consistency.

Concentric Contractions at 60 and 75°

	F(1,11)	R^2 (%)
30° linear	22.90*	4.8
Quadratic	13.98*	2,9
Cubic	12.03*	2.5
60°		
Linear	3.59	
Quadratic	0.14	
Cubic	3.01	
75°		
Linear	1.93	
Quadratic	0.01	
Cubic	0.70	

*$p < .05$.

TABLE 3. *Eccentric trend analysis F and R^2 values.*

The major finding for the concentric contractions was that a linear trend was significant at 75° and that linear and cubic trends were significant at 60°. However, the cubic trend for the 60° position accounted for only 1.7% of the variance. Graphically (Figures 1-2), our results are similar to those of Westing et al (2022) and Thorstensson et al (18) but differ from those of Perrine and Edgerton (15). Using visual analysis rather than a statistical analysis, Perrine and Edgerton reported that as velocity decreased, torque increased in a linear fashion until approximately 96°/sec, at which time the relationship plateaued and began to decline as velocity reached 0°/sec. One possible explanation for their different results may be related to their method of data display. It is generally accepted that the ordinate axis should be approximately 0.75 the length of the abscissa (16). Perrine and Edgerton (15) used an ordinate axis which was approximately twice as long as the abscissa. If our concentric data are plotted on their scale (Figure 3), our results and theirs are very similar. This explanation of the differences between our conclusions and those of Perrine and Edgerton are supported by the results of Wickiewicz et al (23). Using scales similar to Perrine and Edger- ton's (15) and ours, they produced results similar to both studies, suggesting that the conclusions are dependent on the data-plotting method.

Our results are also inconsistent with the classic results of Hill (8). Using isolated frog sartorii muscles, Hill demonstrated that as load increased, the contraction velocity decreased curvilinearly. Westing et al (19) have suggested that neurological inhibition may explain these discrepancies. Using electromyography (EMG), they demonstrated that muscle activity decreased at slower contraction velocities, indicating that at slower velocities, there was a submaximal activation of the muscle. To explain this result, they suggested that joint receptors, free nerve endings, golgi tendon organs, and other neuroreceptors may provide a negative feedback loop to prevent tissue damage. In two separate studies, Lundberg et al (11,12) demonstrated that both cutaneous and joint receptors stimulated the lb inhibitor}' pathways of cats. They proposed that these receptors synapsed on an interneuron which stimulated the lb inhibitory pathway. These studies support Westing et al's possible neuroinhibitory mechanism. Thus, it is possible that neurological inhibition may prevent the muscle from generating enough force to produce the classic force- velocity relationship.

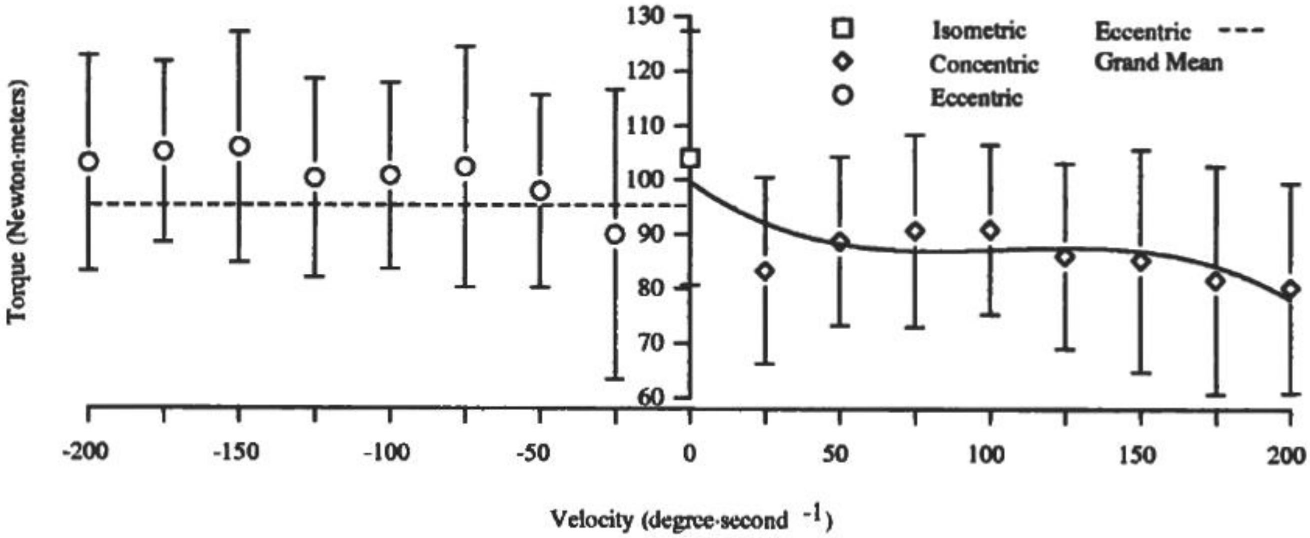

FIGURE 1. *Concentric and eccentric means and standard deviations at 60° of knee flexion.*

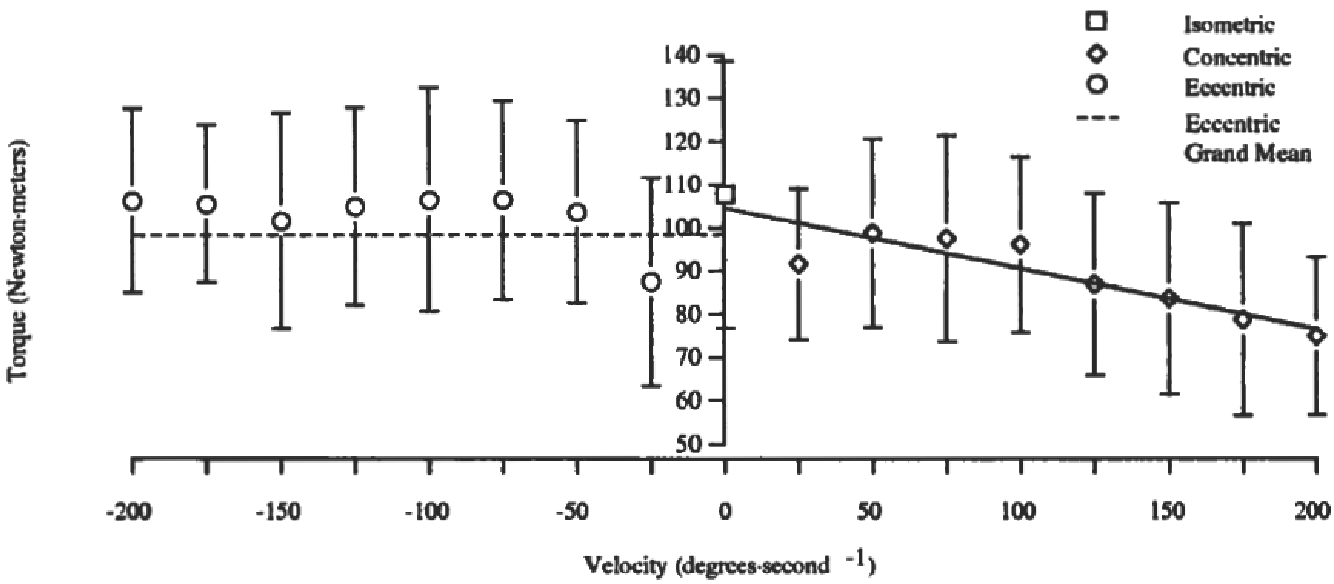

FIGURE 2. *Concentric and eccentric means and standard deviations at 75° of knee flexion.*

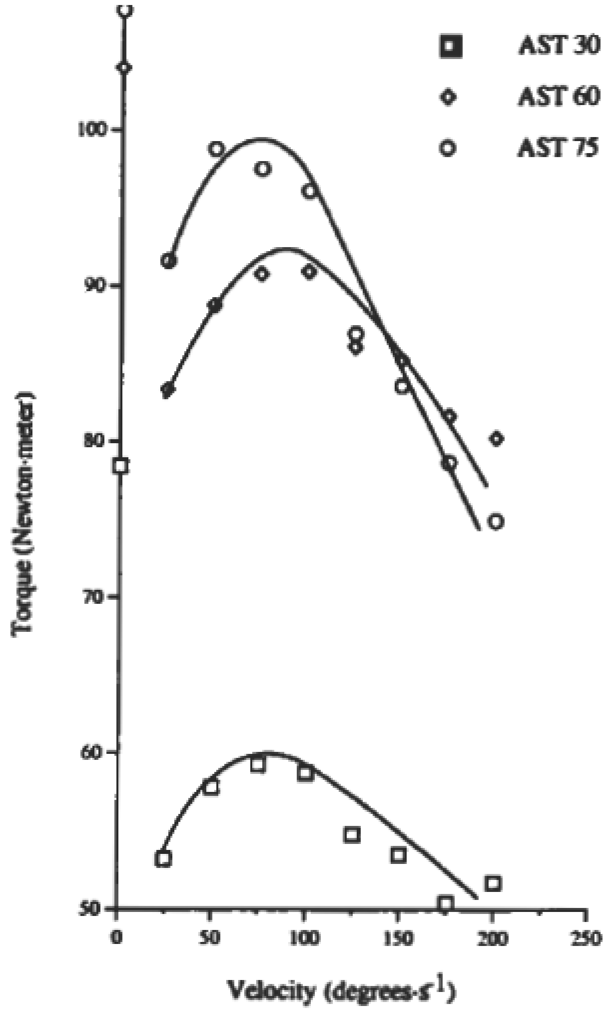

FIGURE 3. *Concentric angle-specific torque (AST)-velocity relationships using Perrine and Edgerton's (1978) scale.*

Eccentric Contractions at 60 and 75°

The major finding for the eccentric contractions at these positions was that there were no significant trends to the data. These results are consistent with those reported by Arnold et al (3) and Westing et al (20-22). In all of these studies, there were no significant differences among the eccentric means, and there was no significant difference between the eccentric means and the isometric mean. This suggests that a flat line best fits the data and that no trend was present. As with the concentric contractions, Westing et al (19,22) proposed that neurological inhibition may be responsible. Westing et al (19) performed an EMG analysis of eccentric muscle contractions and reported that there was no significant change in EMG activity across velocities except for a decrease at 180°/sec for the vastus medialis and an increase at 360°/sec for the vastus lateralis. Furthermore, Westing et al (19), Bigland and Lippold (5), and Tesch et al (17) reported that eccentric EMG values were significantly less than concentric values. Again, Westing et al (19) have suggested that this may be due to a decreased neural drive precipitated by feedback from joint receptors, cutaneous receptors, pain receptors, or the golgi tendon organs.

It should be noted that despite these decreases in EMG, isometric (19) and eccentric (5,17,19) torque values of these studies were higher than the concentric torque. Our results were consistent with these previous findings. This finding is possibly due to differences in the concentric and eccentric force production mechanisms. Based on the cross-bridge theory of muscle contraction, Huxley (9) has suggested that it takes less energy, and thus less force, to produce an actin-myosin bond than it does to pull it apart. This also suggests that isometric force occurs at levels between the concentric and eccentric levels. Thus, it may be possible that at a given submaximal contraction, as indicated by a decreased EMG, the isometric and eccentric contraction will produce more force than the concentric contraction.

The suggestion that a neurological tension-regulating mechanism exists has also been supported by studies (7,22) using electrical stimulation to override the inhibition. Using maximal voluntary contractions, electrical stimulation, and electrical stimulation combined with maximal voluntary muscle contraction, Westing et al (22) demonstrated that maximal voluntary contractions produced less eccentric torque at all velocities than either of the electrical stimulation conditions. Dudley et al (7) also demonstrated that electrical stimulation resulted in greater eccentric torques than voluntary contractions and that stimulated eccentric values were greater than stimulated isometric values. Furthermore, the graphic presentation of Dudley et al's results suggests that the stimulated eccentric torque-velocity relationship is similar to Levin and Wyman's (10). Thus, these studies support the suggestions that neurological inhibition, via joint receptors, cutaneous receptors, etc., may impact eccentric torque production and may impact the shape of the eccentric torque-velocity relationship.

Concentric and Eccentric Contractions at 30°

The major finding for the concentric and eccentric torque produced at 30° was that there were significant linear, quadratic, and cubic trends (Figure 4). The reason for this complex relationship is unclear. However, due to the 90° of hip flexion during testing, the 30° position potentially produces more stretch in the hamstring muscles than does the other two joint positions. Thus, increased stretch in the hamstring and the rate in which it is either increased during concentric contractions or decreased during eccentric contractions may play a role in producing this complex relationship. For example, type Ia and II afferents of the muscle spindle respond to increases in muscle length with greater stimulations occurring with greater length. Additionally, Type la receptors respond to the rate of change of length, with greater stimulations occurring at faster velocities (4). Thus, at 30° of extension, both afferents would respond at a greater rate than at the other two joint angles, and the Type Ia afferents would also respond at a greater rate at higher dynamometer velocities. This possibility appears to fit the relationship in Figure 4. For concentric contractions at higher velocities, when both afferents would be most stimulated, there was a decline in torque. During slower concentric velocities (including isometric) when Type Ia afferents would be less stimulated, there was an increase in torque. Conversely, for eccentric contractions at high velocities, when Type Ia afferents are less stimulated or silent due to a rapid decline in stretch (4), there was an increase in torque. At slower eccentric velocities, when Type Ia afferents would be more active due to a slower decline in stretch, there was a decline in torque.

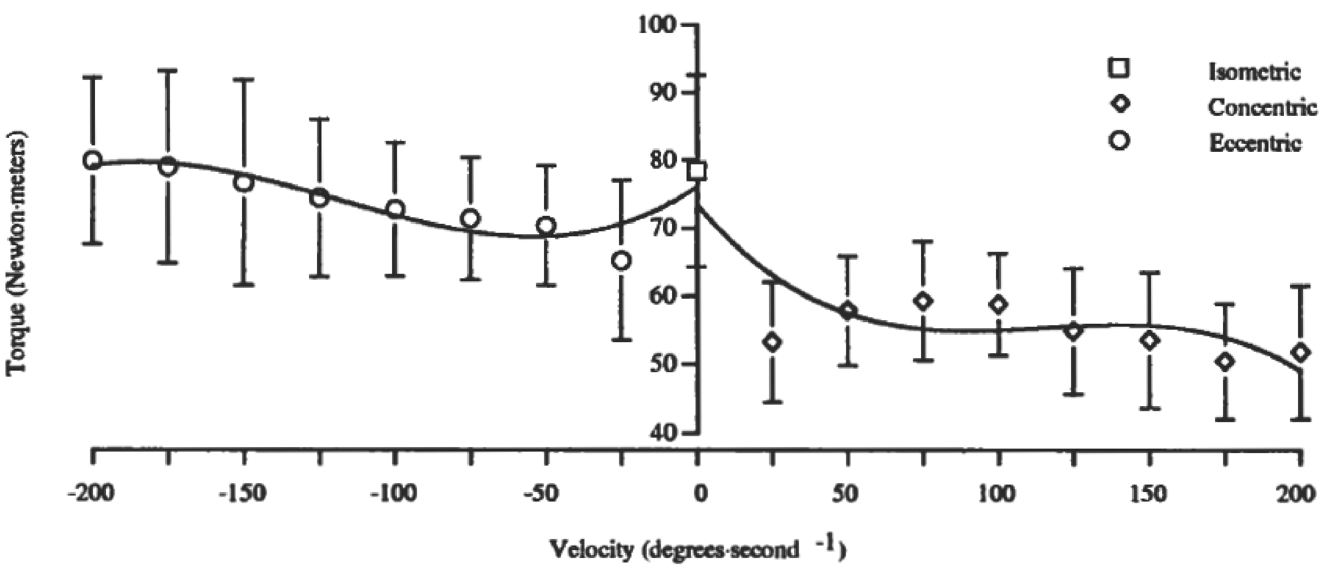

FIGURE 4. *Concentric and eccentric means and standard deviations at 30° of knee flexion.*

CONCLUSION

Our results suggest that the *in vivo* concentric torque-velocity relationship for the quadriceps femoris at 75° is best described by a linear relationship rather than curvilinear as proposed by Perrine and Edgerton (15). One possible explanation for this may be differences in data analysis methods. At 60°, the relationship may be best explained by a third- order polynomial. However, the significant cubic component accounted for only a small portion of the variance. Our results agree with the majority of studies, which suggest that the concentric *in vivo* torque-velocity relationship is different from Hill's (8) *in vitro* relationship. For eccentric contractions at 60 and 75°, we agree with the conclusions of Westing et al (20-22) that the eccentric torque does not change across velocities. This may be due to a negative feedback loop, similar to that discovered in cats, designed to protect against tissue damage (12). The concentric and eccentric relationships at 30° are best characterized by third-order polynomials. This may be due to inhibitory inputs from the hamstring muscle spindles produced by subject positioning. Finally, we recommend that future studies re-examine the torque-velocity relationship of other muscle groups using a trend analysis. We believe that such clarification would be clinically useful in understanding how different muscle groups normally perform across different velocities. Additionally, re-examination of these relationships in the context of gender, muscle type, muscle architecture, training status, and injury might also provide insight regarding appropriate muscle function assessment.

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