

## ***Torque/Velocity Properties of Human Knee Muscles: Peak and Angle-Specific Estimates***

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**Key words:** muscle properties, muscle imbalance, force/velocity, isovelocit, antagonists  
**Mots-clés:** propriétés musculaires, déséquilibre musculaire, force/vélocité, isokinétisme, antagonistes

### **Abstract/Résumé**

*Angle-specific (AS) torque/velocity data have been used to avoid angle related variation in peak torque capacity. However, series elastic structures cause the contractile velocity of active force-producing tissue to differ from external joint velocity except at peak torque. Alternatively, angle related variation may be removed by normalizing peak torque to the isometric maximum at that angular position. The AS, peak (P), and normalized peak (NP) methods were compared in isovelocit knee flexion and extension at velocities between 50 and 250° s<sup>-1</sup> for 8 male subjects. The P and NP methods gave more similar torque/velocity relations than the AS method. Further, very little variation in peak torque was attributed to differences in joint angle. Both the P and AS methods illustrate that relative quadriceps/hamstrings torque capability (flexor/extensor ratio) increases slightly with velocity. It is proposed that antagonist muscle torque capabilities should be compared at different angular positions to assess muscular imbalance.*

*Les mesures de torque et de vélocité sont faites à un certain angle articulaire pour contrer la variation de l'angle correspondant au maximum de torque. Il faut noter cependant que, à cause des structures élastiques en série, la vélocité (linéaire) des structures contractiles (interne) est différente de la vélocité angulaire de l'articulation (externe) sauf lorsque le moment de force est à son maximum. Comme alternative, les variations reliées à l'angle articulaire peuvent être éliminées en normalisant le moment de force par rapport au maximum de tension isométrique à cet angle. Les valeurs de torque à un certain angle*

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*sont comparées aux valeurs maximales selon la vélocité et aux valeurs normalisées en fonction du maximum isométrique à l'angle prédéterminé; 8 sujets exécutent des flexions et des extensions du genou au cours d'exercices isokinétiques variant de 50 à 250°/s. Les deux dernières présentent des relations torque/vélocité beaucoup plus voisines que la première. De plus, il y a peu de variation du moment de force attribuable à l'angle articulaire. Les deux méthodes de mesure non normalisée donnent des ratios des valeurs antagonistes qui augmentent avec la vélocité angulaire. La proposition suivante est faite: que les moments de force des muscles antagonistes soient comparés à différentes positions angulaires afin d'établir s'il y a un déséquilibre.*

## Introduction

The force/velocity (F-V) characteristics of human muscle are important to both researchers and clinicians interested in human strength capabilities. In isolated muscle specimens under controlled maximal stimulation, the relationship between force and contractile shortening velocity is represented by the classic rectangular hyperbola of Hill (1938). For human muscles *in vivo*, the situation is more complex because groups of muscles typically act in consort across one or more joints. Studies on humans therefore typically examine the maximal-effort torque/angular velocity (T-AV) characteristics at a joint.

Although the basic underlying pattern of decreasing muscle force (torque) is seen with increasing contractile (angular) velocity, the shape of the T-AV relation is not identical to the F-V. This is due to several factors, including synergistic contributions from several muscles, differences in muscle fiber composition (Thorstensson et al., 1976) and force/length (F-L) relations (Gordon et al., 1966), variations in muscle moment arms that determine the torque contribution per unit force, and differences in the activation of each muscle by the central nervous system. As a result there are a variety of studies which report that the *in vivo* T-AV characteristics differ from the relation described by Hill (Prietto and Caiozzo, 1989; Taylor et al., 1991).

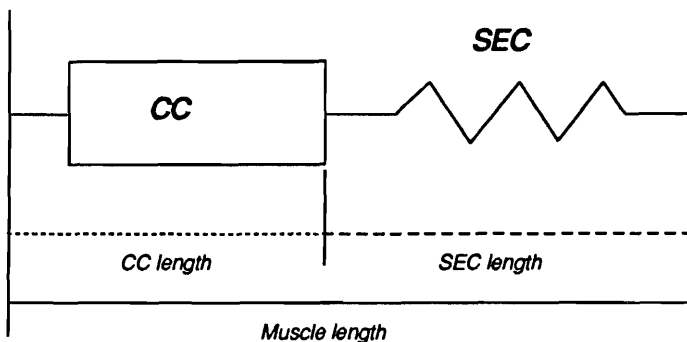
A related question of interest to those in sports medicine concerns the normal balance of muscular strength on opposing sides of a joint. T-AV relations have been used to compare the relative strength capabilities of antagonistic muscle pairs at different contractile velocities (Goslin and Charteris, 1979; Grace et al., 1984; Westing and Seger, 1989). The muscular imbalance revealed by the ratio of flexor to extensor torque may indicate that an athlete has a greater risk of joint injury. At the knee joint, the hamstrings-to-quadriceps torque ratio ranges from 0.3 to 0.7, depending on the exact method of calculation and contractile velocity (Grace et al., 1984; Prietto and Caiozzo, 1989). The hamstrings-to-quadriceps ratio is reported to increase with velocity of contraction (Grace et al., 1984), although the opposite trend also has been reported (Prietto and Caiozzo, 1989). It is possible that these contradictory findings are due to differences in the method of assessing the T-AV relations of the knee flexors and extensors.

One common method of obtaining the T-AV relation is to measure the peak torque during maximal-effort contractions at different shortening speeds, imposed either under inertial conditions by using different load magnitudes (Wilkie, 1950) or under isovelocity conditions by a so-called isokinetic dynamometer (Froese and Houston, 1985; Taylor et al., 1991). This method has been criticized because the peak torques may occur at different angular positions, where the

contributory muscles have different torque capacities due to their F-L relations and varying moment arms. This limitation will “skew” the resulting T-AV relation because there is a trend for the peak torques to occur further from the starting angle with increasing speed (Caiozzo et al., 1983; Prietto and Caiozzo, 1989; Taylor et al., 1991). It has been suggested that measuring torques at one specific angular position (e.g., 30° below the horizontal for knee extensors) for all test speeds will overcome this limitation (Froese and Houston, 1985; Prietto and Caiozzo, 1989; Taylor et al., 1991). The resulting angle-specific torques will therefore all occur with identical contributory effects of the F-L and moment arm factors.

However, consideration of the structure of muscle and the functional consequences of that structure indicates that, in theory, the angle-specific method of estimating T-AV characteristics suffers from a conceptual flaw as well. Muscular force output may be represented by a two-component conceptual model (Figure 1) consisting of an active contractile component (CC) acting in series with a passive elastic component (SEC) (Hill, 1938). The CC exhibits the properties of F-V and F-L and is roughly analogous to the force generation mechanism within individual sarcomeres. The SEC changes its length in a nonlinear fashion as a function of the force generated by the CC and is analogous to all elastic tissues in series with the actin-myosin complex, including both tendon and connective tissues within the muscle fibers.

During any muscular contraction when the force level is changing, the SEC will be undergoing instantaneous alterations in length. This means that the external muscle velocity and the CC velocity are, in general, not equal (Chapman, 1985; Chapman et al., 1985). The difference between external and CC velocities will be at its greatest when force levels are relatively low and the SEC is most compliant. While we often associate these lower forces with submaximal activation, the force may also be at reduced levels due to the F-L and F-V relations, even at maximal activation. The only instant at which the CC and external velocity will be equivalent is at peak force (torque), when the SEC velocity is



**Figure 1.** Two-component conceptual model of muscular function. The active contractile component (CC) produces force as a function of its activity level, length, and velocity. This force is expressed across the series elastic component (SEC), which responds by changing its length in a nonlinear fashion.

instantaneously at zero as the force switches from rising (SEC lengthening) to falling (SEC shortening). Therefore the use of angle-specific torques, which in general do not occur at the peak of the torque-time curve, will introduce error in that the CC velocity will not be equivalent to the externally measured angular velocity. The T-AV relation will be skewed by this error because the difference between the times of peak and angle-specific torques will change in a progressive manner with contractile speed.

There is an alternate method of removing the varying effects of the muscular F-L and moment arm relations, which maintains the use of peak torques and therefore the knowledge that the CC velocity is equivalent to the angular velocity of the joint. In this method the F-L and moment arm effects are determined by assessing the isometric torque-angle (T-A) relation at the joint of interest, and this T-A relation is subsequently used to account for these effects in the peak T-AV relation (Chapman et al., 1985). This normalized peak method therefore addresses the conceptual problems found in both the peak and angle-specific methods.

The present study was undertaken to examine the importance of these conceptual ideas in assessing the T-AV characteristics and relative muscular imbalance. Specifically, we established and compared the T-AV relationship of both knee flexors and extensors using angle-specific (AS), peak (P), and normalized peak (NP) methods. The T-AV relations from the angle-specific and peak methods were each used to assess the ratio of flexor-to-extensor torque at different angular velocities, to determine whether the peak method gives erroneous results as has been claimed (Prietto and Caiozzo, 1989).

## Methods

### TESTING PROCEDURES

Eight male subjects (age  $29 \pm 4$  yrs; body mass  $85.8 \pm 12.4$  kg; height  $180.3 \pm 8.4$  cm) with no history of knee injury participated in the study after giving informed consent. The study was approved by the departmental and university human subjects committees. Each subject was tested on a KinCom Model 125 dynamometer (Chattecx Corp., Chattanooga, TN) operating in its isokinetic mode, in which the angular velocity of movement is controlled at a constant level (isovelocity) set by the investigator. The subject was secured firmly in a seated position with the hip angle at approximately  $105^\circ$ . A series of velcro-fastened straps across the subject's chest, pelvis, and thigh ensured minimal hip motion during all contractions. The KinCom seat and dynamometer head were positioned so that the flexion/extension axis of the knee joint was aligned with the dynamometer arm axis as closely as possible.

After this alignment procedure, the subject's lower leg was secured in a comfortable position to the padded leg attachment on the KinCom arm, again using velcro-fastened straps. The distance from the force transducer on the arm to the axis of rotation was measured carefully to permit accurate calculation of torque from the KinCom force readings. All pertinent linear and angular position measurements were recorded to ensure repeatability across different test days. External calibration with known weights applied to the dynamometer arm prior to testing confirmed the validity of the KinCom torque measurements.

Each subject participated in three testing sessions on different days within a period of approximately 3 weeks. Maximal-effort isometric T-A and dynamic T-AV relations were established for both the knee extensors and flexors for each subject. The T-A relations required a series of isometric contractions at knee joint angles of 85, 100, 115, 130, 145, and 165° for both flexion and extension (maximal extension = 180°).<sup>1</sup> Each subject was required to produce two maximal-effort contractions at each position for each knee action. For some subjects with longer lower legs, the 85° position was replaced with 90° due to physical interference between the KinCom arm and seat support. The T-AV relations required a series of dynamic contractions at the controlled velocities<sup>2</sup> of 50, 100, 150, 200, and 250° s<sup>-1</sup>. Each subject performed three contraction trials at each velocity. It is important to note that 250° s<sup>-1</sup> represents much less than maximal contraction velocity for knee extensors; according to the data of Thorstensson et al. (1976), 250° s<sup>-1</sup> represents about 36% of maximal. Although we have no similar data for the knee flexors, it is doubtful that the 250° s<sup>-1</sup> flexion contraction approached maximal velocity either.

The range of velocities chosen for this study are those commonly seen in clinical evaluations and in the isovelocity literature. Each trial began and ended at the extreme of the tested isometric angles, so that the range of motion for all contractions was consistent within a subject. The trials were performed in a randomized order within each day's testing session, with 2 min rest between trials to avoid fatigue. All trials in which the subject failed to match the specified target velocity were rejected and repeated.

#### DATA TREATMENT AND ANALYSIS

The KinCom dynamometer measures angular position and angular velocity separately, by a potentiometer and tachometer, respectively. In addition, the transducer on the dynamometer arm measures the force exerted by the subject perpendicular to the arm. The force values were converted to torque within the KinCom software using the measured transducer-axis distance. Also, these torque values were corrected for gravity based on the weight of the subject's leg and its angular position (Winter et al., 1981). All measures were recorded using the KinCom software (Chattecx Corp., Chattanooga, TN). For the isometric contractions, the highest torque value was assessed for each trial, with the higher of the two at each position used in that subject's T-A relation. For the dynamic trials, peak torque and the angle at which it occurred was recorded, as were the angle-specific torques at 60° below the horizontal for knee flexion and 40° below the horizontal for knee extension. The 40° position was chosen because some trials exhibited less than the required velocity at 30° below the horizontal, a position used in other studies (Froese and Houston, 1985; Prietto and Caiozzo, 1989). This occurred mostly in the higher velocity contractions, when the dynamometer arm was decelerating from the required velocity at the end of the set range of motion.

<sup>1</sup>These joint angular positions correspond to 1.484, 1.745, 2.007, 2.269, 2.531, and 2.880 radians, respectively, with maximal extension equal to 3.1415 ( $\pi$ ) radians.

<sup>2</sup>These angular velocities are equal to 0.873, 1.745, 2.618, 3.491, and 4.363 rad s<sup>-1</sup>, respectively.

The highest torque value from each T-AV calculation method was chosen from the three dynamic trials at each velocity.

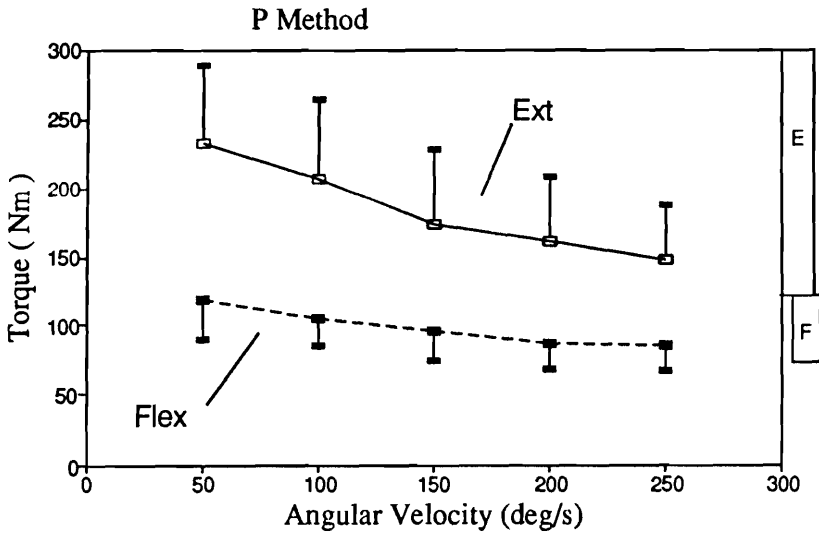
Each subject's isometric T-A data were fit to a third-order polynomial equation. The correlation ( $r^2$ ) values of the goodness of fit of these equations were .976 and .984 for extensors and flexors, respectively. For the normalized peak (NP) method, each peak dynamic torque was divided by the predicted isometric torque for the angle at which it occurred, using the appropriate subject-specific polynomial equation. Finally, the relative strength of the flexors and extensors was assessed by calculation of the ratio between the muscle torques (flexors/extensors) at each velocity, using both the peak (P) and angle-specific (AS) methods.

The flexor and extensor torque measures from the P, AS, and NP data sets each were analyzed statistically using one-way (velocity) within-subjects repeated-measures ANOVA models, with angular velocity as the repeated measure. Contrasts between adjacent velocity pairs (e.g., 50 and 100° s<sup>-1</sup>; 100 and 150° s<sup>-1</sup>) were tested to ascertain more specific information regarding velocity effects. The flexor/extensor ratios were analyzed with a two-way (method and velocity) within-subjects repeated-measures ANOVA, again using angular velocity as the repeated measure. All statistical tests were conducted using SYSTAT version 4.0 software (SYSTAT, Inc., Evanston, IL) on a DOS-based micro-computer.

## Results

The T-AV relation estimated by the P method for both extensors and flexors is illustrated in Figure 2. The torque responses are similar to those found in other studies (Froese and Houston, 1985; Taylor et al., 1991; Westing and Seger, 1989) and demonstrate the greater torque capacity of the extensors at all tested velocities. Significant effects of velocity were found for both the extensor ( $p < 0.001$ ) and flexor ( $p < 0.001$ ) torques. The negative slope of the extensor relation is greater than that of the flexors, so that the relative strength of the flexors compared to the extensors at 250° s<sup>-1</sup> is greater than at 50° s<sup>-1</sup>. This trend was confirmed by the statistical analysis which found the extensor torque at each velocity to differ from the next tested velocity. In contrast, the flexor torques at the two highest velocities (200 and 250° s<sup>-1</sup>) were not statistically different. Statistical  $p$  values for all adjacent velocity tests for P, AS, and NP methods may be found in Table 1.

The T-AV relations as estimated by the AS method demonstrate lower torque values, as shown in other studies (Kannus and Kaplan, 1991). The AS method also demonstrated significant effects of velocity for both extensor ( $p < 0.001$ ) and flexor ( $p < 0.001$ ) torques. However, compared to the P data, these AS data illustrate a more shallow slope, especially for the extensors, and less difference in slope between the two muscle groups (Figure 3). This latter effect is due to the relatively greater reduction of extensor torque measured with the AS method, as compared to the P method, especially at the lower velocities of 50 and 100° s<sup>-1</sup>. Extensor torques between each adjacent velocity are significantly different except for 50 and 100° s<sup>-1</sup> (see Table 1). Much less variation is seen in the flexor torque data, with only the 100 and 150° s<sup>-1</sup> conditions significantly different. The shape of the AS T-AV graph resembles those from other studies,

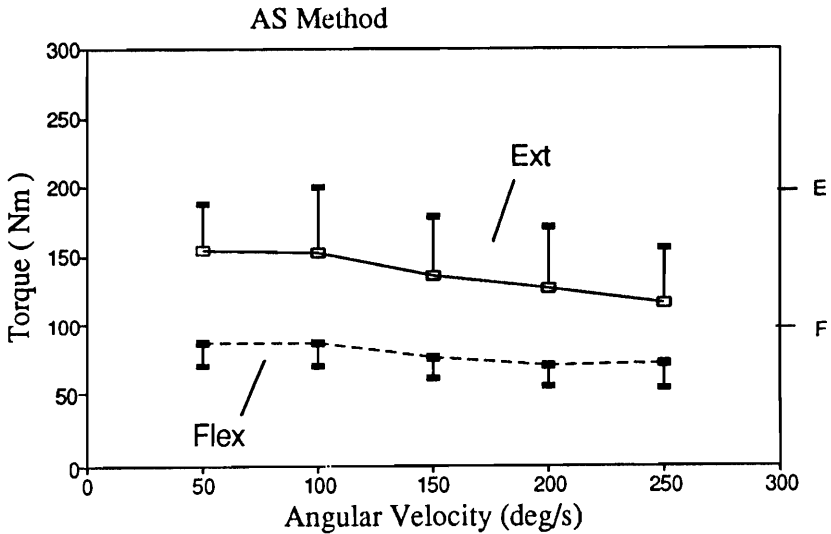


**Figure 2.** MVC torque produced as a function of angular velocity, as estimated by the peak method. Relations shown for both flexors (filled boxes) and extensors (open boxes). Rectangular boxes on the right axis illustrate the range of MVC isometric torques produced at different angular positions for extensors (E) and flexors (F).

**Table 1** Velocity Contrasts for Each Calculation Method

| Specific contrast          | Angle specific | Normalized peak | Peak     |
|----------------------------|----------------|-----------------|----------|
| Flexion                    | <i>p</i>       | <i>p</i>        | <i>p</i> |
| 50 / 100° s <sup>-1</sup>  | 0.883          | 0.233           | 0.022*   |
| 100 / 150° s <sup>-1</sup> | 0.020*         | 0.012*          | 0.001*   |
| 150 / 200° s <sup>-1</sup> | 0.101          | 0.057           | 0.026*   |
| 200 / 250° s <sup>-1</sup> | 0.489          | 0.678           | 0.721    |
| Extension                  |                |                 |          |
| 50 / 100° s <sup>-1</sup>  | 0.868          | 0.021*          | 0.001*   |
| 100 / 150° s <sup>-1</sup> | 0.001*         | 0.001*          | 0.001*   |
| 150 / 200° s <sup>-1</sup> | 0.008*         | 0.003*          | 0.010*   |
| 200 / 250° s <sup>-1</sup> | 0.014*         | 0.015*          | 0.007*   |

\*Significant at  $p \leq .05$ .



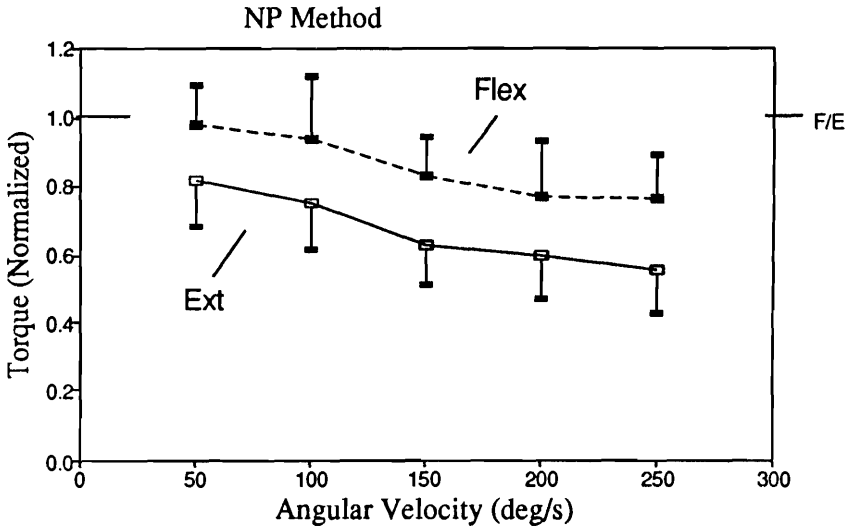
**Figure 3.** MVC torque produced as a function of angular velocity, as estimated by the angle-specific method. Relations shown for both flexors (filled boxes) and extensors (open boxes). Marks on the right axis illustrate the MVC isometric torques produced at the criterion angular positions for extensors (E) and flexors (F).

although the torque magnitudes differ from those in some other reports due to the different criterion angle selected (Froese and Houston, 1985; Prietto and Caiozzo, 1989; Taylor et al., 1991). The difference in relative slope between the P and AS methods is also consistent with other data (Caiozzo et al., 1983).

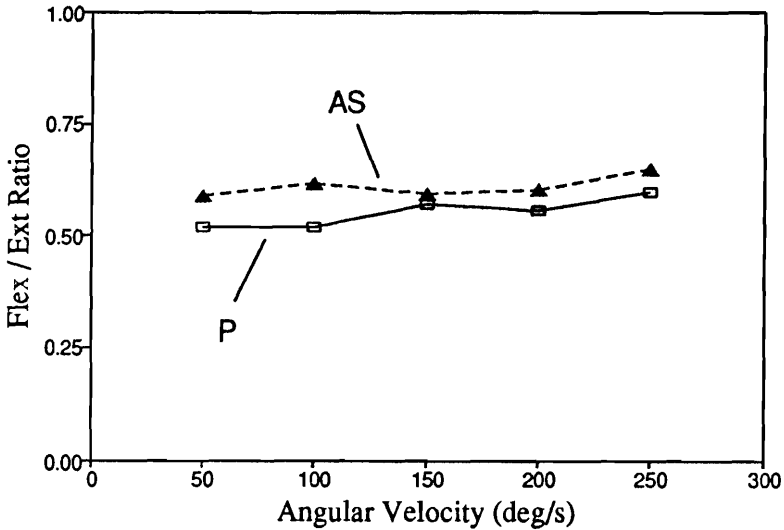
The relation between torque and angular velocity as assessed by the NP method is seen in Figure 4. Because all peak torques are normalized to the isometric value of the angle at which they occurred, the relative strength of the two muscle groups is not illustrated by this graph, although the relative shapes of the separate extensor and flexor T-AV relations are preserved. As with both the P and AS methods, torque is found to vary statistically as a function of velocity for both extensors ( $p < 0.001$ ) and flexors ( $p < 0.001$ ). In agreement with the P method (Figure 2), the flexors are shown to have a less sharp decline in torque than the extensors as angular velocity increases. Torques varied between all adjacent velocity pairs for the extensors, but only between 100 and 150° s<sup>-1</sup> for the flexors, thus illustrating the greater slope of the extensor T-AV relation (see Table 1).

Finally, the ratios of flexor to extensor torque as a function of velocity are shown in Figure 5. These ratios were similar when calculated with the P or AS methods ( $p = 0.448$ ). However, there was a main effect of velocity ( $p = 0.010$ ), although this effect was only seen with large velocity variation since no differences were found between adjacent velocities. Finally, no method-by-velocity effect was observed ( $p = 0.421$ ), indicating that the methods gave similar results at all tested velocities. Results from both methods therefore illustrate a slight increase in the flexor/extensor ratio as speed increases, a trend that agrees with





**Figure 4.** MVC torque produced as a function of angular velocity, as estimated by the normalized peak method. Relations shown for both flexors (filled boxes) and extensors (open boxes). MVC isometric torque for both flexors and extensors at all angular positions is equal to 1.0.



**Figure 5.** The mean ratio of flexor-to-extensor torque as a function of angular velocity. Ratios are estimated from both angle-specific (dashed line with filled triangles) and peak (solid line with open boxes) methods.

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many studies in the literature (Grace et al., 1984; Westing and Seger, 1989) but is contrary to others (Prietto and Caiozzo, 1989).

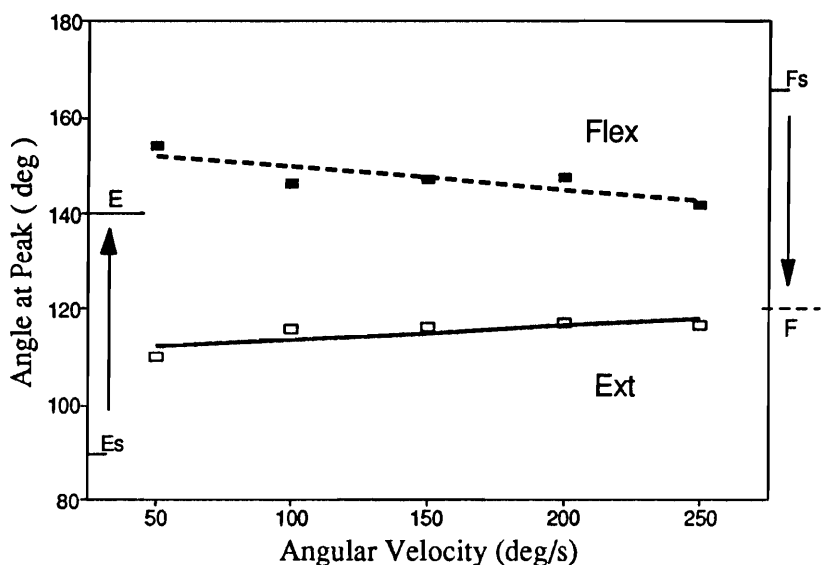
## Discussion

The T-AV relations found in the present data demonstrate that, regardless of calculation method, torque declines with increased shortening velocity, but this relationship does not necessarily resemble the rectangular hyperbola of the F-V equation of Hill (1938). In this respect the data are in agreement with a myriad of other studies that have examined several joints under different loading conditions (Taylor et al., 1991; Wickiewicz et al., 1984; Wilkie, 1950). The results show that the shape of the T-AV relation, in particular its slope, is dependent on the method of calculation used in its determination. However, the flexor/extensor torque ratio is not sensitive to calculation method and is shown to increase with contractile speed, both of which contradict the findings of Prietto and Caiozzo (1989).

The T-AV relation described by the P method has been criticized because the peak torques may occur with the muscle/joint geometry in different positions, a factor that is known to affect the torque capabilities of the muscles. In general the peak torques will tend to occur further from the starting angle as the velocity of contraction increases (Froese and Houston, 1985; Taylor et al., 1991), and the current data illustrate the same trend (Figure 6). The linear regression lines shown in Figure 6 are similar in slope to others in the literature, with the predicted range of angles between  $110^\circ$  ( $50^\circ \text{ s}^{-1}$ ) and  $118^\circ$  ( $250^\circ \text{ s}^{-1}$ ) for knee extensor peak torques and  $152^\circ$  ( $50^\circ \text{ s}^{-1}$ ) and  $142^\circ$  ( $250^\circ \text{ s}^{-1}$ ) for knee flexor torques. One should note that there is considerable variability in these relationships, in the present data as well as in other studies (Taylor et al., 1991). This means that the shift in peak angle does *not always* occur, and in some instances it may be possible to find peak torques from  $50$  and  $250^\circ \text{ s}^{-1}$  contractions that occur at the same or similar angular position.

Both the AS and NP methods are designed conceptually to remove errors due to such angular position deviations. However, in practical terms it is important to know the degree to which the migration in peak angles affects the torque capabilities of the musculature in question. For the range of peak torque angles shown in Figure 6, how much variation is seen in torque capacity due to changes in angular position? One way to assess this variation is to examine the isometric MVC torque-angle relationships (Figure 7). From these relations it can be appreciated that the range of isometric extensor torque corresponding to the angles from  $110$  to  $118^\circ$  is  $290$  to  $273 \text{ Nm}$ , while the flexor torques between  $152$  and  $142^\circ$  range from  $121$  to  $116 \text{ Nm}$ . These torque deviations represent approximately  $6\%$  and  $4\%$  of the larger value for extensors and flexors, respectively.

This small variation is much less than the decrement seen across the range of angular velocities, and represents only a small portion of the torque range across different angular positions (Figures 2 and 7). While these are relatively small deviations, individual subjects display different torque/angle relations and greater shifts in the peak torque angle, so their T-AV relations may be affected to a greater degree than others. Also, other investigators may be interested in a greater range of angular velocities, which would result in a greater shift in peak torque angles. Recall that even the  $250^\circ \text{ s}^{-1}$  contractions may represent only about

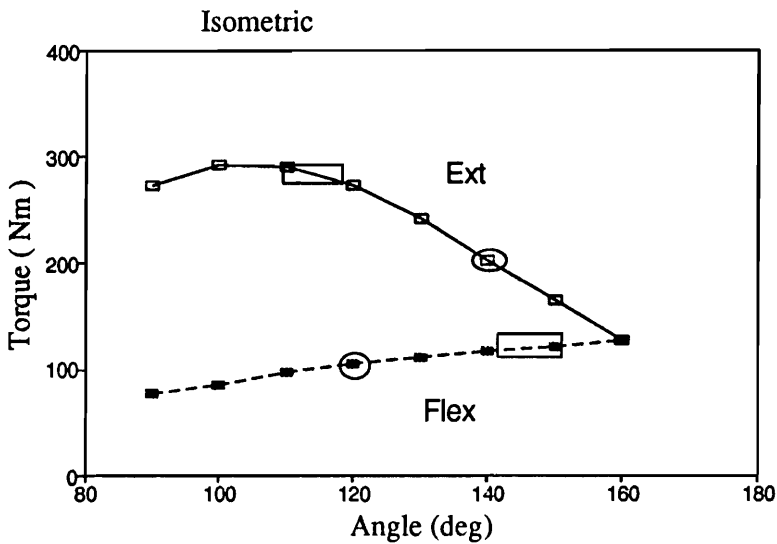


**Figure 6.** The angle at which peak torque occurred as a function of angular velocity. Data means for each velocity are indicated by filled boxes for flexors and open boxes for extensors. Best-fit linear regressions are shown with dashed and solid lines for flexors and extensors, respectively. The starting angles and criterion AS angles are illustrated on the left axis for extensors ( $E_s$  and  $E$ ) and on the right axis for the flexors ( $F_s$  and  $F$ ). Directional arrows along both axes illustrate the direction of angular motion in each condition.

36% of the maximal contractile velocity (Thorstensson et al., 1976). However, in the present data, collected under typical clinical conditions, the shift in the position at which peak torques occur for different contraction velocities has a relatively minor effect on the torque capacity of the muscles.

The NP method of T-AV estimation reflects the rather small shift in peak torque angles, in that the basic shape of the NP and P relations are similar. For the NP method, the decrement in torque between 50 and 250° s<sup>-1</sup> represent 32% and 22% for extensors and flexors, respectively. The same decrements calculated from the P method are 37% and 27% for the extensors and flexors, respectively. The larger figures from the P method are due to the shift in peak torque angle (Figure 6) and the reduction in torque capacity associated with F-L and moment arm characteristics (Figure 7). By normalizing each peak torque with respect to the isometric value at the angle at which it occurs, these characteristics are accounted for and effectively removed as a source of variability.

In contrast, the AS method of calculating T-AV relations predicts much less decrement in torque between 50 and 250° s<sup>-1</sup>: 24% for the extensors and 17% for the flexors. Although the AS method has the advantage of no variability due to angular position effects, it has other conceptual flaws. For example, the selection of criterion angle is subjective, yet the angle will dictate the relative magnitude of the torque measurement. Therefore it is difficult to compare the



**Figure 7.** MVC isometric torque produced as a function of angular position. Data points are means predicted from each subject's polynomial equation. Extensors are represented by the open boxes and solid line; flexors by the filled boxes and dashed line. Circled data points represent the MVC isometric torque at the criterion angles for AS data. Small rectangular boxes indicate the torque variation for the range of peak angles shown in Figure 6.

present extensor data measured at 40° below horizontal with other studies that have chosen 30° below horizontal (or from full extension) as their criterion (e.g., Prietto and Caiozzo, 1989). Further, the fact that the muscle SEC is changing length when the torque is not at peak means that the active CC will be at some velocity other than the external joint angular velocity.

In the present data all AS torque measurements occurred after the peak torque had been attained (see Figure 6). With the torque level decreasing, the SEC would be shortening, so the CC velocity would be less than the external joint velocity. This means that the CC is at a lower velocity than those that appear on the T-AV graph, and that the entire relation should be shifted to the left. However, since the torques measured at lower velocities display peaks that are further removed from the criterion angle than do those measured at the higher velocities, the discrepancy between external and CC velocities will be a function of velocity. Therefore the amount of shift for each data point to yield true CC velocities will differ, resulting in an altered shape of the T-AV curve. Following this logic, one concludes that the AS method will give an incorrect assessment of the CC force/velocity characteristics. Quantification of the error in CC velocity may be achieved with a muscle model that permits the calculation of CC velocity in relation to externally measured joint velocity (Baidon and Chapman, 1983; Caldwell and Chapman, 1989).

The P and NP methods appear to give more similar results than the AS method. For the extensor torques, the P and NP data show significant differences

between each pair of adjacent velocities, while the AS method failed to detect a difference between the 50 and 100° s<sup>-1</sup> conditions. Flexor torque data were similar, with the P method detecting differences between all adjacent velocity pairs except for the highest velocities. Both the NP and AS analyses detected only one difference between flexor torques in adjacent velocities, that between the 100 and 150° s<sup>-1</sup> conditions. However, the *p* value of the NP method for the 150/200° s<sup>-1</sup> difference was very close to significance (*p* = 0.057). Overall, the AS method appears somewhat less sensitive to velocity related differences in isovelocity torque production.

Examination of the NP data in Figure 4 illustrates differences in the shape of the T-AV relation for extensors and flexors. The smaller decrement of torque between the 50 and 250° s<sup>-1</sup> conditions for the flexors (22%) as compared to the extensors (32%) demonstrates the less dramatic effect of velocity on the hamstrings. There are several physiological reasons for muscle groups to exhibit such differences, such as inherent variations in the muscle fiber composition (percentage of slow vs. fast twitch), with "faster" muscles expected to exhibit less decrement in force production at higher velocities. Johnson et al. (1973) reported that hamstrings have a higher percentage of slow-twitch fibers than quadriceps, although it has been suggested that other musculoskeletal attributes offset this difference in fiber composition (Prietto and Caiozzo, 1989). One such factor could be the geometry of the muscle/joint interface. The transformation between linear muscle velocity and angular joint velocity is predicated by the muscle length and its line of action with respect to the joint axis of rotation (i.e., the muscle moment arm) (Hinson et al., 1979). Experimental moment arm data illustrate that marked differences are seen between the flexors and extensors as a function of joint angle (Spoor and van Leeuwen, 1992).

Another important factor may be muscle architecture. Wickiewicz et al. (1983, 1984) described the functional consequences of sarcomeres arranged *in series* (designed for displacement and velocity) as opposed to *in parallel* (designed for tension), and predicted that these differences alone should result in 40% greater force production for quadriceps relative to hamstrings, but that hamstrings should display maximal shortening velocity 30% higher than quadriceps. This is a good example of two offsetting factors (fiber content vs. muscle architecture) that contribute differing effects to the overall T-AV relations of these two muscle groups. Therefore it can be appreciated that the shape of the T-AV relation for any specific muscle group will be a weighted combination of a variety of factors.

Differences in the relative weighting of these factors will lead to differences in T-AV shape between muscle groups. Further, these factors can counteract the effect of each other, meaning that similar T-AV relations can result from quite different underlying physiological mechanisms. For both clinicians and researchers these underlying mechanisms may be more important than the functional relationship itself.

#### RELATIVE FLEXION/EXTENSION STRENGTH

The issue of muscular imbalance at a joint has been addressed by several investigators (e.g., Grace et al., 1984; Westing and Seger, 1989). One common method of quantifying the relative strength of antagonist muscle groups is by expressing their torque capacity as a ratio (e.g., knee flexor torque/knee extensor torque). In this way the relative strength may be examined under different kinematic

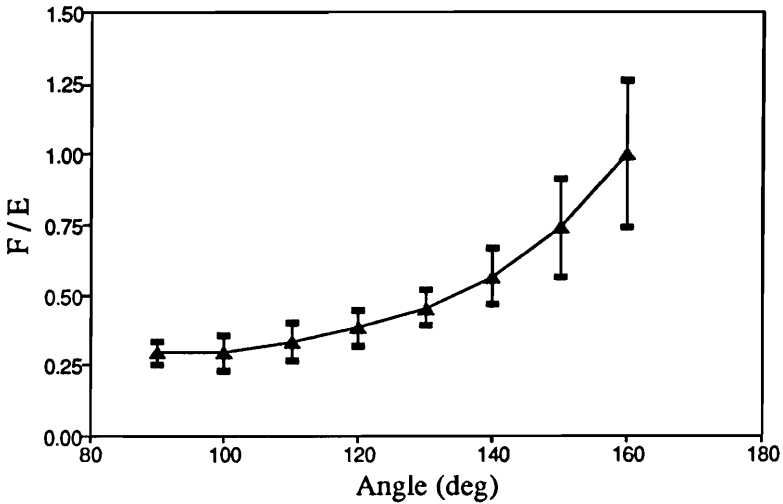
conditions, such as at different angular velocities. Most studies have shown results similar to the present data—the ratio of flexor to extensor torque is less than 1.0 (i.e., the flexors produce less torque than the extensors), and this ratio increases with test speed (Grace et al., 1984; Westing and Seger, 1989). However, Prietto and Caiozzo (1989) found that this hamstring-to-quadriceps ratio *decreased* with speed when assessed with an AS method. They claimed that their data deviated from others in the literature because all other studies were based on the peak torque method, which biased the results due to the shift in peak angles at higher speeds. The present data illustrate that both the AS and P methods give similar results, and the difference in method may not be the reason that their data were contrary to earlier studies.

The arbitrary choice of criterion angles is an important consideration when comparing antagonist muscle torques with the AS method. With the selection of criterion angles in the present study, flexor/extensor ratios ranged between 0.5 and 0.7, much higher than the values of 0.33 to 0.38 reported by Prietto and Caiozzo (1989). This discrepancy is likely related to the difference in extensor criterion angles and both flexor and extensor starting angles. However, the use of two *different* angular positions for this comparison, whatever their specific values, makes the resulting ratios meaningless from a clinical viewpoint. In terms of muscular imbalance, the only meaningful comparisons will be the relative strength at any given position, since it is anatomically impossible for the joint to be simultaneously at both 30° (or 40°) and 60° below the horizontal! This criticism also applies to the P method, since the peak torques of flexion and extension occur at different angular positions (see Figure 6).

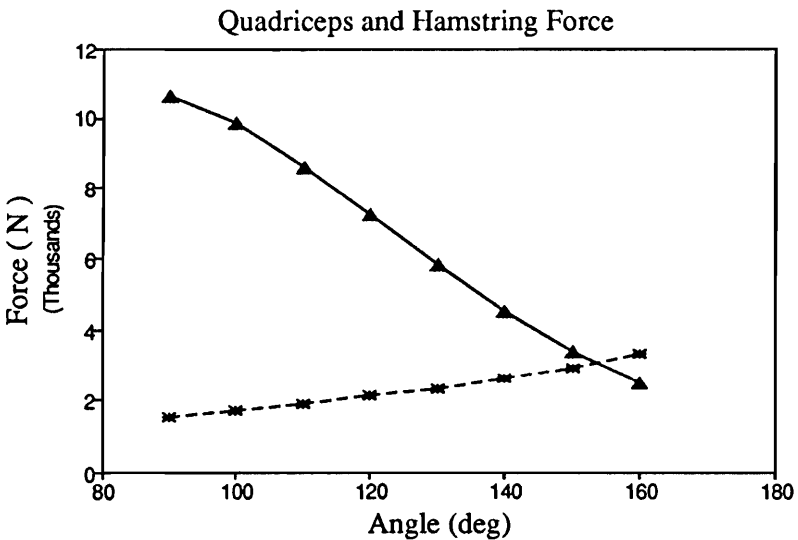
Two approaches seem sensible in assessing muscular imbalance. The first is to compare muscular torque capabilities at specific angles throughout the joint range of motion. In this way specific positions of imbalance may be identified. Ideally this should be done for all kinematic conditions, including isometric, and both concentric and eccentric at different velocities. Figure 8 displays the flexor/extensor ratios calculated from the isometric T-A relations of the current subjects. It is clear that the balance between flexors and extensors changes dramatically as a function of position when assessed isometrically. Producing similar graphs at different dynamic velocities is somewhat more involved, because of the difficulties in obtaining maximal effort peak torques at each position for each desired velocity.

A second approach to studying muscular imbalance would be to systematically explore all physiological and mechanical phenomena that contribute to the expressed muscular torques, such as the specific aspects of muscle morphology and function that affect the shape of the T-AV relationship of antagonist muscle groups. For example, Fuglevand (1987) has investigated the neural (EMG) response of both agonist and antagonist muscle groups during maximal-effort knee extension, in an effort to more fully understand the shape of the three-dimensional torque/angle/angular velocity plot. Others have investigated the contribution of neural mechanisms through either experimental or modeling techniques (Bobbert and van Ingen Schenau, 1990; Perrine and Edgerton, 1978). Another method is to separate the contributions of muscle length (F-L) and moment arm variations to the muscular (im)balance between the quadriceps and hamstrings at different joint positions.

Figure 9 illustrates the predicted variation of muscle force with joint angular position, calculated by dividing the isometric torque magnitudes (Figure 7) by



**Figure 8.** The ratio of flexor-to-extensor MVC isometric torques as a function of angular position. Mean data are illustrated as filled triangles.



**Figure 9.** Predicted isometric muscle forces as a function of angular position. Quadriceps force is shown as filled triangles with solid line; hamstrings force as crosses with dashed line. Muscle moment arm data estimated from Spoor and van Leeuwen (1992) were used in the calculations.

moment arms taken from the data of Spoor and van Leeuwen (1992). While the hamstrings force-joint angle plot resembles the flexor T-A, the quadriceps force displays a more linear relation with joint angle than does the extensor torque. It is possible to further explore the muscle characteristics by transforming the joint angle scale into muscle length and/or estimating muscular velocities from joint angular velocities (Marshall et al., 1990).

## Conclusion

Although the AS method of describing human T-AV relations is convenient and fairly prevalent in the literature, the conceptual flaw concerning CC velocity is a serious source of variability that affects the shape of the desired relationship. The NP method can account for variation due to differing angle at which peak torques occur, although in the present study this variation is rather small. However, one is not able to examine the issue of muscular imbalance with the NP method. The comparative strength of antagonistic muscle groups should be assessed at specific angular positions, as this will indicate possible positions at which an athlete may be at risk. Finally, more information concerning the underlying reasons for such muscular imbalance may be gained by exploring neural, mechanical, and physiological mechanisms of torque production.

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