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RELATIONSHIPS BETWEEN TORQUE, VELOCITY AND POWER OUTPUT DURING PLANTARFLEXION IN HEALTHY SUBJECTS

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ABSTRACT. This study investigated the relationships existing between torque, velocity and power output during plantarflexion. Using a Biodex dynamometric system, 15 healthy subjects performed three maximal dynamic tests, ranging from −12° (−0.209 rad) of dorsiflexion to +47° (+0.818 rad) of plantarflexion and one static test (test 4) at an angle of +10° (+0.174 rad). The dynamic assessment included a 30° s^{-1} (0.52 rad s^{-1}) concentric isokinetic test (test 1) preceded by a 2-sec maximal pre-loading contraction. The other two dynamic tests were performed using the isotonic mode of testing with a selected torque of 27 N m; one of these tests was executed with pre-loading (test 2) while the other was performed without pre-loading (test 3). The results indicated that the dynamic peak torque, the peak power and the peak velocity were obtained in test 1, test 2 and test 3, respectively. These peak values, as well as the values of torque (test 1 and test 4), power (test 2) and velocity (test 3) obtained at a constant angle +10° (+0.174 rad), were selected for the correlation analyses. The results showed that the torque, velocity and power output during plantarflexion were linearly related to one another with significant correlations (0.71 < r < 0.92; $p < 0.01$). This finding suggests that a common factor of muscular performance is assessed. Furthermore, these results indicated that the maximal torque produced by a subject can be predictive of his or her maximal velocity and power. Consequently, a stronger subject can generate higher velocity and power than a weaker subject when tested with the same load during maximal effort.

Key words: modes of testing, muscular parameters, plantarflexors.

INTRODUCTION

The diversity of instrumented dynamometers that have been developed in the last two decades allows the evaluation of muscular performance under various modes of testing. As evidenced from the literature, the most popular methods are static, isokinetic or isotonic in nature. The static mode has been used mainly to evaluate the ability of a group of muscles to exert maximal forces at a specific joint angle (33). The isokinetic mode of testing is particularly relevant for measuring the muscular strength during movement at selected constant velocities (22). In the isotonic mode, a maximal contraction is performed against a constant resistance through the total range of motion and the dependent variable becomes the maximal velocity reached during the movement (23). When the maximal velocity is measured for a range of selected loads it is demonstrated that the lowest resistance gives the highest velocity (16). It must be noted that selecting the isotonic or the isokinetic mode of testing on an instrumented dynamometer does not imply that an isotonic or isokinetic contraction is achieved by the muscles. Rather, the mode of testing referred as isotonic is one with constant force applied against the dynamometer lever arm, while the isokinetic mode means that the system regulates the velocity of the lever arm during the movement (for review, see 2, 11).

Previous studies have investigated the relationships between muscular parameters such as torque, velocity and power in order to determine whether a common factor exists between these parameters. Results of studies on arm movement did not reveal any significant relationship between strength and velocity (3, 4, 27). Nelson & Fahrney (21) have suggested that certain methodological factors may explain this lack of association. Nelson & Fahrney as well as Larson & Nelson (18), demonstrated the existence of a significant positive association between velocities and static torques for the elbow flexion movement. For the same movement, Stothart (28) showed higher levels of correlation between maximal velocity and maximal dynamic torque. More recently, De Koning et al. (5)

reported that maximal torque, velocity and power values were significantly higher for arm-trained athletes than for untrained males and females. However, they did not find significant differences in the shape (concavity) of the force-velocity curves between these different groups of subjects. This suggests that the torque-velocity curves could have a similar shape between subjects and could differ only by their absolute torque values. Consequently, it is postulated that a stronger subject will produce a higher velocity and power than a weaker subject when tested with the same load during maximal effort.

The aim of the present study was to determine, across subjects, the relationships between torque, velocity and power values obtained during plantarflexion movement. It was hypothesized that the mechanical parameters would be linearly related to one another, i.e. that stronger subjects will produce higher power and velocity values than weaker subjects.

METHODS

Subjects

Fifteen healthy subjects, 6 women and 9 men, volunteered to participate in this study. None of them had a history of injury or disorder to the right lower extremity. Their mean age (± SD) was 27.7 (± 6.1) years and their mean height and weight were 169.5 (± 5.7) cm and 68.2 (± 10.7) kg, respectively. All subjects gave their informed consent before participating in the study.

Dynamometric measurements

Muscle performance was measured with a Biodex system (Biodex Corporation, Shirley, NY, USA), which is recognized as a highly reliable and valid testing tool (7, 14, 29, 32). Basically, this dynamometer allows testing using four different methods: isokinetic (concentric or eccentric), isometric, isotonic and passive modes. Isokinetic velocity ranges from 30 to 450° s^{-1} (0.52 to 7.830 rad s^{-1}) and isotonic testing can be done against a constant torque ranging from 0.7 Nm to 339 Nm.

Before each session, calibration of the dynamometer was verified using a known load and lever arm length. Following the calibration procedure, the subject was seated in the dynamometer chair with his or her hips positioned at an angle of 80° (1.392 rad) of flexion and with the right knee stabilized in full extension. The subject's right foot was tightly fixed in a boot attached to the dynamometer and the ankle joint was aligned with the axis of the dynamometer. The reference angle (0°) corresponded to an angle of 90° (1.57 rad) between the sole of the foot and the tibia. Positive angles refer to plantarflexion while negative angles refer to dorsiflexion.

Testing protocol

During each testing session, all the subjects performed three concentric tests. The range of motion on the Biodex was set to allow plantarflexion movement from −12° (−0.209 rad) of dorsiflexion to +47° (+0.818 rad) of plantarflexion. The angle, velocity and torque output during three maximal efforts were recorded for each test with a 2-minute rest period between each effort. Test 1 consisted of a 30° s^{-1} (0.52 rad s^{-1}) isokinetic test preceded by a 2-second maximal pre-loading action (static contraction) before the beginning of the movement. Tests 2 and 3 were executed using the isotonic mode of testing with a selected torque of 27 Nm; test 2 was performed with a maximal pre-loading action, while test 3 was done without pre-loading. These three dynamic tests were selected because they produced, according to a preliminary study (20), the highest values of torque (test 1), power (test 2) and velocity (test 3).

The maximal static pre-loading of 2 seconds was done at the beginning of the range of motion (ROM) with the system set in the stop mode. Two seconds after the beginning of the static contraction, the system was put into the start mode by the experimenter. The subjects were asked to maximally contract their plantarflexors "as hard and fast as possible" and to maintain this maximal effort until the movement stopped. To assess the possibility of fatigue, the maximal static contractions were recorded at +10° (+0.174 rad; test 4) before and after the dynamic testing.

To correct the torques produced during voluntary contractions, for the effect of gravity and visco-elastic torques, passive movements of the ankle from −12° to +47° (−0.209 rad to +0.818 rad) at a velocity of 30° s^{-1} (0.52 rad s^{-1}) were performed at the end of the session. The passive torques (mean values of three repetitions) were used to calculate the correction for each angle throughout the range of movement.

Torque, angle and velocity values recorded by the Biodex dynamometer were sampled at 720 Hz by a data acquisition card (Data Translation, model DT2821) and stored on a disk for further processing. The corrected torque, the velocity and the power (calculated by the product of torque and velocity) values were computed at each degree of the ROM to establish the mean curves of all subjects for each test condition. The mean static torques at +10° (+0.174 rad) values in test 4 were also determined. These mean values were used for the statistical analyses.

Statistical analyses

Pearson correlation coefficients were used to estimate the strength of the relationships existing between the peak values of torque (PT), velocity (PV) and power (PP) across subjects. Using the values obtained at +10° (+0.174 rad), additional correlations were calculated to assess the strength of the relationships between static torque (test 4), dynamic torque (test 1), power (test 2) and velocity (test 3). Thus, these relationships were estimated at a constant angle which did not correspond to the angles where the peak values of these variables were obtained.

RESULTS

Static tests

The mean values (±SD) of the static torques at +10° (S10) performed before and after the three dynamic tests were 140.2 (± 23.12) Nm and 139.0 (± 20.79) Nm, respectively. Statistical comparisons of these values did not reach a significant level (paired t-test; $p > 0.05$).

Consequently, these results suggest that a fatigue effect was not present during the experimental session.

Dynamic tests

The results revealed that all subjects could attain the +30° (+0.52 rad) plantarflexion angle. Thus, the mean torque-angle, velocity-angle and power-angle curves were presented for values ranging from −10° (−0.209 rad) to +30° (+0.52 rad) of plantarflexion (Fig. 1). The mean (± SD) peak torque (PT = 158.0 ± 24.2 Nm) was recorded, in test 1, that is the isokinetic test preceded by a maximal pre-loading. The mean torque at −10° (−0.174 rad) was selected to ensure that the value corresponded to the isokinetic peak torque and not to the pre-load peak torque, which was observed at −12° (−0.209 rad). The mean peak velocity (PV = 405° ± 32.5 s^{-1}; 7.047 ± 0.567 rad s^{-1}) was obtained at +20° (+0.348 rad) in test 3, which is the isotonic test executed without pre-loading. The mean peak power (PP = 335 ± 72.9 watts) was produced at +5° (+0.087 rad) of plantarflexion using the isotonic mode of testing with the movement preceded by a maximal pre-loading (test 2). In this last test, note that the Biodex dynamometer is unable to rapidly adjust the torque at a constant value of 27 Nm. In fact, the torque-angle curve of test 2 is similar to that of test 1 (Fig. 1A). However, the velocity profiles of these two tests are different, with higher velocities observed in test 2 than in test 1 (Fig. 1B). At the angle of +10° (+0.174 rad), the torque (T10) obtained in test 1 was 94 ± 15 Nm (60% of PT), the power (P10) obtained in test 2 was 324 ± 70.4 watts (97% of PP) and the velocity (V10) obtained in test 3 was 400° ± 22.6 s^{-1} (6.960 ± 0.393 rad s^{-1}; 99% of PV).

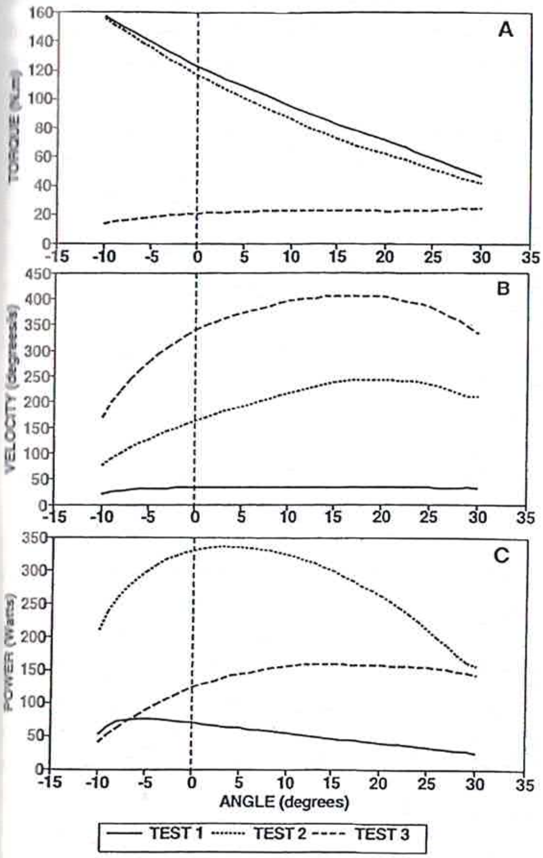

Fig. 1. Torque-angle (A), velocity-angle (B) and power-angle (C) curves obtained in the dynamic tests. Test 1: 30° s^{-1} (0.52 rad s^{-1}) isokinetic concentric test preceded by a 2-second maximal static pre-loading; Test 2: dynamic test preceded by maximal pre-loading and executed using the isotonic mode of testing with a selected load of 27 Nm. Test 3: isotonic test performed against a selected load of 27 Nm and executed without a maximal static pre-loading.

Relationships among the muscular parameters

The results of the intercorrelations for the selected parameters are presented in Table I. In general, the peak values and the values taken at +10° (+0.174 rad) of plantarflexion showed moderate to high correlation coefficients ($0.72 < r < 0.92$). The static torque (S10) was also correlated with the velocity and power values ($0.74 < r < 0.88$). Both the relationships between the torque and velocity, and the torque and power, were linear (Fig. 2).

DISCUSSION

The major findings of the present study are the strong positive relationships found, across subjects, between torque, velocity and power obtained in three different dynamic conditions of testing on the Biodex system. Therefore, our initial hypothesis, implying that a stronger subject produces higher velocity and power than a weaker subject when tested with the same load in a maximal effort, was confirmed.

Selected tests / muscular parameters

In this study, it was important to select tests that could maximize each parameter (torque, velocity or power). Preliminary results obtained with the Biodex dynamometer (20) indicated that the tests used in the

Table I. *Intercorrelation matrix for muscular parameters obtained in the different testing modes. PT (test 1), PV (test 3) and PP (test 2) are the peak values of torque, velocity and power, respectively. T10, V10, P10 and S10 correspond to values of dynamic torque, velocity, power and static torque obtained at +10° (+0.174 rad) of plantarflexion in test 1, test 3, test 2 and test 4, respectively*

	Peak values			Values at +10°			
	PT(−10°) Test 1	PV (+20°) Test 3	PP (+5°) Test 2	T10 Test 1	V10 Test 3	P10 Test 2	S10 Test 4
PT(−10°)		0.830	0.800	0.842	0.834	0.866	0.820
PV(+20°)			0.727	0.846	0.910	0.823	0.778
PP(+5°)				0.720	0.745	0.914	0.767
T10					0.822	0.752	0.872
V10						0.743	0.741
P10							0.752

present study meet this criteria. The PT was observed at −10° (−0.174 rad) in the isokinetic test preceded by maximal pre-loading (test 1). In an isokinetic test, the torque is the dependent variable while the velocity is the control variable. According to the classical force-velocity relationship (12) higher torques are generated at slower velocities. Moreover, for joints with a small range of movement, such as the ankle, it is important

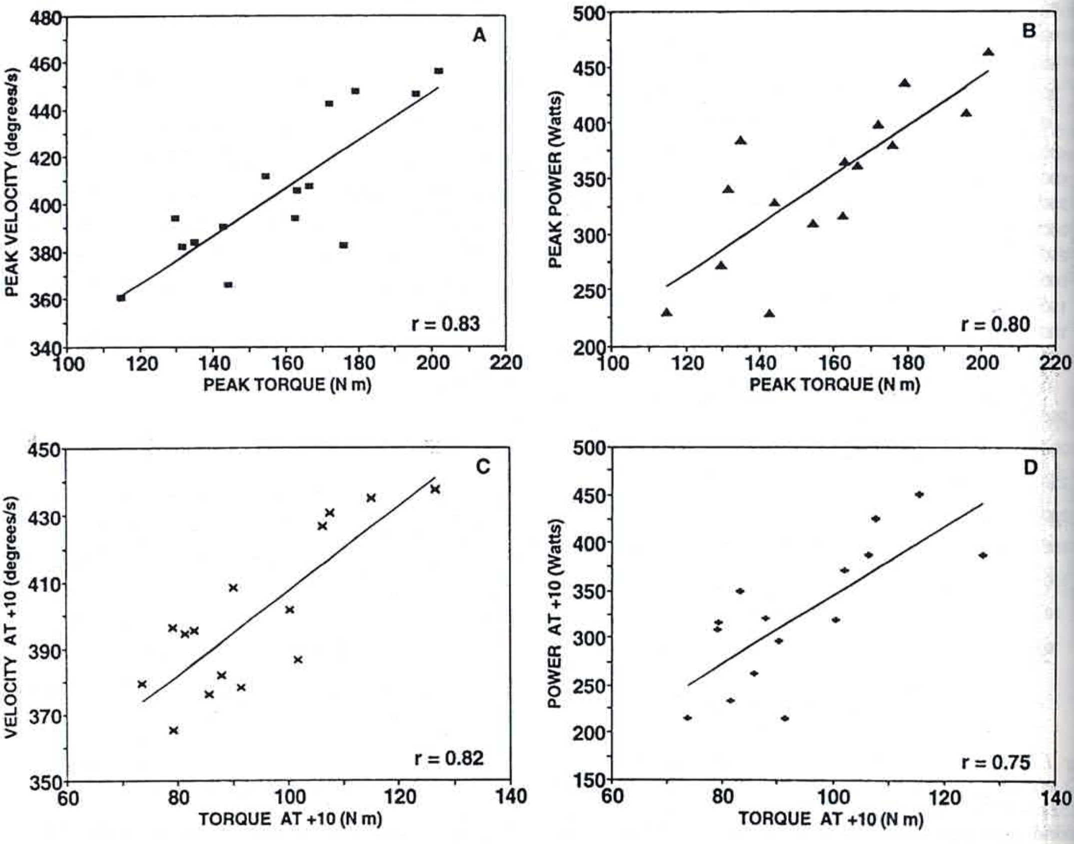

Fig. 2. Scatterplots of the relationships between muscular parameters: (A) Peak values of torque obtained in test 1 versus peak values of velocity measured in test 3, and (B) peak values of torque in test 1 versus peak values of power calculated in test 2. The scatterplots C and D presented the relationships between values recorded at +10° (+0.174 rad): (C) torque values (test 1) versus velocity values (test 3), and (D) torque values (test 1) versus power values (test 2).

to execute maximal pre-loading before the movement to eliminate the influence of the force development phase during the initial part of the range of motion (8, 10, 13, 24). This ensures that the maximal torque is produced at the beginning of the movement. Thus, testing at the slow velocity of $30° s^{-1}$ ($0.52 rad s^{-1}$) using a maximal static pre-loading appears appropriate to obtain the peak torque. The PV was obtained with the isotonic mode of testing using a selected torque of 27 Nm without executing a maximal pre-loading at the beginning of the movement (test 3). In an isotonic test, the velocity is the dependent variable and the load is the controlled variable. We chose a torque of 27 Nm because it represented a load that could be displaced throughout the plantarflexion movement (from $-10°$ to $+30°$; -0.174 rad to $+0.520$ rad) by healthy subjects (9). Incidentally, this torque is large enough to keep the measured velocities in the range available on the Biodex dynamometer ($\approx 450° s^{-1}$: $7.830 rad s^{-1}$). The PP, calculated by the product of torque and velocity, was also obtained with the isotonic mode of testing, but here the movement was preceded by a maximal pre-loading (test 2). In this test, the torque becomes a dependent variable despite the fact that we selected a constant torque of 27 Nm. This is both an effect of the maximal pre-loading which gave a higher level of force production at the initiation of the movement and an effect of the dynamometer which controls the acceleration of the lever arm preventing the torque from quickly reaching the selected constant torque. The mean torque-angle curve clearly indicated that test 2 could not be considered as an isotonic movement (Fig. 1A). Based on the velocity profile, which changed at a constant rate from $-10°$ (-0.174 rad) to $+15°$ ($+0.262$ rad), test 2 could be considered as an isoaccelerative movement. The high level of torques and velocities obtained in test 2 enabled obtaining higher power values during the movement. Finally, the observation that test 2 presented a torque-angle curve similar to that of the isokinetic one (test 1), whereas the velocity-angle curve differed in these two tests, corroborated the finding of Sawaï et al. (26), who have demonstrated that pre-loading modified the classical torque–velocity relationship by increasing the torques generated at high shortening velocities.

Relationships among the muscular parameters

The results of the intercorrelations between the peak values supported those of previous papers which have shown the existence of a moderately high relationship between strength and velocity (18, 21). The linear relationship found between the present torque and velocity values suggests that the torque–velocity curves have, in general, a similar shape across subjects and differ only in the absolute values of torque produced. Consequently, when subjects move the same load (torque), the peak velocities reached during the movement are proportional to peak torques. However, 30% to 50% of the variance across subjects remains unexplained and other factors appear to affect the relationship between peak torque and peak velocity. With regard to this, the first factor that can be advanced is the inter-subject variability in the muscle fibre composition. From the literature, it is recognized that subjects who have a large proportion of type II muscle fibres lose less torque with increasing velocity of shortening than subjects with a low proportion (17, 19, 30, 31). This implies that the shape of the torque–velocity curves could not be exactly the same across subjects. Since the peak torque values used in the present study to compute the correlations are taken in the low velocity–high torque range of the torque–velocity curve and that peak velocities are obtained with a small torque in the high velocity–low torque region, differences in the shape of the torque–velocity could account for the unexplained variance across subjects. The second factor which incidentally also changes the shape of the torque–velocity curve is the inter-subject variability in the neural inhibition at low shortening velocities (6, 25). If neural inhibition on plantarflexor muscles is variable across subjects, as demonstrated by Belanger & McComas (1), the shape of the torque-velocity curve could be different between subjects and could contribute to decreasing the relationship between peak torques and peak velocities.

The intercorrelations found between the muscular parameters at $+10°$ were also statistically significant ($p < 0.05$). It was decided to correlate the torque, velocity and power at $+10°$ to remove a possible angle effect since the peak values were obtained at three different angles (PT: $-10°$ [-0.174 rad]; PV: $+20°$ [$+0.348$ rad] and PP: $+5°$ [$+0.087$ rad]). The correlation coefficients obtained were close to those calculated with the peak values. At $+10°$ ($+0.174$ rad), changes in the absolute values of V10 and P10 were very small when compared to PV and PP, that is 1% and 3%, respectively. The change in the torque value (T10) from −10° to +10° (−0.174 rad to +0.174 rad) was more important (41%). However, the level of correlation found between torques measured at −10° and +10° (−0.174 rad to +0.174 rad) was high (r = 0.84). This last observation, and the fact that small changes were observed in the velocity and power values, probably explains the similarity of the correlations found at +10° (+0.174 rad) with those found at the peak values.

In agreement with previous studies (15, 28), we found a strong association ($r \geq 0.82$) between the static (S10) and the dynamic torques measured in the isokinetic test (PT and T10). This indicates that the static mode of testing may adequately predict a large portion of the strength obtained in a dynamic isokinetic test performed at a slow velocity such as $30° s^{-1}$ ($0.52 rad s^{-1}$). Moreover, the static torque also correlated significantly with velocity and power values, although the coefficients decreased slightly compared to those obtained with the isokinetic torques. These findings support the conclusion of Stothart (28), who considered static performance as a special case of dynamic performance in which the force is maximal and velocity is zero.

CONCLUSION

From the results of this study, which were obtained with a Biodex dynamometer, we conclude that torque, velocity and power values produced during plantarflexion are interrelated, indicating that they are assessing similar components of muscular performance. Furthermore, the relationship between the peak values, across subjects, allows us to conclude that a stronger subject presents a higher velocity and power than a weaker subject when tested with the same selected load in a maximal effort on the Biodex system. However, results may be different if the torque, velocity and power values were recorded with a flexed knee which decreases the contribution of the gastrocnemius muscles. It would be of interest to establish whether similar relationships exist in patient populations with neuro-musculo-skeletal disorders.

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