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DYNAMOMETRIC ASSESSMENT OF THE PLANTARFLEXORS IN HEMIPARETIC SUBJECTS: RELATIONS BETWEEN MUSCULAR, GAIT AND CLINICAL PARAMETERS

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ABSTRACT. The aims of this study were to investigate, in 16 subjects with hemiparesis, the plantarflexor muscle performance of the paretic side and to determine the level of the relationships between muscular parameters, clinical measures and gait performance. A Biodex dynamometric system was used to evaluate static and dynamic torques, power and maximal rate of tension development of the plantarflexor muscles. The clinical measures included the Fugl-Meyer assessment (FMA), the "Up & Go" test and an evaluation of ankle muscle tone. Velocity, cadence, stride length and gait cycle duration were determined for each subject at both comfortable and maximal safe speeds using foot contacts and videographic data. Results indicated that dynamometric values produced by the hemiparetic subjects were reduced in comparison to those reported for healthy subjects. Their torque-angle curves had a curvilinear shape which indicated pronounced decrease of torque for plantarflexion efforts at the beginning of the movement. Torques produced at different velocities of testing did not demonstrate significant differences (MANOVAs: $p > 0.05$) but power values were significantly different. Results also showed that all the selected muscular parameters (torque, power and maximal rate of tension development) were moderately to highly interrelated ($0.65 < r < 0.94$; $p < 0.01$) suggesting that a common factor of muscular performance was assessed. Furthermore, the dynamometric data were significantly associated with some of the clinical measures (sensation and lower limb motor control scores of the FMA) but were not related to the gait variables (Pearson's $r < 0.45$; $p > 0.05$). This last finding suggests that the relationship between plantarflexor strength and the level of gait performance in adults with stroke is complex. The relationship may be influenced by other factors such as muscular compensations within and between limbs and motor control impairments.

Key words: function, gait, hemiplegia, plantarflexors, stroke.

INTRODUCTION

Muscular strength of the lower limbs is recognized as an important factor related to the level of independence of individuals with stroke. Previous studies have investigated the degree of the relationship between muscle strength and a number of clinical dependent variables including the capacity to move the limb (4), balance (6), transfer capacity (5) and gait performance (3, 27). In general, significant, although sometimes weak, correlations between muscle strength and various clinical variables were found. Many correlational studies have also disclosed the fact that the muscle strength of the paretic side provides a stronger indication of the capabilities in a bilateral task such as gait than muscle strength on the non-paretic side (7, 27).

Daily activities require the ability to generate muscular tension at different velocities and at successive joint positions and, in several tasks, a specific level of muscular tension must be reached very rapidly. Thus, in addition to static and dynamic torques, the assessment of other parameters such as maximal power (torque by velocity), maximal velocity of contraction and fatigue is relevant to better document the relationship existing between motor deficits and functional performance. Dynamic testing of the knee flexors and extensors have shown that hemiparetic subjects have difficulty developing muscular tension rapidly (8, 39). Others have demonstrated that these subjects have a prolonged interval between reciprocal contractions, show muscle fatigue at high velocity of testing (41) and have maximal knee extension velocity on the paretic side which is lower than that on the non-paretic side (8). Moreover, walking capacity has been found to be better correlated with dynamic measures of quadriceps' strength than with static measures (27).

In healthy subjects, the plantarflexor muscles are considered particularly important for gait performance because they produce more than half of the positive work during the push-off phase (42). In hemiparetic subjects, Olney et al. (28) have demonstrated that the moment and power of the plantarflexors produced during gait are highly related to gait velocity, suggesting that the plantarflexors are of importance in hemiparetic gait performance. Considering this role of the plantarflexor muscles in the energy generation during gait and the fact that weakness is pronounced in distal lower limb muscles (1, 37) one may postulate that decreased strength of the plantarflexors could be one factor explaining the reduced gait performance of hemiparetic subjects. Consistent with this hypothesis, significant correlations between plantarflexors' static strength and gait velocity have been reported in hemiparetic subjects (3, 7). However, in order to improve our understanding of the relation existing between plantarflexor muscular weakness and gait performance, dynamic as well as static muscular parameters have to be examined on the paretic side of hemiparetic subjects.

The purpose of the present study was threefold. Firstly, to describe the plantarflexor muscle performance (static, isokinetic and isotonic) on the paretic side of ambulatory adults with a stroke. Secondly, to examine the level of association existing between selected muscular parameters (torque, power and maximal rate of tension development). Thirdly, to estimate the relationships existing between dynamometric data, clinical measures and gait performance. It was supposed that the hemiparetic subjects would demonstrate lower dynamometric results relative to those previously reported in healthy subjects. Moreover, it was hypothesized that torque, power and maximal rate of tension development evaluate a common factor of muscular performance. Consequently, these muscular parameters would need to be interrelated. Finally, based on the results of previous papers, we further hypothesized that stronger hemiparetic subjects would demonstrate better gait and clinical performances than those who are weaker. Thus, this would indicate that dynamometric measures of the plantarflexor muscles are related to both clinical and gait parameters.

METHODS

Subjects

A sample of convenience composed of 16 patients (4 females and 12 males) with hemiparesis due to cerebrovascular accident was studied (Table I). Twelve subjects presented with a right-sided hemiparesis. Their mean (± SD) age was 47.9 (± 15.6) years and their mean time post-stroke was 43.9 (± 36.5) months. All participants were able to communicate and follow instructions. The subjects had voluntary motor control in the involved lower limb as well as an almost complete passive range of motion at the ankle, knee and hip joints. Subjects were painfree in the lower limbs and were all able to walk independently with or without a cane, with the exception of one individual who used an electric wheelchair for long distances. The testing procedures required that all subjects be able to walk without an ankle-foot orthosis or any other type of brace. Informed consent was obtained prior to subjects' assessment.

Assessments

Three types of assessments were performed: (I) a clinical assessment including the evaluation of motor function, spasticity and functional mobility skills, (II) a walking assessment of spatio-temporal parameters measured on the paretic side, and (III) a dynamometric assessment of the plantarflexor muscle performance.

I. Clinical assessment

Motor function level of each subject was evaluated using the Fugl-Meyer assessment (FMA; 17). This test, designed to evaluate physical recovery following stroke, is reported to be reliable (14, 35) and valid (13, 17). The FMA uses a cumulative numerical scoring system of items ranging from 0 (cannot be performed) to 2 (can be fully performed). The items assessed motor performance, range of movement, pain, sensation and balance (17). The Fugl-Meyer motor items take into consideration the sequential stages of motor recovery in stroke patients, as described by Twitchell (40).

Presence of spasticity was evaluated by the method proposed by Levin & Hui-Chan (22). This clinical assessment offers a composite score of spasticity which includes three measures: (1) Achilles tendon jerks, ranging from 0 (no reflex) to 8 (maximally hyperactive response), (2) passive ankle dorsiflexion from 0 (no resistance), to 8 (maximally increased resistance), and (3) the amount and duration of ankle clonus with scores ranging from 0 (not elicited) to 4 (sustained clonus) points. Composite scores ranging from 0 to 5, 6 to 9, 10 to 12 and 13 to 16 correspond to normal, mild, moderate and severe spasticity, respectively.

Functional mobility skills were assessed with the timed "Up & Go" test described by Podsiadlo & Richardson (33). This test is reliable (ICC = 0.99) both between and within raters and it has

Table I. *Characteristics of hemiparetic stroke patients (n = 16)*

Cerebral infarction	8		
Cerebral haemorrhage	5		
Unspecified cause	3		
Involved side (left/right)	4/12		
Dominance (left/right)	1/15		
Gender (F/M)	4/12		
	MEAN	SD	RANGE
Age (yrs)	47.9	15.6	18–73
Weight (kg)	74.6	14.2	54.0–110.0
Height (m)	1.71	0.07	1.62–1.87
Time post-stroke (months)	43.9	36.5	2–105

demonstrated content and concurrent validity (33). It requires that the subject be able to rise from a standard armchair (seat height 42 cm, arm height 63 cm), walk 3 m to a line on the floor, return to the chair and sit down. This is done as quickly as possible. After a practice run the subject performs the test twice and the mean time, measured in seconds, from the two tests is calculated.

II. Walking assessment

The subjects were instructed to walk at their most comfortable speed, along a 9-m walk-way and then at their maximal safe speed. Five to seven walking cycles were collected at both speeds. Stride characteristics were recorded with three foot-contacts located on the sole of the subjects' shoe (heel, metatarsal heads and first toe). The foot-contact signals were sampled at a frequency of 120 Hz with a data-acquisition card (Data Translation, model DT2821). From these signals, the cadence and the cycle duration of the gait cycle were obtained. Stride length and velocity parameters were determined using videographic data (not reported) collected simultaneously with the foot-contact signals. The reference data utilized were the coordinates of the heel marker on the affected side and the corresponding images at two successive initial foot-contacts. The spatio-temporal parameter calculations were done using a computer program developed at our centre.

III. Dynamometric assessment

Muscle performance of the plantarflexors was measured with a dynamometric Biodex system (Biodex Corporation, Shirley, NY, U.S.A.), which is recognized as a highly reliable and valid testing device (15, 38). This dynamometer allows testing using four different modes: static, isokinetic, isotonic and passive. Before each session, the calibration of the dynamometer was verified using a known weight. Following this, the subject was seated comfortably on the dynamometer chair with the hips at 80° of flexion and the knee stabilized in full extension. The subject's paretic foot was tightly fixed in a boot attached to the dynamometer and the ankle joint was aligned with the axis of the dynamometer. In this study, the reference angle (0°) corresponded to the ankle in the neutral position. Positive angles refer to plantarflexion and negative angles indicate dorsiflexion.

Moment, angle and velocity measurements of the plantarflexion movement were recorded during four maximal concentric tests executed from maximal dorsiflexion to maximal plantarflexion. All dynamic contractions were preceded by a maximal static preloading. Tests ISOK30, ISOK90, ISOK180 were executed using the isokinetic mode of testing at preset angular motion velocities of $30° s^{-1}$ ($0.52 rad s^{-1}$), $90° s^{-1}$ ($1.57 rad s^{-1}$) and $180° s^{-1}$ ($3.14 rad s^{-1}$), respectively. The fourth test (ISOT14) was performed using the isotonic mode of testing and a selected torque of 14 newton meters. Previous results on healthy subjects (25) have shown that the isotonic mode of testing uses both with a small torque and preloading produces high power (torque X angular velocity) values. This fourth test was thus added to measure the maximal power which could be produced by the hemiparetic subjects. For each dynamic effort, the subjects were asked to maximally contract their plantarflexors "as hard and as fast as possible" and to maintain this maximal effort until the movement stopped. An additional maximal static test (S10) was executed at +10° (+0.174 rad) of plantarflexion. For this test, the subjects were asked to contract their plantarflexors "as fast and as hard as possible" and to hold the contraction for a short period of time before relaxing. Three maximal efforts were requested for each test and a 2-minute rest period was allowed between each effort. To correct the torque data for the effect of gravity and visco-elastic torques, passive movements of the ankle, 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. Thus, only the active torque and power values are reported in the present study.

Moment, angle and velocity measurements 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 active torque, the velocity and the power values were computed at each degree of the range of motion to establish the mean curves for each subject for the four dynamic conditions. The peak values of torque and power, identified as PT and PP, produced in test ISOK30 (angle of −10°; −0.174 rad) and test ISOT14, respectively, were then computed. From these same two tests the values of torque (T10) and power (P10) at an angle of +10° (+0.174 rad) of plantarflexion were also retained. For the static test (S10), the maximal static torque as well as the maximal rate of tension development (MRTD10) were determined for the three repetitions and mean values were computed for each subject. All the aforementioned mean values were used for the statistical analyses.

Statistical analysis

Descriptive statistics were calculated for subjects characteristics, clinical scores, gait parameters (cadence, velocity, stride length, gait cycle duration) and dynamometric data. For the dynamometric data, one way analyses of variance for repeated measures (MANOVAs) were applied to depict differences between the four dynamometric tests with respect to torque, velocity and power values at −5° (−0.087 rad), +5°(+0.087 rad) and +15° (+0.261 rad). When the MANOVAs revealed significant differences ($p < 0.05$), paired t-tests with adjusted probability values were then performed to depict differences between the data. Furthermore, the level of the relationships among the muscular parameters of the plantarflexor muscles was examined using the Pearson product moment correlation coefficient. The peak values of torque, power and the muscular parameters (T10, P10, S10 and MRTD10) computed at +10° (+0.174 rad) were used for these analyses. Similarly, correlation coefficients were also calculated to determine the degree of the relationships existing between dynamometric measures, clinical scores and gait parameters. The dynamometric values, normalized to body mass, were also included because they are frequently used in such correlational studies (3).

RESULTS

Clinical and gait assessments

Descriptive statistics for the FMA (total and subsections), the spasticity index and the "Up & Go" test are summarized in Table II. The total score of the FMA ranged from 151 to 223 with a maximum score attainable of 226. For the motor function score (upper and lower extremities), the subjects achieved a mean value of 69.6 (± 16.7) indicating, as described by Fugl-Meyer (18), a marked motor impairment. The mean score for the lower extremity was 26.8 (± 4.7) while the mean value of the sensation score of the lower limb was 10 (± 2.8) with four subjects presenting scores lower than 8 points. In general, subjects scored high on the balance section of the FMA, with the exception of one subject who scored 9/14. Concerning the spasticity score, the mean value was 7.1 (± 3.0). Two subjects reached a value of 13 indicating the presence of severe spasticity at the ankle, while other subjects demonstrated mild spasticity or normal tone at the ankle joint. The average time of the "Up & Go" test was less than 10 seconds. It should be noted that four subjects used a cane when they performed the "Up & Go" test and the walking assessment.

The mean (± SD) comfortable velocity of walking was 0.76 (± 0.27) m/s with values ranging from 0.41 to 1.50 m/s (Table II). All subjects, except two, walked slower than 1 m/s. The mean maximal safe velocity reached a value of 1.08 (± 0.33) m/s and was characterized by an increase in cadence and stride length and a decreased gait cycle duration. The lowest and highest maximal velocities were 0.58 and 1.76 m/s, respectively. Seven subjects presented a maximal safe speed which was slower than 1 m/s.

Dynamometric assessment of the plantarflexors

The mean, standard deviation and range of the peak values and the values at +10° (+0.174 rad) are reported in Table II. The dynamic torque (T10) measured at +10° (+0.174 rad) was less than half the value of peak torque (23.9 vs 65.4 N.m) while the static torque (T10) was slightly lower (50.8 vs 65.4 N.m). The power (P10) measured at +10° (+0.174 rad) in test ISOT14 was greatly reduced in comparison to the peak power value which was obtained when the ankle was dorsiflexed.

The mean results for torque, velocity and power for the four dynamic tests are presented in Table III. At the selected angles [−5° (−0.087 rad), +5° (+0.087 rad) and +15° (+0.261 rad)], the MANOVAs did not depict

Table II. *Mean, standard deviation and range of scores obtained from different assessments of stroke patients (n = 16)*

Variables		Mean	SD	Range
Clinical assessment				
Fugl-Meyer:	Total (226)*	184.3	20.8	151–223
	Motor Function (100)	69.6	16.7	46–98
	Upper extremity (66)	42.8	15.0	19–64
	Lower extremity (34)	26.8	4.67	15–34
	Balance (14)	11.8	1.2	9–14
	Sensation lower limb (12)	10.0	2.8	5–12
Spasticity score (16)		7.1	3.05	1–13
"Up & Go" (s)		9.20	2.40	5.8–13.8
Walking assessment				
Comfortable speed:	Velocity (m/s)	0.76	0.27	0.41–1.50
	Cadence (steps/min)	82.3	14.6	63.2–121.0
	Stride length (m)	1.07	0.21	0.76–1.49
	Cycle duration (s)	1.50	0.24	0.99–1.90
Maximal safe speed:	Velocity (m/s)	1.08	0.33	0.58–1.76
	Cadence (steps/min)	102.9	13.6	80.2–131.6
	Stride length (m)	1.24	0.24	0.82–1.61
	Cycle duration (s)	1.19	0.16	0.91–1.50
Dynamometric assessment**				
Peak values:	PT: Torque (N.m)	65.4	36.9	2.4–123.6
	PP: Power (Watts)	119.6	65.0	4.4–226.6
Values at +10° (+0.174 rad):				
	T10: Torque (N.m)	23.9	15.7	0–41.8
	P10: Power (Watts)	67.9	50.0	2.0–174.8
	S10: Static torque (N.m)	50.8	24.4	4.2–91.8
	MRTD10: Max. rate of tension development(N.m/s)	110.5	56.7	7.0–172.1

* Values in parentheses indicate the maximum score attainable.

** PT = Peak value of torque produced in test ISOK30; PP = Peak value of power obtained in test ISOT14; T10 and P10 = Values of torque and power at +10° obtained in tests ISOK30 and ISOT14, respectively; S10 and MRTD10 = Static torque and maximal rate of tension development obtained at +10°.

significant differences in the torque values between the four testing conditions ($p > 0.05$). However, note that torques tended to be slightly higher with test ISOK30 at the three angles. Paired *t*-tests revealed that test ISOT14 produced the highest velocity values and allowed, as expected, the subjects to develop the highest power values, except at +15° (+0.261 rad) where no significant differences were detected in the velocity and power values between tests ISOK180 and ISOT14.

Fig. 1 displays mean torque-angle and mean power-angle curves with their respective standard deviations obtained during the isokinetic test (ISOK30) executed at $30^\circ s^{-1}$ (0.52 rad s^{-1}) and the test performed with the isotonic mode of testing (ISOT14), respectively. The curves are presented from −10° (−0.174 rad) because all subjects were able to reach this dorsiflexion angle. From the torque-angle curve, one should note that the peak torque [mean(± SD); 65.4(± 36.9) N.m] occurred at the beginning of the movement when the ankle was in dorsiflexion. The torque-angle relationship tends to have a curvilinear shape, indicating a more pronounced decrease in torque with plantarflexion efforts at the beginning rather than at the end of the movement. Hemiparetic subjects produced peak power [mean(± SD); 119.6(± 65.0) W] between −12° (−0.209 rad) and 0° when the ankle was dorsiflexed; after this, power values decreased quasi-linearly with plantarflexion angles. In both torque-angle and power-angle curves, the respective standard deviations indicated that absolute differences between individuals were greatest in the first part of the plantarflexion movement. One should note that one subject could not perform test ISOK180 and ISOT14 and seven other subjects could not reach actively, at least in one of the dynamic tests, 30° of plantarflexion. This contributed to enlarging the between-subjects variability for the dynamometric parameters reported in Tables II and III and in Fig. 1.

Table IV offers evidence indicating that muscular parameters of the plantarflexors found across subjects were moderately to highly correlated. PT showed moderate to close relationships ($0.74 < r < 0.94$) with all variables, while correlations with torque values (T10) at +10° (+0.174 rad) were slightly lower ($0.65 < r < 0.74$) than those observed for PT. The range of correlations obtained with PP ($0.68 < r < 0.94$) were also higher than those obtained with P10 ($0.65 < r < 0.80$). MRTD10 was highly correlated to PT ($r = 0.82$), PP ($r = 0.74$) and S10 ($r = 0.88$) but less to T10 ($r = 0.69$) and P10 ($r = 0.66$). The scatterplot of the relation between S10 and MRTD10 is presented in Fig. 2.

Muscular parameters versus clinical and gait variables

The coefficients of correlation obtained while contrasting the dynamometric measures taken at the ankle, gait and clinical variables are reported in Table V. Results showed that all the muscular parameters correlated moderately with the lower limb sensation score while only some were significantly related to the FMA lower limb motor scores. It should be noted that with regard to PT and PP values the four weakest subjects were those who had the lowest scores on the lower limb sensation section of the FMA. The spasticity scores were not

Table III. *Mean (± SD) values of torque (N.m), velocity ($^\circ s^{-1}$) and power (W) obtained at −5° (−0.087 rad), +5° (+0.087 rad) and +15° (+0.261 rad) under the four dynamic testing conditions*

		Dynamometric tests			
		ISOK30	ISOK90	ISOK180	ISOT14
−5°	Torque*	53.8 (30.9)	53.3 (26.4)	51.6 (27.4)	48.0 (26.4)
	Velocity	30.1 (2.0)	59.4 (9.8)	84.2 (14.3)	135.9 (23.2)
	Power	28.8 (17.1)	53.4 (34.0)	77.5 (43.2)	115.9 (64.8)
+5°	Torque*	32.1 (19.7)	28.3 (17.7)	29.7 (17.7)	25.8 (16.8)
	Velocity	29.4 (7.8)	78.5 (21.3)	122.5 (8.7)	184.7 (25.8)
	Power	17.6 (10.8)	42.1 (26.8)	64.3 (39.0)	87.5 (58.5)
+15°	Torque*	17.5 (13.0)	12.6 (9.5)	13.1 (10.2)	12.3 (10.6)
	Velocity**	29.3 (7.8)	83.4 (22.7)	139.4 (38.0)	153.5 (87.9)
	Power**	9.5 (7.1)	19.8 (15.2)	34.5 (27.2)	42.7 (38.8)

* The torque values did not differ between the four tests at −5°, +5° and +15° ($p > 0.05$).
** The velocity and power values obtained at +15° are not significantly different between tests ISOK180 and ISOT14 ($p > 0.05$).

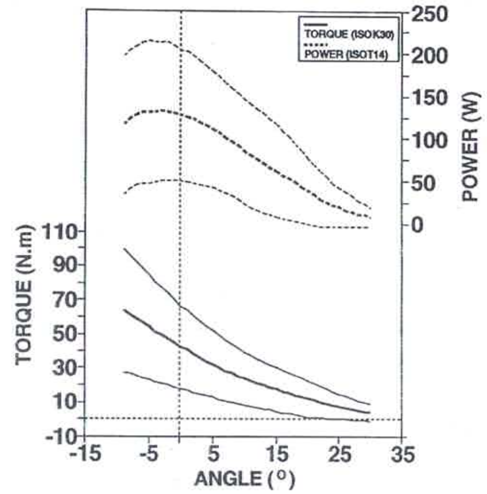

Fig. 1. Ankle torque-angle (——) and power-angle (- - - -) curves (mean ± SD) of hemiparetic subjects obtained respectively in the concentric isokinetic test (ISOK30) performed at $30° s^{-1}$ (0.52 rad s^{-1}) and the test (ISOT14) executed using the isotonic mode of testing with the torque set at 14 N.m.

significantly related to any of the plantarflexor muscular parameters. In general, the level of association found between the muscular parameters tended to be higher for the normalized data.

None of the muscular parameters, normalized or not against body mass, were correlated significantly with gait measures including the "Up & Go" test. The normalization procedure increases the level of association between the muscular parameters and gait velocities but values do not reach the selected level of significance. The largest correlation ($r = 0.44$) was observed between T10 (N.m/kg) and maximal safe velocity. Scatterplots presented in Fig. 3 show that subjects with similar PT (Fig. 3A) or PP (Fig. 3B) values may have had important differences in their maximal safe velocity.

Table IV. *Intercorrelation matrix for muscular parameters obtained in the different testing conditions of the ankle (n = 16)*

	PT	PP	T10	P10	S10
PP	0.93**				
T10	0.75**	0.69*			
P10	0.79**	0.90**	0.73*		
S10	0.91**	0.87**	0.66*	0.77**	
MRTD10	0.82**	0.74**	0.68*	0.66*	0.88**

** = $p < 0.001$; * $p < 0.01$.
PT, PP, T10, P10, S10 and MRTD10 same as Table II.

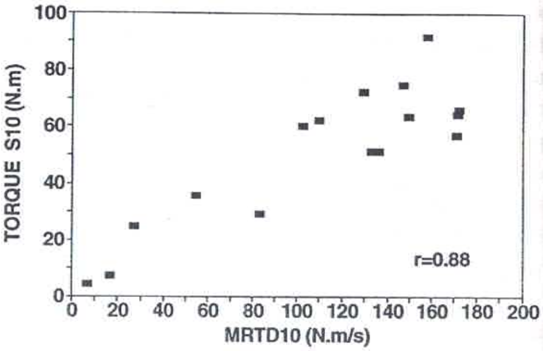

Fig. 2. Scatterplot of the relation between static torque (S10) and maximal rate of tension development (MRTD10).

DISCUSSION

Gait and clinical status

The 16 hemiparetic subjects studied could walk independently with or without a cane for short distances. Their mean comfortable velocity of 0.76 m/s represents a velocity equal to approximately 76% of that of elderly normals (13) and had a mean maximal safe velocity slightly lower than the natural velocity of healthy subjects reported elsewhere (2, 16, 24). In general, the results of the clinical assessments crudely classified the hemiparetic group as moderately affected with subjects presenting a wide range of deficits. With a mean score below 10 seconds, the "Up & Go" test classified the group as "freely independent" with regard to their physical mobility (33).

Dynamometric performance of the plantarflexor muscles

Results of the dynamometric assessment support the first hypothesis of the present study since hemiparetic subjects presented with muscular performance that was lower than that of healthy subjects. In our study, the maximal dynamic ankle plantarflexion torque was, on average, 65.4 (± 36.9) N.m, which is around 50% less than the mean torque reported in healthy subjects for similar testing conditions (19, 26, 31) indicating a marked weakness of the plantarflexor muscles. These results agree with those of Sjöström et al. (37) who reported that both static strength and dynamic plantarflexion strength were markedly decreased in the plegic leg of 19 hemiparetic subjects. Moreover, we have noted that, after maximal static preloading efforts, hemiparetic subjects demonstrated torque values which appeared to decline more rapidly in the first part of the plantarflexion movement in comparison to healthy subjects who showed a more linear decrease in their torques values

Table V. *Correlation coefficients obtained between ankle dynamometric measures, gait and clinical variables in hemiparetic subjects (n = 16)*

		Fugl-Meyer assessment					
		Motor control lower limb	Sensation lower limb	Spasticity score	"Up & Go" test	Comfortable velocity	Maximal velocity
Peak values							
PT	N.m	0.43	0.60*	0.13	−0.34	0.21	0.29
	N.m/kg	0.51*	0.62*	0.18	−0.34	0.34	0.41
PP	W	0.35	0.53*	0.15	−0.21	0.04	0.18
	W/kg	0.43	0.57*	0.19	−0.20	0.15	0.29
Values at +10°							
T10	N.m	0.50*	0.73***	0.02	−0.41	0.33	0.37
	N.m/kg	0.52*	0.67**	−0.03	−0.39	0.42	0.44
P10	W	0.23	0.52*	−0.02	−0.11	−0.09	0.12
	W/kg	0.29	0.54*	0.01	−0.10	−0.02	0.19
S10	N.m	0.38	0.66**	0.18	−0.19	0.11	0.18
	N.m/kg	0.46	0.66**	0.23	−0.17	0.25	0.29
MRTD10	N.m/s	0.42	0.66**	0.05	−0.24	0.16	0.16
	N.m/kg/s	0.50*	0.62*	0.12	−0.25	0.31	0.31

***$p < 0.001$; **$p < 0.01$; *$p < 0.05$
PT, PP, T10, P10, S10 and MRTD10 same as Table II.

at the beginning of the plantarflexion movement (19, 26, 31). In other words, hemiparetic subjects lose more strength than healthy subjects at the beginning of the movement. Changes in the activation of motor units as well as a problem in the modulation of motor unit firing frequencies previously reported in hemiparetic subjects (12, 34) could probably explain this finding. Larger between-subjects variability for the torque and power data were observed when the ankle was dorsiflexed. Thus, as previously suggested in healthy subjects (19), torque and power values recorded in dorsiflexion probably better discriminate between hemiparetic subjects than measures taken in plantarflexion positions.

When hemiparetic subjects were evaluated with different methods of testing on the Biodex system, the behaviour of the plantarflexors was similar to that observed for the same conditions in healthy subjects (25), except that absolute values were lower. Therefore, preloading, in addition to allowing higher torque levels at the beginning of movement, renders the torque less dependent on the shortening velocity (25, 36). Thus, for the tests executed with the isokinetic mode, no significant differences were found between the torque values at 30° s^{-1} (0.52 rad s^{-1}), 90° s^{-1} (1.57 rad s^{-1}) and 180° s^{-1} (3.14 rad s^{-1}). As expected, using the isotonic mode of testing with maximal preloading determined high power values because torque values are high at the beginning of movement when high ankle velocities are present. It is important to note that the torque values recorded in test ISOT14 were not 14 N.m. As revealed in Table III, the torques measured in test ISOT14 were similar to those generated in the isokinetic tests and thus values decreased gradually throughout the plantarflexion movement. This is a limitation of the Biodex system which controls the acceleration of the lever arm and does not regulate the torque at 14 N.m when preloading is used. Consequently, using the isotonic mode of testing preceded by preloading allows the production of high torque combined with higher velocity than the isokinetic mode at 180° s^{-1} (3.14 rad s^{-1}) resulting in the generation of higher power values than in the isokinetic mode.

The muscular parameters were interrelated suggesting, as expected, that they assessed a common component of the plantarflexor performance. These results also indicated that stronger hemiparetic subjects generate more power than weaker ones when tested under the isotonic mode of testing. The correlations found between the maximal rate of tension development (MRTD10), PT ($r = 0.82$) and S10 ($r = 0.88$) were an interesting aspect of this study. This association provides evidence that

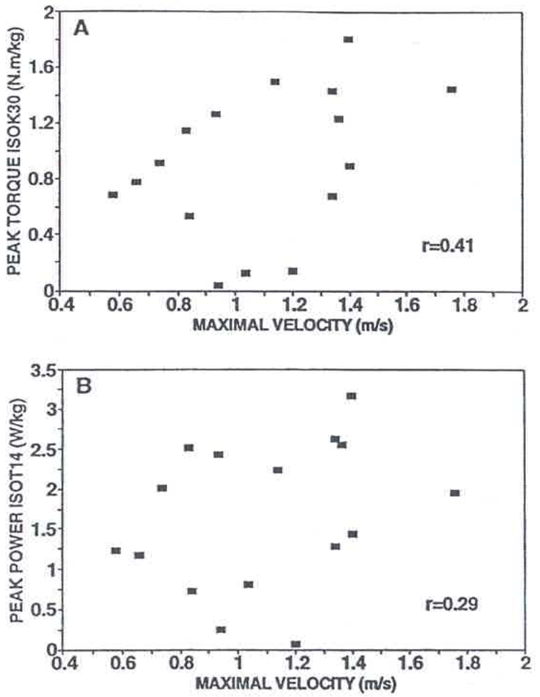

Fig. 3. Scatterplots of the relations between peak values of (A) torque, (B) power and maximal gait velocity.

stronger hemiparetic subjects could also develop maximal tension more rapidly than weaker ones. Such an association has also been observed by Tsuji & Nakamura (39) for paretic knee extensors ($r = 0.85$). Several functional tasks require the ability to activate rapidly the muscles and thus it is relevant to provide information about this muscular parameter. To summarize, these levels of correlation suggest that stronger hemiparetic subjects could be more functional than weaker ones because they could generate higher static torques, dynamic torques, power and maximal rate of tension development.

Muscular parameters versus clinical measures

In general, the plantarflexor muscular parameters demonstrated low to moderate levels of correlation with the selected clinical measures (Table V). All of the muscular parameters were positively related to the lower limb sensation scores and this possibly provides additional evidence to show that motor recovery is related to the degree of sensory impairment (21). However, these associations could also indirectly indicate that some hemiparetic subjects are simply more severely affected. The results also revealed that subjects with the lowest sensation scores, in addition to generating weak plantarflexor torques, were not among the fastest walkers. This is an interesting finding which supports that of Brandstater et al. (11), who stated that the quality of gait is poorer in patients with a sensory deficit.

Like Sjöström et al. (37), who reported that maximum strength of the affected leg was associated with motor score (Spearman's r_s 0.66), we have found significant correlations between muscular parameters of the plantarflexors and FMA lower limb motor score (Pearson's $0.22 < r < 0.53$). Thus, clinicians could assume that an hemiparetic subject who produces strong active plantarflexion movement would also score high on the lower limb motor subscore of the FMA. However, since the plantarflexors explained less than 30% of the lower limb motor score variance, one should also consider other factors such as strength of other muscular groups, muscular coordination, subject's ability to produce selective movement at each joint of the lower limb and spasticity to totally explain this score.

The absence of relationships between dynamometric data and spasticity at the ankle corroborates previous results (27) and suggests, that the plantarflexors' performance are not associated with hyperactivity or spasticity at the ankle joint. However, as reported by Knutsson (20), assessing ankle spasticity at the bedside using a passive method probably poorly represents the role of spastic activity in voluntary plantarflexion movements where active as well as maximal efforts are required.

Muscular parameters versus gait velocity

The maximal plantarflexor parameters measured with an instrumented dynamometer were not significantly related to gait performance in spite of the fact that plantarflexor muscles are considered to play a dominant role in the propulsion phase of locomotion in healthy (42) and in hemiparetic subjects (28, 29). Although, the correlations were not significant, they reach a similar level of association in contrast to those reported by Bohannon (3) between static strength of the plantarflexors and comfortable gait speed for a group of 20 hemiparetic subjects (Pearson's $r = 0.47$). Such a weak correlation strongly suggests that the strength of the plantarflexors cannot be considered as the unique determinant of the maximal gait velocity of hemiparetic subjects.

The scatterplots of the relation between peak torque (or power) values and maximal gait velocity showed that some hemiparetic subjects could not walk rapidly even though they had a plantarflexor strength as good as that of some faster walkers. It is hypothesized, here, that these subjects probably had other deficits which affected their gait performance. Deficits such as alterations of the dynamic balance and/or postural adjustments, and reduction of selective movements, muscular incoordination, weakness at the knee and hip joints and impaired sensation of the lower limb have been previously described in hemiparetic subjects (9, 10, 32). All of these other problems could thus affect, separately or in combination, gait performance and should be considered in order to explain why some hemiparetic subjects with good plantarflexors strength could not walk at faster speeds.

On the other hand, the scatterplots also revealed that some hemiparetic subjects with decreased plantarflexor performance can walk at relatively fast velocity over 1 m/s. Apparently, individuals can produce the same gait velocity by using different strategies (30). These strategies could include compensations within muscle groups of the affected side as well as compensations of the unaffected limb. The most important compensation within muscle groups of the paretic limb is probably provided by the action of the hip flexors. Similar to the plantarflexion moment, the hip flexion moment during gait is found to be closely associated ($r = 0.86$) with gait speed in hemiparetic patients (30). Thus, instead of pushing-off the leg at the end of the stance phase, subjects with weak plantarflexors can pull-off their leg forward with the hip flexors during swing. Both groups of muscles, ankle extensors and hip flexors are able to produce the energy required to move the leg forwards during gait when strong enough (23, 43). Thus, according to their muscle strength, subjects could use either ankle, hip or a combined strategy (hip and ankle) to compensate for the weakness present in one or both of these muscle groups. In the present study we cannot explain why one strategy would be preferred to another by a given subject. However, it is suggested that the relative level of strength deficit in these two muscle groups has to be considered.

Finally, one should not neglect the fact that the production of a maximal voluntary torque requires, as mentioned by Perry (32), selective control as well as the ability to activate fully the appropriate muscles. Thus, it is possible that some hemiparetic patients could have greater difficulty in producing an isolated movement at the ankle, as compared to during gait, where plantarflexion is coupled with movements at the hip and knee. Perry (32) has reported that some hemiparetic patients produced less activity under manual muscle testing than during gait. This impairment of the voluntary control could have contributed toward decreasing the level of the relationship found between dynamometric data and maximal gait velocity.

This study provides additional information related to static and dynamic performances of the plantarflexor muscles in hemiparetic subjects. It demonstrated the feasibility of evaluating several muscular parameters using the static, isokinetic and isotonic modes of testing on an instrumented dynamometer and revealed that these parameters (static torque, dynamic torque, power and maximal rate of tension development) are interrelated ($0.65 < r < 0.94$; $p < 0.01$). Weakness of the plantarflexors in hemiparetic subjects is characterized by decreased absolute dynamometric values in comparison with those previously reported for healthy subjects. Significant associations were found between the plantarflexor muscular parameters and the Fugl-Meyer subsections of the lower limb (motor control and sensation; ($0.49 < r < 0.74$; $p < 0.05$), whereas those assessed between muscular parameters, spasticity scores, "Up & Go" results and gait parameters, were not significant ($r < 0.45$; $p > 0.05$). Concerning the latter, it has been suggested that the relationship between the strength of the plantarflexors and gait velocity was influenced by other factors which probably involve motor control components and compensations within and between the limbs.

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REFERENCES

1. Adams, R. W., Gandevia, S. C. & Skuse, N. F.: The distribution of muscle weakness in upper motoneuron lesions affecting the lower limb. Brain *113:* 1459–1476, 1990.
2. Bassey, E. J., Bendall, M. J. & Pearson, M.: Muscle strength in the triceps surae and objectively measured customary walking activity in men and women over 65 years of age. Clin Sci *74:* 85–89, 1988.
3. Bohannon, R. W.: Strength of lower limb related to gait velocity and cadence in stroke patients. Physiother Can *38:* 204–206, 1986.
4. Bohannon, R. W.: Relationship between strength and movement in the plegic lower limb following cerebrovascular accidents. Int J Rehab Res *10:* 420–422, 1987.
5. Bohannon, R. W.: Determinants of transfer capacity in patients with hemiparesis. Physioth Can *40:* 236–239, 1988.
6. Bohannon, R. W.: Correlation of lower limb strengths and other variables with standing performance in stroke patients. Physiother Can *41:* 198–202, 1989.

7. Bohannon, R. W.: Selected determinants of ambulatory capacity in patients with hemiplegia. Clin Rehabil *3:* 47–53, 1989.
8. Bohannon, R. W. & Walsh, S.: Nature, reliability, and predictive value of muscle performance measures in patients with hemiparesis following stroke. Arch Phys Med Rehabil *73:* 721–725, 1992.
9. Bourbonnais, D. & Vanden Noven, S.: Weakness in patients with hemiparesis. Amer J Occup Ther *43:* 313–319, 1989.
10. Bourbonnais, D., Vanden Noven, S. & Pelletier, R.: Incoordination in patients with hemiparesis. Can J Public Health *2:* S58–S63, 1992.
11. Brandstater, M. E., de Bruin, H., Gowland, C. & Clack, B. M.: Hemiplegic gait: Analysis of temporal variables. Arch Phys Med Rehabil *64:* 583–587, 1983.
12. Dengler, R., Kontanzer, A., Heese, S., Wolf, W. & Struppler, A.: Abnormal behaviour of single motor units in central weakness. *In* Motor Disturbance II, pp. 379–384. Acadamic Press Limited, 1990.
13. Dettmann, M. A., Linder, M. T. & Sepic, S. B.: Relationship among walking performance, postural stability, and functional assessments of the hemiplegic patient. Am J Phys Med *66:* 77–90, 1987.
14. Duncan, P. W., Propst, M. & Nelson, S. G.: Reliability of the Fugl-Meyer Assessment of sensorimotor recovery following cerebrovascular accident. Phys Ther *63:* 1606–1610, 1983.
15. Feiring, D. C., Ellenbecker, T. S. & Derscheid, G. L.: Test-retest reliability of the Biodex isokinetic Dynamometer. J Orthop Sports Phys Ther *11:* 298–300, 1990.
16. Finley, F. R. & Cody, K. A.: Locomotive characteristics of urban pedestrians. Arch Phys Med Rehabil *51:* 423–426, 1970.
17. Fugl-Meyer, A. R., Jaasko, L., Leyman, L., Olsson, S. & Steglind, S.: The post-stroke hemiplegic patient: A method for evaluation of physical performance. Scand J Rehab Med *7:* 13–31, 1975.
18. Fugl-Meyer, A. R.: Post-stroke hemiplegia assessment of physical properties.: Scand J Rehab Med Suppl *7:* 85–83, 1980.
19. Gravel, D., Richards, C. L. & Filion, M.: Angle dependency in strength measurements of the ankle plantarflexors. Eur J Appl Physiol *61:* 182–187, 1990.
20. Knutsson, E.: Gait control in hemiparesis. Scand J Rehabil Med*13:* 101–108, 1981.
21. Kusoffsky, A., Wadell, I. & Nilsson, B. Y.: The relationship between sensory impairment and motor recovery in patients with hemiplegia. Scand J Rehab Med *14:* 27–32, 1982.
22. Levin, M. F. & Hui-Chan, C. W. Y.: Relief of hemiparetic spasticity. Tens is associated with improvement in reflex and voluntary motor functions. Electroenceph Clin Neurophysiol *85:* 131–142, 1992.
23. Mueller, M. J., Minor, S. D., Sahrmann, S. A., Schaaf, J. A., Strube, M. J.: Differences in the gait characteristics of patients with diabetes and peripheral neuropathy compared with age-matched controls. Phys Ther *74:* 299–313, 1994.
24. Murray, M. P., Kory, R. C. & Clarkson, B. H.: Walking patterns in healthy old men. J Gerontol *24:* 169–178, 1969.
25. Nadeau, S., Gravel, D., Arsenault, A. B. & Goyette, M.: Preloading and range of motion effect on plantarflexor muscle performance. Arch Phys Med Rehab *77:* 1000–1004, 1996.
26. Nadeau, S., Gravel, D. & Arsenault, A. B.: Relationships between torque, velocity and power output during plantarflexion in healthy subjects. Scand J Rehab Med *29:* 49–55, 1997.
27. Nakamura, R., Hosokawa, T. & Tsuji, I.: Relationship of muscle strength for knee extension to walking capacity in patients with spastic hemiparesis. Tohoku J Exp Med *145:* 335–340, 1985.
28. Olney, S. J., Monga, T. N. & Costigan, P. A.: Mechanical energy of walking of stroke patients. Arch Phys Med Rehabil *67:* 92–98, 1986.
29. Olney, S. J., Griffin, M. P., Monga, T. N. & McBride, I. D.: Work and power in gait of stroke patients. Arch Phys Med Rehabil *72:* 309–314, 1991.
30. Olney S. J., Griffin, M. P. & McBride, I. D.: Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: A regression approach. Phys Ther *74:* 872–885, 1994.
31. Peeters, M., Svantesson, U. & Grimby, G.: Effect of prior isometric muscle action on concentric torque output during plantarflexion. Eur J Appl Physiol *71:* 272–275, 1995.
32. Perry, J.: Determinants of muscle function in the spastic lower extremity. Clin Ortho Rel Res *288:* 10–26, 1993.
33. Podsiadlo, D. & Richardson, S.: The timed "Up & Go": A test of basic functional mobility for frail elderly persons. J Am Geriatr Soc *39:* 142–148, 1991.
34. Rosenfalck, A. & Andreassen, S.: Impaired regulation of force and firing pattern of single motor units in patients with spasticity. J Neurol Neurosurg Psychiatry *43:* 907–916, 1980.
35. Sanford, J., Moreland, J., Swanson, L. R., Stratford, P. W. & Gowland, C.: Reliability of the Fugl-Meyer assessment for testing motor performance in patients following stroke. Phys Ther *73:* 447–454, 1993.
36. Sawaï, K., Kuno, M., Mutoh, Y. & Miyashita, M.: The effect of static pre-loading on isokinetic plantar flexion. XIVth congress ISB *Paris*: 1196–1197, 1993.
37. Sjöström, M., Fugl-Meyer, A. R., Nordin, G. & Wählby, L.: Post-stroke hemiplegia; crural muscle strength and structure. Scand J Rehab Supp *7:* 53–67, 1980.
38. Taylor, N. A. S., Sanders, R. H., Howick, E. I. & Stanley, S. N.: Static and dynamic assessment of the Biodex dynamometer. Eur J Appl Physiol *62:*180–188, 1991.
39. Tsuji, I. & Nakamura, R.: The altered time course of tension development during the initiation of fast movement in hemiplegic patients. Tohoku J Exp Med *151:* 137–143, 1987.
40. Twitchell, T. E.: The restoration of motor function following hemiplegia in man. Brain *74:* 443–480, 1951.
41. Watkins, M. P., Harris, B. A. & Kozlowski, B. A.: Isokinetic testing in patients with hemiparesis a pilot study. Phys Ther *64:* 184–189, 1984.
42. Winter, D. A.: Energy generation and absorption at the ankle and knee during fast, natural and slow cadences. Clin Orthop Rel Res *175:* 147–154, 1983.
43. Winter, D. A., Olney, S. J., Conrad, J., White, S. C., Ounpuu, S., Gage, J. R.: Adaptability of motor patterns in pathological gait. *In* Multiple Muscle Systems: Biomechanics and Movement Organization ((eds.) Winters and Woo), pp. 680–693, Springer-Verlag, 1990.

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