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Mechanical measures during maximal velocity knee extension exercise and their relation to fibre composition of the human vastus lateralis muscle

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Summary. A method for measuring the maximal velocity of knee extension exercise is described using a very light lever arm. Instrumentation of the lever arm with a potentiometer and accelerometer also allows for the measurement of peak acceleration, time to peak acceleration, the average rate of development of acceleration (jerk) and peak torque. With this apparatus and surface electromyography, electromechanical delay (EMD) was also determined. This apparatus was tested using 17 female and 10 male subjects, and the measures obtained were related to the percentage of fast twitch fibres (% FT) and the relative area of fast twitch fibres (% FTA) in the vastus lateralis determined from duplicate muscle biopsy samples. Peak velocity of unloaded knee extension averaged 12.1 ± 1.2 and 12.2 ± 1.7 rad · s^{-1} for females and males, respectively, and were not significantly different. As well, peak acceleration, time to peak acceleration jerk and EMD values were not significantly different between the female and male subjects, but the mean peak torque for the female subjects (73.5 ± 14.7 N · m) was significantly lower than that for the males (98.4 ± 31.5 N · m). Peak acceleration was significantly correlated with %FT ($r=0.40$, $P=0.04$) for the total subject population. None of the other measures was significantly related to either %FT or %FTA for the male and female subjects or the combined population of subjects.

Key words: Maximal velocity of knee extension — Acceleration — Peak torque — Electromechanical delay-Muscle fibre type

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Introduction

The relationship between muscle fibre composition of the quadriceps and performance during knee extension work has been a subject of a number of experimental studies. In this regard, the Cybex II isokinetic dynamometer has been perhaps the single most commonly used instrument for assessing knee extension performance. Some studies employing the Cybex II have demonstrated positive correlations between peak torque measures at different angular velocities and the percentage of fast twitch fibres in the vastus lateralis portion of the quadriceps muscle group (Thorstensson et al. 1976; Gregor et al. 1978; Ivy et al. 1981). However, this has not been observed in other studies (Clarkson et al. 1982; Schantz et al. 1983; Froese and Houston 1985). The lack of agreement in these studies between muscle fibre composition and dynamic knee extension performance may be related both to errors associated with the use of the Cybex II and to obtaining muscle biopsy samples that truly reflect the in vivo fibre composition of the knee extensor muscles; these problems have been discussed recently (Winter et al. 1981; Froese and Houston 1985).

One of the limitations of the Cybex II dynamometer is that the maximum velocity that can be studied is 5.23 rad · s^{-1} (300° · s^{-1}). However, velocities greater than 11 rad · s^{-1} have been reported during all-out knee extensions against very light lever arms (Thorstensson et al. 1976; Larsson et al. 1979; Houston and Goemans 1982). In the present study we report on a protocol for obtaining peak velocity of unloaded knee extensions using a instrumented, light, lever arm. Moreover, this protocol provides the opportunity to also measure peak acceleration, time to peak acceleration, the rate of development of acceleration

Table 1. Physical characteristics of the subjects; values shown are means ±SD with ranges in parentheses

	n	Age (year)	Weight (kg)	Height (cm)
Females	17	19.9±1.9 (18–24)	60.3±7.0 (46.2–70.9)	166±6 (160–174)
Males	10	22.2±2.5 (19–29)	72.8±6.4 (61.8–83.6)	176±6 (166–185)

(jerk) and peak torque. We have tested this protocol using 27 female and male subjects, and have studied the relationship between the above measures and fibre composition of the vastus lateralis determined from two muscle biopsy samples.

Methods

Subjects. Twenty-seven university students (17 females and 10 males) volunteered to participate in this study after being informed of the nature and risks of the procedures and signing approved subject consent forms. These subjects were occasionally to moderately active in a range of recreational activities, but none of the subjects was engaged in any regular training program. The physical characteristics of the subjects are summarized in Table 1.

Muscle sampling. Muscle samples were obtained from two sites of the vastus lateralis of the right leg of each subject using the needle biopsy technique (Bergström 1962). The two biopsies were obtained at the same time, no less than four days before any muscle testing. The longitudinal distance between muscle sampling sites averaged 3 cm, and care was taken to ensure that the depth of the muscle sampling form each subject was consistent. Muscle samples were mounted on a freezing chuck in embedding medium, frozen in isopentane cooled in liquid nitrogen and stored at −80°C for subsequent histochemical analysis. Cross sections (10 μm) were cut in a cryostat at −20°C. Histochemical reactions were carried out for myofibrillar adenosine triphosphatase (ATPase) subsequent to preincubation at pH 10.3 (Padykula and Herman 1967) and pH 4.3 (Brooke and Kaiser 1970) and for reduced nicotinamide adenine dinucleotide tetrazolium reductase (NADH-TR) (Novikoff et al. 1961). From the two muscle biopsy samples obtained from each of the 227 subjects, 1561±665 (mean ±SD) fibres (range 497–3478) were clearly identified as slow twitch (ST) or fast twitch (FT) based on their staining responses for myofibrillar ATPase. The cross sectional areas of 20 representative ST and FT fibres were determined on enlarged photomicrographs of NADH-TR-stained sections with the aid of a nunonics digitizer (Green et al. 1979). The mean area of ST and FT fibres was determined for each subject, and the mean area occupied by FT fibres in the muscle samples from each subject was calculated and expressed as the total area occupied by the FT fibres (%FTA).

Performance testing. The peak velocity of unloaded knee extension was determined using a very light lever arm which rotated vertically on an axle on low friction bearings. The apparatus had a very low moment of inertia ($lo = 0.07$ kg · m^2), and thus knee extension was virtually unrestricted. The lever arm was instrumented with a linear potentiometer and a uniaxial piezoresistive accelerometer (Endevco ±2000 g) to allow for the measurement of angular displacement (rad) and acceleration (rad · s^{-2}), respectively. The potentiometer signal was differentiated and filtered at 13 Hz to produce a velocity output (rad · s^{-1}). The accelerometer signal was amplified using a Litton carrier preamp. In addition, the subjects were prepared with bipolar surface electrodes positioned longitudinally over the vastus lateralis muscle in order to record muscle electrical activity by electromyography (EMG). The EMG signal was amplified using a bioamplifier and recorded without further processing. All data were recorded in analog form on an instrumentation reel-to-reel recorder at 38 cm · s^{-1}. All trials were observed on a Hewlett Packard four channel storage oscilloscope as they were being recorded. A pulse was inserted between trials to facilitate their identification for analysis. The overall experimental set-up is outlined in Fig. 1.

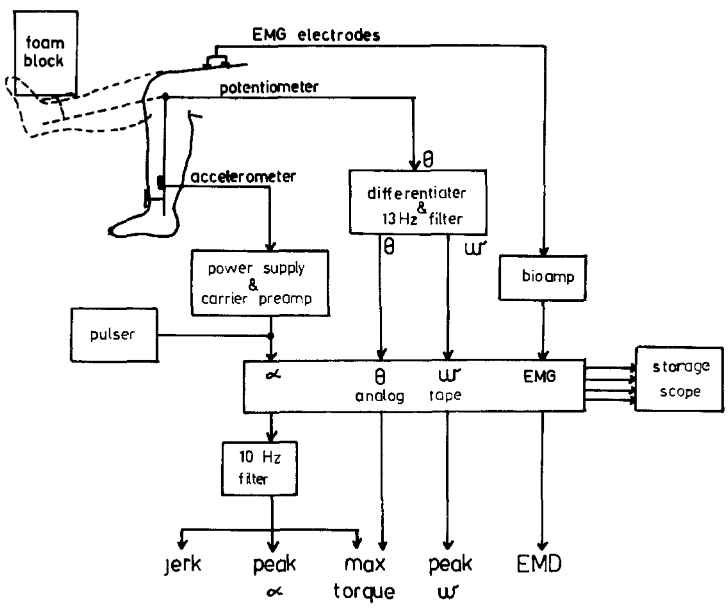

Fig. 1. Schematic outline of the experimental setup for the measurement of the peak velocity of knee extension and electromechanical delay (EMD). (Θ = knee angle) (w = angular velocity) (α = angular acceleration)

To measure maximal velocity of unloaded knee extension, subjects were seated in a Cybex chair with the back supported and with straps across the lap and upper thigh to reduce excess movement. The centre of rotation of the lever arm was adjusted to the centre of rotation of the knee. The lever arm was secured to the right leg of the subjects at the ankle. The subjects were instructed to kick as fast as possible from the resting position (knee angle at 1.57 rad or 90° from full extension) into a foam block that stopped the leg just before full extension. Subjects were tested on two separate days, separated by at least four days. At each testing session, practice trials were permitted until the subject felt comfortable with the procedure; five trials were then recorded for analysis. Hard copy records of the data were made by playing the analog tape back on a Litton four channel pen recorder. Velocity ($rad \cdot s^{-1}$) was calculated using tangential analysis of the displacement curve at peak velocity. The accelerometer output was filtered at 10 Hz using a Krohn Hite tuneable filter, and this was used to determine peak acceleration ($rad \cdot s^{-2}$), the average rate of development of acceleration or jerk ($rad \cdot s^{-3}$) and peak dynamic torque ($N \cdot m$). The accelerometer was periodically calibrated during testing trials at 0 and 1 g, and this was recorded on the analog tape.

Mean values for peak velocity and peak acceleration, calculated for each subject from the five trials on each testing day, were shown to be statistically similar. However, to maximize the possibility of finding relationships with fibre type, the single largest value for peak velocity and peak acceleration was taken from the 10 trials and employed in subsequent calculations.

Jerk was determined as the peak acceleration divided by the time to peak. Peak dynamic torque ($N \cdot m$) was calculated from an equation considering the moment of inertia of the system, including the moments of inertia of the apparatus and leg, and angular acceleration. The moment of inertia of the apparatus was calculated with an oscillation technique (equation in Fig. 2). The moment of inertia of the leg and foot was estimated, based on the leg length and body mass of each subject and tabular values for radii of gyration determined by Plagenhoef (1971). The influence of gravity acting on the leg and apparatus was included in the calculation of the dynamic torque (Fig. 2).

The EMG data, along with the unfiltered accelerometer output, were played back on chart paper at a tape speed that was 10 times slower than recording speed in order to allow for the assessment of electromechanical delay (EMD). This was determined as the time lag between the onset of muscle electrical activity and the onset of acceleration (Norman and Komi 1979). Time was measured accurately from the strip chart records to ±3 ms. The EMD values used in subsequent statistical calculations represented the average from all testing trials for each subject, whereas single peak values were employed for velocity, acceleration, jerk and torque. It was considered necessary to use average EMD values since EMD was determined from the visually observed onset of increased EMG activity.

All male and female data were initially treated independently for the statistical analyses. Differences between males and females were analyzed using a Student's t test for the significance of differences between means of two independent groups. Correlation coefficients between the data recorded during maximal knee extension and muscle fibre type were first calculated separately for the male and female subjects, and later were determined on the combined population ($n = 27$). A 0.05 level of significance was accepted for all tests.

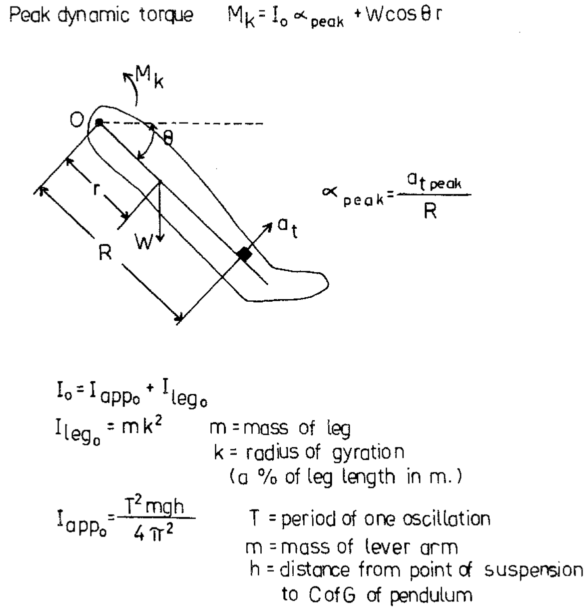

Fig. 2. Equations used to calculate the peak dynamic torque (M_K) in unloaded knee extension, angular acceleration (α) and moments of inertia about the knee (I_0), of the apparatus (I_{appo}) and leg (I_{lego}). W is the weight of the leg and apparatus at the centre of gravity of the system; a_t is the tangential acceleration measured from a linear accelerometer from which α was calculated as shown

Results

Means ±SD and ranges for the percent of FT fibres (%FT), the percent of relative area occupied by FT fibres (%FTA) and the absolute cross-sectional areas of the FT and ST fibres for the female and male subjects are shown in Table 2. There were no significant differences between the male or female subjects for %FT or %FTA, but the cross-sectional areas of both FT and ST fibres were smaller in female compared to male subjects ($P < 0.01$).

Mean values for the measures obtained during maximal effort knee extensions and their correlations with %FT and %FTA are shown in Table 3 for the two separate subject groups. None of the measures showed a significant correlation to percentage composition of FT fibres or relative area occupied by FT fibres for the female subjects, and with one exception for the male subjects. Peak acceleration was significantly related to %FTA for males, but a plot of peak acceleration as a function of %FTA showed that this correlation was markedly influenced by an outlier (data not shown). Peak knee extension velocity was highly correlated with peak acceleration for male subjects ($r = 0.81$, $P < 0.01$), and to a lesser extent for the female subjects ($r = 0.55$, $P < 0.05$). Peak veloc-

Table 2. Muscle fibre composition, expressed as the percentage of fast twitch fibres (%FT) and the relative area occupied by FT fibres (%FTA) and muscle fibre areas for male and female subjects

	Fibre Composition		Fibre area mm²	
	%FT	%FTA	FT	ST
Females	43.3±7.8	43.7±9.9	2934±757[a]	2907±531[a]
	(31.8–62.6)	(27.0–64.8)	(2071–4821)	(2132–3935)
Males	48.9±14.7	54.5±14.3[b]	4381±1394[c]	3931±906
	(19.0–63.6)	(21.8–67.4)	(3230–6626)	(2258–5676)

Values shown are means±SD with ranges in parentheses
[a] Significantly smaller than corresponding male values ($P<0.01$)
[b] Significantly greater than %FT ($P<0.05$)
[c] Significantly greater than ST ($p<0.05$)

Table 3. Mean values (±SD) of measures obtained during maximal velocity knee extensions and their correlation coefficients (*r*) and significance probabilities (*P*) related to the percentage of fast twitch fibres (%FT) and the percentage of relative area occupied by FT fibres (%FTA) for female and male subjects

		Peak velocity (rad · s⁻¹)	Peak acceleration (rad · s⁻²)	Time to peak acceleration (ms)	Jerk (rad · s⁻³)	Peak torque (N · m)
Females		12.1±1.2	184.7±24.7	9.3±2.9	2279±771	73.5±14.7[a]
%FT	*r*	−0.22	0.15	−0.09	0.16	0.26
	P	0.39	0.57	−0.72	0.53	0.31
%FTA	*r*	−0.18	0.06	−0.04	0.12	0.10
	P	0.50	0.83	0.88	0.65	0.70
Males		12.2±1.7	187.5±33.1	10.3±3.0	2257±1160	98.4±31.5
%FT	*r*	0.36	0.60	−0.48	0.42	0.16
	P	0.30	0.07	0.16	0.23	0.66
%FTA	*r*	0.45	0.68	−0.55	0.50	0.34
	P	0.19	0.03	0.10	0.14	0.34

[a] Significantly less than corresponding value for males ($P<0.05$)

Table 4. Mean values (±SD) of measures obtained during maximal velocity knee extensions and their correlation coefficients and significance probabilities related to the percentage of fast twitch fibres (%FT) and the percentage of relative fast twitch fibre area (%FTA) for the combined population of female and male subjects

		Peak velocity (rad · s⁻¹)	Peak acceleration (rad · s⁻²)	Time to peak acceleration (ms)	Jerk (rad · s⁻³)	Peak torque (N · m)
		12.1±1.4	185.6±27.6	9.7±3.0	2271±912	82.7±21.9
%FT	*r*	0.13	0.40	−0.25	0.30	0.28
	P	0.52	0.04	0.20	0.12	0.16
%FTA	*r*	0.16	0.37	−0.19	0.28	0.37
	P	0.43	0.06	0.33	0.15	0.06

ity of knee extension was almost identical for the male and female subjects (12.2 rad $\cdot$ s^{-1} or 699° $\cdot$ s^{-1} vs. 12.1 rad $\cdot$ s^{-1} or 694° $\cdot$ s^{-1}), and less than 2% difference in peak acceleration was observed for the males and females (187.5 vs. 184.7 rad $\cdot$ s^{-2}, respectively).

When the correlational analyses were carried out for the combined population of male and female subjects ($n=27$), no major changes were found for the relationships reported when the two groups were studied separately (Table 4). The only significant fibre type correlation observed was between peak acceleration and %FT fibres ($r=0.40$, $p=0.04$). Similarly, peak velocity was correlated with peak acceleration ($r=0.69$, $p<0.01$).

Electromechanical delay (EMD) or the time lag between the onset of muscle electrical activity and the beginning of acceleration was similar for the female and male subjects (43.3 ± 7.8 and 38.7 ± 11.9 ms, respectively). No significant correlations were noted between EMD and %FT or %FTA for either subject group or the combined subject population.

Discussion

In earlier studies, peak knee extension velocity has been determined from the time taken for the leg to pass through an arc of 0.70 rad or 40° (Houston and Goemans 1982) or an arc of 0.87 rad or 50° (Thorstensson et al. 1976; Larsson et al. 1979). However, the angular velocities determined by this procedure are average velocities over the arc of measurement, and possibly not peak velocities. Nonetheless, the values reported for young men using this protocol, that is 11.9 $rad \cdot s^{-1}$ (Thorstensson et al. 1976) 11.1 $rad \cdot s^{-1}$ (Larsson et al. 1979) and 11.0 $rad \cdot s^{-1}$ (Houston and Goemans 1982) are only marginally smaller than the peak velocities we measured with the female and male subjects using the present protocol, that is 12.1 and 12.2 $rad \cdot s^{-1}$, respectively. Although the method we describe for measuring the peak velocity of unloaded knee extension is unquestionably more complex, instrumentation of the lever arm with an accelerometer and potentiometer allows for the measurement of performance variables not previously described for this activity.

Using the present protocol, maximal velocity of unloaded knee extension was significantly correlated with peak acceleration for both males and females. Moreover, no significant differences were found for peak velocity, peak acceleration, time to peak acceleration and jerk when female subjects were compared with male subjects. Similar maximal contraction velocities have been noted for male and female subjects during elbow flexion (Nygaard et al. 1983), but more recently de Koning et al. (1985) reported that the maximal velocity of unloaded arm flexion for untrained females averaged only 90% of that of untrained males. The present results and those of Nygaard et al. (1983) suggest that sex differences in muscle size do not influence peak velocity of unloaded muscle shortening. However, the sex differences observed for peak velocity of arm flexion by de Koning et al. (1985) were suggested to be due in part to differences in dimensions in the arm and muscle between males and females.

On the other hand, the female peak torque measured during the maximal velocity knee extensions was 75% of that of the male subjects. This sex difference is consistent with torque-velocity relationships reported previously for male and female subjects using the Cybex II isokinetic dynamometer (Froese and Houston 1985). Laubach (1976) also reported female isometric knee extension strenght to be about 78% of that of males. Since peak accelerations in the present study were the same for males and females, the calculated difference in torques must be attributed to differences in moments of inertia (i.e., leg mass and mass distribution). The males were apparently able to generate sufficient knee extension torque to accelerate their legs to the same level as the females, even though the mean moment of inertia of the female legs was considerably lower than that of the males (0.40 vs. 0.53 $kg \cdot m^2$, respectively). The greater ability of male subjects to produce torque at various angular velocities is most likely due to larger muscle cross-sectional areas for males. In this regard, Schantz et al. (1983) have shown that maximal dynamic torques produced per unit of muscle cross-sectional area were not different in female and male subjects.

A major factor that must be considered whenever human muscle performance measures are related to muscle fibre type concerns the reliability of small muscle biopsy samples to accurately reflect the true fibre composition of the muscle or muscles being studied. This issue has been addressed for the vastus lateralis muscle in some recent studies (Blomstrand and Ekblom 1982; Elder et al. 1982; Lexel et al. 1985). For example, the precision of fibre type estimates can be greatly increased by sampling two or more sites, with a variability of approximately 6% between two sites (Blomstrand and Ekblom 1982; Elder et al. 1982). Increasing the number of fibres counted can also affect sampling, with decreases in variability within a single biopsy from 5 to 2.5% as fibre number is increased from 100 to 350 (Blomstrand and Ekblom 1982). More recently, Lexel et al. (1985) recommended the counting of >150 fibres in each of three muscle biopsy samples obtained from different depths of the vastus lateralis. Although we counted a mean of 1561 fibres from only duplicate biopsies with the present material, we believe that this undoubtedly improves our estimation of true vastus lateralis fibre composition compared to a single biopsy sample per subject (Blomstrand and Ekblom 1982; Elder et al. 1982; Lexel et al. 1985).

An unexpected finding in this study was the absence of a significant relationship between muscle fibre type and maximal velocity of knee extension. Indeed the only significant correlation with FT fibre composition for the measures obtained was peak acceleration. Previous reports have suggested that the correlation between force-velocity performance and fibre composition is most apparent at high contraction velocities (Thorstensson et al. 1976; Coyle et al. 1979). This has been attributed to a higher rate of tension development in FT fibres (Thorstensson et al. 1976; Gregor et al. 1979; Ivy et al. 1981). However, convincing experimental evidence for a major influence of muscle fibre composition of the vastus lateralis or maximal knee extension velocity is not readily apparent for humans. Thorstensson et al. (1976) reported correlation coefficients for maximal knee extension velocity and %FT and %FTA to be 0.50 ($P<0.5$) in 15 male subjects. With a population of 114 male subjects, Larsson et al. (1979) found that maximal knee extension velocity did not correlate significantly with the total population of FT fibres, but only correlated weakly ($r=0.31$, $P<0.05$) with an increasing proportion of the FTB fibre subgroup.

It may also be suggested that maximal, unloaded knee extensions may represent a novel task for subjects unaccustomed to explosive type activities. Accordingly, subjects with a preponderance of FT fibres may be unable to exploit the potential of their fast motor units for rapid force development. In support of this suggestion, Häkkinen et al. (1985) observed that the extent of improvement in fast force production during a 24 week program of "explosive type strength training" correlated significantly with the percentage of FT fibres.

The values obtained for electromechanical delay with the vastus lateralis during the maximal velocity knee extensions were similar to those reported during forearm flexion (41 ± 14 ms; Norman and Komi 1979) and isometric knee extension (38.3 ± 8.3 ms; Viitasalo and Komi 1981). It has been suggested that the force-time characteristics of fast and slow motor units should produce shorter EMD values in muscles with a greater proportion of FT fibres (Norman and Komi 1979; Viitasalo and Komi 1981). With the present male and female subjects, no significant correlations were observed between EMD and %FT or %FTA. No conclusions can be reached on this issue at this time.

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