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The influence of variable resistance moment arm on knee extensor performance

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Abstract

To enhance muscular strength, resistance training machines with a cam, incorporating a variable resistance moment arm, are widely used. However, little information is available about the influence of the variable resistance moment arm on torque, velocity, and power during muscle contraction. To address this, a knee extensor machine was equipped with a cam or with a semi-circular pulley that imposed a variable or a constant resistance moment arm, respectively. Fourteen physically active men performed two full knee extensions against loads of 40–80 kg in both conditions. Participants developed significantly higher torque with the pulley than with the cam ($P < 0.001$). The relative differences between pulley and cam conditions across all loads ranged from 8.72% to 19.87% ($P < 0.001$). Average knee extension velocity was significantly higher in the cam condition than in the pulley condition. No differences were observed in average and peak power, except at 50 and 55 kg. Torque–velocity and power–velocity relationships were modified when the resistance moment arm was changed. In conclusion, whatever the link, namely cam or pulley, the participants produced similar power at each load. However, the torque–velocity and power–velocity relationships were different in the cam and pulley conditions. The results further suggest that the influence of the machine's mechanism on muscular performance has to be known when prescribing resistance exercises.

Keywords: *Knee, extension, torque, moment arm*

Introduction

Limited attention has been paid to measuring force and power production during training, although gains in strength are related to the conditions of muscle contraction during resistance training (Behm & Sale, 1993; Coyle et al., 1981). For example, resistance training at a specific velocity increases the muscular strength at or near that velocity (Coyle et al., 1981). Moreover, training at light loads with maximal effort thereby involves high accelerations, thus improving muscular power (Moss, Refsnes, Abildgaard, Nicolaysen, & Jensen, 1997). Consequently, strength enhancement appears to be closely related to the specificity of training. For that reason, monitoring the force and power production of athletes during resistance training is necessary to match the intensity of the training programme to the sport performance requirement (Morrissey, Harman, & Johnson, 1995).

Most studies of muscular strength are performed with an isokinetic dynamometer (Orri & Darden, 2008; Prietto & Caiozzo, 1989). Such dynamometers measure maximal torque during single-joint movement at a constant imposed velocity. As the velocity is controlled, safety is assured in clinical investigations. Nonetheless, although these machines are widely accepted for testing the muscular function in both clinical and research conditions, they do not allow natural and ballistic movement velocity, which is freely chosen by the individual. Furthermore, isokinetic equipment is expensive and difficult to use in training conditions.

Unlike isokinetic dynamometers, isoinertial machines are widely used in resistance training (Fleck & Kraemer, 1997). For these machines, the source of resistance consists of a stack of load plates. By means of cables, pulleys, and cams, the direction and the moment arm of resistance are imposed on the athlete during movement. To control resistance torque

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during movement, a cam with variable radius was used (Cabell & Zebas, 1999; Harman, 1994) to adapt the length of the resistance moment arm to the torque capacity of the muscles. Thus the resistance moment arm is higher when the muscles can exert a greater torque (Folland & Morris, 2008). Therefore, by means of the link between the load and the lever moved by the athlete, the moment arm of resistance could be modified throughout the range of motion. However, no study has addressed the influence of the resistance moment arm on muscular performance (i.e. measurements of torque, velocity, and power).

The aim of the present study was to assess how the variable resistance moment arm can modify torque, velocity, and power production during explosive knee extension. Two conditions were used, one with a variable resistant moment arm and one with a constant resistance moment.

Materials and methods

Equipment set-up

To test the influence of the resistance moment arm on muscular performance, a knee extensor machine (Leg Extension FIT 22, Panatta, Italy) was instrumented to record knee extensor torque, angular velocity, and power (Figure 1). Factory built, the machine was equipped with a cam that imposed a non-constant resistance moment arm throughout the leg movement. A semi-circular pulley was added to the machine to impose a constant resistance moment arm (Figure 1A). By changing the link between the load plates and the lever, the moment arm of the resistance was modified and could be either variable with the cam or constant with the pulley. The force transmitted by the cable to the load plates was measured by means of a force transducer (K25-200kg, SCAIME, France) (Figure 1B) that included a signal conditioner (Mazet Electronique, Le Mazet St Voy, France). The angular displacement of the lever was measured by means of a potentiometer (CP50, Feretis Components France, Valence, France) (Figure 1B). A custom-built conditioner including signal amplification was used to make the sensor output suitable. The potentiometer was calibrated at varying angles between 0° and 180° while voltage output from the sensor was recorded. A linear regression equation showed that voltage was a strong predictor of angle ($R^2 = 0.99$). The linear accuracy was less than 0.1% of the full scale. All sensors were connected to a personal computer through a specific acquisition interface that encompassed a 12-bit analog-to-digital converter (National Instruments, USB6009, Texas, USA). Signals were synchronized and sampled at 1000 Hz and recorded for 5 s. Specific software in Labview (National Instruments, Texas, USA) was developed for sampling, display, and storage of the data. The data were digitally filtered with an eighth-order low-pass Butterworth filter at a 12-Hz cut-off frequency and with zero phase lag. The following mechanical calculations were performed with Matlab R2007 (Mathworks, Massachusetts, USA).

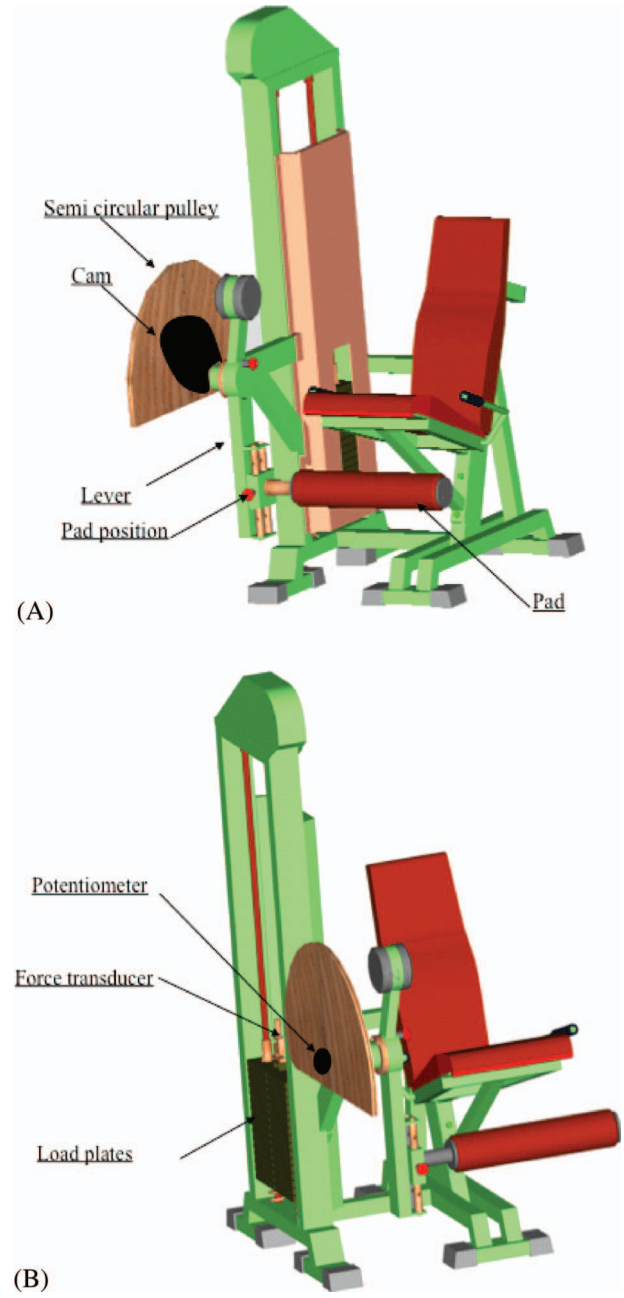

Figure 1. Leg extensor machine equipped with mechanical sensors.

Mechanical calculations

Knee extension was assumed to take place mainly in the sagittal plane. Taking into account the mechanical system that encompassed the lever, the cam, the

pulley, and the foot–leg segments (Figure 2), the Euler equation gave:

$$\sum M = I_{syst}\alpha \qquad (1)$$

where I_{syst} is the mass moment of inertia of the moving mechanical system, α its angular acceleration, and ΣM the sum of the moments of force exerted on it.

Of these moments, we considered knee extension torque, M_K, the moment due to the resistance of the load plates, M_{Load}, the moment due to the weight of the lever, M_{LA}, the moment due to the weight of the foot–leg segments, M_{FLS}, and the moment due to the cam–pulley system weight, M_{CP}. All of these moments were calculated about the axis of rotation of the lever that was considered aligned with that of the knees. During knee extension, M_{Load}, M_{LA}, and M_{FLS} represented resistant moments, while M_K and M_{CP} represented motor moments. We thus obtained the equation:

$$M_K - M_{Load} - M_{LA} - M_{FLS} + M_{CP} = I\alpha \qquad (2)$$

From equation (2), knee extension torque was calculated as:

$$M_K = M_{Load} + M_{LA} + M_{FLS} - M_{CP} + I\alpha \qquad (3)$$

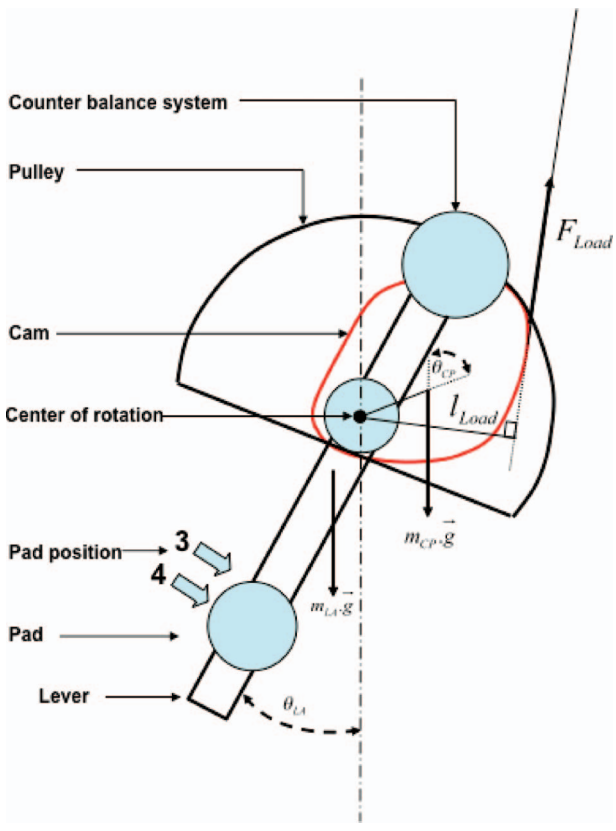

Figure 2. Mechanical description of the moving system only.

Determining the moment due to the loads (M_{Load}). We had $M_{Load} = F_{Load} \star l_{Load}$, where F_{Load} is the resistance force due to the load plates and l_{Load} is the moment arm of this resistance. F_{Load} was measured by the force transducer. When the cam was used, l_{Load} (in metres) was equal to

$$l_{Load} = (-0.0288 * \theta_{LA}^2 + 3.6765 * \theta_{LA} + 232.61) * 10^{-3}$$

where θ_{LA} (in degrees) is the angle between the longitudinal axis of the lever and the vertical axis (Figure 2). When the pulley was used, l_{Load} was constant and equal to 0.33 m. Hence, the pattern of resistance was modified and the resistant moment had different values according to the moment arm.

Determining the moment due to the weight of the lever (M_{LA}). The moment due to the weight of the lever was dependent on the position of the pad (Figure 2). Five different positions of the pad can be adopted with the machine used. It was necessary to know the position of the centre of mass of the lever for a given pad position. M_{LA} was calculated as $M_{LA} = m_{LA}gL_{LA}\sin(\theta_{LA})$, where m_{LA} is the mass of the lever (19.46 kg), g is acceleration due to gravity, L_{LA} is the distance between the centre of rotation and the centre of mass of the lever, and θ_{LA} is the angle with respect to the vertical axis. L_{LA} was determined by the reaction board method, described by Winter (1979), where the lever lies on a rigid board supported at one end by a force plate (AMTI, BP400600, Newton, MA) and by a triangular support at the other end. L_{LA} is small, since the lever has a counterbalance system. For the present experiment, only two pad positions were used, corresponding to positions 3 and 4 (see Figure 2), where L_{LA} was equal to 0.059 m and 0.070 m, respectively.

Determining the moment due to the cam–pulley system weight (M_{CP}). M_{CP} was calculated as $M_{CP} = m_{CP}gL_{CP}\sin(\theta_{CP})$, where m_{CP} is the total mass of the cam–pulley (9.763 kg), g is acceleration due to gravity, L_{CP} is the distance between the centre of rotation and the centre of mass, and θ_{LA} is the angle with respect to the vertical line. The centre of mass of the cam–pulley system was determined by suspending the system from two different locations near an edge and by tracing the plumb lines. The centre of mass was at the intersection of the two lines. Distance L_{CP} was measured as 0.072 m.

Determining the moment due to the weight of the foot–leg segments (M_{FLS}). M_{FLS} was calculated as $M_{LFS} = m_{FLS}gL_{FLS}\sin(\theta_{FLS})$, where m_{FLS} is the mass of the foot–leg segments, g is acceleration due to gravity, L_{FLS} is the distance between the centre of rotation

and the centre of mass, and θ_{FLS} is the angle with respect to the vertical line. m_{FLS} and L_{FLS} were estimated using de Leva's (1996) anthropometric table.

Determining the mass moments of inertia (I_A and I_{FLS}) and angular acceleration (α). The mass moment of inertia was the same in the two conditions whatever the linkage system as the cam and the pulley were attached and moved together during knee extension. I_{Syst} comprised the mass moment of inertia of the rotating mechanical components of the machine, I_A, and that of the participant's foot–leg segments, I_{LFS}. By swinging the mechanical system as a pendulum around its rotation axis, the mass moment of inertia, I_A, was calculated for each position of the pad from the period of free oscillations. In the present investigation, only positions 3 or 4, corresponding to $I_A = 2.20$ and $2.43\ \mathrm{kg \cdot m^2}$, respectively, were used. The mass moment of inertia of the participant's foot–leg segments with respect to the knee rotation axis was calculated using de Leva's (1996) tables. Finally, the angular position (in rads), measured with the potentiometer, was twice differentiated with respect to time to obtain the angular acceleration, α (in $\mathrm{rad \cdot s^{-2}}$).

Methods

Participants

Fourteen young men volunteered for the study. Their mean physical characteristics were as follows: age, 24 ± 2 years; body mass, 71.6 ± 7.3 kg; height, 1.76 ± 0.05 m. The participants were physically active and familiar with resistance training. All participants provided consent after being fully informed of the procedure and of the associated risks, and the study was approved by the local ethics committee.

Protocol

The testing was conducted in two sessions separated by at least 3 days of rest. One session used the circular pulley (pulley condition) and the other the non-circular cam (cam condition). The order of the two sessions was randomized among participants. At the beginning of each session, the participant performed a warm-up consisting of several knee extensions at different loads. After a 5-min rest period, the measurements were conducted on the knee extensor machine. Each participant was asked to perform a full knee extension at maximal velocity for applied loads of 40–80 kg in increments of 5 kg. Loads less than 40 kg were not tested because of damage to the equipment due to movement of the light load plates. The participants performed two trials at each load. Between trials, a rest period of at least 2 min was allowed or until the participant recovered completely.

Torque–angular velocity and power–angular velocity relationships

For each lifted load, average and peak values for velocity, torque, and power were calculated during the concentric contraction of the knee extensors. In agreement with Rahmani et al. (1999), the theoretical maximal torque T_0 and angular velocity V_0 corresponding to the intercept of the torque–velocity axes were calculated. The maximal power P_{MAX} and the corresponding optimal velocity V_{OPT} were determined from the power–velocity relationships.

Statistical analysis

To assess the reliability of the measurements, we calculated the intra-class correlation coefficient (ICC) between the two trials using analysis of variance (ANOVA) with repeated measures. The torque, velocity, and power values in the two resistance moment arm conditions were compared with the non-parametric Wilcoxon test at each load. Relative differences (%) were recorded, with values in the pulley condition taken as the reference. All statistical tests were done with SPSS software (SPSS Inc., Chicago, IL). Statistical significance was set at $P < 0.05$ for all analyses.

Results

Tables I and II show the average and peak torque values, Tables II and IV those for average and peak velocity, and Tables V and VI those for average and peak power. High significant trial-to-trial intra-class correlation coefficients (from 0.80 to 1) were obtained in both conditions and at each imposed load.

Participants developed significantly higher average torque with the pulley than with the cam ($P < 0.001$). The average torque values ranged from $134.68 \pm 12.19\ \mathrm{N \cdot m}$ at 40 kg to $249.13 \pm 11.38\ \mathrm{N \cdot m}$ at 80 kg with the pulley, and $113.27 \pm 11.10\ \mathrm{N \cdot m}$ at 40 kg to $213.57 \pm 11.08\ \mathrm{N \cdot m}$ at 80 kg with the cam. The relative differences ranged from –19.87% at 45 kg to –13.12% at 50kg. Figure 3 presents the evolution of average torque according to load. The peak torque values were significantly higher with the pulley than with the cam. With the pulley, the values ranged from 8.72% at 45 kg to 15.49% at 80 kg. Average and peak torque values increased linearly with the load ($P < 0.001$).

Table I. Average torque (N · m) at each load.

	Pulley			Cam			
Load (kg)	Mean	*s*	ICC	Mean	*s*	ICC	Diff%
40	134.68	12.19	0.99	113.27#	11.10	0.99	−15.90
45	149.74	11.53	1.00	119.98#	8.88	0.99	−19.87
50	153.83	11.76	0.99	133.65#	9.38	0.95	−13.12
55	170.00	11.91	0.99	146.91#	10.19	0.97	−13.59
60	186.71	13.31	0.99	160.31#	10.28	0.97	−14.14
65	202.73	14.17	0.99	173.73#	11.18	0.97	−14.30
70	220.91	14.95	0.99	187.61#	11.73	0.97	−15.07
75	236.52	13.07	0.99	200.67#	10.89	0.97	−15.16
80	249.13	11.38	0.99	213.57#	11.08	0.99	−14.27

Note: Mean and standard deviation (*s*) within group and trial-to-trial intra-class correlation are reported. Diff% = (value in cam condition – value in pulley condition)/value in pulley condition × 100. #Significant difference between conditions (Wilcoxon's test).

Table II. Peak torque (N · m) at each load.

	Pulley			Cam			
Load (kg)	Mean	*s*	ICC	Mean	*s*	ICC	Diff%
40	272.44	26.31	0.93	239.35#	29.26	0.99	−12.15
45	283.40	27.61	0.98	258.68#	27.56	0.93	−8.72
50	311.02	35.08	0.98	267.77#	27.52	0.95	−13.91
55	322.29	34.57	0.98	276.83#	27.04	0.95	−14.10
60	332.85	34.73	0.97	285.89#	27.92	0.98	−14.11
65	342.67	36.01	0.97	291.09#	24.39	0.93	−15.05
70	355.79	39.13	0.97	302.37#	23.45	0.80	−15.01
75	367.44	35.16	0.97	311.79#	25.71	0.93	−15.14
80	385.32	32.22	0.93	325.64#	22.07	0.81	−15.49

Note: Mean and standard deviation (*s*) within group and trial-to-trial intra-class correlation are reported. Diff% = (value in cam condition – value in pulley condition)/value in pulley condition × 100. #Significant difference between conditions (Wilcoxon's test).

Table III. Average velocity (rad · s^{-1}) at each load.

	Pulley			Cam			
Load (kg)	Mean	*s*	ICC	Mean	*s*	ICC	Diff%
40	2.25	0.24	0.91	2.58#	0.31	0.98	14.67
45	2.08	0.26	0.97	2.59#	0.31	0.94	24.52
50	2.21	0.35	0.99	2.42#	0.29	0.97	9.50
55	2.06	0.32	0.99	2.25#	0.28	0.98	9.22
60	1.91	0.35	0.99	2.11#	0.28	0.99	10.47
65	1.76	0.37	0.99	1.99#	0.27	0.97	13.07
70	1.62	0.42	0.99	1.85#	0.27	0.98	14.20
75	1.61	0.27	0.98	1.80#	0.24	0.97	11.80
80	1.55	0.27	0.98	1.71#	0.23	0.97	10.32

Note: Mean and standard deviation (*s*) within group and trial-to-trial intra-class correlation are reported. Diff% = (value in cam condition – value in pulley condition)/value in pulley condition × 100. #Significant difference between conditions (Wilcoxon's test).

At each load, the average velocity of movement was lower in the pulley condition than in the cam condition ($P < 0.001$). Figure 4 displays the evolution of average velocity across the imposed loads. Whatever the condition, average velocity decreased linearly with the load ($P < 0.001$). Knee extension velocity ranged from 2.25 ± 0.24 rad · s^{-1} at 40 kg to 1.55 ± 0.27 rad · s^{-1} at 80 kg with the pulley, and from 2.58 ± 0.31 rad · s^{-1} at 40 kg to 1.71 ± 0.23 rad · s^{-1} at 80 kg with the cam. No difference was observed between the peak velocity values in the pulley and cam conditions. The relative difference ranged from 1.23% at 55 kg to 7.99% at 40 kg.

No differences were observed in average power at each load between the two conditions. Average power ranged from 262.78 ± 23.94 W at 40 kg to 373 ± 32.27 W at 80 kg in the pulley condition, and from 269 ± 11.90 W at 40 kg to 376.24 ± 38.95 W

Table IV. Peak velocity (rad · s–1) at each load.

	Pulley			Cam			
Load (kg)	Mean	*s*	ICC	Mean	*s*	ICC	Diff%
40	4.10	0.44	0.94	4.43	0.71	0.99	7.99
45	3.82	0.46	0.98	4.11	0.45	0.93	7.46
50	3.74	0.45	0.98	3.82	0.42	0.96	2.22
55	3.49	0.43	0.99	3.53	0.41	0.97	1.23
60	3.24	0.48	0.96	3.31	0.43	0.99	2.03
65	3.02	0.47	0.99	3.12	0.43	0.97	3.41
70	2.78	0.57	0.99	2.90	0.40	0.97	4.61
75	2.64	0.45	0.96	2.81	0.35	0.96	6.59
80	2.61	0.39	0.98	2.67	0.33	0.97	2.34

Note: Mean and standard deviation (*s*) within group and trial-to-trial intra-class correlation are reported. Diff% = (value in cam condition – value in pulley condition)/value in pulley condition × 100. #Significant difference between conditions (Wilcoxon's test).

Table V. Average power (W) at each load.

	Pulley			Cam			
Load (kg)	Mean	*s*	ICC	Mean	*s*	ICC	Diff%
40	262.78	23.94	0.87	269.21	11.90	0.81	2.45
45	271.70	35.86	0.98	293.69	19.63	0.86	8.09
50	308.47	35.12	0.98	312.58	22.74	0.82	1.33
55	320.84	35.74	0.98	326.68	27.02	0.93	1.82
60	329.87	43.66	0.98	338.01	31.61	0.97	2.47
65	333.98	50.44	0.99	347.95	33.97	0.96	4.18
70	337.80	71.95	0.99	354.91	36.09	0.97	5.07
75	352.20	59.4	0.96	368.58	37.54	0.94	4.65
80	373.49	32.22	0.98	376.24	38.95	0.95	0.74

Note: Mean and standard deviation (*s*) within group and trial-to-trial intra-class correlation are reported. Diff% = (value in cam condition – value in pulley condition)/value in pulley condition × 100. #Significant difference between conditions (Wilcoxon's test).

Table VI. Peak power (W) at each load.

	Pulley			Cam			
Load (kg)	Mean	*s*	ICC	Mean	*s*	ICC	Diff%
40	708.80	78.34	0.85	701.41	112.03	0.99	−1.04
45	722.31	98.10	0.97	716.07	85.30	0.95	−0.86
50	750.61	110.39	0.97	715.82#	88.84	0.97	−4.64
55	746.03	113.11	0.98	705.43#	96.08	0.96	−5.44
60	737.73	129.20	0.94	704.01	110.89	0.99	−4.57
65	721.11	127.22	0.97	696.60	112.41	0.97	−3.40
70	702.16	152.47	0.97	681.73	102.25	0.96	−2.91
75	702.82	133.26	0.96	695.00	95.51	0.96	−1.11
80	724.88	117.77	0.98	696.66	94.71	0.95	−3.89

Note: Mean and standard deviation (*s*) within group and trial-to-trial intra-class correlation are reported. Diff% = (value in cam condition – value in pulley condition)/value in pulley condition × 100. #Significant difference between conditions (Wilcoxon's test).

at 80 kg in the cam condition. Peak power ranged from 708.80 ± 78.34 W at 40 kg to 724.88 ± 117.77 W at 80 kg in the pulley condition, and from 701.41 ± 112.03 W at 40 kg to 695.00 ± 95.51 W at 75 kg in the cam condition. Only at 50 kg and 55 kg did the participants exhibit higher peak power in the pulley condition than in the cam condition.

For each participant, a linear relationship was obtained between average torque and average velocity. From the torque–velocity relationship, the theoretical maximal torque, T_0, ranged from 492.97 to 311.50 N · m in the pulley condition, and from 441.54 to 322.71 N · m in the cam condition. In the pulley condition, T_0 was significantly higher than in the cam condition ($P < 0.01$). In the cam condition, the theoretical maximal velocity, V_0, was significantly higher than in the pulley condition ($P < 0.01$). The V_0 values varied from 3.11 to 3.94 rad · s^{-1} and

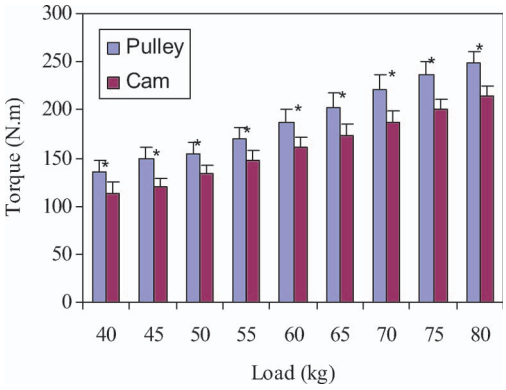

Figure 3. Relationship between knee extensor torque (N · m) and the loads (kg) for the two conditions (pulley and cam). *Significant difference between pulley and cam condition.

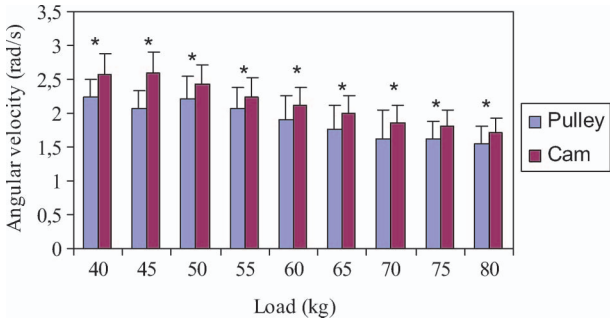

Figure 4. Relationship between knee extensor angular velocity (rad · s^{-1}) and the loads (kg) for the two conditions (pulley and cam). *Significant difference between pulley and cam condition.

from 3.28 to 4.40 rad · s^{-1} in the pulley and cam condition, respectively. A significant difference in the slope of the torque–velocity relationship was obtained by modifying the resistant moment arm (-120.86 ± 17.78 in the pulley condition vs. -101.71 ± 15.01 in the cam condition) ($P < 0.01$).

The power–velocity relationship was fitted by a second-order polynomial regression for each participant and in each condition ($r^2 = 0.71$–0.99 in the pulley condition vs. $r^2 = 0.81$–0.99 in the the cam condition) ($P < 0.01$). No typical curve was observed for the whole group. A few participants exhibited an inverted U-shaped curve (as in Figure 5), whereas the others exhibited either an ascending or descending curve.

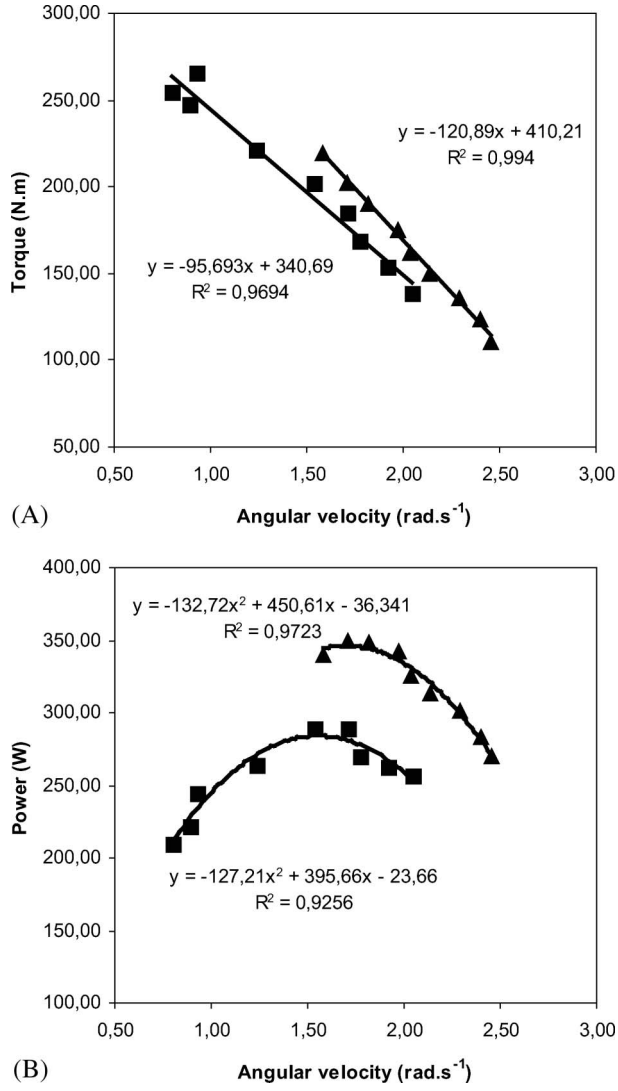

Figure 5. Torque–velocity (A) and power–velocity relationships for one representative participant. ■, pulley condition; ▲, cam condition.

Discussion

The equipment setting was designed to measure the muscular performance of the participants with very high reliability. In the literature, torque and power of the knee extensors have mostly been reported in isokinetic conditions (Prietto & Caiozzo, 1989; Theoharopoulos, Tsitskaris, Nikopoulou, & Tsaklis, 2000). Prietto and Caiozzo (1989) reported knee extensors torques between 146.4 and 246.5 N · m for angular velocities of 0.84–4.19 rad · s^{-1}. Theoharopoulos et al. (2000) reported torques of 287 N · m at 1.04 rad · s^{-1} and of 151 N · m at 3.14 rad · s^{-1} for the dominant limb of professional basketball players. Despite the isokinetic condition, previous values are in line with those of the present study. In a non-isokinetic condition, Rahmani et al. (1999) reported torques of 81.9 N · m at 3.81 rad · s^{-1} and 190.1 N · m at 1.36 rad · s^{-1} using a similar ballistic method. These values were lower than those in the present study, but they were obtained with elderly men. Taking into account the velocity condition and the population examined, our data are in line with those in the literature.

The mechanism of the cam adapts the resistance moment arm to the individual's angle–torque relationship during a knee extension (Cabell & Zebas,

1999; Folland & Morris, 2008). The moment arm of the quadriceps varies according to the knee angle (Krevolin, Pandy, & Pearce, 2004; Sheehan, 2007; Tsaopoulos, Baltzopoulos, Richards, & Maganaris, 2007; Ward, Terk, & Powers, 2005). Ward et al. (2005) reported that the quadriceps moment arm decreases for knee flexion angles above 60°. Sheehan (2007) further indicated that the patellar tendon moment arm increases on average from 20 mm to 50 mm as the knee extends from 40° to full extension. Consequently, if the resistance moment arm corresponds to the quadriceps moment arm, the quadriceps force produced by the participant depends mainly on the resistance force regardless of the moment arm. In the present study, the resistant moment arm could not be individualized but its pattern limited the resistance torque when the quadriceps moment arm was unfavourable. However, the participants developed higher torque in a constant resistance arm condition (pulley condition) than in the variable resistance arm condition (cam condition). The difference in torque according to the link condition may in part be explained by the misalignment of the rotation axis of the knee with that of the lever. Indeed, Deslandes and colleagues (Deslandes, Mariot, & Serveto, 2008) showed that an offset of rotation centres may induce a relative difference in torque of $\pm$ 10%. Although an exact alignment is difficult to obtain, we standardized the position of the participant. In addition, all torque values were 10% better in the pulley than in the cam condition. This systematic overestimation supports the influence of the resistance moment arm on muscular performance. The use of a resistance training machine equipped with a pulley thus seems to be of benefit in developing muscular force over the range of knee extension.

As the cam resistance arm is low at the beginning of the movement, the participant can move the lever more rapidly compared with the pulley condition. However, the radius of the pulley used is equal to the maximal radius of the cam used. A lower pulley radius should lead to an increase in knee extension velocity. Therefore, the differences in knee extension velocity could be non-significant at loads below 40 kg. Further modifications of the machine should be made to verify this point. Nonetheless, the cam-equipped machine still addresses the training of contraction velocity.

A finding of the present study is that the torque–velocity and power–velocity relationships were modified when using different resistant moment arms. The negative slope of the torque–velocity relationship was significantly lower in the pulley than in the cam condition. The reason for this alteration of the muscular characteristics based on choice of resistant moment arm is unclear. One might hypothesize that the relative contribution of each muscle of the quadriceps in net knee torque may be changed with the use of the pulley or cam. In addition, the lack of resistance at the beginning of movement in the cam condition may limit recruitment of the muscles. However, without direct measurement of neuromuscular activation, these proposals are speculative. Further research is needed to highlight the neuromuscular strategies according to the variation of the resistance moment arm. Moreover, a typical power–velocity relationship was observed for only a few participants. For the other participants, maximal power was not reached, leading to a modification of the shape of the power–velocity relationships. It could be attributed to the lack of lighter or heavier loads ($<$ 40 kg or $>$80kg) as reported by Rahmani and colleagues (Rahmani, Viale, Dalleau, & Lacour, 2001). Nonetheless, if we extrapolate the maximal power and corresponding optimal velocity from the linear torque–velocity relationship, after multiplying the linear equation ($T = aV + b$) by V, we observe that these two parameters, maximal power and optimal velocity, are also significantly modified by the link condition. The optimal velocity, V_{OPT}, was significantly higher in the cam condition than in the pulley condition ($P < 0.01$). In the pulley condition, maximal power was significantly higher than in the cam condition ($P < 0.05$). Previous studies have reported that optimal velocity was related to the percentage of fast-twitch fibres in athletes (Hautier, Linossier, Belli, Lacour, & Arsac, 1996). The present results highlight that the optimal velocity should be determined with caution. Coaches should monitor the gain in strength training with the same isoinertial machine by taking into account all of its mechanical components.

Given the above differences between the two conditions for torque and for angular velocity, power production was not significantly modified in the cam condition versus pulley condition. Thus, both conditions can be used to enhance muscular power production. However, the constraints on the anatomical structures are not the same in the two conditions. Furthermore, the patellofemoral compressive force and the strain on the anterior cruciate ligament (ACL) depend on the joint angle and the quadriceps contraction. Indeed, during knee extension, the patellofemoral compressive force increases and the patellofemoral contact area decreases (McGinty, Irrgang, & Pezzullo, 2000), thereby increasing the contact stress with knee extension. Moreover, knee extension produced anterior tibia shear force that implies strain on the ACL. Both patellofemoral compressive force and ACL strain are related to the quadriceps force. Knowing that the patellofemoral joint reaction force/quadriceps force ratio is high when the knee is bent

(Ward et al., 2005), high quadriceps force at the beginning of knee extension involves high compressive force. Thus, the machine with a pulley increases the constraint at the beginning of the movement. In contrast, with a variable resistance moment arm, the cam appears more suited to preserve the anatomical structures.

In conclusion, whatever the link, namely cam or pulley, the participants produced similar power. However, the torque–velocity and power–velocity relationships were different in the cam and pulley conditions. Use of the cam involved a higher theoretical maximal velocity and a higher optimal velocity, whereas the pulley involved a higher maximal theoretical torque and a higher maximal power. According to the training aims, the pulley condition facilitated torque production while the cam condition facilitated velocity. However, the cam condition appears more suited to preserve anatomical structures mainly at the beginning of knee extension. The results further suggest that the influence of the machine's mechanism on muscular performance has yet to be elucidated for prescribing resistance exercises.

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