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Bilateral eccentric and concentric torque of quadriceps and hamstring muscles in females and males

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Summary. This study assessed maximum eccentric (ECC) and concentric (CON) torque of quadriceps (QUAD) and hamstring (HAM) muscle groups in healthy females ($n = 13$) and males ($n = 27$). Peak torques (PT) of bilateral muscle actions were recorded at constant angular velocities of 0.52, 1.57 and 2.61 $\text{rad} \cdot \text{s}^{-1}$. The QUAD_{CON} and HAM_{CON} PT decreased ($p < 0.05$) with increasing angular velocity. The QUAD_{ECC} and HAM_{ECC} PT increased ($p < 0.05$) in females, whereas QUAD_{ECC} PT decreased ($p < 0.05$) and HAM_{ECC} PT showed no change in males. In general, ECC PT was higher ($p < 0.05$) than CON PT and QUAD PT was higher ($p < 0.05$) than HAM PT, for any given angular velocity. Males displayed higher ($p < 0.05$) PT than females but when PT were adjusted for body mass the sex differences in QUAD_{CON} and HAM_{CON} were reduced ($p < 0.05$), whereas the differences in QUAD_{ECC} and HAM_{ECC} were abolished. The CON and ECC PT were, on average, 60% and 41% greater, respectively, in males than in females. The corresponding differences, when adjusted for body mass, were 23% and 8%. ECC:CON PT for QUAD were higher ($p < 0.05$) in females than in males. CON and ECC HAM:QUAD PT ratio increased ($p < 0.05$), as a function of velocity. This study suggests, that bilateral ECC PT is higher than CON PT and CON HAM:QUAD PT ratio is higher than ECC HAM:QUAD PT ratio. Moreover, females and males display different ECC torque-velocity patterns, whereas CON torque-velocity patterns are similar and females possess greater QUAD_{ECC} PT relative to QUAD_{CON} PT than males.

Key words: Torque velocity relationship — Human skeletal muscle mechanics

Introduction

The pioneering work of Wilkie (1950) described the force-velocity relationship during voluntary muscle actions. Since then, numerous reports have compared peak torque or angle specific torque at different angular velocities during unilateral concentric (CON) knee extensions (Thorstensson et al. 1976; Gregor et al. 1979; Tihanyi et al. 1982; Yates and Kamon 1983). Due to methodological limitations, less information is available regarding the torque-velocity relationship for eccentric (ECC) muscle actions. It is generally agreed, though, that the maximum ECC torque is greater than the maximum CON torque, when compared over a wide range of different joint angles (Doss and Karpovich 1965; Singh and Karpovich 1966; Olson et al. 1972) and movement speeds (Asmussen et al. 1965; Komi and Rusko 1974; Rodgers and Berger 1974; Komi and Viitasalo 1977; Griffin 1987; Rizzardo et al. 1988).

The CON hamstring:quadriceps muscle (HAM:QUAD) peak torque relationship has been established with emphasis on sex (Wyatt and Edwards 1981), athletic training (Costain and Williams 1984; Stafford and Grana 1984) or rehabilitation procedures (Grimby et al. 1980; Campbell and Glenn 1982). Surprisingly, there is a paucity of information available on QUAD and HAM function during voluntary ECC muscle actions (Highgenboten et al. 1988) despite the availability of commercial equipment necessary for such evaluations (Farrell and Richards 1986; Klopfer and Greij 1988). In addition, data on bilateral muscle actions in all these respects is, to the authors' knowledge, non-existent. Females seem to utilize stored elastic energy in jumping activities to a greater extent than males (Komi and Bosco 1978), thus there may exist a sex-dependent difference in ECC strength. To compare ECC and CON

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HAM:QUAD peak-torque ratios, we examined QUAD and HAM peak-torque during bilateral ECC and CON muscle actions in females and males at various constant angular velocities.

Material and methods

The physically active female ($n=13$) and male volunteers ($n=27$), had asymptomatic knee function, and no previous history of strength training or involvement in competitive sports emphasizing muscular strength or power. Their physical characteristics are shown in Table 1. The protocol utilized was approved by the Karolinska Institute Ethics Committee and all participants gave their informed consent.

The subjects visited the laboratory on three separate occasions. Two visits were intended to familiarize the subjects with the protocol and the dynamometer utilized in the study. The third session was the test session for each subject. Briefly, the dynamometer is supplied by an electrical motor and developed for uni- and bilateral CON and ECC knee extensor and flexor muscle actions. Angular velocity is controlled through tachometer feed-back and allows for functional measurements up to 2.61 rad·s^{-1} (150°·s^{-1}; Tesch et al. 1989).

In order to standardize the experiments and localize the muscle actions, the subjects were positioned in a chair providing support for the thigh, pelvis, back and shoulders. The thigh, pelvis and chest were strapped to the chair. The hip angle was 1.57 rad (90°). The bilateral motion axis of the knee, at 1.57 rad of flexion, was aligned with the centre of rotation of the dynamometer. Synergistic muscle actions, were avoided by requesting the subjects to hold their arms crossed over the chest during the test procedure.

After a 10-min warm-up period on a cycle ergometer, followed by stretching of the thigh muscles, the QUAD and HAM muscle groups were examined bilaterally in the following order: concentric quadriceps (QUAD$_{\mathrm{CON}}$), concentric hamstring (HAM$_{\mathrm{CON}}$), eccentric quadriceps (QUAD$_{\mathrm{ECC}}$) and eccentric hamstring (HAM$_{\mathrm{ECC}}$). The CON muscle actions were performed prior to ECC muscle actions, since a bout of maximum ECC muscle actions may reduce CON torque production, whereas a bout of maximum CON muscle actions appears not to influence maximum ECC torque production (Colliander and Tesch, unpublished observations).

The CON and ECC muscle actions were accomplished at constant angular velocities in the following order 0.52, 1.57 and 2.61 rad·s^{-1} (30, 90 and 150°·s^{-1}). The subjects performed a submaximal practice trial before each new mode of muscle action and angular velocity. Each muscle action was performed through a 1.57 rad range of motion and was followed by a 30–45 s rest. Four trials were allowed at each angular velocity. The torque curves produced during muscle actions were recorded on a strip-chart recorder (Gould 2400; Gould, Cleveland, Ohio, USA) and the peak torques (PT) were subsequently calculated.

Table 1. Physical characteristics of subjects. Values are mean ± SD

	Females ($n=13$)	Males ($n=27$)
Age (years)	27±4	27±5
Mass (kg)	57±6	74±7
Height (cm)	166±6	180±6

The HAM:QUAD PT ratios were calculated at each angular velocity. In addition, female:male PT and ECC:CON PT were determined.

Mean and standard deviation (SD) were calculated and potential intra- and inter-group variations were tested for, using analysis of variance (ANOVA). The following model was applied: $x_{ijkl}=\mu+\alpha_i+B_{j(i)}+\gamma_k+\delta_l+$interaction terms where μ = grand mean of test subjects; α_i = fixed effect of group; $i=1$ for females and 2 for males; $B_{j(i)}$ = random effect of subject within group; j = number of subjects; γ_k = fixed effect of muscle action type; $k=1$ for CON and 2 for ECC; δ_l = fixed effect of angular velocity; $l=1$ for 0.52 rad·s^{-1}, 2 for 1.57 rad·s^{-1} and 3 for 2.61 rad·s^{-1}. A Studentized Range test (Snedecor and Cochran 1967) was used wherever the ANOVA demonstrated statistically significant differences. The level of significance was set at $p<0.05$. All results presented as different fulfil this criterion.

Results

The ECC and CON torque velocity patterns for QUAD and HAM are shown in Fig. 1. The

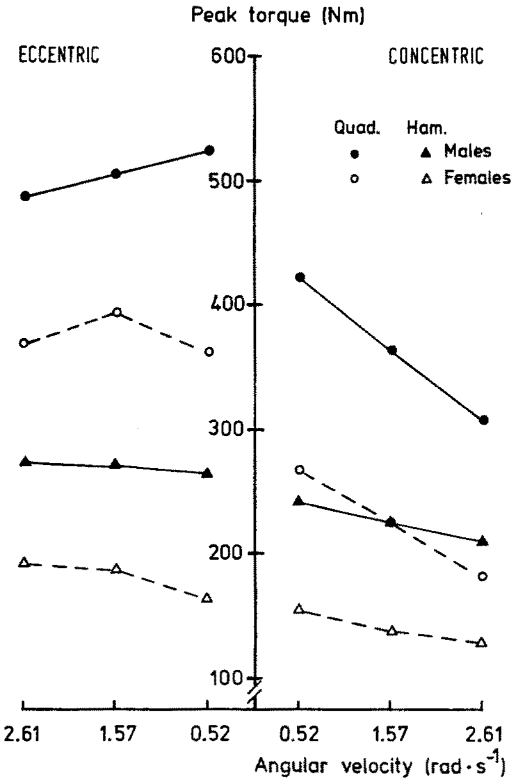

Fig. 1. Mean *eccentric* (*left panel*) and *concentric* (*right panel*) *peak torque* for quadriceps (*Quad.; circles*) and hamstring (*Ham.; triangles*) in *males* (*filled symbols*) and *females* (*open symbols*). For differences between mean values and slope of curves see Results

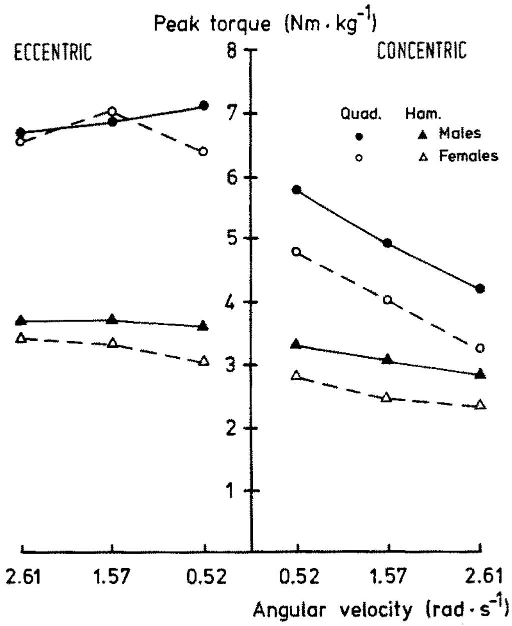

Fig. 2. Mean *eccentric* (*left panel*) and *concentric* (*right panel*) *peak torque* adjusted for body mass for quadriceps (*Quad.; circles*) and hamstring (*Ham.; triangles*) in males (*filled symbols*) and females (*open symbols*). For differences between mean values and slope of curves see Results

$QUAD_{CON}$ and HAM_{CON} PT decreased with increasing angular velocity. This decrease was greater for $QUAD_{CON}$ than HAM_{CON} PT. The $QUAD_{ECC}$ PT decreased with increasing angular velocity in males (i.e. PT at 0.52 rad·s^{-1} was greater than at 2.61 rad·s^{-1}), whereas females showed a slight increase. For females the $QUAD_{ECC}$ PT observed at an angular velocity of 1.57 rad·s^{-1} was greater than that observed at 0.52 rad·s^{-1}. The HAM_{ECC} PT increased in females (i.e. PT at 0.52 rad·s^{-1} was lower than PT at any other angular velocity), whereas males showed no change in PT with increasing angular velocity. With one exception (females at 0.52 rad·s^{-1} in the HAM mode) ECC PT were greater than CON PT at any velocity. QUAD PT were higher than HAM PT. The PT at any given angular velocity and mode of muscle action was higher in males than females (Fig. 1, Table 2). The sex differences in $QUAD_{CON}$ and HAM_{CON} PT relative to body mass, were smaller, yet statistically different (Fig. 2, Table 3). The $QUAD_{ECC}$ and HAM_{ECC} PT, relative to body mass, were similar in males and females.

The female:male ratios for ECC PT were, on average, 0.74 and 0.68 for QUAD and HAM, respectively, whereas CON PT ratios were 0.62 and 0.63 for QUAD and HAM, respectively (Table 2). Relative to body mass, the female:male PT quotients were 0.97 and 0.89 for $QUAD_{ECC}$ and HAM_{ECC} PT. The corresponding CON ratios were 0.80 (QUAD) and 0.82 (HAM; Table 3).

The ECC:CON PT quotients increased with increasing angular velocity. This pattern was more pronounced for QUAD than HAM PT. ECC:CON PT quotients were greater for QUAD than HAM PT. The QUAD and HAM ECC:CON PT ratios (at 1.57 and 2.61 rad·s^{-1}) were higher for females than males (Table 4).

Table 2. Peak torque (Nm) for quadriceps and hamstring concentric (CON) and eccentric (ECC) muscle actions. Ratio shows peak torque in females relative to males. Values are mean ± SD. * = significant difference and NS = non-significant difference between CON and ECC peak torque

Angular Velocity (rad·s^{-1})	Quadriceps					
	Concentric			Eccentric		
	Females	Males	Ratio	Females	Males	Ratio
0.52	268 ± 26	422 ± 74	0.64	363 ± 61*	525 ± 107*	0.69
1.57	227 ± 14	363 ± 53	0.62	394 ± 55*	505 ± 89*	0.78
2.61	184 ± 11	308 ± 46	0.60	371 ± 41*	486 ± 93*	0.76

Angular Velocity (rad·s^{-1})	Hamstring					
	Concentric			Eccentric		
	Females	Males	Ratio	Females	Males	Ratio
0.52	156 ± 24	242 ± 32	0.64	169 ± 21 NS	263 ± 50*	0.64
1.57	139 ± 17	225 ± 25	0.62	188 ± 19*	271 ± 56*	0.69
2.61	129 ± 14	209 ± 25	0.62	193 ± 19*	273 ± 57*	0.71

Table 3. Peak torque relative to body mass (Nm·kg^{-1}) for quadriceps and hamstring concentric (CON) and eccentric (ECC) muscle actions. Ratio shows peak torque relative to body mass in females compared to males. Values are mean±SD. For comparisons between CON and ECC at different angular velocities see Table 2

Angular Velocity (rad·s^{-1})	Quadriceps					
	Concentric			Eccentric		
	Females	Males	Ratio	Females	Males	Ratio
0.52	4.78±0.76	5.76±1.07	0.83	6.47±1.42	7.17±1.62	0.90
1.57	4.03±0.47	4.96±0.86	0.81	7.02±1.32	6.90±1.37	1.02
2.61	3.26±0.27	4.22±0.80	0.77	6.58±1.04	6.67±1.63	0.99
Angular Velocity (rad·s^{-1})	Hamstring					
	Concentric			Eccentric		
	Females	Males	Ratio	Females	Males	Ratio
0.52	2.78±0.53	3.30±0.48	0.84	3.00±0.54	3.59±0.71	0.84
1.57	2.46±0.40	3.06±0.35	0.80	3.32±0.43	3.70±0.79	0.90
2.61	2.29±0.38	2.84±0.35	0.81	3.41±0.44	3.71±0.76	0.92

The HAM:QUAD PT ratios increased with increasing angular velocity in both CON and ECC muscle actions but more so for CON. The CON HAM:QUAD PT ratio was higher than ECC HAM:QUAD PT ratio for any given angular velocity. The HAM:QUAD PT ratio was similar in males and females for any given angular velocity (Table 5).

Table 4. Eccentric:concentric ratio for quadriceps and hamstring peak torque. Values are mean±SD. * = significant difference between quadriceps and hamstring. $^{+}$ = significant difference between females and males

Angular Velocity (rad·s^{-1})	Females		Males	
	Quadriceps	Hamstring	Quadriceps	Hamstring
0.52	1.35±0.21	1.10±0.16*	1.26±0.23	1.09±0.23*
1.57	1.74±0.24	1.37±0.17*	1.40±0.22^{+}	1.21±0.26*$^{+}$
2.61	2.01±0.22	1.50±0.14*	1.59±0.29^{+}	1.31±0.24*$^{+}$

Table 5. Concentric and eccentric hamstring:quadriceps (HAM:QUAD) peak-torque ratio for females and males. Values are mean±SD. * = significant difference between concentric and eccentric HAM:QUAD peak-torque ratio

Angular Velocity (rad·s^{-1})	Females		Males	
	Concentric	Eccentric	Concentric	Eccentric
0.52	0.59±0.10	0.48±0.08*	0.58±0.08	0.51±0.10*
1.57	0.61±0.07	0.48±0.08*	0.63±0.08	0.54±0.10*
2.61	0.70±0.09	0.53±0.08*	0.69±0.10	0.57±0.09*

Discussion

In vivo torque-velocity relationship of QUAD has been thoroughly examined in man (Thorstensson et al. 1976; Gregor et al. 1979; Tihanyi et al. 1982; Yates and Kamon 1983). Studies of the unilateral concentric torque-output pattern confirm original reports on the mechanical responses of isolated skeletal muscle (Fenn and Marsh 1935; Hill 1938). The present data on bilateral QUAD$_{CON}$ and HAM$_{CON}$ peak torque yielded patterns similar to those shown for unilateral muscle actions, i.e. the peak torque decreased with increased angular velocity.

The torque-velocity relationship of ECC muscle actions in the present study revealed different patterns for females and males. In the latter, QUAD$_{ECC}$ peak torque decreased, whereas HAM$_{ECC}$ peak torque showed no change with increasing angular velocity. In contrast, females demonstrated increased QUAD$_{ECC}$ and HAM$_{ECC}$ peak torque as a function of increased angular velocity. Previous studies, examining elbow flexors, are not conclusive as to whether eccentric force increases at angular velocities comparable to those reported here (Komi 1973; Rodgers and Berger 1974). Also, and not contradicting our observations, QUAD force in females appeared to decrease between 120°·s^{-1} (2.09 rad·s^{-1}) and 180°·s^{-1} (3.14 rad·s^{-1}) after an initial increase (Rizzardo et al. 1988). We, therefore, suggest that

ECC peak torque does not necessarily increase as a function of angular velocity.

The $QUAD_{ECC}$ peak torque was greater than $QUAD_{CON}$ peak torque, thus confirming previous reports examining various muscle groups (Asmussen et al. 1965; Doss and Karpovich 1965; Singh and Karpovich 1966; Olson et al. 1972; Komi and Rusko 1974; Komi and Viitasalo 1977; Griffin 1987). The HAM_{ECC} peak torque was greater than HAM_{CON} peak torque at all angular velocities, except at 0.52 $rad \cdot s^{-1}$ in females. The HAM_{ECC} peak torques were on average 32% and 20% greater than HAM_{CON} peak torque in females and males, respectively. The corresponding values for $QUAD_{ECC}$ peak torque relative to $QUAD_{CON}$ peak torque were 70% and 42%. It therefore appears that the knee extensor relative to the knee-flexor muscle group possesses greater capacity during eccentric muscle action.

In general, males displayed higher absolute peak torque than females at all muscle action modes and all angular velocities. Thus, males showed on average 60% greater CON PT than females. This difference is similar to that found previously, for either isometric or concentric muscle actions (Maughan et al. 1983; Wyatt and Edwards 1981). The ECC peak torque, however, was only 41% greater in males. When peak torque was adjusted for body mass the differences in CON peak torque decreased, whereas ECC peak torque was comparable between sexes. Hence, males showed 23% and 8% greater peak torque, per unit of body mass, than females for CON and ECC modes, respectively. The body mass corrected value for CON muscle actions is in accordance with values noticed elsewhere (Maughan et al. 1983; Wyatt and Edwards 1981). These findings suggest, that the muscle mechanical response to ECC relative to CON muscle actions differs between the sexes. This is in accordance with previous findings by Komi and Bosco (1978), suggesting that women are able to utilize stored elastic energy to a greater extent than men, when performing counter-movement jumps. A possible reason is that the visco-elastic properties (Komi 1979) of muscles, that contribute to ECC force production, is more developed in females than in males. Another explanation may be that females are unable to recruit their entire motor-unit pool during CON muscle actions. Furthermore, bilateral isometric muscle actions in non-trained individuals are known to produce a lower force relative to the sum of unilateral muscle actions, suggesting restricted motor unit recruitment during high force production (Secher et al. 1976). Whether such a presumably central nervous inhibition differs between males and females, or between ECC and CON muscle actions, is at the present only a matter for speculation. Also, the higher absolute peak torque produced by males during ECC muscle actions may have had an inhibiting effect on the acting muscles, due to subliminal periosteal pain (Nisell 1985).

The finding of a steeper slope of the torque-velocity curve during $QUAD_{CON}$ peak torque compared to HAM_{CON} peak torque confirms earlier reports (Wyatt and Edwards 1981). As a consequence, CON HAM:QUAD peak-torque ratios increased with increased angular velocity. Also, the ECC HAM:QUAD peak-torque ratios increased with angular velocity, although this increase was smaller than that observed during CON muscle action. Furthermore, for the range of angular velocities measured (0.52–2.61 $rad \cdot s^{-1}$) CON HAM:QUAD peak-torque ratios were higher than ECC HAM:QUAD peak-torque ratios for both sexes. It therefore appears that the HAM:QUAD peak-torque ratio is influenced by angular velocity and type of muscle action, i.e. ECC vs CON. In addition, the HAM:QUAD peak-torque ratio varies throughout the arc of motion, as a function of changes in torque exerted by the lower limb mass (Fillyaw et al. 1986). It is also known that angle specific HAM:QUAD torque ratio varies considerably throughout the arc of motion, and does not allow assessment of peak torque at optimal length for both muscle groups (Figoni et al. 1988).

In conclusion, this study demonstrates bilateral ECC peak torque to be higher than CON peak torque in both females and males. The ECC peak torque did not increase with increasing angular velocity in males, whereas females showed an increase. We therefore suggest that ECC peak torques does not necessarily increase as a function of increasing angular velocity. Moreover, females display greater $QUAD_{ECC}$ relative to $QUAD_{CON}$ peak torque than males.

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