# ORIGINAL ARTICLE

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# Power output of the lower limb during variable inertial loading: a comparison between methods using single and repeated contractions

**Abstract** The power–inertial load relationship of the lower limb muscles was studied during a single leg thrust using the Modified Nottingham Power Rig (mNPR) and during cycling exercise in nine young male subjects. The relationship between peak power and inertial load showed a parabolic-like relationship for mNPR exertions, with a peak [937 (SD 246) W] at 0.158 kg m$^2$, this being significantly ($P < 0.05$) different from the power generated at both the lowest [723 (162) W] and highest [756 (206) W] inertial loads. In contrast, for cycling exercise power output did not differ significantly between inertial loads, except at the lowest inertia where power output was significantly ($P < 0.05$) less compared with all other inertial loads. Maximum peak power output during cycling was 1,620 (336) W, which was significantly ($P < 0.05$) greater than that recorded on the mNPR. However, a close association was observed between the mean power generated by each method ($r = 0.84$, $P < 0.05$). The results suggest that during a single contraction a range of inertial loads is required to allow peak power to be expressed. Above a certain critical value, this is unnecessary during cycling movements where the load can be repeatedly accelerated.

**Keywords** Muscle · Power · Exercise

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## Introduction

Over the years numerous methods have been utilised for studying the power-generating ability of human skeletal muscle, either for actions in which the whole body is utilised, such as during running (e.g. Margaria step test), jumping (e.g. Sargent jump) or cycling, or during isolated joint rotations. The latter two have been extensively studied using either isokinetic apparatus where the velocity of joint rotation is controlled, or in the case of cycle ergometry, against a friction-braked flywheel. Aagaard et al. (1994) studied power output during knee extension movements using a flywheel system, without friction braking, to provide the muscle with an inertial plus gravitational load. Whilst Bassey and Short (1990) developed the Nottingham Power Rig (NPR) whereby average power during a single thrust of the lower limb could be determined against an inertial load, using a leg press type action.

We have recently modified the NPR (mNPR) and demonstrated that the power–inertial load relationship is parabolic in nature (Pearson et al. 2001). This is in contrast to the study by Martin et al. (1997) who reported no effect of inertial load on the peak power output generated with cycling exercise. In addition, we observed that the maximum values of power obtained with the mNPR were lower than those cited in the literature for sprint cycling against either inertial (Martin et al. 1997, Baron et al. 1999) or isokinetic movements (Davies et al. 1983; McCartney et al. 1983; Sargeant et al. 1981).

Cycling and mNPR generate power output using the lower limbs, and both methods allow the generation of power with only one limb at a time. However, during cycling a torque is repeatedly applied to the flywheel during a given bout of exercise, whereas during exertions on the mNPR only a single thrust of the lower limb is performed. The aim of the present study was to compare the power output–inertial load relationship whilst performing exertions against a range of inertial loads,

during a single thrust on the mNPR and also repeated thrusts in the form of cycling exercise.

## Methods

### Subjects

Nine untrained, healthy young males were tested on both the mNPR and the inertial cycle. The physical characteristics (SD) of the subjects were age 31.6 (5.5) years, weight 82. 6 (5.2) kg, height 179.9 (4.9) cm. Each test was carried out on a separate day and there were at least 2 days between tests.

### Protocols

#### Single leg thrusts on the mNPR

Testing consisted of performing three maximal leg thrusts against five different inertial loads on the mNPR as previously described (Pearson et al. 2001) (Fig. 1A). Lower limb power was calculated from careful determination of the rotation of the inertial flywheel. This was achieved using a rotary encoder (Hengstler RI58 0/360ASO.41RB), (Fig. 1C for flywheel details) which gave 360 pulses per revolution of the flywheel. The rotary encoder pulses were sampled on the falling edge of each pulse by the A/D system (CED micro 1401), which allowed a cumulative time to be recorded for the movement of the flywheel during the exertion period with a resolution of 2 μs. The time–displacement data were collected by Spike 2 software (CED Ltd), and analysed as previously described (Pearson et al. 2001), by exporting to a mathematical software programme (Mathcad ver 2001, Mathsoft Inc).

#### Inertial cycling

For cycling, the rear wheel of a standard cycle was replaced with the inertial flywheel assembly described above. A large (80 tooth), non-standard chainwheel was utilised in order to increase the gear ratio to that similar to the mNPR to allow sufficient equivalent inertia (resistance) at the pedals. A purpose built crank and axle assembly was constructed in order to attach the chainwheel to the cycle. The cycle was made rigid and attached securely to the floor (Fig. 1B). Testing consisted of three maximal sprints on a stationary cycle at five inertial loads (0.024–0.540 kg m$^2$). Cycle sprints
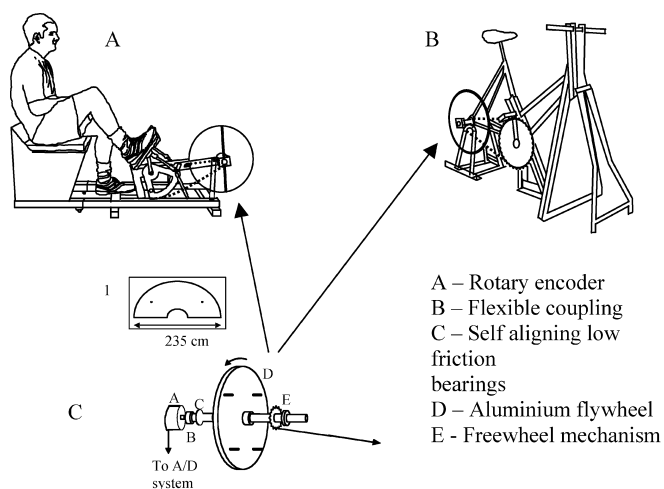


**Fig. 1** The setup used for mNPR (**A**) and inertial cycling (**B**) experiments. Details of the inertial flywheel can be seen in **C** and loading plates (*inset* 1)

lasted between 1 and 5 s, depending on the ability to accelerate the inertial load. All sprints started from stationary and the crank position was vertical, using the same leg as that used in mNPR. Toe clips were used to secure the feet to the pedals.

All testing (mNPR and cycling) was preceded by a standardised 5 min warm-up (50 W, 60 rpm cycling). A standardised rest period of 2 min was given between each exertion. Subjects were familiarised with the apparatus on a separate visit to the laboratory prior to testing. The Royal Free Hospital Ethics Committee approved all experimental procedures and all subjects gave written informed consent.

### Calculation of torque and power

In order to calculate the values of power and torque during contractions for both the mNPR and cycle, the digital signal from the rotary encoder was utilised. The instantaneous angular acceleration was calculated by double differentiation of the rotary encoder pulses. This value was then multiplied by the moment of inertia of the system to give a torque value. Finally, the torque value was multiplied by the rotational velocity (first-order differential of rotary encoder signal) to give a power value.

### Data analysis

A polynomial fitting method was utilised in order to determine the maximal values of mean power for both the mNPR and cycling exertions (see Appendix). Repeated ANOVA was used in order to identify any significant differences in power output between inertial loads for both inertial cycling and the mNPR tests. Where a significant difference was detected, paired $t$-tests with Bonferroni corrections were applied to identify the specific load. The alpha level was set to $P = 0.05$.

## Results

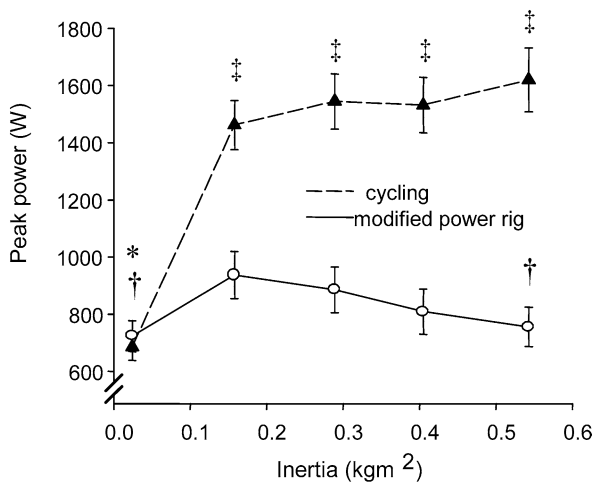### Power–inertial load relationship: mNPR versus cycling

Typical examples of power output profile obtained from the mNPR and cycling are shown in Fig. 2 (all data from one subject). The mean peak power generated by the subjects on the mNPR was 937 (246) W and occurred at an inertial load of 0.158 kg m$^2$, after which the power declined. This was significantly lower than the 1620 (336) W of peak power which occurred at 0.543 kg m$^2$ during cycling exercise. The values of power output obtained under the two test conditions and across the different inertial loads are shown in Fig. 3. At the lowest inertial load there was no difference in power between the two test conditions. However, at 0.158 kg m$^2$ the peak power achieved was 56% ($P < 0.05$) higher during cycling and continued to be significantly higher compared to the mNPR at each subsequent inertial load. In contrast to the mNPR no statistically significant changes were observed in power output during cycling with increasing inertial load (beyond 0.158 kg m$^2$).

### Peak power output characteristics during cycling

During cycling peak power reached a plateau after the lowest inertial load (Fig. 3). However, the time taken to generate peak power increased significantly with increasing inertial load (Fig. 4), with peak power
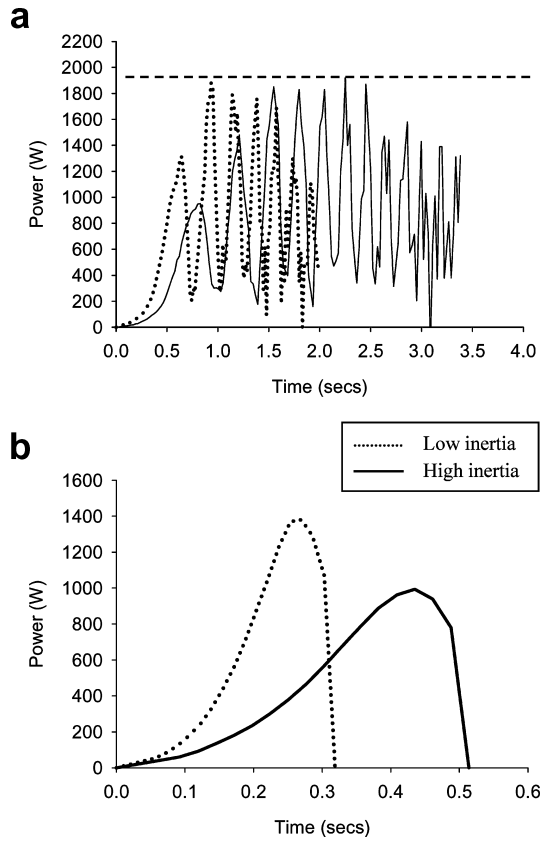
**Fig. 2** Typical records obtained from exertions at both high (0.543 kg m$^2$) and low (0.158 kg m$^2$) inertial loads during **a** cycling exercise and **b** on the mNPR. It can be seen in **a** (*horizontal dashed line*) that peak power is similar at both high and low inertial loads for cycling. At the lower inertia peak power output is generated more quickly than at the higher inertial load, but declines rapidly with the increase in velocity
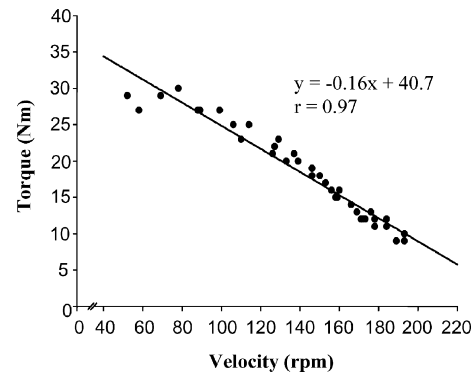
occurring typically within 0.5, 0.75, 1.5, 2.5 and 3 revolutions of the cranks for inertial loads of 0.024, 0.158, 0.289, 0.405 and 0.543 kg m$^2$ respectively. The group mean values for instantaneous torque and velocity determined at the point where peak power occurs were calculated. It can be seen from Fig. 5 that the torque–velocity relationship is almost linear ($r = 0.97$). The instantaneous peak power–velocity relationship was also plotted using data points across the full range of inertial loads (Fig. 6). The optimal velocity using the polynomial equation from Fig. 6 is ∼123 rpm, whilst the maximum pedal revolution velocity, extrapolating the data from Fig. 5, is ∼250 rpm. This is in keeping with the linear torque–velocity relationship that we observed. The optimal velocity is half of this (125 rpm), which is in general agreement with the value calculated from the polynomial method. See Appendix for details of optimal velocity calculation from linear torque–velocity relationship. Figure 7 shows the relationship between the calculated power outputs for both test methods. It can be seen that a very strong ($r = 0.84$, $P = 0.0001$) relationship exists between the two different methods of measuring power.
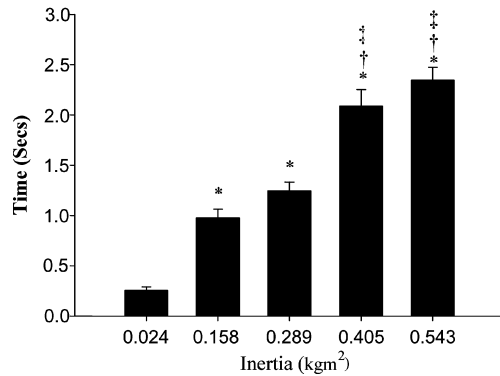


**Fig. 4** Time taken to reach peak power during cycling with respect to inertial load. *Significantly different to 0.024 kg m$^2$. †Significantly different to 0.158 kgm$^2$. ‡Significantly different to 0.289 kg m$^2$



**Fig. 3** Peak power output obtained from exertions on the mNPR (○) and during cycling (▲). Values are mean ± SE, ($n = 9$). *Significantly different from subsequent inertias (cycling). † Significantly different from 0.158 kg m$^2$ (mNPR) ($P < 0.05$). ‡ Significantly different from mNPR



**Fig. 5** Mean group values of instantaneous torque and velocity (determined at peak power) across the range of inertial loads for cycling
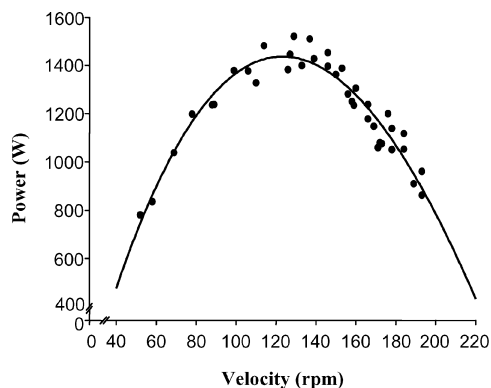
Fig. 6 Relationship between mean group values of instantaneous power and associated velocity across the range of inertial loads for cycling
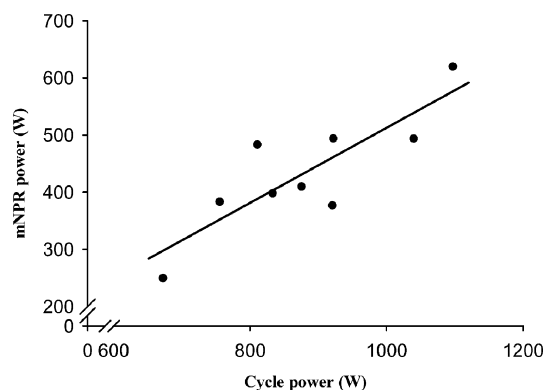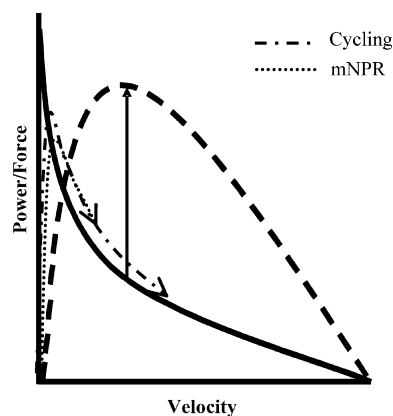


Fig. 7 Relationship between the mean power output during inertial sprint cycling and on the mNPR for all subjects ($y=0.66-144$, $r=0.84$, $P<0.05$). Power values were obtained from polynomial fitting of power velocity data for each protocol



Fig. 8 Hypothetical characteristics of power generation for cycling and mNPR under identical inertial loading conditions. Here for mNPR (*dotted line*) it can be seen that the acceleration is insufficient to allow sufficient time to arrive at the velocity at which peak power occurs (*solid arrowed vertical line*). Whereas for cycling (*dot dashed line*) acceleration is continuous hence the "optimal velocity" at which peak power occurs is passed (*dashed black line*)

## Discussion

The main findings of the present study are that when a single thrust of the lower limb muscles is performed in a time-limited movement, as in the mNPR, then the inertial load at which the exertion is made is an important determinant of power output. However, when repeated contractions are performed, as during cycling exercise when a load may be accelerated and rotary kinetic energy and impulse increased in a cumulative manner, then the inertial load is not a determinant of peak power output. This is providing that, firstly, the load is above a critical level and, secondly, that it is below a level which might result in fatigue prior to the flywheel achieving the rotational velocity at which peak power would be expressed.

Martin et al. (1997) reported that peak power output during inertial-loaded cycling was independent of inertial load. The experiments described in this study show that above a certain level of inertial load (critical load) the power output is indeed independent of inertial load, i.e. a plateau develops, but that it takes a greater amount of time (i.e. cycle revolutions) for peak power to be expressed (see Figs. 2, 4) at the higher inertial loads. In isolated muscle preparations a muscle will generate its peak power output at ~30% of its maximum shortening velocity ($v_{max}$) (Hill 1938), whereas, when making measurements at the whole body level during a given exertion, maximal muscle power output corresponds to an optimal angular velocity at the articular level. Therefore, muscle power output should be maximal when the optimal angular velocity is reached, provided that optimal levels of torque are generated, independently of the flywheel inertia. When contractions begin below this velocity a plateau in power output is likely to occur as cycling exercise allows the inertial load to be repeatedly accelerated. This allows the muscle to travel along its force–velocity curve until a velocity is achieved at which peak power occurs (see Fig. 8). In theory, this position will always be attained provided sufficient time is allowed for the individual to accelerate the load and the subject does not become fatigued. However, if the inertial load is very low, power output is lower than that for all subsequent loads (Fig. 3). This is in part due to the inability of the muscle to generate sufficient acceleration at this load to develop optimal levels of torque to generate peak power. In contrast to isolated muscle, the data in the present study, and that reported by others (Baron et al. 1999) for cycling exercise, show an essentially linear relationship between crank rotation velocity and the torque applied to the flywheel. As such, peak power would be expected to occur at ~50% of the maximum velocity (see Appendix for explanation). The optimal velocity here is in general agreement with that cited in the literature. Previously, Martin et al. (2000) reported optimal velocity values of 124 rpm during cycling exercise.

In contrast to the cycling exercise, the power–inertial load relationship shows a significant ($P<0.05$)

reduction of power at both high and low inertial loads during single thrust exertions on the mNPR. This may be because it involves a single action over a fixed distance. At the low inertial loads it appears that the limbs (whose inertia becomes relatively greater with respect to the flywheel loading) are unable to accelerate the load to generate sufficient torque to produce peak power. However, at the higher loads the inertial load is too great for the muscles to accelerate the load to a sufficient velocity in order to reach peak power before the end of the movement. Therefore, if it is required to determine maximal power output over a given, fixed range of movement period, one must be aware of the possible differences in the time required to reach peak power, dependent on inertial load and the relative ability of the individual to accelerate the load. Thus, for a group of subjects who may differ in their muscle torque/power generating characteristics, a range of inertial loads may be required in order to elicit maximal peak power.

Figure 7 shows the close association between the mean power generated by the two methods ($r = 0.84$). However, bot peak and mean power output during cycling was shown to be considerably higher than mNPR at all inertial loads, apart from the lowest. It seems that at this lowest level of loading, the muscle is unable to generate sufficient acceleration to generate optimal levels of power output with either protocol. As the inertial load increases, however, power output is greater during cycling. There are a number of possible reasons for this. As previously discussed, the acceleration of the flywheel in the mNPR is limited to that which can be obtained over a fixed distance during a single lower limb thrust. However, during cycling, at any given inertia, a greater amount of time is allowed in order for the muscle to fully accelerate the load. This allows for an optimal level of torque and velocity, and therefore power to be reached.

Anatomical position of the subject during testing will also have an effect on the measured power output. Only the lower limb was able to participate in power generation with the mNPR. During sprint cycling, the legs are actively accelerating the inertial load, but there may also be additional input from ancillary muscles. In addition, the foot position with respect to the pedal may be different during the contraction phase for each protocol, which could affect the ability to generate torque tangential to the crank (Fig. 1).

It has also been reported that the knee extensor muscles may be active on the recovery stroke ($\sim 40$–$50^0$ prior to top dead centre) (Faria and Cavanagh 1978). This effect could provide additional ability to generate power by utilising the stretch shortening cycle. Various mechanisms have been suggested to explain the increased output due to the stretch shortening cycle, including: enabling the concentric phase of force generation to start from a state of full activation (Bobbert et al. 1996); re-utilisation of stored elastic energy (Hawkins and Hull 1990, Svantesson et al. 1991); and reflex contributions (Dietz et al. 1978). In addition, the arms act as anchors

during cycling and may help transfer forces from other muscle groups. It has been reported that there is an increased ability to generate power output with the hands holding the handlebars as opposed to not so doing (Baker et al. 2001). The use of toe clips has also been shown to increase power output during cycling (Capmal and Vandewalle 1997). They reasoned that this was due to the pulling action during return of the foot to top dead centre after reaching the bottom of the stroke, allowing input to the system from both limbs simultaneously. In the present study toe clips were used and the levels of absolute peak power were in general agreement with those of Martin et al. (1997), Baron et al. (1999), Martin et al. (2000) and Sargeant et al. (1987).

In conclusion, this study has shown that the power output profiles during exertions against a range of inertial loads are different, depending upon whether a single contraction over a fixed range is performed (mNPR), or whether repetitive contractions where the load can be cumulatively accelerated (cycling) are performed. This appears to be a reflection of the time allowed to accelerate a given load and the torque that can be produced in that time. The power output obtained during cycling exercise is greater than that on the mNPR, even when the load on the mNPR is optimised, reflecting the distinct time-related conditions of the two measuring methods.

# Appendix

Polynomial fitting

In order to determine power output, a second-order polynomial (mNPR) and third-order polynomial (Cycle) were fitted to the power velocity data. These specific polynomials were chosen based on the best fit to the data ($r^2$ value). The differentiated equation was then used in order to calculate the maximal velocity and subsequent power.

Linear torque–velocity relationship

From the torque–velocity relationship shown in Fig. 5 the equation of the line can be represented by: $T = -a \times v + b$. Where $T$ is instantaneous torque, $v$ is instantaneous velocity and both a and b are constants. Power can then be calculated as the product of torque and velocity which, if the above equation is substituted for torque, yields: $P = av^2 + bv$. Thus maximal power will be achieved when the gradient of the power curve is zero, i.e. when $2 \times a \times v + b = 0$. From this formula it can be seen that the velocity at peak power ($v_{opt}$) is $-b/2 \times a$.

Knowing that torque is zero at $v_{max}$, $v_{max}$ can be written as $0 = a \times v_{max} + b$. $v_{max}$ is therefore $-b/a$, half this value equates to $-b/2 \times a$ or $v_{opt}$.

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