Eur J Appl Physiol (1998) 12: 231–235

ORIGINAL ARTICLE

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A method for assessing muscle fatigue during sprint exercise in humans using a friction-loaded cycle ergometer

Accepted: 5 March 1998

Abstract This study investigated the mechanical changes induced by muscle fatigue caused by repeated sprints and determined whether a friction-loaded cycle ergometer has any advantages for assessing muscle fatigue. Nine subjects performed 15 sprints, each of 5 s with a 25-s rest, on a friction-loaded cycle ergometer. The averaged force, power and velocity of each push-off were calculated. Maximal power decreased by 17.9%, with a concomittent slowing of muscle contraction, but without any change in the maximal force. These results demonstrated that repeated sprints slow down muscle contraction, leading to a fall in maximal power without any loss of force. This would suggest that fast twitch fibres are selectively fatigued by repeated sprints. However, the ergometer used in the present study made it difficult to evaluate the relative influences of contraction velocity and sprinting time. This was certainly the most important limitation. On the other hand, it showed the advantage of measuring instantaneous power and total work dissipated in the environment simultaneously. It also permitted a force-velocity relationship to be obtained from a single sprint and this relationship is known to be closely related to the muscle fibre composition.

Key words Fatigue · Sprint repetition · Force-velocity · Friction-loaded cycle ergometer

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Introduction

Muscle fatigue has been defined as the failure to maintain a required or expected power output (Edwards 1983). More recently, Fitts (1994) has stated that the ability to maintain a given work capacity requires the maintenance of both force and velocity. Other authors have also investigated the force-velocity relationship in isolated skeletal fibres or whole muscle during the production of fatigue (Fitts and Holloszy 1978; De Haan et al. 1989). Fitts and Holloszy (1978) have found no reduction in the maximal velocity associated with a net loss of tetanic force; whereas De Haan et al. (1989) have demonstrated that the force and velocity of contraction were decreased in muscle fatigue. Thus muscle fatigue seems capable of having different effects on the force-velocity curve. Therefore, if fatigue were to be assessed only by the loss of force, it would seriously underestimate the functional impairment which results from the accompanying reduction of maximal shortening velocity. Hence, the force-velocity relationship should be used to assess fatigue in both single muscle fibres and whole muscles.

Exercise cycles have been widely used in protocols to examine fatigue; but the type of ergometer would seem to have an important influence on the fatigue observed. Fatigue has been shown to be manifest as a decrease in force in isokinetic cycle exercise, when the pedalling frequency is fixed (Sargeant et al. 1981; Beelen and Sargeant 1991), while maximal velocity decreases with muscle fatigue with the friction-loaded cycle ergometer, when the friction force is fixed (Bogdanis et al. 1994). Simple friction-loaded cycle ergometers have recently been designed and used to draw force-velocity and power-velocity relationships from a single all-out period of exercise (Seck et al. 1995; Arsac et al. 1996; Hautier et al. 1996; Buttelli et al. 1996). Any change in the force-velocity relationship must be analysed in the light of the study of Sargeant (1994), who has demonstrated that the contributions of the different types of human muscle fibre to maximal power depends on their contraction velocity. It has also been demonstrated that the optimal velocity for maximal power production in non-isokinetic cycling depends on the contribution of the various muscle fibre types (Hautier et al. 1996). The relative force produced at high contraction velocity, the maximal power and the optimal velocity, are all directly related to the contribution of fast twitch fibres. De Haan et al. (1989) have demonstrated that the overall characteristics of the muscle shift when fast twitch fibres are selectively fatigued and become the characteristics of slower fatigue-resistant fibres, which remain largely unaffected.

Many sprint sports, such as soccer, basket-ball and hockey require maximal intensity intermittent exercise. Balsom et al. (1992 a, b; 1993) have demonstrated that 6 s of work followed by 30 s of rest caused muscle fatigue. Colliander et al. (1988) have used a comparable fatigue protocol to demonstrate that subjects with a high percentage of fast twitch fibres were more sensitive to fatigue than those with more slow fibres. The present study was carried out to investigate the mechanical manifestations of fatigue during repeated brief bursts of maximal exercise. The novelty of this study is that a non-isokinetic cycle ergometer permitted us to deduce individual force- and power-velocity relationships from a single sprint (see Arsac et al. 1996; Hautier et al. 1996) whereas isokinetic ergometers need several sprints to measure the force produced by the subjects at each cycling velocity. Thus, the ergometer used in the present study made it possible to measure the fall in performance at every velocity of contraction. However, this method does have several disadvantages which are discussed and used to determine the extent to which mechanical results can be related to muscle fatigue.

Methods

Subjects

Nine subjects took part in this study [mean age 20.3 (SD 0.7) years, mean height 174.6 (SD 7.2) cm, mean body mass 65.5 (SD 8.6) kg]. The study was approved by the Ethics Committee of the University Hospital of Saint-Etienne, France. All the subjects were volunteers and signed an informed consent form. The subjects were trained for the cycling task for 9 weeks and detrained during 7 weeks. The fatigue trials were conducted before training, after training and after detraining. The present study was based on the experiments performed after 7 weeks of detraining because muscle fatigue was greater at that time.

Protocol

Fatigue was produced by a sequence of 15 sprints, of 5-s duration with a 25-s rest after each, on a friction-loaded cycle ergometer. Sprints were performed without toe-clips. Loads [33.8 (SD 11.8) N] had been determined in previous tests, to obtain a maximal velocity of about 150 rpm during the first sprint. The mechanical data for sprints numbers 1 and 13 were stored in a computer.

Mechanical data analysis

The friction-loaded cycle ergometer we used has been described in previous studies (Arsac et al. 1996; Hautier et al. 1996). The ergometer (Monark 818E, Stockholm, Sweden) was equipped with both a strain gauge (200 N, bandwidth 500 Hz) for measuring frictional force and an optical encoder (1969.2 points per metre of displacement or 11 815 points per pedal revolution) for measuring flywheel displacement. Force and displacement signals were sampled (200 Hz) and stored on a personal computer via a 12-bit analogue-to-digital interface card. First and second order derivatives of the flywheel displacement were calculated to obtain flywheel velocity and acceleration. External force produced by the subject was calculated as the sum of frictional (given by the strain gauge) and inertial (depending on the acceleration) forces (see Lakomy 1986).

Force and velocity were averaged for each down stroke from top dead centre of one foot to top dead centre of the other (see Williams et al. 1988). Each sprint provided a minimum of 15 downstrokes, and hence 15 points in the individual force-velocity relationship. According to the recommendations of Buttelli et al. (1996) and as has previously been discussed by Hautier et al. (1996), the first downstrokes made at low velocities were not taken into account because the relationship is not complete (the subject cannot start from the top dead centre) and the force produced is greater than the body mass. The subjects should be anchored above the saddle to measure their real maximal force. The force-velocity relationships were therefore drawn excluding the first two pushes. This resulted a linear force-velocity relationship, as described by Buttelli et al. (1996). The power-velocity relationship was calculated from individual force-velocity relationships. The optimal velocity is the velocity at maximal power (see Sargeant et al. 1984) and is half the maximal velocity.

Each sprint provided information on the force-velocity relationship, making it possible to calculate the maximal force (F_0), the force at 150 rpm, the maximal power ($P_{\max}$), and maximal and optimal velocities (v_0 and v_{opt}).

Statistics

The relationships between data were evaluated by linear regression analysis and confirmed with the nonparametric Spearman rank correlation test. Differences between sprints were evaluated using ANOVA for repeated measures. The level of significance was set at $P < 0.05$.

Results

The mechanical data obtained during the sprints numbers 1 and 13 are summarized in Table 1. The mean force-velocity relationship was linear in the first sprint and tended to be curved during the last sprint at high velocities: any increase in pedalling rate resulted in a constant decrease in force (Fig. 1). The F_0 was slightly but non-significantly different in sprints 1 and 13,

Table 1 Mechanical results obtained during sprints 1 and 13. F_0 Maximal force, v_0 maximal velocity, $P_{\max}$ maximal power

	Sprint 1		Sprint 13		Difference
	Mean	SD	Mean	SD	
F_0 (N)	120	20	119	26	NS
v_0 (rpm)	252	33	209	31	$P < 0.05$
$P_{\max}$ (W)	763	190	630	174	$P < 0.05$

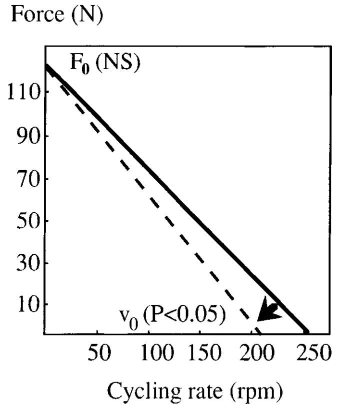

Fig. 1 Linear force-velocity relationship: changes between sprint 1 (*full line*) and 13 (*dotted line*). F_0 and v_0 are the intersections between the extrapolated force-velocity curve and y and x axes. Extrapolated F_0 and v_0 are higher than the mean measured points shown in Fig. 2a and b

whereas v_0 decreased significantly. Similarly, $P_{\max}$ and v_{opt} decreased significantly with repeated sprints.

The relative fall in $P_{\max}$ (expressed as a percentage of $P_{\max}$) was related to the decreases in v_0 and v_{opt} ($r = 0.95$, $P < 0.001$), but not to the decrease in F_0.

The forces produced during sprints 1 and 13 were not significantly different throughout the sprints whatever the push-off number and the duration (Fig. 2a). The velocities in the first two downstrokes were not different but started to be different after push-off number 3 (Fig. 2b). The cumulated work performed during sprints 1 and 13 was significantly different from push-off number 3 to the end of each sprint (Fig. 2c).

Discussion

The data obtained at the beginning of the sprint when the cycling rate was below 60 rpm have been removed because they corresponded to forces greater than the total body mass of the subjects, i.e. the subjects relied on their arms to stay in place over the cycle. It is thus impossible to evaluate the relative contributions of the legs and arms to the total force exerted. The strong link obtained in these subjects between $P_{\max}$ and the relative area of fast twitch fibres, during another part of the same experiment (Hautier et al. 1996) demonstrated that the mechanical parameters obtained from a single sprint on a friction-loaded cycle ergometer are strongly related to muscle fibre type composition, whatever the method used.

Maximal power decreased significantly with sprint repetition in agreement with previous studies (Beelen and Sargeant 1991; Bogdanis et al. 1994; Buttelli et al. 1996). The size of the decrease in power observed in the present study (17.9%) is in line with the results of Bogdanis et al. (1994; 15%), but is much lower than that reported by Buttelli et al. (1996). These differences are explainable by the 25-s and 30-s rest periods in the study of Bogdanis et al. (1994) and the present one, whereas there was no recovery in the study of Buttelli et al. (1996). The decrease in $P_{\max}$ observed in the present study was due to a slowing of the contraction velocity (v_0 and v_{opt}), but not to a decrease in force. Buttelli et al. (1996) in contrast, observed that F_0 and v_0 declined in parallel. These differences could also be attributed to differences in the experimental protocols, whether they included rest periods or not.

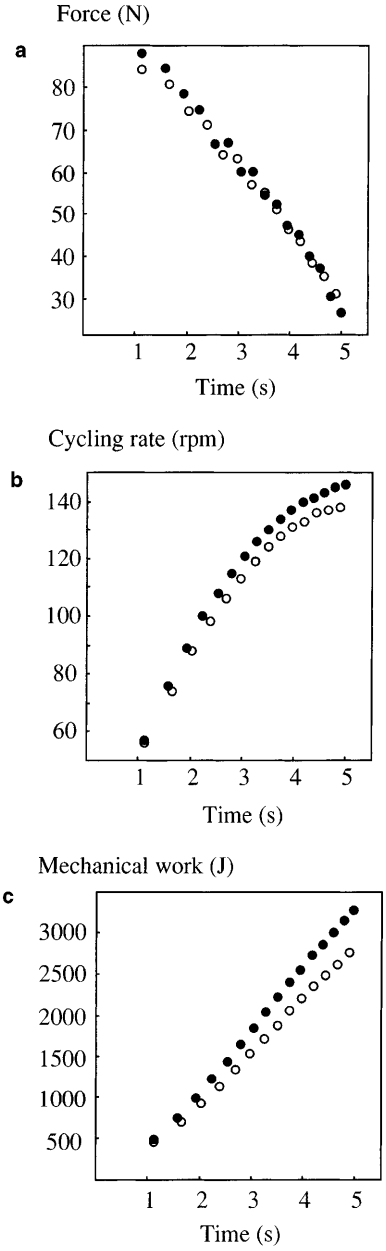

Fig. 2a Mean force-time curves during sprints 1 (●) and 13 (○). The first push-off was not taken into account. **b** Mean velocity-time curves during sprints 1 ● and 13 ○. The first push-off was not taken into account. **c** Mean work-time curves during sprints 1 (●) and 13 (○). The first push-off was not taken into account

The changes in the force-velocity relationship observed in the present study (Fig. 1) were much more marked at high contraction velocity. This would suggest that fatigue was directly associated with a slowing of contraction. This should be analysed in the light of the model proposed by McIntosh et al. (1993) and Sargeant (1994). These authors have postulated that the force produced at low contraction velocity depends on the number, the area and the training status of muscle sarcomeres, whereas the force produced at a high contraction velocity depends on the relative contributions of fast twitch fibres to the total force. This is based on the debatable assumption that slow fibres cannot contract fast enough to contribute to total muscle force, once the cycling rate exceeds 150 rpm. Thus, a decrease in v_0 and v_{opt} would seem to indicate that the fast twitch fibres are fatigued, whereas a decrease in F_0 could be interpreted as fatigue of both slow and fast fibres. The net decrease in contraction velocity observed in the present study plus the lack of a change in F_0 would suggest that fast twitch fibres were selectively fatigued by repeated sprints. The fact that the decrease in P_{max} was correlated with changes in both v_0 and v_{opt} but not with the changes in F_0, is in accordance with the study of De Haan et al. (1989). They have demonstrated that fatigue can be seriously underestimated by observing only the loss of force. They have also observed that fatigue in fast twitch fibres can be expressed through a temporary transformation, fatigued muscles becoming slower and much less powerful, thus behaving like muscles having a high proportion of slow twitch fibres. The present results would also suggest that muscle fatigue was much greater during the last few seconds of the sprint, since higher velocities were achieved after 3 or 4 seconds of sprinting. The rest periods probably allowed the resynthesis of phosphocreatine (PCr), making the generation of high forces possible during the first 2 s of the sprint. However, the PCr stores may not have been sufficient to provide for the total energy expenditure during a 5-s sprint. Thus, the loss of force at high contraction velocities may have been an indirect effect of a failure of the energy supply during the last few seconds of the sprint.

The decreases in power and force observed after repeated sprints could thus be attributed to the combined effects of contraction velocity and sprint duration on muscle fatigue. Figure 2a shows that the loss of force did not depend on the sprint duration, since the force-time curves of sprints 1 and 13 are very similar. The subjects were still able to produce the same force after 4 s of sprint cycling. However, this was associated with a decrease in the velocities produced during the sprints (Fig. 2b). Fatigue also resulted in fewer push-offs produced during the sprint, and hence in less total work completed. Figure 2c shows that the total cumulated work decreased from sprint 1 to 13, confirming that the decrease in force at the end of the 13th sprint was due to contraction velocity rather than to sprint duration.

There was no difference in the velocity of contraction during the initial downstrokes, whereas the force was slightly, but not significantly, different (Fig. 2a, b). On the other hand, the slight difference in force resulted in lower velocities from the 3rd downstroke. Thus the subjects produced less work for a given time in the sprint (Fig. 2c) and they produced the same force, but at a lower cycling rate. The more marked loss of force at high contraction velocities (Fig. 1) would indicate that fatigue depended on the cycling rate (whatever the duration of the sprint, the work performed and the push-off number). Fatigue could thus have been due to the fast twitch fibres being selectively sensitive to repeated sprints or to a drop in the cross-bridge cycling rate in fatigued muscle. But, whatever the mechanism responsible for slowing the muscle, it was not a lack of cell energy during the last 2 s of sprint number 13.

The first part of this discussion demonstrated that the fatigue that occurred at high contraction velocity was not an artefact due to the effect of the sprint duration on the force-velocity relationship. Interpretation of the force-velocity curves obtained on friction-loaded cycle ergometers has been based on a number of assumptions (Seck et al. 1995; Arsac et al. 1996; Hautier et al. 1996; Buttelli et al., 1996), some of which need to be re-examined under fatigue conditions. Fatigue may indeed influence intra- and inter-muscle coordination as well as transmission of muscle force.

Fatigue may lead to more imprecise movements at high contraction velocities (Chapman 1982; Nummela et al. 1994). Several studies have shown that muscle fatigue can modify the kinematic parameters of human performance and increase the co-contraction of antagonist muscles (Psek and Cafarelli 1993). It has been suggested that this increased co-activation may reduce the power that subjects can transfer to the pedals, especially at high cycling rates (Doorenbosch and Ingen Schenau 1995).

Intra-muscular coordination, muscle fibre conduction velocity and electro-mechanical delay are all very sensitive to muscle fatigue (Zwarts et al. 1987; Krogh-Lund and Jørgensen 1991; Brody et al. 1991; Taylor et al. 1997). Capmal and Vandewalle (1997) have demonstrated that peak torque occurred at 80° at low velocities and 140° at high velocities, even without fatigue. The reduced ability of a subject to produce a high force in a short time when fatigued may alter the angle at which maximal torque is produced. These manifestations of muscle fatigue do not influence the maximal force measured during the first down-strokes at low contraction velocity, but they may reduce the percentage of force that can be produced during a short push-off at 120 rpm.

It has been reported that muscle fatigue also reduces the rate of muscle relaxation (Viitasalo and Komi 1981; De Haan et al. 1989). This could increase the residual force in the muscles of the contralateral limb and contribute to the loss of force observed at the flywheel. On the other hand, Sahlin and Seger (1995) have reported no significant change in the rates of contraction and relaxation after cycling exercise to fatigue. However, the relative mass of the contra-lateral limb is emphasized, at high cycling rate, when total force is lower and may contribute to the non-linearity of the force-velocity curve even under non-fatigued conditions (Fig. 1).

Capmal and Vandewalle (1997) have studied the negative torque produced by the contralateral leg. They have demonstrated that it was negligible at low velocities, but reached about half the positive torque in several subjects at high velocities, with and without toe clips. This resisting force of the passive leg as well as the possible buffering action of the tendon on the velocity of shortening are the most important biomechanical features that would limit the interpretation of the force-velocity curves obtained on friction-loaded cycle ergometers.

We have shown that 13 repeated sprints of 5-s duration separated by a 25-s rest can cause a decrease in maximal power with a slowing down of muscle contraction velocity. The fall in power can be attributed to the reduced contraction velocity, but not to a loss of maximal force. This indicates that fast twitch fibres are selectively fatigued by repeated sprinting. It was possible to distinguish the time and velocity effects on muscle force production under conditions of fatigue. However, a number of methodological limitations should be kept in mind when analysing force-velocity and power-velocity curves. In spite of recent studies that have shown a close relationship between the muscle fibre profile and power production on a friction-loaded cycle ergometer (Hautier et al. 1996), any change in the force-velocity curve should be interpreted carefully. It cannot be totally attributed to a loss of muscle fibres contractility. Nevertheless, the friction-loaded cycle ergometer is a very useful tool because it permits the measurement of force, power, velocity and work simultaneously during simple all-out exercise lasting from 5 s to several hours.

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