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Comparison of Physiological Responses and Muscle Activity During Incremental and Decremental Cycling Exercise

Fernando G. Beltrami, Christian Froyd, Alexis R. Mauger, Alan J. Metcalfe, and Timothy D. Noakes

Objective: To investigate whether a cycling test based on decremental loads (DEC) could elicit higher maximal oxygen uptake ($\dot{V}O_2max$) values compared with an incremental test (INC). ***Design:*** Nineteen well-trained individuals performed an INC and a DEC test on a single day, in randomized order. ***Methods:*** During INC, the load was increased by 20 W·min^{-1} until task failure. During DEC, the load started at 20 W higher than the peak load achieved during INC (familiarization trial) and was progressively decreased. Gas exchange and electromyography (EMG) activity (n = 11) from 4 lower-limb muscles were monitored throughout the tests. Physiological and EMG data measured at $\dot{V}O_2max$ were compared between the 2 protocols using paired *t* tests. ***Results:*** $\dot{V}O_2max$ during the DEC was 3.0% (5.9%) higher than during INC (range 94%–116%; $P = .01$), in spite of a lower power output (−21 [20] W, $P < .001$) at $\dot{V}O_2max$. Pulmonary ventilation ($P = .036$) and breathing rate ($P = .023$) were also higher during DEC. EMG activity measured at $\dot{V}O_2max$ was not different between tests, despite the lower output during DEC. ***Conclusions:*** A DEC exercise test produces higher $\dot{V}O_2max$ in cycling compared with an INC test, which was accompanied by higher pulmonary ventilation and similar EMG activity. The additional O_2 uptake during DEC might be related to extra work performed either by the respiratory muscles and/or the less oxidatively efficient leg muscles.

Keywords: maximal oxygen uptake, $\dot{V}O_2max$ plateau, exercise testing

Maximal oxygen uptake ($\dot{V}O_2max$) represents the upper limit of cardiorespiratory capacity during exercise. Because of its association with several performance and even health indicators, it is important that $\dot{V}O_2max$ is properly assessed during testing, and a substantial body of literature has been dedicated to it.[1] Current standards dictate that $\dot{V}O_2max$ should be assessed during incremental (INC) exercise tests, in which the workload increases at given time intervals until the participant is exhausted. In these tests, leveling off of $\dot{V}O_2$ with increasing exercise intensities—the $\dot{V}O_2max$ plateau phenomenon—is seen as evidence that $\dot{V}O_2max$ is, indeed, maximal. When evidence of a plateau is not present, a second test at a higher workload is recommended to confirm the attainment of $\dot{V}O_2max$, the so-called verification phase or verification test.[1]

A few studies, however, have shown that alternatives to the INC exercise test can produce even higher values of $\dot{V}O_2max$. Some of these tests are based on cycling time-trial efforts[2,3] or self-paced and closed-loop exercise,[4] and even decremental (DEC) exercise tests in runners[5] and elite runners.[6] While these studies have called into question whether the $\dot{V}O_2max$ measured during INC tests (with or without the verification phase) truly represents a cardiorespiratory limitation, later studies have not always corroborated these findings, for instance, showing no difference between traditional INC tests and self-paced tests in cycling[7,8] or DEC tests in runners.[9]

Some of these contradicting results might be specific to the conditions of each particular study. For example, Jenkins et al[10] found that a self-paced protocol produced higher $\dot{V}O_2max$ values in younger, but not in older, individuals. Furthermore, $\dot{V}O_2max$ not only varies according to one's training background,[11] but is also specific to a given exercise modality.[8] In this context, to date, only one independent attempt has been made to replicate the finding of a higher $\dot{V}O_2max$ during a DEC test, also in runners.[9] Therefore, the aim of this investigation was to test whether the findings of a higher $\dot{V}O_2max$ during DEC running exercise tests originally reported in well-trained individuals[5] would also be present in a group of well-trained cyclists. In addition, we wished to determine whether muscle activity of the lower limbs would be different at the time that $\dot{V}O_2max$ was achieved in both tests. We postulated that a higher $\dot{V}O_2max$ would be present during the DEC exercise test and that, in spite of a lower power output at $\dot{V}O_2max$, the electromyography (EMG) activity would be higher, indicating greater muscle activation.

Methods

Subjects

The study was approved by the Ethics and Research Committee of the Faculty of Health Sciences of the University of Cape Town (253/2009). The participants were clearly informed about the risks and procedures involved in this investigation and gave their written consent for participation. The study was divided in 2 parts (see Figure 1). In part A, 11 participants (10 males and 1 female, (mean [SD] age 29.0 [7.4] y, body mass 75.2 [7.8] kg, and height 181 [9] cm), all accustomed to high-intensity cycling, visited the laboratory on 2 occasions. In part B, 8 male participants (age 23.8 [5.5] y, body mass 69.8 [8.1] kg, and height 179 [4] cm), all

Beltrami, Froyd, and Noakes are with the Dept of Human Biology, Exercise Sciences and Sports Medicine Unit, University of Cape Town, Cape Town, South Africa. Beltrami is also with the Exercise Physiology Lab, Inst of Human Movement Sciences and Sport, ETH Zurich, Zurich, Switzerland. Froyd is also with the Western Norway University of Applied Sciences, Sogndal, Norway. Mauger is with the Endurance Research Group, School of Sport and Exercise Sciences, University of Kent, Kent, United Kingdom. Metcalfe is with the Dept for Molecular and Cellular Sports Medicine, Inst for Cardiovascular Research and Sports Medicine, German Sport University, Cologne, Germany. Noakes is also with the Centre for Communication Studies, Cape Peninsula University of Technology, Cape Town, South Africa. Beltrami (fernando.beltrami@hest.ethz.ch) is corresponding author.

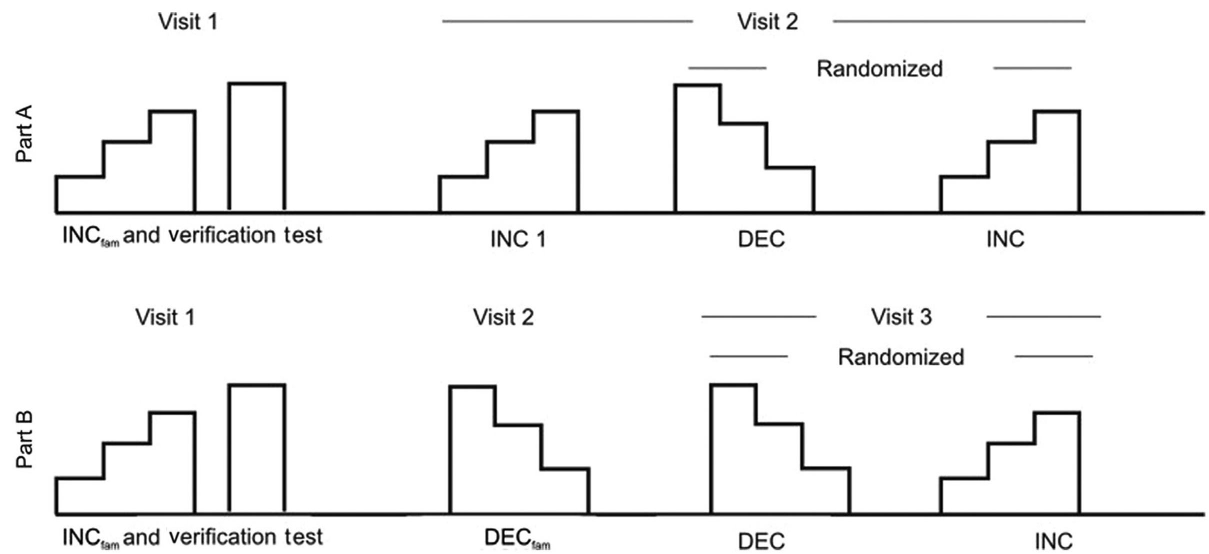

Figure 1 — Study design diagram. Visits were separated by 2 to 3 days. See text for detailed description of each testing protocol. Part A tested the $\dot{V}O_2$max between protocols when subjects had never been exposed to a DEC test before. In part B, 1 familiarization procedure had been performed on a previous session. DEC indicates decremental; DEC$_{fam}$, familiarization with the DEC; INC, incremental; INC$_{fam}$, familiarization with the INC; $\dot{V}O_2$max, maximal oxygen consumption.

accustomed to high-intensity cycling, visited the laboratory on 3 occasions, each separated by 2 to 3 days.

Design

This investigation was set up as a repeated-measures design, where $\dot{V}O_2$max was defined as the dependent variable and primary outcome, and the exercise test (ie, INC or DEC exercise test) as the independent variable. Both exercise tests were performed on the same day (see below), and the order in which the tests were performed was randomized and balanced between participants, so that an equal number of participants performed each of the 2 test orders. Other outcomes of interest were gas exchange, heart rate, and workload at the time of $\dot{V}O_2$max.

Furthermore, based on prior data from our group that showed that both trained[5] and elite runners[6] showed a higher $\dot{V}O_2$max during an INC test following 2 exposures to the DEC test (in contrast to a control group with stable $\dot{V}O_2$max over 5 consecutive INC test trials), we subdivided the present study into 2 parts (Figure 1). Part A was designed to ensure that no adaptative effect from the DEC test could take place (ie, no familiarization with the protocol was allowed prior to the main comparison), whereas, in part B, an additional visit was included where participants were familiarized with the DEC test.

In part A, the participants visited the laboratory on 2 occasions. On their first visit (familiarization), the participants performed a maximal INC exercise test on a cycle ergometer (INC$_{fam}$), followed 15 minutes later by a verification test to confirm the attainment of $\dot{V}O_2$max. On visit 2, the participants performed 3 exercise tests, each separated by approximately 1 hour. First, they performed an INC test (INC$_1$), following which a DEC and another INC test were performed in randomized, counter-balanced order. During the trials on visit 2, gas exchange data, heart rate, and EMG activity of 4 leg muscles (vastus lateralis, biceps femoris, vastus medialis, and gastrocnemius medialis) were continuously monitored. Prior to the first INC test, a 10-second sprint was performed, with the ergometer set in linear (cadence dependent) mode. This sprint served as a reference for the EMG analysis in the time domain, as has been recommended.[12]

In part B, the participants visited the laboratory on 3 occasions, each separated by 2 to 3 days. The first visit was similar to that described in part A, and on the second visit, a familiarization with the DEC exercise test (DEC$_{fam}$) was performed. On their third visit, the participants repeated the INC and DEC exercise tests in randomized, counter-balanced order, separated by at least 60 minutes of rest. Gas exchange data, heart rate, and power output were monitored throughout the tests.

Cycling Tests

All exercise trials were performed on an electronically braked cycle ergometer (Lode Excalibur Sport, Lode, the Netherlands). Prior to each exercise test, the participants warmed up for 10 minutes at a self-selected cadence and power output. The INC tests started at 200 W for men and 160 W for women, with increments of 20 W applied every 60 seconds thereafter, until cadence fell below 60 revolutions per minute (rpm). Strong verbal encouragement was given whenever the pedaling cadence approached the 60-rpm mark. The verification test consisted of a square wave test to exhaustion performed at 1 stage higher (20 W) than the last completed stage during INC$_{fam}$. Immediately prior to the test, the participants cycled for 3 minutes at 150 W (120 W for women). The load was then increased to the desired power within 20 seconds, and the participants were instructed to cycle for as long as they could. The DEC test started with 3 minutes of light cycling (150 W for men and 120 W for women), following which the load was raised within 20 seconds to the equivalent used during the verification test (that is, 20 W higher than the load of the last completed stage during INC$_{fam}$). The initial load was maintained for 60% of each individual's time-to-task failure recorded during the verification phase test. The average duration for the first stage of DEC was 90 seconds (range 75–105 s). Following the first stage, the load was decreased by 20 W and maintained for 30 seconds. Subsequent decrements of 10 W were maintained for 45, 60, 90, and 120 seconds, thus totaling ~7 minutes 15 seconds of test time. If this protocol proved too demanding for the subject (time to fatigue <3 min during DEC_{fam}, part B only), on the second occasion that they performed the DEC protocol (DEC, Part B), the first decrement in the workload was increased from 20 to 30 W.

Cardiorespiratory Variables

Gas exchange and heart rate were continuously monitored during the exercise tests using calibrated metabolic carts. In part A, a MOXUS Modular Metabolic System was used (AEI Technologies, Bastrop, TX), paired with a Polar S410 (Polar Electro OY, Kempele, Finland). In part B, a Cortex Metalyser was used (3B, Biophysik, Leipzig, Germany), paired with a Polar T31. All gas exchange and heart rate data were exported as consecutive 5-second means. $\dot{V}O_2$max was defined as the highest 60 seconds moving average measured during a test, and all other physiological variables were recorded at the same time as $\dot{V}O_2$max. For a comparison of $\dot{V}O_2$max values on day 1 between the INC and verification tests, 30-second moving averages were used in order to compensate for the much shorter duration of the verification tests, where $\dot{V}O_2$max was not necessarily constant for a full minute.

Muscle Electrical Activity

In part A, EMG signals from the vastus lateralis, vastus medialis, gastrocnemius medialis, and biceps femoris of the right leg were continuously recorded (Part A) using DE-2.1 single differential surface sensors with 10-mm interelectrode distance (Delsys Inc, Boston, MA). SENIAM[13] and Delsys recommendations for the placement of the sensors on the skin were followed. Before electrode placement, the skin was shaved to remove excessive hair and wiped with isopropyl alcohol. A reference electrode was applied over the patella. The EMG signals were sampled at 2000 Hz and amplified using Bagnoli-8 (Delsys Inc). The EMG signals were transferred into Power Lab (ADInstruments, Colorado Springs, CO) and filtered using a 15- to 500-Hz band-pass filter in Lab Chart Pro software (ADInstruments). Root mean square EMG activity was calculated for every 20 milliseconds and averaged over the minute in which $\dot{V}O_2$max was measured. Only the periods of active contraction were used for analysis, which were determined as root mean square EMG values >10% above baseline (quiet sitting on ergometer). The EMG activity was expressed as a percentage of the root mean square activity recorded during the 10-second sprint, which was performed immediately prior to the first exercise trial (but after the 10-min warm-up period). The percentage of activation was also multiplied by the fraction of time in which the muscle was active to obtain an estimate of total activation, akin to the integrated EMG signal.[14] The frequency contents of the EMG signal were analyzed using fast Fourier transformation, and the mean and median frequency from the EMG signal during the period in which $\dot{V}O_2$max was measured were determined. Prior to the sprint, the participants cycled at a low-power output for 2 minutes. The EMG data is presented as n = 7 for the vastus lateralis, gastrocnemius medialis, and biceps femoris and n = 9 for the vastus medialis due to technically inadequate data for at least one test on some participants, usually the result of electrode detachment/excessive noise midtest.

Statistics

All data are presented as mean (SD), unless stated otherwise. The reproducibility of the $\dot{V}O_2$max and EMG variables between INC_1 (performed before the experimental trials) and INC (performed in randomized order with DEC) was analyzed by calculating the intraclass correlation coefficient, the typical error of measurement (the SD of the difference between measurements divided by the square root of 2), and the individual coefficient of variation.[15] The physiological responses from the participants in both parts of the study were pooled together, and the physiological responses between the DEC and INC analyzed used Student paired *t* tests, with the normality of residuals analyzed using Q-Q plots. Comparisons are presented with the *t* statistic, 95% CI, and the effect size as Cohen *d* for independent samples (mean difference divided by the pooled SD of both groups) or Cohen d_z for dependent samples (mean of differences divided by the SD of the difference scores). The effect of adding a specific familiarization trial for the DEC test (part B vs part A) was analyzed by comparing the DEC/INC $\dot{V}O_2$max ratio in parts A and B of the study, using a Student independent *t* test. The significance level was set at $P < .05$, and all statistical procedures were calculated using Prism 8.3 (GraphPad, La Jolla, CA) or dedicated Excel spreadsheets.

Results

$\dot{V}O_2$max During the INC and Verification Tests

During INC, the participants were able to exercise for 8.3 (1.7) minutes, reaching a $\dot{V}O_2$max of 55.8 (8.2) mL kg^{-1}·min^{-1} (parts A and B pooled). In the familiarization visits, $\dot{V}O_2$max obtained from the INC test was not different from that measured during the verification tests (30-s moving averages, 4139 [743] vs 3989 [717] mL·min^{-1} respectively, 95% CI, −345 to 46 mL·min^{-1}, $P = .125$). The 30-second moving averages of $\dot{V}O_2$ were used in both tests due to the much shorter nature of the verification test. When the $\dot{V}O_2$max of the familiarization session was compared with that from the main experimental session, there was no statistical difference between the two (mean difference 0.0 mL·min^{-1}, 95% CI, −195 to 196 mL·min^{-1}, $P = .99$). This is in spite of a significant difference increase in exercise tolerance on the second attempt (+0.6 min, 95% CI, 0.2 to 1.0 min, $P = .008$).

On the experimental day of part A of the study, when 2 INC tests were performed (INC_1 and INC), the $\dot{V}O_2$max values were very similar between them (4366 [464] vs 4354 [499] mL·min^{-1} for INC_1 and INC respectively, 95% CI, −80 to 57 mL·min^{-1}, $P = .716$). The intraclass coefficient for $\dot{V}O_2$max (INC_1 vs INC) was .98, and the typical error of measurement was 72 mL·min^{-1} (1.7%).

$\dot{V}O_2$max During the DEC Test

During DEC (parts A and B pooled), $\dot{V}O_2$max values were on average 3.0% higher than during INC (4259 [695] vs 4139 [657] mL·min^{-1} respectively, 95% CI, 16 to 224 mL·min^{-1}, $d_z = 0.56$, $P = .025$; Figure 2), although they were exercising at a significantly lower power output at the time that $\dot{V}O_2$max was achieved (312 [43] vs 333 [47] W for DEC and INC respectively, 95% CI, 10.8 to 31.1 W, $d_z = 1.03$, $P < .001$). Individual data for 60-second moving averages in both tests are provided in Supplemental Figure 1 (available online). An additional comparison was performed between DEC and INC using 30-second moving averages and yielded similar results (data not shown). Test termination during DEC occurred at 5.7 (1.6) minutes (range

2.5–9.5 min, not considering the preceding 3-min lead-in phase at moderate power), which was significantly shorter than the INC test (–2.9 min, 95% CI, –4.3 to −1.6 min, $P = .0002$). Importantly, 2 DEC tests were interrupted by the experimenter as the participants reached the end of the protocol. All physiological data measured during the exercise tests are shown in Table 1. During DEC, the participants also reached 4.5% higher pulmonary ventilation (V_E) in comparison to INC ($P = .036$), due to an increased breathing rate ($P = .023$; Table 1). The respiratory exchange ratio, carbon dioxide output, and heart rate were not different between the 2 exercise tests at $\dot{V}O_2$max (Table 1).

Effects of Familiarization on the DEC Test

In part B, there were no differences in $\dot{V}O_2$max between DEC_{fam} and DEC (3904 [718] vs 3953 [758] mL·min^{-1} respectively, 95% CI, −17 to 71 mL·min^{-1}, $d_z = 0.34$, n = 8, $P = .371$). Likewise, when parts A and B were compared with regard to the ratio of DEC/INC $\dot{V}O_2$max elicited, there were no significant differences (1.017 [0.042] vs 1.047 [0.069] for parts A and B respectively, 95% CI, –0.02 to 0.08, $d = 0.54$, $P = .258$).

Muscle Electrical Activity

For the EMG variables, the reliability data for each muscle between INC_1 and INC are shown in Table 2. Overall, all 4 analyzed muscles showed a good degree of reliability (intraclass correlation coefficient = .85–.98).

The individual data for EMG activity of the 4 evaluated muscles are presented in Figure 3. There were no significant differences in the mean EMG activity or total activation measured at $\dot{V}O_2$max between INC and DEC for any of the analyzed muscle groups. There were also no significant differences between INC and DEC for any of the muscles for mean or median frequency (Table 3).

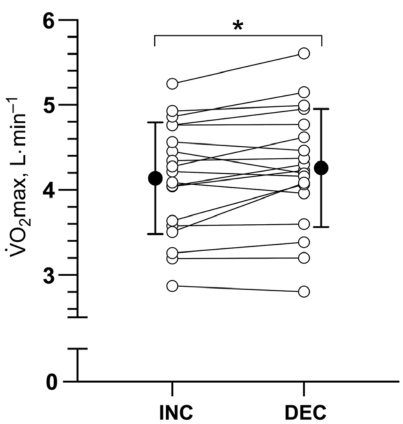

Figure 2 — Individual and mean (SD) $\dot{V}O_2$max responses during an INC and a DEC exercise test. DEC indicates decremental; INC, incremental; $\dot{V}O_2$max, maximal oxygen consumption. $^*P < .05$.

Discussion

The main findings from this study are that (1) trained subjects achieved higher $\dot{V}O_2$max values during a cycling DEC in comparison to INC, (2) the higher $\dot{V}O_2$max during DEC was accompanied by higher $\dot{V}$E in comparison to INC, (3) EMG activity for 4 lower-limb muscles was similar at the time of $\dot{V}O_2$max in both testing protocols, and (4) the order of the tests or previous familiarization with DEC did not affect the $\dot{V}O_2$max results.

The ideal protocol for the assessment of $\dot{V}O_2$max has been the topic of research for years. Under the current paradigm of INC tests, it has become clear that $\dot{V}O_2$max is robust over a wide range of protocols and test durations.[16] Furthermore, it has also been shown that simply requiring higher energetic output does not result in higher $\dot{V}O_2$max, whether the additional output comes from the exercising limbs, as in the case of the verification test,[17] or the upper arms.[18] Our data confirm these findings, as the values

Table 2 Reproducibility of Normalized Root Mean Square Activity (%RMS_{max}) for 4 Lower-Limb Muscles During a Maximal INC Cycling Test

	ICC	CV, %	Typical error (percentage points)
VL (%RMS_{max})	.98	9.8	5.8
VM (%RMS_{max})	.85	23.5[a]	15.0[a]
BF (%RMS_{max})	.96	5.7	3.2
GM (%RMS_{max})	.97	6.6	4.8

Abbreviations: BF, biceps femoris; CV, coefficient of variation; GM, gastrocnemius medialis; ICC, intraclass correlation coefficient; INC, incremental; VL, vastus lateralis; VM, vastus medialis; $\dot{V}O_2$max, maximal oxygen uptake.
[a] Removal of 1 extreme participant would reduce CV to 7.6 and the typical error to 8.1; ICC would increase to .98.

Table 1 Physiological Data at $\dot{V}O_2$max and *P* Value for Student *T* Tests Between an INC and a DEC Exercise Test

	INC	DEC	*t* test	95% CI	d_z
$\dot{V}O_2$max, mL·min^{-1}	4139 (657)	4259 (695)	$t_{(18)} = 2.433$, $P = .026$	16 to 224	0.56
HR, beats·min^{-1}	180 (9)	179 (11)	$t_{(18)} = .691$, $P = .495$	–3 to 1.6	0.16
$\dot{V}$E, L·min^{-1}	153.7 (26.7)	160.7 (29.5)	$t_{(18)} = 2.263$, $P = .036$	0.5 to 13.5	0.52
BR, breaths·min^{-1}	49.0 (4.8)	54.2 (6.6)	$t_{(10)} = 2.670$, $P = .023$	0.8 to 9.5	0.80
V_T, mL	3.30 (0.53)	3.05 (0.40)	$t_{(10)} = 2.073$, $P = .65$	–0.51 to 0.02	0.62
RER	1.13 (0.18)	1.11 (0.14)	$t_{(17)} = .945$, $P = .357$	–0.05 to 0.02	0.22
$\dot{V}CO_2$, mL·min^{-1}	4770 (852)	4817 (826)	$t_{(18)} = .738$, $P = .470$	–80 to 177	0.17

Abbreviations: BR, breathing rate; DEC, decremental; HR, heart rate; INC, incremental; RER, respiratory exchange ratio; $\dot{V}CO_2$, carbon dioxide output; $\dot{V}$E, ventilation (BTPS); $\dot{V}O_2$max, maximal oxygen consumption; V_T, tidal volume.

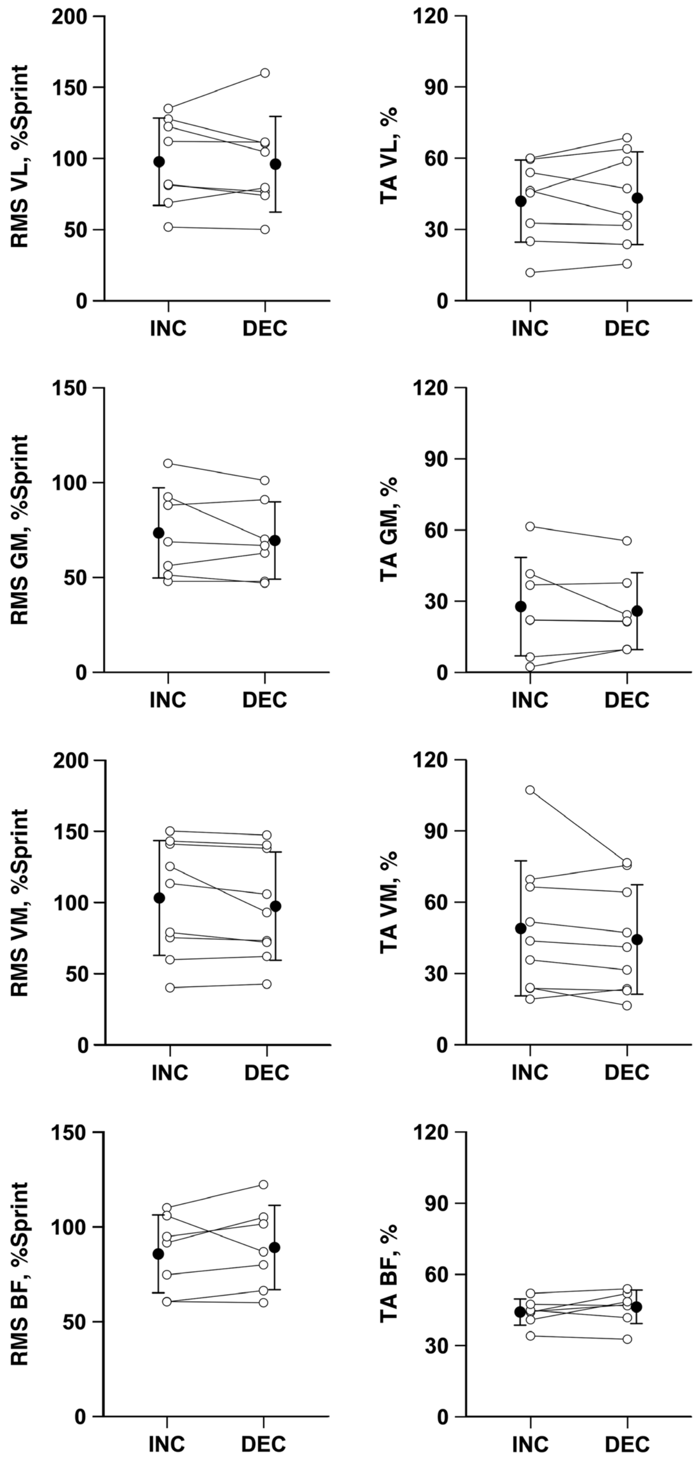

Figure 3 — Individual and mean (SD) RMS of EMG activity (as a percentage of sprint RMS) and TA (%RMS multiplied by the fraction of active time within a minute) at $\dot{V}O_2$max during an INC exercise test and a DEC exercise test. BF indicates biceps femoris (n = 7); DEC, decremental; EMG, electromyography; GM, gastrocnemius medialis (n = 7); INC, incremental; RMS, root mean square; TA, total activation; VL, vastus lateralis (n = 7); VM, vastus medialis (n = 9).

obtained during the verification tests were, if anything, lower (although the difference did not reach statistical significance) than those measured during the preceding INC test. Thus, the $\dot{V}O_2$max determined during the INC test in our study is within what is currently considered best practice in terms of protocol and analysis.

In this context, the DEC exercise actually operates within a similar range of workloads, as the test starts at the same workload as the verification test and only goes down. This eliminates the possibility that any differences between protocols would be the result of a poor choice of work rate increase from the INC tests. Based on our previous research and pilot testing, however, it became evident that a perfect mirror image of an INC test would lead to a too rapid decrement in workload, and eventually, all cardiorespiratory responses would turn downward before $\dot{V}O_2$max could be reached. Exercise intensities within the so-called "severe" domain are known to eventually lead to $\dot{V}O_2$max,[19] and in trying to balance a prolongation of the protocol toward more than 2 to 3 minutes while eliciting the highest possible physiological response, a protocol with decreasing workloads of increased durations was envisioned. Although the DEC and INC protocol differ in terms of the time taken to reach $\dot{V}O_2$max, as well as the work performed, this should not prevent a comparison between the two, much like different INC tests with slightly different ramps are routinely compared and also do not show differences in $\dot{V}O_2$max,[16] or even the comparison between all-out exercise and INC tests.[20]

In spite of the lower power output at $\dot{V}O_2$max during DEC, EMG activity was similar between DEC and INC at the time of $\dot{V}O_2$max. The increase in $\dot{V}O_2$ during all-out exercise tests (where $\dot{V}O_2$ increases up to $\dot{V}O_2$max despite decreasing power output and EMG activity) has been proposed to be a "slow-component"-like phenomenon,[21] resulting from the loss of efficiency in the exercising muscles. $\dot{V}O_2$ then increases during exercise because of the progressive recruitment of the less efficient, type IIx fiber, which increases the O_2 cost for force production per fiber. An alternative explanation is that, while an initial bout of very intense exercise creates the demand for O_2, a subsequent decrease in power output might improve limb blood flow, as muscle contraction intensity and vasoconstriction would be likely reduced, thereby improving O_2 extraction. The similar EMG activity coupled with lower power output found in the present study likely facilitated higher blood flow, which could indeed have facilitated higher O_2 extraction.

To test whether our EMG measures were sensitive enough to detect differences caused by a 20-W change in power output (ie, the difference between INC and DEC at $\dot{V}O_2$max), we compared the root mean square and total activation of the analyzed muscles in the minute prior to $\dot{V}O_2$max during the INC test, since our INC protocol had a load rate of 20 W·min^{-1}. For both the vastus lateralis and vastus medialis, the root mean square and/or total activation were sufficiently sensitive to have detected changes equivalent to a 20-W change in power output, at least during a ramp-up protocol (Table 4). We did not find differences in the mean or median frequency of the EMG signal of any of the analyzed muscles, which precludes any suggestion of change in recruitment pattern. Furthermore, the total EMG activity was similar between INC and DEC, suggesting, indeed, a lower efficiency of muscle contraction rather than exclusively higher oxidative metabolism per se. Although our results suggest a loss of efficiency in producing mechanical work, as shown by a higher $\dot{V}O_2$ for a similar EMG activity, it is not possible to argue conclusively that the measured difference in $\dot{V}O_2$ (~125 mL·min^{-1}) is related to changes in muscle efficiency.

The results from the present study extend the findings originally reported during uphill running,[5] showing ~3% higher $\dot{V}O_2$max during DEC in comparison to INC when exercise is performed on a cycle ergometer. These results were seen even

Table 3 Frequency Domain Variables of EMG During the INC and DEC Tests (at $\dot{V}O_2$max)

	INC	DEC	*t* statistic	95% CI	d_z
Vastus lateralis, Hz					
Median frequency	44.6 (3.8)	44.2 (4.1)	$t_{(7)} = 1.206$, $P = .267$	−1.3 to 0.4	0.43
Mean frequency	46.3 (3.6)	45.8 (3.8)	$t_{(7)} = 1.042$, $P = .332$	−1.6 to 0.6	0.37
Vastus medialis, Hz					
Median frequency	41.1 (3.1)	41.1 (2.5)	$t_{(8)} = .056$, $P = .957$	−1.6 to 1.7	0.01
Mean frequency	43.2 (3.2)	43.3 (2.4)	$t_{(8)} = .104$, $P = .919$	−1.3 to 1.5	0.03
Biceps femoris, Hz					
Median frequency	81.9 (16.9)	84.1 (16.5)	$t_{(8)} = 1.935$, $P = .101$	−0.6 to 4.8	0.73
Mean frequency	100.8 (19.3)	103.3 (19.9)	$t_{(6)} = 1.606$, $P = .159$	−1.3 to 6.3	0.60
Gastrocnemius medialis, Hz					
Median frequency	43 (2.5)	42.7 (2.4)	$t_{(6)} = .515$, $P = .625$	−1.6 to 1.0	0.19
Mean frequency	45 (1.8)	45 (2.2)	$t_{(6)} = .175$, $P = .866$	−0.7 to 0.8	0.06

Abbreviations: DEC, decremental; EMG, electromyography; INC, incremental; $\dot{V}O_2$max, maximal oxygen consumption.

Table 4 Changes in EMG Activity Prior to $\dot{V}O_2$max of the INC Test

	@ $\dot{V}O_2$max	@ $\dot{V}O_2$max − 20 W	*t* statistic	95% CI	d_z
Vastus lateralis					
RMS (%Sprint)	100.1 (32.4)	92.8 (28.6)	$t_{(6)} = 2.441$, $P = .050$	−14.6 to 0.02	0.92
TA, %	44.3 (17.2)	40 (15.5)	$t_{(6)} = 2.930$, $P = .026$	−7.8 to −0.7	1.10
Vastus medialis					
RMS (%Sprint)	103.3 (40.4)	99.8 (32.1)	$t_{(8)} = .906$, $P = .391$	−12.4 to 5.4	0.30
TA, %	49.1 (28.5)	45.5 (27.4)	$t_{(8)} = 3.384$, $P = .010$	−6.0 to −1.1	1.06
Biceps femoris					
RMS (%Sprint)	85.7 (20.5)	76.5 (31.1)	$t_{(6)} = .747$, $P = .483$	−39.2 to 20.8	0.28
TA (%)	44.0 (5.5)	38.5 (14.2)	$t_{(6)} = .993$, $P = .359$	−18.9 to 8.0	0.37
Gastrocnemius medialis					
RMS (%Sprint)	76.5 (24.7)	77.7 (24.4)	$t_{(5)} = .232$, $P = .825$	−12.4 to 14.8	0.09
TA, %	31.8 (19.2)	34.1 (19.0)	$t_{(5)} = .426$, $P = .688$	−11.3 to 15.9	0.17

Abbreviations: DEC, decremental; EMG, electromyography; INC, incremental; RMS, root mean square; %Sprint, percentage of value achieved during a 10-s all-out sprint; TA, total activation (the product of RMS activity and activation time); $\dot{V}O_2$max, maximal oxygen uptake. Note: Values refer to the minute in which @ $\dot{V}O_2$max was measured (@ $\dot{V}O_2$max) or the preceding minute (@ $\dot{V}O_2$max − 20 W). All comparisons performed using Student *t* test for paired samples.

though participants had performed a verification test, current seen as the best standard to ensure the attainment of "true" $\dot{V}O_2$max. The additional O_2 uptake requires either additional blood supply and/or increased oxygen extraction to take place during exercise, be it in the respiratory muscles, exercising muscles, or elsewhere. Mauger et al[4] hypothesized that a better distribution of blood flow in the active limbs due to a decrease in power output[22,23] could explain the higher $\dot{V}O_2$max measured during a self-paced test, but this proposition remains purely speculative. In muscle preparations, $\dot{V}O_2$max can be altered by increasing O_2 extraction while O_2 delivery is kept constant when independently manipulating SaO_2 and PaO_2, although, to our knowledge, this not been demonstrated in vivo.[24]

In the present study, both the $\dot{V}E$ and breathing rate were higher during DEC at the time of $\dot{V}O_2$max, different from the findings of Beltrami et al[5] and Taylor et al.[9] Thus, at least in cycling, part of the difference in $\dot{V}O_2$max measured between tests might be related to the additional O_2 cost of breathing. The 7.0 L·min^{-1} difference in $\dot{V}E$ measured between DEC and INC could raise $\dot{V}O_2$ by approximately 20 to 30 mL·min^{-1},[25] or explain 15% to 25% of the difference in $\dot{V}O_2$max measured between DEC and INC (120 mL·min^{-1}). It must be noted, however, that differences in $\dot{V}E$ do not always result in measurable differences in pulmonary $\dot{V}O_2$.[26] Moreover, simply forcing the respiratory muscles to perform more work does not increase whole-body $\dot{V}O_2$max or cardiac output,[27] similar to what happens when an additional (supramaximal) load is imposed on the muscles of the exercising limbs.[18] Therefore, while the respiratory muscles can be seen as the receiver of the additional $\dot{V}O_2$, it does not serve a mechanistical explanation of how $\dot{V}O_2$ was increased.

The differences in $\dot{V}O_2$max between DEC and INC in the present study were independent of whether the participants were allowed a specific familiarization trial for DEC or not and were also independent of the order in which INC and DEC were performed. This contrasts with previous findings, in which following DEC participants retained the higher $\dot{V}O_2$max on a subsequent INC despite an unchanged performance in the final INC test.[5] Should the same have happened in the present study, $\dot{V}O_2$max would have increased from INC_{fam} to INC (Part B), since the participants performed the DEC_{fam} trial between these 2 tests. Also, if the participants had retained the higher $\dot{V}O_2max$ values following DEC, the $\dot{V}O_2max$ differences between INC and DEC would have been blunted for all participants who performed INC after DEC, which did not happen. Although these findings do not help to explain why the running studies showed a persistent increased $\dot{V}O_2max$ following the DEC protocol, they show that future research using cycling exercise can be performed using a familiarization trial for both INC and DEC.

This investigation is not without its limitations. First, the DEC test per se could be criticized for the tailored approach and the duration of the first stage (60% of the time to exhaustion during the verification test). From our experience, this proved to be a good compromise between sufficient intensity to drive O_2 uptake upward and preventing premature exhaustion. In contrast to our running experiments, anecdotally, the cyclists often reported not even feeling the first 2 (20 W each) drops in workload, but merely a nonworsening of the associated pain and discomfort. While it is entirely possible that a different duration of the first stage—or indeed, a different rate of load decrement—would have led to different results, this remains speculative. Another possibility would be the use of a *V*-shaped protocol, as recently proposed[6]; however, it remains to be seen how tolerable such a protocol would be in cycling. Second, the participants in part A performed an additional INC test (always first of the day). The reason for this test was that, as the participants were unfamiliarized with the DEC protocol, the initial INC test provided an updated value of peak power output, from which the starting load of the DEC protocol could be more accurately calculated. Although this additional test might have caused some level of fatigue (despite over 60 min of recovery), we note that the $\dot{V}O_2max$ from this test was not different from the one performed in randomized order with the DEC test. Furthermore, it has been demonstrated that trained individuals can perform up to 4 INC tests in a day (with a 1.5-h passive rest) without losses to $\dot{V}O_2max$ or peak power output.[28] Finally, even if some fatigue was present, this would have affected both the DEC and INC tests, as the order of the two was balanced. At present, we see no reason to believe that increased fatigue should lead to higher $\dot{V}O_2max$, as, if this were the case, the verification tests—performed within minutes of an INC test—should have shown this effect. Finally, while the DEC protocol might be able to elicit higher $\dot{V}O_2max$ values, an important pitfall of the protocol is that it does not allow for the determination of commonly assessed variables, such as ventilatory or lactate thresholds or cycling efficiency, or even peak power output, as this is a function of the starting load and thus imposed by the experimenter.

Practical Applications

The DEC exercise tests open a new paradigm for exercise testing, possibly leading to higher $\dot{V}O_2max$ than INC tests. Muscle activity at $\dot{V}O_2max$ suggests that, during cycling tests, DEC protocols lead to greater physiological strain, with loss of metabolic efficiency. While a more optimal protocol might emerge, at present, a successful alternative is a starting load equal to the verification test with 60% of time to exhaustion and 2 subsequent decreases of 20 W within 30 seconds in order to prevent exhaustion, after which, decreases can be attenuated and stages elongated. It is possible that the $\dot{V}O_2max$ measured during a DEC exercise test presents a different relationship with markers of health and performance, but this remains to be established. Due to the nature of the workload and physiological response, however, the DEC test paradigm is unable to produce other markers that could be of interest in athletic settings, such as lactate or ventilatory thresholds.

Conclusion

Trained individuals achieved higher $\dot{V}O_2max$ during a DEC cycling protocol in comparison to a traditional INC exercise test. The additional $\dot{V}O_2$ may partly be attributed to the extra work performed by the respiratory muscles and less efficient lower limbs, but it remains unclear whether it originates from higher O_2 delivery and/or extraction. These results argue against the notion that $\dot{V}O_2max$, as determined from an INC test, represents an absolute ceiling in cardiorespiratory capacity.

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