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The aims of the study were to investigate whether starting cadence had an effect on 10-s sprint-performance indices in friction-loaded cycle ergometry and to investigate the influence of method of power determination. In a counterbalanced order, 12 men and 12 women performed three 10-s sprints using a stationary (0 rev/min), moderate (60 rev/min), and high (120 rev/min) starting cadence. Calculated performance indices were peak power, cadence at peak power, time to peak power, and work to peak power. When the uncorrected method of power determination was applied, there was a main effect for starting cadence in female participants for peak power (stationary 635 ± 183.7 W, moderate 615.4 ± 168.9 W, and high 798.4 ± 120.1 W) and cadence at peak power (89.8 ± 2.3 rev/min, 87.9 ± 21.5 rev/min, and 113.1 ± 12.5 rev/min). For both the uncorrected and directly measured methods of power determination in men and women, there was a main effect for starting cadence for time to peak power and work to peak power. In women, for an uncorrected method of power determination, it can be concluded that starting cadence does affect peak power and cadence at peak power. This effect is, however, negated by a direct-measurement method of power determination. In men and women, for both uncorrected and directly measured methods of power determination, time to peak power and work to peak power were affected by starting cadence. Therefore, a higher-cadence start is unsuitable, particularly when sprint-performance indices are determined from an uncorrected method.

Key Words*:* peak power, friction-braked, flywheel inertia

The Wingate test was designed to evaluate peak power output, mean power output, and fatigue index as indices of performance using friction-loaded cycle ergometry.[1] The Wingate test has since been modified following studies examining resistive load,[2] averaging period,[3] test duration,[4] and correction for flywheel inertia.[5-7]

The traditional calculations employed in the Wingate test assume that the flywheel revolves at a constant angular velocity and has no moment of inertia,

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but this is not the case.[3] It has been observed that power values obtained in this way are lower than those obtained by other methods such as stair climbing or isokinetic cycling.[8] These observations have led to the development of correction procedures[5,7,9,10] that attempt to account for the energy that is stored in the flywheel during the acceleration phase and then released during the deceleration phase.

If an ergometer is unable to translate all the required resistance to the flywheel at high resistive forces,[11] peak power might be overestimated even with the use of a correction procedure. A solution might be to use strain gauges, in the form of a power-measuring crank, allowing the calculation of power using the torque produced at the crank. Any inconsistency with resistance translation to the flywheel will not cause an error with the power-measuring cranks. In addition, direct measurement from the crank, as opposed to measurements at the flywheel, takes into account flywheel inertia without the need for a correction procedure. Power-measuring cranks of the type used in the present study have been previously shown to be a valid and reliable method of determining power output,[12] but these cranks have had limited use in studies determining peak power output.

The original Wingate test used a protocol in which the participant accelerated the flywheel up to maximum cadence against a minimal resistance before the resistive force was applied and the test commenced. A maximum-cadence approach results in flywheel deceleration throughout the test. Because the flywheel is a rotating mass, it can act as an energy reservoir during acceleration. This energy is then released during deceleration and is used to accomplish mechanical work. Therefore, the participant is being credited with this work, despite it having been stored in the flywheel against a minimal resistance rather than the applied resistive load.[10,13]

In a short (ie, 10-second) sprint, the use of a stationary start[7,14,15] will reduce the mechanical work done as a result of the kinetic energy stored by the flywheel. Participants might find it hard initially to overcome the effects of inertia, however, particularly if a large braking force is also used. The traditional uncorrected method of calculating power output has been shown to cause peak power to be underestimated.[3] If a stationary start is used, a correction procedure should be applied to calculate the power involved in accelerating the flywheel.

A compromise between the stationary and maximal-cadence starts might be to use a moderate-cadence rolling start.[3,16,17] A moderate-cadence start would involve the participants' accelerating the flywheel up to a set cadence before the braking force is applied and the commencement of the test. Therefore, the purposes of the present study are to determine whether, in men and women, the choice of starting cadence has any effect on sprint-test indices during friction-loaded cycle ergometry and whether the method of power-output determination has an influence on the findings.

Methods

Participants

Twelve men (age 24.8 ± 5.0 years, height 182.3 ± 8.1 cm, mass 73.3 ± 10.7 kg) and 12 women (age 24.2 ± 4.3 years, height 166.7 ± 5.6 cm, mass 64.8 ± 7.7 kg) took part in the study. All participants regularly participated in competitive sport. They completed a health questionnaire and provided written informed consent before the start of testing. The procedures employed in this study were granted prior approval by the institution's research ethics committee.

Experimental Design

The study investigated 3 starting conditions. The order of administration of the conditions was counterbalanced using a Latin-square design[18] to control for potential order and carryover effects. The emphasis was on peak power, so a 10-second version of the Wingate test was used.[4] After the completion of each trial, a minimum of 10 minutes of recovery time elapsed before the next trial was started.[19] A loading of 10% body mass, as recommended for adult athletes,[20] was used for all trials.

Protocol

Before testing, the participants performed a warm-up according to a standardized routine. This consisted of a 5-minute cycle at 60 rev/min against a 1.0-kg load. The participants then did 3 minutes of static stretching according to each individual's normal stretching routine. This was followed by a 3-second sprint from a stationary start against a loading of 4% body mass. After 2 minutes of recovery, there was a second 3-second sprint from a stationary start against a loading of 7% body mass. This also acted as a habituation procedure and was followed by a further 2 minutes of recovery.

The 3 trials included a stationary (0 rev/min) start, a moderate-cadence (60 rev/min) rolling start, and a high-cadence (120 rev/min) rolling start. The stationary start involved applying the braking force before the test. The participant was then instructed to pedal all out for 10 seconds. The moderate-cadence rolling start involved the participant achieving a cadence of 60 rev/min against minimal resistance. The high-cadence rolling start involved the participant pedaling to 120 rev/min against minimal resistance. This cadence has been shown to be above the optimal cadence needed to generate peak power.[2] Selecting a cadence for the high-cadence rolling start allowed standardization across participants. The braking force was applied in both conditions when the starting cadence was achieved, at which point the 10-second test commenced.

Data Acquisition

A Monark 864 friction-loaded cycle ergometer (Monark Exercise AB, Varberg, Sweden) was modified by adding 80 black and 80 white strips around the flywheel rim. These were used to monitor flywheel angular displacement and were read by an optical sensor. A 56-tooth chain ring was used to give a gear ratio of 4 flywheel revolutions to 1 pedal revolution. The ergometer was fitted with pedals and toe clips and bolted to the floor for stability. (Participants who had their own specialized clipless pedals and shoes were permitted to use them.) A 4-strain-gauge "professional" power-measuring crank set (Schoberer Rad Messtechnik, Fuchsend, Germany) was used, with a reported accuracy of ±2.1 W.[12] This measured torque, which was transmitted to a microcomputer on the handlebars of the ergometer. A zero value was taken statically, with the cranks unloaded, before each use. A 170-mm-length crank was used.

The weight basket was also modified so that a circuit was created when the braking force was applied. This acted as a switch in the moderate- and high-cadence rolling starts to indicate when the test started. Data were captured before the start of the test so that there was a record of start cadence.

The torque from the pedal cranks, the switch point, and the flywheel-velocity signals were interfaced to a PC via the digital inputs of a 1401 data-acquisition system (Cambridge Electronic Design, Cambridge), which sampled at 82.5 kHz. The digital inputs were set up as event channels in Spike 2 software (Cambridge Electronic Design, Cambridge), which recorded the leading edge of the pulse train as discrete time intervals. This software produced 4 channels of data in binary format, which were then converted to text format via the software.

Data Analysis

The data were exported to a text file and run through a specially designed program. This program first identified the switch position and matched it with the equivalent position in the flywheel data. This was then matched with the torque data and used as the start point. The flywheel velocity was multiplied by the gear ratio (14:56) to convert it to pedal velocity. This was then multiplied by 2π so that the pedal velocity was measured in rad/s. An average of the samples over 16 strips on the flywheel and an equivalent period of torque data from the pedal cranks were taken, and these were used to calculate power. Because of problems with the data recorded from the flywheel 2 female and 1 male participant's data had to be removed from the study, resulting in a total of 21 participants (11 men and 10 women). The data were averaged using a 1-pedal-revolution rolling average (averaging increment of 0.05 pedal revolutions). These indices included peak power, time to peak power, work to peak power, and cadence at peak power. Each of these indices was calculated using both directly measured and uncorrected power data.

For each power-determination method and performance index, interactions were evaluated using a 2×3 (sex × starting cadence) model. If an interaction was found, then the men's and women's results were analyzed separately. For each within-subject factor, the mean of the Huynh–Feldt and Greenhouse–Geisser epsilons was then calculated to correct for any violation of the sphericity assumption. If significant main effects were found, post hoc analysis using paired *t* tests with a Bonferroni correction were conducted to identify the location of any differences. The level of significance was set at .05.

Results

The results for the different starting conditions are shown in Tables 1 and 2.

Peak Power Output

For the uncorrected method of power determination, an interaction (sex × starting cadence; $P = .010$) was found for peak power. For the female participants a significant main effect ($P = .010$) for starting cadence was revealed. Post hoc analysis revealed a difference between the stationary and high starts ($P = .010$) and the moderate and high starts ($P = .003$). The peak power output for the high-cadence

Table 1 Sprint-Test Indices for Male and Female Participants for 3 Different Start Protocols on a Friction-Loaded Cycle Ergometer*

	Stationary (0 rev/min)		Moderate (60 rev/min)		High (120 rev/min)	
	Men	Women	Men	Women	Men	Women
PPO, W (U)	1000.4 ± 280.5	635.0 ± 183.7	976.9 ± 289.2	615.4 ± 168.9	1029.5 ± 213.0	798.4 ± 120.1
PPO, W (D)	1048.2 ± 309.8	643.9 ± 195.2	1192.7 ± 454.7	696.5 ± 237.0	1064.5 ± 295.1	668.7 ± 179.0
Cadence at PPO, rev/min (U)	126.5 ± 18.7	89.8 ± 23.3	124.9 ± 20.4	87.9 ± 21.5	131.3 ± 10.9	113.1 ± 12.5
Cadence PPO, rev/min (D)	116.0 ± 12.1	86.7 ± 20.5	114.6 ± 21.4	78.7 ± 18.5	122.3 ± 12.1	94.1 ± 16.8

*Data are expressed as mean ± SD. PPO indicates peak power output; U, uncorrected method; and D, direct method.

Table 2 Sprint-Test Indices for All Participants for 3 Different Start Protocols on a Friction-Loaded Cycle Ergometer*

	Stationary (0 rev/min)	Moderate (60 rev/min)	High (120 rev/min)
Time to PPO, s (U)	4.84 ± 1.78	4.72 ± 1.23	0.92 ± 1.15
Time to PPO, s (D)	3.31 ± 1.52	2.73 ± 0.98	2.36 ± 1.00
Work to PPO, J (U)	3147.62 ± 1394.21	2874.00 ± 935.63	963.29 ± 1133.06
Work to PPO, J (D)	2029.48 ± 647.96	1313.95 ± 944.31	859.33 ± 469.79

*Data are expressed as mean ± SD. PPO indicates peak power output; U, uncorrected method; and D, direct method.

condition (798.4 ± 120.1 W) was clearly higher than for both the stationary condition (635.0 ± 183.7 W) and the moderate-cadence condition (615.4 ± 168.9 W; Figure 1, panel a). For the male participants, in contrast, no main effect was found for starting cadence ($P = .146$) for the uncorrected method.

For the directly measured method of power determination, no interaction (sex × starting cadence) was found ($P = .130$). No significant main effect was found for starting cadence ($P = .228$).

Cadence at Peak Power

An interaction (sex × starting condition) was found for both the uncorrected ($P < .001$) and the directly measured ($P = .001$) methods for cadence at peak power. For the women, there was a main effect for starting cadence for both the uncorrected ($P = .029$) and the directly measured ($P < .001$) methods of power determination. Post hoc analysis revealed differences between the stationary and high starts (uncorrected $P = .009$, directly measured $P = .001$) and the moderate and high starts ($P = .002$, $P < .001$, respectively; Figure 2, panel a).

In the male participants, no main effect was found for starting cadence for cadence at peak power for both the uncorrected ($P = .176$) and the directly measured ($P = .086$) methods of power determination (Figure 2, panel b).

Time to Peak Power

No interaction (sex × starting condition) was found for either the uncorrected ($P = .370$) or the directly measured ($P = .271$) method of power determination for time to peak power. For the uncorrected method, a main effect was found for starting cadence ($P < .001$). Post hoc analysis revealed differences between the stationary and high-cadence starts ($P < .001$) and the moderate and high starts ($P < .001$). For the directly measured method, there was also a main effect for starting cadence ($P = .009$), with post hoc tests revealing differences between the stationary and high starts only ($P = .017$; Figure 3).

Work to Peak Power

No interaction (sex × starting cadence) was found for either the uncorrected ($P = .496$) or the directly measured ($P = .226$) method for the work to peak power. For

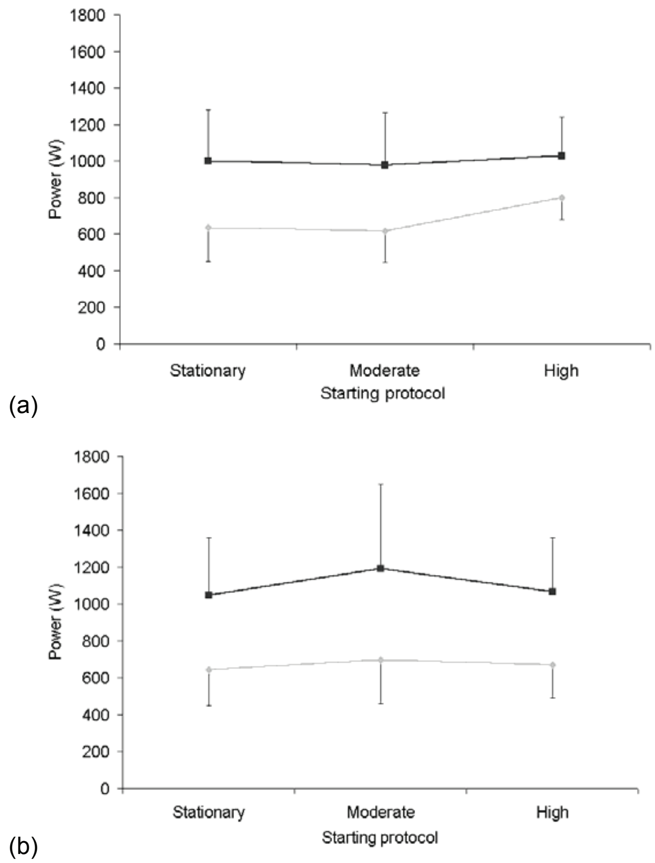


Figure 1 — Sprint-test indices for men (■) and women (♦) across different starting protocols. Peak power: (a) uncorrected and (b) direct methods.

the uncorrected method, a main effect was found for starting cadence ($P < .001$). Post hoc analysis revealed differences between the stationary and high starts ($P < .001$) and the moderate and high starts ($P < .001$). For the directly measured method, there was also a main effect for starting cadence ($P < .001$). Post hoc tests revealed differences between the stationary and moderate-cadence starts ($P = .013$) and between the stationary and high-cadence starts ($P < .001$; Figure 4).

Discussion

The purpose of the present study was to compare performance indices obtained from 3 different starting cadences in a 10-second maximal-effort cycle-ergometer test and examine the influence of method of power determination. To our

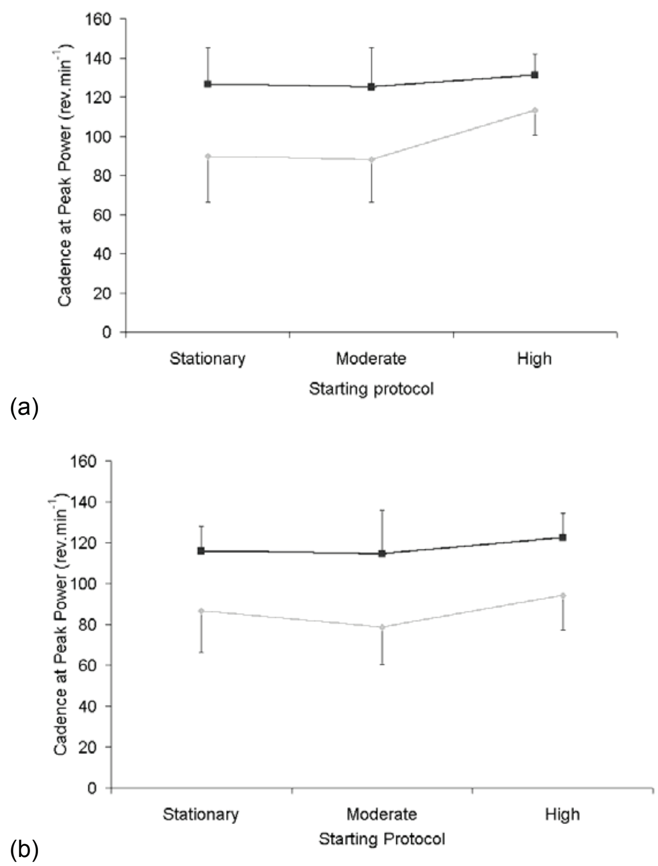
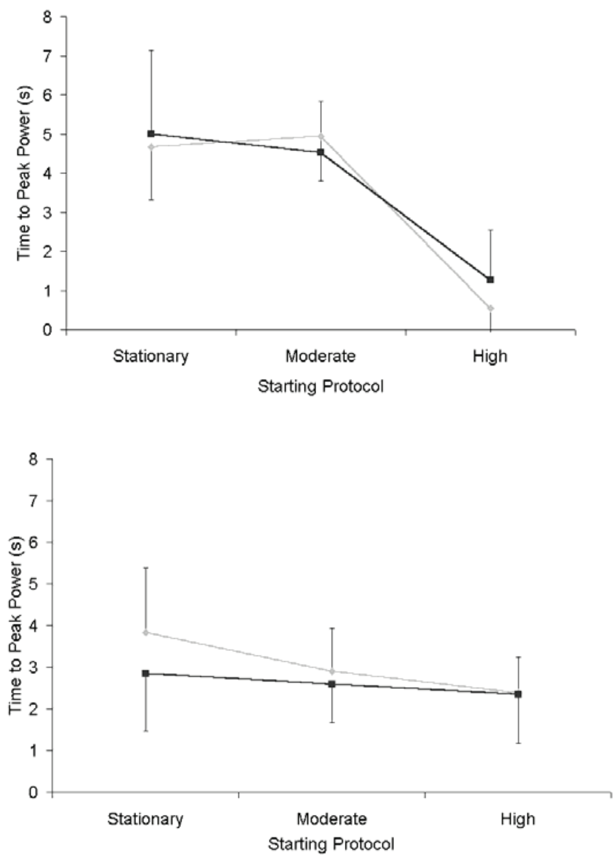


Figure 2 — Sprint-test indices for men (■) and women (♦) across different starting protocols. Cadence at peak power: (a) uncorrected and (b) direct methods.

knowledge, this is the first time that a comparison has been made between 3 commonly used starting cadences using both uncorrected and direct (ie, crank-based) methods for determination of power output. Traditionally, the flywheel inertia and transmission-system friction has been accounted for in correction techniques.[3,6] Although these techniques are well regarded, it is possible that in a situation when the load is not adequately transmitted to the flywheel, power output could be overestimated.[11] A direct (ie, crank-based) measurement system overcomes these potential limitations.

The key findings of the present study are as follows. (1) In female participants, with the direct method of power determination, peak power is independent of start cadence, but cadence at peak power is dependent of start cadence. (2) In female participants with the uncorrected method of power determination, however, peak power and cadence at peak power both depend on start cadence. (3) In men and women, time to peak power is underestimated with the high-cadence rolling start,



(a)

(b)

Figure 3 — Sprint-test indices for men (■) and women (♦) across different starting protocols. Time to peak power: (a) uncorrected and (b) direct methods.

regardless of power-determination method. (4) In men and women, work to peak power is underestimated with the high-cadence rolling start, regardless of the method of power determination.

Comparison of the 3 start cadences using the uncorrected method showed a disproportionately higher peak-power measurement in the high-cadence rolling start than in the other conditions for the female participants. Similar results were found for both male and female athletes between a stationary and maximal-cadence rolling start in an earlier study.[13] With the stationary and moderate-cadence rolling starts, the participants were able to accelerate the flywheel up to peak power. With the high-cadence start, the high cadence was achieved before the start of the test, and the flywheel was decelerating throughout the test. With the calculations for uncorrected data, peak power occurs at peak flywheel velocity, so peak power occurs almost instantaneously in a test with a high-cadence start. This velocity has

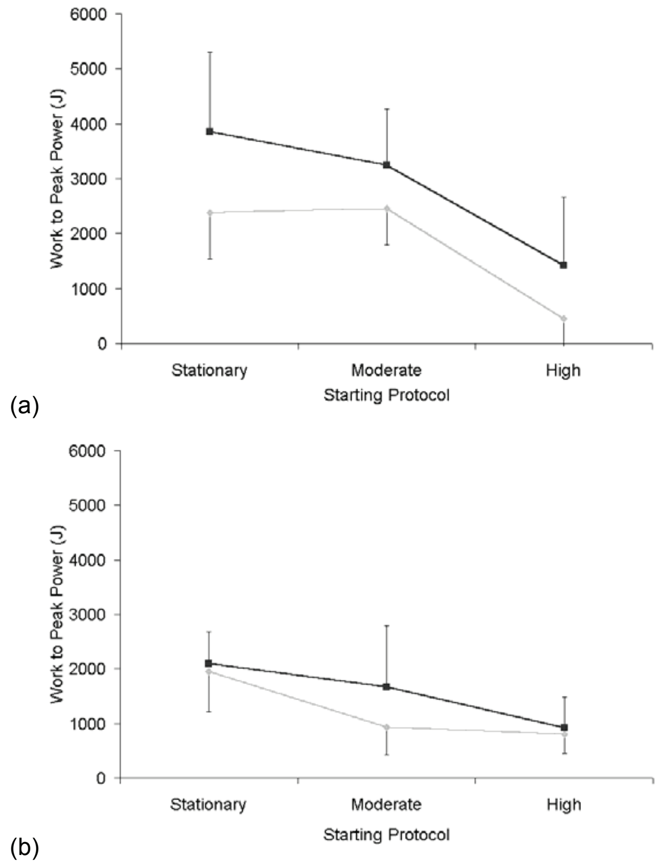


Figure 4 — Sprint-test indices for men (■) and women (♦) across different starting protocols. Work to peak power: (a) uncorrected and (b) direct methods.

been generated against a minimal resistance, however, rather than the required test load, so peak power is overestimated.[10] This is supported by the uncorrected value for peak power being higher than the directly determined peak power in the present study, demonstrating that stored energy in the flywheel is being released throughout the test. This explains the higher value achieved using this starting protocol and suggests that this is not a suitable protocol for female participants when using the uncorrected method of power determination.

The cadence at peak power was higher for the uncorrected method than with the direct method in all 3 starting protocols for both male and female participants. This shows a limitation of the uncorrected method for determining peak power, which assumes that peak power occurs at peak cadence. This is clearly not the case and has been shown previously.[3] When data from the direct method of power determination are examined, in both the stationary and moderate-cadence starts, peak power occurs during the acceleration phase of the test. This is because high torques are produced initially to accelerate the flywheel. In the high test for the male participants, peak power occurs during the acceleration phase of the test, as the participants are able to accelerate the flywheel in excess of the 120 rev/min starting cadence. With the female participants during the high-cadence rolling start, genuine peak power does not occur immediately when cadence is at its peak; rather, genuine peak power occurs when the participant is able to slow the rate of deceleration of the flywheel the most. It has been suggested that this is because the test starts at a velocity above the optimal velocity for peak power, and it is only when the flywheel has slowed down to this optimal velocity that peak power is achieved.[13]

Time to peak power can provide important information about how quickly a participant can reach peak work rates.[21] Time to peak power might also provide an indirect way of estimating the relative proportions of fast-twitch to slow-twitch muscle fibers.[22] Work to peak power is partly dependent on time to peak power, so it is not surprising that these indices show similar findings. If these performance indices are required, it appears that a test with a high-cadence rolling start would be unsuitable in men and women. The derived time to peak power would give a false indication of how quickly a participant can reach a peak work rate, and the derived work to peak power would be underestimated.

In conclusion, in trained participants, time to peak power and work to peak power cannot be compared across starting cadences, regardless of the method of power determination. In addition, in women, cadence at peak power should be treated with caution, regardless of power determination method. Finally, in men and women, peak power is independent of starting cadence when a direct method of power determination is applied.

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