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Section: Invited Brief Review

Article Title: Effects of Cycling Training at Imposed Low Cadences - A Systematic Review

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Journal: *International Journal of Sports Physiology and Performance*

Acceptance Date: December 23, 2016

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DOI: http://dx.doi.org/10.1123/ijspp.2016-0574

"Effects of Cycling Training at Imposed Low Cadences - A Systematic Review" by Hansen EA, Rønnestad BR
International Journal of Sports Physiology and Performance
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Effects of cycling training at imposed low cadences - a systematic review

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To be submitted to IJSPP as an invited brief review article.

Running head: Cycling training at imposed low cadences

Word count: 4663

Abstract word count: 243

Number of tables: 1

Number of figures: 1

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ABSTRACT

The present article reviews effects of training at low imposed cadences in cycling. We performed a systematic literature search of MEDLINE and SPORTDiscus up to April 2016 to identify potentially relevant articles. Based on the titles and abstracts of the identified articles, a subset of articles was selected for evaluation. These articles constituted original research articles on adaptation to training at different imposed cadences in cycling. Seven articles were selected for evaluation. With regard to the terminology in the present article, “low cadences” refers to cadences below the freely chosen cadence. Eighty rpm can for example be considered a low cadence if effort is maximal. On the other hand, the cadence has to be lower than 80 rpm (e.g. 40-70 rpm) to be considered low if cycling is performed at low power output. The reason is that the choice of cadence is dependent on power output. In conclusion, there is presently no strong evidence for a benefit of training at low cadences. It can tentatively be recommended to consider including training bouts of cycling at low cadence at moderate to maximal intensity. The reason for the restrained recommendation is the following. Some of the selected studies indicate no clear performance enhancing effect of training at low cadence, or even indicate a superior effect from training at freely chosen cadence. Furthermore, the selected studies are considerably dissimilar with respect to e.g. participant characteristics and to the applied training regimens.

Keywords: Endurance, Exercise, Pedal rate, Pedaling frequency, Pedalling frequency,

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INTRODUCTION

Cyclists’ exercise consists primarily of outdoor cycling, which is typically performed for 2-30 hours per week, depending on the category of the cyclists.[1] Besides, a number of alternative types of exercise are occasionally applied. These types of exercise comprise e.g. indoor ergometer cycling,[2] strength training,[3] and alternative endurance training activities such as cross country skiing and running.[4]

A special kind of cycling training consists of one or more cycling bouts, each lasting in the range of approximately 5-20 min, and being performed at an imposed low cadence. In the present context, the cadence is considered to be low when it is below the freely chosen cadence (Fig. 1). This kind of training is commonly applied by competitive cyclists and widely denoted “power training”, “heavy low cadence training”, or “functional strength training”. Power output during the cycling bouts is moderate to high. Our experience with competitive cyclists is that the bouts are often performed on an ascent. The low cadence causes pedal force to be high in each pedal thrust. Exactly how high the pedal force in each pedal thrust becomes is a result of the combination of power output and cadence.

Based on our experience with competitive cycling environments, it appears evident that cycling training at imposed low cadences is currently widely applied, and has been for a number of years. The question is whether or not this training in fact enhances endurance cycling performance? A number of research studies have been performed to investigate that question during the recent years. However, the scientific literature within the field has not been systematically reviewed previously. Therefore, that is the purpose of the present review article.

METHODS

A systematic search for relevant literature using MEDLINE, through pubmed.com, and SPORTDiscus was performed on 5. April, 2016. Keywords used were ((cycling OR cyclists) AND training) AND (cadence OR pedal rate OR pedal frequency OR pedalling OR pedaling).

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The search identified 222 articles from MEDLINE and 190 articles from SPORTDiscus. Seven of the articles were considered of primary relevance based on the titles and abstracts and selected for further evaluation. These 7 articles were original-research peer-reviewed articles on adaptation to training at different imposed cadences. In addition, the reference lists in the 7 selected articles were studied to identify additional articles of secondary relevance that were eligible for this review. Finally, our own article archives were scrutinised for relevant articles. Because of the modest amount of identified relevant literature, all 7 selected studies were evaluated regardless of the participants' characteristics and training background.

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RESULTS

This chapter contains an evaluation of the selected articles. Key information from the 7 articles which were selected based on the systematic literature search is presented in Table 1.

With regard to the characteristics of the participants, these ranged across the studies from healthy sedentary males[5] to endurance-trained cyclists with an average maximal oxygen uptake (VO_{2max}) of 65 ml kg^{-1} min^{-1}.[6] In the present context, it could generally be expected that less trained individuals would obtain training adaptations faster, and of larger relative magnitude, as compared with more trained individuals. The duration of the training periods ranged from 2 weeks[5] to 12 weeks.[7, 8] In the present context, 2 weeks could generally be considered relatively short while 4 weeks could be considered sufficient for initial neuromuscular adaptations. Twelve weeks could be considered appropriate for initial musculoskeletal adaptations. One of the selected studies was performed in the main competition season,[9] while other studies were performed in the off-season period.[7, 8] Not all articles contained information on this aspect, which is unfortunate since indications on training status at the beginning of the training intervention including information on training performed during the months prior to the intervention is of great relevance. To further meet this challenge,

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a control group should obviously be included in training intervention studies, whenever it is possible.

With regard to the training regimens, the selected studies showed great variation. Imposed cadences from 35 crank revolutions per min (rpm)[5] to 140 rpm[10] were applied. The intensity during the cycling bouts at specified cadences ranged from submaximal at lactate threshold, corresponding to on average approximately 63 W,[5] to maximal effort.[8, 9] The characteristics of the performed bouts ranged from 4-8 sets of 12 maximal crank revolutions which were completed twice per week[8] to a single bout of 60 min which was completed 5 times per week.[5] The major outcomes of the training in the selected articles were a mixture between performance and indicators of performance. An example of a performance measurement is average power output in a time trial. For comparison, the physiological response of lactate concentration during cycling at a submaximal power output is considered an example of an indicator of performance because of its indirect nature.

Interestingly, two of the selected studies used an approach, which is somewhat unusual and more similar to the approach of heavy strength training. Koninckx et al. (2010)[8] compared 4-8 sets of 12 maximum crank revolutions at a relatively low cadence (80 rpm) and high power output (775-875 W) with traditional heavy strength training (3 sets, 8-15RM). Both groups showed similar improvements in performance and indicators of performance, except for maximal power output at a high cadence, where the strength-training group showed improvement whereas the low cadence group did not (and actually showed impaired pedal stroke efficiency). In another study by Paton et al. (2009), 5 sets of 30-s maximal cycling bouts at either high or low cadence were compared.[9] The low cadence group was able to perform a higher power output during the training sessions. After 4 weeks of training, this group achieved a "likely beneficial" effect on performance, and on indicators of performance, as compared to the high cadence group. The authors observed a larger upregulation of the anabolic hormone

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testosterone after low cadence sessions compared with the high cadence sessions. This made them suggest that some of the superior adaptations to the low cadence training may be related to this anabolic hormone. However, the impact of acute upregulation of anabolic hormones on training adaptations is uncertain. Some results indicate an additive effect on training adaptations,[11] while other results show no additive effect.[12] Indeed in the study by Paton et al. (2009),[9] the low cadence group increased their VO_{2max}, while no change occurred in the high cadence group. This is, as the authors' stated, the most likely explanation for the observed group differences.[9]

Kristoffersen et al. (2014)[7] investigated the effects of 12 weeks of two different types of training. Two weekly sessions of 5×6 min intervals at a moderate intensity was performed. One group performed the intervals at low cadence (40 rpm) while another applied a freely chosen cadence. The low cadence group showed no change on performance and indicators of performance. The freely chosen cadence group showed increases in all these variables. In this case, in trained master cyclists (≈47 years old), intervals performed with freely chosen cadence appears to be better than intervals at imposed low cadence. In another study by Ludyga et al. (2016), a comparison was made between training with high and low cadence intervals. Similar increases in indicators of performance were observed in the two groups.[10] Both groups showed larger improvements than a control group that merely performed basic low-intensity endurance training with a lower volume and no high intensity sessions (while the high and low cadence group included high intensity sessions). The authors concluded that both high and low cadence training provide effective training stimuli, when identical exercise intensities are prescribed.[10] Another study by Nimmerichter et al. (2012) which applied a similar design as the latter, observed no significant differences in improvements during a graded exercise test between a low (60 rpm) and a high (100 rpm) cadence interval-training group (6×5 min at 300 W) and a control group that did not perform the intervals.[13] A fine detail of that particular study that

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actually increases the ecological validity of the study was that the low cadence intervals were performed uphill and the high cadence intervals were performed in flat terrain. The study revealed larger improvements in time trials performed in the terrain in which the interval-training sessions were performed. Interestingly, only the low cadence group increased time trial performance in both flat and uphill terrain.[13] Therefore, the authors concluded that training at imposed low cadences results in a potentially higher training stimulus with a crossover effect to flat time trials. The same research group performed a longitudinal study of elite cyclists in which the training time spent on intervals (lasting 2-20 min and performed at 40-60 rpm) was strongly correlated with the classification of the riders (r=–0.86) and the improvement of 20-min time trial power output during the season (r=0.83).[14] In line with Nimmerichter et al.'s (2012)[13] confirmation of the training principle of specificity, it has been suggested that in order to improve performance in both uphill and flat terrain, a cyclist should train in the specific terrains like flat and uphill road with high and low cadence.[15]

Somewhat different training adaptations to high and low cadence training was observed by Whitty et al. (2016) in trained cyclists. A low cadence group trained specific interval (4-6×4 min at 70% of maximal aerobic power) sessions of 45-60 min duration at a cadence 20% below the freely chosen cadence. For comparison, another group performed the interval sessions at a cadence 20% above the freely chosen cadence.[6] Both groups achieved similar increases in VO_{2max} and maximal aerobic power, but only the high cadence group improved the efficiency at 90 and 110 rpm. Despite the seemingly better adaptations in the high cadence group on efficiency, the low cadence group achieved a greater improvement of average power output during a 15-min all-out trial as compared to the high cadence group (16% vs 8%, respectively).

Hirano et al. (2015) observed that values of oxygen uptake (VO_2) and heart rate were lower during cycling at low cadences compared with higher cadences, despite of identical

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power output at the two cadences.[5] In addition, pedal force was higher at low cadence at the same time as peripheral oxygenation was lower. After 2 weeks of 5 weekly sessions with low cadence cycling, the increases in power output at the lactate threshold was larger than after high cadence sessions in previously untrained males.[5] The authors suggested that high pedal forces with concomitant low muscle oxygenation caused by pedalling at low cadence (35 rpm) constituted the peripheral stimuli for aerobic improvements.[5] Whether the same would be the case for well-trained cyclists remains to be investigated.

DISCUSSION

During prolonged strenuous cycling, or during intensive cycling at high effort, cyclists typically find it difficult to apply anything other than their freely chosen cadence. Still, it is of course possible, with volitional control and exertion, to apply particular cadences that are considerably higher or lower than the freely chosen cadence. However, if for example a low cadence is applied during cycling at high power output, performance will most likely be impaired.[16] It follows, that a cyclist rarely would do that in a test or competition situation. During training, on the other hand, where adaptation rather than performance is in focus, there might be a point in applying a low or high cadence in certain cycling bouts. Consequently, it is important to acknowledge the difference between governing the cadence during training versus during test or competition.

With regard to the terminology in the present article, 80 rpm can for example be considered a low cadence if effort is maximal. On the other hand, the cadence has to be lower than 80 rpm (e.g. 40-70 rpm) to be considered low if cycling is performed at low power output (Fig. 1). The reason is that the choice of cadence is dependent on power output. As an example, freely chosen cadence in 10 professional cyclists during uphill road cycling was reported to be on average approximately 78 rpm at 50 W as compared to an average of approximately 88 rpm at 750 W.[17] At an even higher power output of on average 1020 W, during sprinting at maximal

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effort in road cycling, freely chosen cadence was on average 110 rpm in 6 professional cyclists.[18] The freely chosen cadence during cycling appears to be basically consistent within an individual.[19, 20] However, at the same time it varies considerably between individuals. As an example of the latter, the freely chosen cadence in 10 professional cyclists ranged from average values of 62-89 rpm during a 1. category mountain ascent in Tour De France.[17] Slope also influences the freely chosen cadence. As an example, the freely chosen cadence in 8 well-trained cyclists was on average 91 and 59 rpm during flat and uphill cycling, respectively, at a power output of on average 280-292 W.[21] For a more thorough review of factors external and internal to the cyclist, which affect the freely chosen cadence, the reader is referred to a previously published review article.[22]

Terms like "heavy low cadence training" or "functional strength training" signals that this kind of training has a substantial effect on muscle strength. Further, that any potential performance enhancing effect is related to mechanisms involved in adaptations to heavy strength training. However, the effect on maximal muscle strength of cycling training at imposed low cadence is rarely investigated. In the few cases where it has been investigated, there seems to be no effect on maximal muscle strength.[7, 8] The seemingly lack of effect of imposed low cadence training on maximal strength is due to the relatively low force development during low cadence cycling as compared to the maximal force capacity of the leg muscles. In that context, 40-60 repetitions per min for 5-20 min is more similar to endurance training than to heavy strength training. Therefore, potential mechanisms underpinning positive effects of heavy strength training on endurance performance, including increases in maximal strength, rate of force development and muscle mass (reviewed previously),[23, 24] are somewhat unlikely to explain any potential benefits of training at imposed low cadence. It should be noted that the study by Konincks et al. (2010) indicated that it is possible to obtain almost similar performance enhancing effects from heavy strength training and cycling at imposed low

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cadence when the protocol for the latter aims at maximal force production for a short duration of time. In addition from a strict scientific point of view, it should be remarked that the two studies by Konincks et al. (2010) and Paton et al. (2009) did not include control groups, which trained with freely chosen cadence. Therefore, for these two studies we cannot conclude that intervals performed at imposed low cadence are more advantageous than the same intervals performed at the same intensity at a freely chosen cadence.

The power output is the most important variable to improve with regard to performance, but the study by Whitty et al. (2016) highlights some potential different adaptations by imposed low and high cadences. Further, this indicates that a combination of high and low cadence training might be a good choice. Nimmericher et al. (2012)[13] observed no differences between high and low cadence training on improvements of indicators of performance, but they too noticed a slight advantage of low cadence training on overall time trial performance. It might be speculated that there are some slight effects of the low cadence training that are only detectable when the cyclists are becoming quite fatigued as compared to standard indicators of performance being tested in a more unfatigued condition. Cycling at a low cadence increases quadriceps muscle activation[25] and recruitment of type II muscle fibres[26] as compared with cycling at a higher cadence at the same power output. Therefore, it can be speculated that cycling at imposed low cadences results in increased neuromuscular stimulus and an increased stimulus on type II muscle fibres. It could also be suggested that during imposed low cadence bouts at all-out intensity for 15-30 s (like applied in the studies by Koninckx et al. (2010)[8] and Paton et al. (2009)[9]), type IIX fibres can be activated and thus converted to the more efficient type IIA fibres. Indeed, heavy strength training induced a decrease in the proportion of type IIX fibres that was associated with improvement of power output during a 40-min all-out trial in well-trained female cyclists (r=–0.63).[27] This potential mechanism can, in theory, have a larger effect on performance than on indicators of performance.

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By imposing low or high cadences during cycling, a number of acute responses can be influenced. These responses can turn out to be of relevance with respect to for example the loading, perception, function, and performance of the cyclist. As a consequence, the cadence applied during training can affect the training adaptation. The following paragraphs focus on responses in some selected key variables of biomechanical and physiological characteristics.

When cycling at a constant power output, pedal force increases with a decrease in cadence.[28, 29] In terms of magnitude of force, peak pedal force amounted to approximately 440 N during cycling at 61 rpm at a power output of 260 W.[19] That force corresponded to approximately 47% of the peak pedal force applied during cycling at maximal effort at the same cadence.[19] Similar absolute values of pedal force have been reported by others.[29] It is possible that a change from high to low cadences, and thereby from low to high pedal forces, shifts the muscle fibre recruitment pattern in direction of more type II muscle fibre and less type I fibre recruitment. This is supported by a previous report of more glycogen depletion of type II muscle fibres after cycling at 50 rpm as compared to 100 rpm at an intensity of 80% of the VO_{2max}.[26]

Brain activity also varies with cadence. As an example, the cerebral activation during ergometer cycling was investigated by oxygen-15-labelled H_2O positron emission tomography (PET) in 7 healthy individuals.[30] The study showed that compared to rest, active cycling at an ergometer "loading" of 1-12 kg (corresponding to not stated power outputs) significantly activated sites bilaterally in the primary sensory cortex, primary motor cortex, supplementary motor cortex and the anterior part of cerebellum. Comparing passive cycling movements with rest, an almost equal activity was observed. When subtracting activity recordings during passive cycling movements from recordings during active cycling, significant activity was only observed in the leg area of the primary motor cortex and the precuneus, whereas not in the primary sensory cortex. The primary motor cortex activity was positively correlated with the

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cadence of the active cycling. However, with regard to that particular result, it should be noted that power output was most likely increased with increasing cycling cadence as load rather than power output was maintained constant. Imagination of cycling, compared to rest, activated bilaterally sites in the supplementary motor cortex. Christensen et al. (2000)[30] suggested that higher motor centres, including the primary and supplementary motor cortices as well as the cerebellum, take an active part in the generation and control of rhythmic motor tasks such as cycling. Still, it was also noted by the authors that perhaps the main part of the cerebral activity observed during the passive cycling was in fact caused by the sensory feedback evoked by the moving limbs and that a similar mechanism also explains a very significant part of the cerebral activity during active cycling. As another example, functional magnetic resonance imaging (fMRI) was applied to record human brain activity during ergometer cycling at 30 rpm, 60 rpm, a variable cadence, and during passive pedalling at 30 rpm.[31] Ten healthy adults participated and exercised at, again, a not stated power output. After identifying regions of interest, the intensity and volume of brain activity in each region was calculated and compared across conditions. The results showed that the primary sensory and motor cortices, supplementary motor area and cerebellum were active during cycling. The intensity of activity in these areas increased with increasing cadence and complexity. The cerebellum was the only brain region that showed significantly lower activity during passive as compared to active cycling. The authors concluded that primary sensory and motor cortices, supplementary motor area and cerebellum have a role in modifying continuous, bilateral and multi-joint lower extremity movements, and further, that much of this brain activity may be driven by sensory signals from the moving limbs. A recent study highlights the importance of including high cadence cycling in the training.[32] That study found enhanced neural efficiency, in the form of reduced cortical activity, after training at imposed high cadence while not after low cadence training.[32] This adaptation might allow a reservation of cortical resources for for extending the

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cycling or increasing the power output and therefore enhancing the capacity for allocating resources in a sports-specific task.[32]

Electromyographic activity is yet another variable that varies with cadence. As an example, surface linear envelope electromyographic activity normalized to electromyographic activity during isometric maximal voluntary contraction was investigated in 11 healthy individuals during ergometer cycling at 0-240 W at 40-100 rpm.[33] The study showed that an increase in cadence increased the electromyographic activity over the gluteus maximus, gluteus medius, vastus medialis, medial hamstring, gastrocnemius medialis, and soleus muscles. As another example, root-mean-square electromyographic activity was investigated from 7 leg muscles in 8 active male individuals during ergometer cycling at 100-400 W at 50-120 rpm.[34] The study showed that a second-order polynomial equation fitted the average root-means-square electromyographic activity data of all muscles vs. cadence (r^2 ranging from 0.870-0.996) for each power output. The cadence with the lowest amplitude of electromyographic activity (denoted the optimal cadence by the authors) for a given power output increased with increases in power output from on average 57 rpm at 100 W to on average 99 rpm at 400 W. Thus, cycling at low cadences results in relatively high values of muscle activation.

VO_2, energy turnover, and efficiency all vary with cadence. Values of VO_2 can be converted to estimates of rate of energy turnover, alternatively termed metabolic power output, by taking into account respiratory exchange ratio. Further, when mechanical power output is known from cycle ergometer recordings, gross efficiency can be calculated.[35] In addition, alternative forms of efficiency can be calculated. These can, for example, account for estimates of "internal power", generated by muscles to overcome energy changes of moving body segments, and/or account for the resting VO_2.[36, 37] When VO_2 is depicted as a function of cadence, the relationship is approximately U-shaped.[38] For comparison, the relationship is inverted-U-shaped when gross efficiency is depicted as a function of cadence [39]. The cadence

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with the lowest VO_2 or highest gross efficiency can be termed the energetically optimal cadence and it occurs at approximately 50-80 rpm. Thus, cycling at lower cadences results in relatively high values of VO_2 and energy turnover as well as low values of efficiency. In more details, the energetically optimal cadence increases with increasing exercise intensity.[40] The exact reasons for VO_2 to be relatively high at low and high cadences are unknown. However, it is possible that a large type II muscle fibre recruitment at low cadences[26] accounts for the high VO_2 in that condition since type II muscle fibres are less efficient than type I muscle fibres.[19, 35] Besides, it is possible that high internal power accounts for the high VO_2 during cycling at relatively high cadences.[37]

Perceived exertion also varies with cadence and constitutes the final variable reviewed here. Subjective rating of perceived exertion (RPE) during exercise can be determined by having individuals indicating their rating on a 15-point (6-20) scale.[41] As an example, overall RPE was investigated in 6 healthy male individuals during ergometer cycling at a range of cadences from 40-100 rpm at two power outputs corresponding to 70% and 100% of VO_{2max}.[42] After fitting of parabolic curves to the group average scores, the RPE data revealed U-shaped relationships. Minimum RPE-values occurred at 65 and 73 rpm at the low and high power output, respectively. As another example, overall RPE was investigated in 20 healthy males during treadmill cycling at a range of cadences from 61-115 rpm at two power outputs corresponding to 40% and 70% of the power output at which VO_{2max} was attained.[19] After fitting of second-degree polynomials to the group average scores, the RPE-data revealed parabolic relationships with minimum RPE values occurring at 63 and 72 rpm at the low and high power output, respectively. Thus, cycling at cadences below 60 rpm results in relatively high RPE-values.

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Limitations

Based on the chapters above, it appears challenging to firmly point at certain recommendable commonalities in the training regimens. The reasons are for example that there is a considerable variation between studies in participant characteristics, as well as in study design and applied procedures. Other limitations with regard to interpretation of the outcomes of the selected studies are that some articles are missing key information on for example the time of the year at which the study was conducted, the training performed prior to the intervention, as well as on the training performed in addition to the specific intervention. Besides, some of the studies lack a pure control group, which merely should have continued the usual training.

Suggestions for future research

More research is needed to enhance our knowledge on adaptations to cycling training at different imposed cadences. Especially, research is needed that in particular systematically investigates the influence of the following variables:

- training background and fitness status of the studied participants.
- season in which the training is performed (pre-, in-, or post-competition).
- duration of the training period.
- characteristics of the applied training regimens including for example the frequency of training, the duration and number of bouts, the intensity of training, and the applied cadences.
- training and/or races performed in addition to the specific imposed cadence intervention.

In addition, it appears relevant to include a control group that simply continues the usual training (as done by Nimmerichter et al., 2012[13] and Ludyga et al., 2016[10]) or performs similar

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intervals (at the same intensity, but at a freely chosen cadence) as the different high/low cadence groups.[7]

Such new research will be useful with regard to providing additional valuable information on how different groups of individuals can benefit from cycling training at different imposed cadences.

Practical applications

With respect to practical applications, it is first and foremost worth noting that training at a large range of cadences, from very low to very high, probably will be beneficial for performance in competitive cycling. A reason is that work demands in competitive cycling are multifaceted and include pedalling at both low and high cadences. Furthermore, from a practical point of view, it appears to make sense for a single individual cyclist to perform a particular kind of cycling training if that training is assessed to improve the cyclist's performance. Though, to be able to provide evidence-based training advice, which can be recommended for cyclists in general, it is necessary to evaluate randomized controlled studies involving groups of cyclists. That was the focus of the present review.

Conclusions

To conclude, new knowledge was obtained from the present systematic review. Seven original articles were considered relevant and selected for further evaluation. The 7 articles contained information on adaptations in endurance performance (and in indicators of endurance performance) to cycling training at different imposed cadences, including low cadence. For example, competitive male cyclists who trained 30-s bouts at maximal effort at low cadence (60-70 rpm) twice per week for 4 weeks obtained increased peak power in an incremental cycling test as well as increased power output at set submaximal physiological responses.[9] In addition, healthy sedentary males who trained 60-min bouts at low cadence (35 rpm) 5 times per week for 2 weeks improved their power output at the lactate threshold.[5] Another study

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observed no differences in training adaptations between groups of cyclists that performed high and low cadence training,[10] while yet another actually favoured freely chosen cadence training over low cadence training in cyclists.[7] There is presently no strong evidence for a benefit of training at low cadences. The overall interpretation is that it tentatively can be recommended to consider including training bouts of cycling at low cadence at moderate to maximal intensity.[6, 8, 9, 13] The reason for the restrained recommendation is the following. Some of the selected studies indicate no clear performance enhancing effect of training at low cadence or even indicate a superior effect from training at freely chosen cadence. Furthermore, the selected studies are considerably dissimilar with respect to for example participant characteristics as well as to the applied training regimens.

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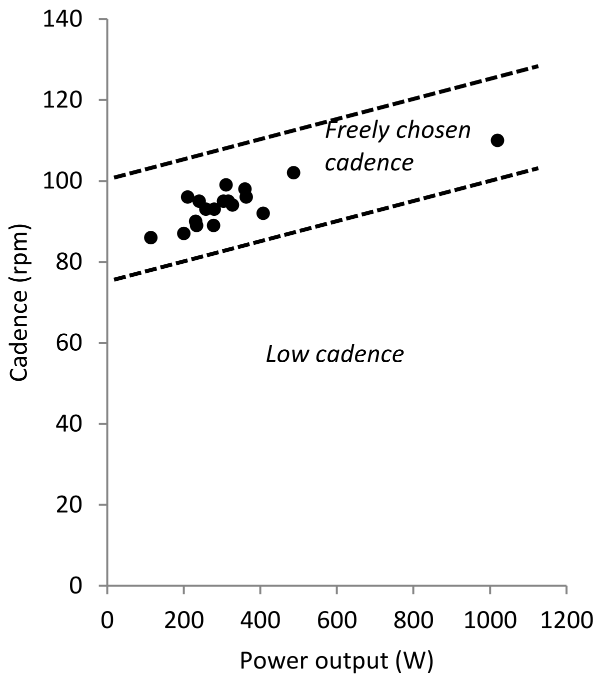

Figure 1. Cadence is presented as a function of power output. Data constitute a representative selection of average published values of freely chosen cadences for cyclists during cycling at a range of power outputs on ergometer, treadmill, or road. Data are taken from a number of previously published articles.[18, 43-50] The figure illustrates that the freely chosen cadence increases with increasing power output. This means that the term "low cadences" in the present article represents cadences below a value, which is not set but rather increases with power output as the freely chosen cadence.

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Table 1. Key information from the 7 articles, which were selected based on the systematic literature search.

Article	Participants	Duration of training period etc.	Training regimens	Major outcomes
Paton et al. (2009)[9]	Competitive male cyclists with a minimum of three years competitive experience (*n*=18) participated. Average values of age, body mass, VO_{2max}, and maximal incremental power output were 25.9 years, 81.2 kg, 4.46 l min^{-1}, and 388 W, respectively.	The training intervention lasted 4 weeks. The study was performed in the main competitive phase of the year, during which all cyclists were competing in endurance (>60 min) road or mountain bike races at least once per week. The cyclists had not participated in any gym-based strength training in the 3 months before the study.	The cyclists were divided (matched pairs) into 2 groups. One group performed training at low cadence. Another group performed training at high cadence. Both groups continued their usual competition program, but replaced part of their usual training with 30-min laboratory training sessions performed on an ergometer. The sessions were performed twice per week and consisted of 3 sets of maximal effort single-leg jumps alternating with 3 sets of maximal intensity cycling efforts. The jump part of the training required subjects to perform 20 explosive step-ups off of a 40-cm box. The jump efforts were completed for the right and then left legs consecutively over a 2-min period. The cycling part required the cyclist to complete 5×30-s maximal intensity cycling efforts at 500-520 W at a cadence of either 60-70 rpm or 110-120 rpm with 30-s recovery between repetitions. A transition period of 2 min separated each cycle and jump set. During the study period, the cyclists spent approx. 10-15 h wk^{-1} of training and competing.	The low cadence group, as compared to the high cadence group, displayed on average 3.6 percentage points larger increase in peak power in an incremental test. The better training response in the low cadence group was termed "likely beneficial". In line with that, the low cadence group displayed on average 7 percentage points larger increase in power output at 4 mM blood lactate, which was termed "very likely beneficial". Further, VO_{2max} improved on average 3.3 percentage points more, which was termed "likely beneficial". Finally, exercise economy at 50% of the maximal incremental peak power output improved on average 5.1 percentage points more, which was termed "likely beneficial".
Kon-inckx et al. (2010)[8]	Trained male cyclists (*n*=20) with an average of 6 years of experience and 7,111 covered km per year during those years. Average values of age, height, body mass, VO_{2max}, and maximal incremental power output were 27 years, 1.82 m, 74.0 kg, 60 ml kg^{-1} min^{-1}, and 305 W, respectively.	The training intervention lasted 12 weeks. The study was performed in the off-season following a 3-week period rest period. The cyclists on average trained endurance for 4-5 h $week^{-1}$ in addition to the specific training intervention. The cyclists had no prior experience with the specific training.	The cyclists were divided (matched pairs) into 2 groups. One group performed conventional strength training (3 sets of parallel half-squat and leg press exercises at 15RM-8RM) for leg extensor muscles. Another group performed maximal effort isokinetic cycling in 4-8 bouts of each 12 crank revolutions at 775-875 W at 80 rpm. Recovery between bouts was 3 min. Isokinetic cycling was performed on a custom-built ergometer. Both groups performed the specific training twice per week.	The two different training groups increased average power output by a similar magnitude (5-8%) in a 30-min endurance performance test. In line with that, lactate threshold power output and peak power output obtained in an incremental test were increased to similar extents for both groups. The isokinetic (low cadence) group did not increase maximal power output during isokinetic cycling at 120 rpm. That was in contrast to the strength training group.
Nimme-richter et al. (2012)[13]	Trained male cyclists (*n*=18) with a training history of at least 5 years participated. Average values of age, height, body mass, VO_{2max}, and maximal incremental power output were 31 years, 1.79 m, 72.6 kg, and 58.4 ml kg^{-1} min^{-1}, and 392 W, respectively.	The training intervention lasted 4 weeks. The cyclists on average trained for 12 h $week^{-1}$ during 12 weeks prior to the study.	The cyclists were randomised into 3 groups. One group performed uphill interval training at a low cadence (60 rpm). Another group performed level-ground interval training at a high cadence (100 rpm). The training was performed in two interval-training sessions per week. Intervals were performed as 6×5 min at 300 W, with 5 min recovery periods at 90-150 W. A third group acted as controls and continued their steady training, without performing any intervals. Training was performed on the road. During the study period, the cyclists spent approx. 7-16 h wk^{-1} of training.	The low cadence group increased power output during both an uphill time trial (4.4±5.3%) and a flat time trial (1.5±4.5%). For comparison, the changes were -1.3±3.6 and 2.6±6.0%, respectively, for the high cadence group. For the third group, the changes were 4.0±4.6% and -3.5±5.4%, respectively. Time trials were performed on the road and lasted approx. 20 min. The authors stated that these findings suggest that higher forces during the low-cadence intervals are potentially beneficial for performance enhancement.

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Article	Participants	Duration of training period etc.	Training regimens	Major outcomes
Kristof-fersen et al. (2014)[7]	Well-trained male veteran cyclists (*n*=22) participated. Average values of age, body mass, VO_{2max}, and maximal incremental power output were 47 years, 78 kg, 57.9 ml kg^{-1} min^{-1}, and 402 W, respectively.	The training intervention lasted 12 weeks. The study was performed post season.	The cyclists were randomly assigned into 2 groups. One group performed training at low cadence (40 rpm). Another group performed training at freely chosen cadence. The low cadence group performed interval training as group sessions on spinning bikes, twice a week, in addition to their usual training. Intervals were performed as 5×6 min at 73-82% of the maximal heart rate, with 3 min active recovery periods at low intensity (60-72% of maximal heart rate) and freely chosen cadence. In total, the low cadence group added 60 min week^{-1} of training to the usual training. The freely chosen cadence group added 90 min of cycling at moderate intensity (73-82% of maximal heart rate) and freely chosen cadence to their usual training. In total, the cyclists in the low cadence training group on average completed 91h of training during the 12 weeks, while the cyclists in the freely chosen cadence group completed on average 88 h of training.	The low cadence group did not improve VO_{2max}, maximal incremental power output, average power output in a 30-min cycling trial, and leg strength. For comparison, the freely chosen cadence group seemed to adapt in a beneficial way with respect to physiological adaptations (e.g. increased VO_{2max}) and performance (e.g. increased average power output in a 30 min cycling trial). Tests were performed at freely chosen cadence.
Hirano et al. (2015)[5]	Healthy, sedentary males (*n*=16) participated. Average values of age, height, body mass, VO_{2max}, and maximal incremental power output were 23.4 years, 1.71 m, 64.3 kg, 46.1 ml kg^{-1} min^{-1}, and 258 W, respectively.	The training intervention lasted 2 weeks.	The participants were randomly assigned into 2 groups. One group performed training at low cadence (35 rpm). Another group performed training at high cadence (75 rpm). Sixty-min training sessions were performed 5 times per week. Training was conducted on an ergometer at a power output at lactate threshold (corresponding to on average approximately 63 W).	The low cadence group displayed increased power output during cycling at 50 rpm at the lactate threshold after the training period. The same did not occur for the high cadence group.
Ludyga et al. (2016)[10]	Male and female cyclists (*n*=36) participated. Average values of age, height, body mass, VO_{2max}, and maximal incremental power output were: 27 years, 1.77 m, 71.8 kg, 52.6 ml kg^{-1} min^{-1}, and 310 W, respectively.	The training intervention lasted 4 weeks. The cyclists had trained at least 4 h week^{-1} of cycling during the 6 months before the study.	The cyclists were randomly assigned into 3 groups. All groups performed 4 h week^{-1} of cycling training. The average intensity of the training was 70-80% of the heart rate at the lactate threshold. One group performed training at low cadence (60 rpm). Another group performed training at high cadence (120-140 rpm). A third group acted as controls and performed basic endurance training. The training of the low and high cadence groups consisted of 4 weekly 60-min sessions. Two of the sessions were completed at constant load, while two other sessions contained 6-8 intervals of 3-min bouts at high intensity at 60 rpm or 120-140 rpm. Recovery between bouts consisted of 3 min of pedalling. Training was performed on an ergometer.	In contrast to the control group, the low and high cadence groups attained similar improvements of VO_{2max} and power at the lactate threshold. Besides, there was a reduction of alpha-, beta-, and overall-power spectral density in the high cadence group, which was more pronounced at high cadences. Improvements of variables associated with endurance performance were correlated with reductions of EEG spectral power at 90 and 120 rpm.
Whitty et al. (2016)[6]	Endurance-trained male cyclists (*n*=16) participated. Average values of age, body mass, VO_{2max}, and maximal incremental power output were 31.4 years, 74.6 kg, and 4.85 l min^{-1}, and 364 W, respectively.	The training intervention lasted 6 weeks.	The cyclists were randomly assigned into 2 groups. One group performed training at low cadence (20% below their freely chosen cadence, corresponding to 60-81 rpm). Another group performed training at high cadence (20% above their freely chosen cadence, corresponding to 96-121 rpm). Three interval sessions were completed each week. Each session lasted 45-60 min and included 4-6×4 min bouts at 70% of the maximal incremental power output corresponding to on average approximately 255 W. Recovery between bouts consisted of 2 min of pedalling at 100 W. The training described above replaced a part of the usual training and was performed on an ergometer. The cyclists trained >300 km wk^{-1}.	The low cadence group, as compared to the high cadence group, displayed a larger increase (on average 16% vs. 8%) of the average power output in a 15-min time trial performed at freely chosen cadence. The high cadence group increased the freely chosen cadence from on average 92 to 101 rpm during submaximal cycling at 60% of the maximal incremental power output. For comparison, no change occurred in the low cadence group. Both groups increased the VO_{2max} and maximal incremental power output during the training period. The high cadence group displayed an increased gross efficiency at 90 and 110 rpm.

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