Variable power pacing decreases finishing time compared to constant pacing in cycling time trials: A systematic review and meta-analysis

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ABSTRACT

Aims

This meta-analysis aims to evaluate the effects of variable pacing strategies for outdoor cycling time trials in relation to reducing event time by optimising power distribution in parallel with course characteristics. Secondly, this meta-analysis seeks to compare the proposed time savings of variable pacing strategies to constant pacing during cycling time trails.

Methods

Pubmed, SportsDiscus and Scopus were used with the academic search engines Google Scholar and ResearchGate. The databases were searched for randomised control trials and repeated measures design studies and any other study type which met the inclusion criteria. Two repeated measures design studies, one randomised control trial and eight mathematical modelling and simulation studies were included after screening a total of 281 studies. Sample sizes range from 1-20 consisting of either mathematically modelled cyclists or well trained racing cyclists.

Results

Three different variable pacing strategies were explored (5%, 10% and 15% power variation) concerning three different course lengths; 10, 16.1 and 40-km. For all course profiles and conditions where it was possible, a 15% variation in power output resulted in the most significant time savings compared to constant pacing. The standardised mean difference for 15% variability for a 10-km time trial was -77.682 (s). For 40-km the time saving was -63.684(s). For courses where a 15% variation in power was not

achievable (e.g. courses with long steep uphill segments where a 15% variation would result in a power output significantly above critical power output) a 10% variation power resulted in the biggest time-saving.

Conclusion

The primary finding of this meta-analysis was that variable pacing strategies applied in parallel to course characteristics will always result in a significant time saving compared to constant pacing. Cyclists should aim to vary power output by 15% to experience maximal time savings. However, for a variation in power to be successful, it needs to be applied in parallel to course characteristics (course profile or wind conditions). A variable pacing strategy based on distance and irrespective of course characteristics was always detrimental to performance.

Keywords: Cycling, Time trial, power output, pacing, strategy, *physiology*

INTRODUCTION

Changes in environmental conditions have previously been reported to have a significant impact on cycling speed (Atkinson et al., 2003). In outdoor cycling time trial races where the environmental conditions are often highly variable, prior research has calculated that pacing strategies which attempt to maintain a constant speed should equal a faster average velocity compared to pacing strategies which focus on a constant effort or power output. (Atkinson and Brunskill 2000; Atkinson et al., 2007a; Martin et al., 1998). Past literature indicates that the possible time advantage of variable power output pacing strategies is proportional to the magnitude and frequency of changes in environmental resistive forces, most commonly changes in road gradient, wind speed and wind direction. (Atkinson et al., 2003)

In recent years there has been extensive research into different pacing strategies in an attempt to optimize cycling time trial race performance by decreasing finishing time. Most commonly, constant power output pacing strategies have been explored concerning maintaining a constant percentage of critical power depending on race distance or predicted race time. However, the theory behind a variable pacing strategy is to attempt to minimize the overall variation in speed experienced as a result of environmental characteristics. (Atkinson and Brunskill 2000) Subsequently, a variable pacing strategy seeks to solve the time trial course as an optimal control problem (Fayazi et al., 2013) and to achieve the fastest time power is varied in response to changes in course gradient and wind conditions.

Swain 1997 was one of the first investigators to draw attention to the mechanical performance advantage that could be obtained by varying power output (expressed as $\text{VO}_{2\text{max}}$) in response to variance in wind and gradient. Some of the original research on variable pacing strategies calculated time savings to be 4-8% of total time on a 10km course with ten symmetrical climbs. With a variable pacing strategy, the athlete will experience increased oxygen consumption (VO_2) and increased blood lactate concentration (HLA) during periods of increased effort where the power exceeds the cyclist's critical power. (Abbiss et al., 2006) Therefore it is unclear if the proposed time savings of a variable pacing strategy outweigh the possible detrimental physiological costs which result from periods of increased effort compared to constant pacing.

However, some studies have shown that variable pacing strategies have no effect on finishing time or increase finishing time for certain course types. It has been documented that some professional cyclists use variable pacing (Smith et al., 2001). However, it is currently unclear if amateur cyclists with a lower

average power output will experience the same time advantages that are experienced at high average power outputs. Other considerations need to be accounted for when deciding if a variable pacing strategy will be beneficial for a chosen course. It is unclear how varying the environmental conditions need to be for a variable pacing strategy to be beneficial compared to constant power output pacing. Equally, it is unknown how detrimental the periods spent above critical power when increasing the effort regarding course changes, are to race finishing time and at what point a variable pacing strategy becomes negative to the performance because of an overall increased effort.

In recent years there have been several attempts to make it easy to use computerized models available to the public to help optimise time trial pacing. The most prominent of these models is the maths and physics engine best bike split. (BestBikeSplit, 2020) The software allows individuals to input known course data and known system variables (cyclists and bike data) to identify possible power distribution models to reduce event time when posed as an optimal control problem. However, there are still many problems with this system such as how much individuals should vary their power by, having to remember all the different power output segments and then being able to execute that pacing strategy during a race environment. Therefore, this systematic review and meta-analysis will perform a qualitative evaluation of the effectiveness of variable pacing strategies regarding its ability to reduce race finishing time in outdoor cycling time trials, when compared to constant pacing strategies.

Methods

Search strategy

A systematic literature search on articles published up to 01/08/2020 was carried out in the electronic databases Pubmed (MEDLINE), SportsDiscus and Scopus. Additionally, both academic search engines Google Scholar and ResearchGate were used to identify studies that met the inclusion criteria. A search strategy was developed using the Pico model (Costa Santos et al., 2007; Eriksen et al., 2018). The PICO model is an evidence-based process used for framing a question using the following system: identifying a problem, creating an intervention, comparing pre and post-intervention and measuring the outcome of interest. Depending on the capabilities of the databases the Boolean operators "AND" and "OR" were used to combine multiple search terms. Throughout the search query, several search combinations were applied in an attempt to analyse all relevant articles and scientific material. However, Mesh search terms are not supported in the Scopus database. Subsequently, a modified search was conducted on this platform. Key terms searched included: "cycling", "time trial", "pacing" and "strategies".

Figure 1 Prisma Flow Diagram (Moher et al., 2010)

Quality Assessment Tool for Before-After (Pre-Post) Studies With No Control Group													
	Was the study question or objective clearly stated?	Were eligibility/criteria for the study population prespecified and clearly described?	Were the participants in the study representative of those who would be eligible for the test/service/intervention in the general or clinical population of interest?	Were all eligible participants that met the prespecified entry criteria enrolled?	Was the sample size sufficiently large to provide confidence in the findings?	Was the test/service/intervention clearly described and delivered consistently across the study population?	Were the outcome measures prespecified, clearly defined, valid, reliable, and assessed consistently across all study participants?	Were the people assessing the outcomes blinded to the participants' exposures/interventions?	Was the loss to follow-up after baseline 20% or less? Were those lost to follow-up accounted for in the analysis?	Did the statistical methods examine changes in outcome measures from before to after the intervention? Were statistical tests done that provided p values for the pre-to-post changes?	Were outcome measures of interest taken multiple times before the intervention and multiple times after the intervention (i.e., did they use an interrupted time-series design)?	If the intervention was conducted at a group level (e.g., a whole hospital, a community, etc.) did the statistical analysis take into account the use of individual-level data to determine effects at the group level?	
Cangley et al., 2011	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	NO	NO	9/12
Atkinson et al., 2007	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12
Boswell 2012	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12
Atkinson et al., 2007b	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	NO	NO	9/12
Wells and Marwood 2016	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	9/12
Atkinson and Brunsell 2000	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	NO	NO	9/12
Yamamoto (2018)	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12
Wells et al., 2013	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12
Gordon 2005	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12
Sundstorm et al., 2013	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12
Swain 1997	YES	No	YES	YES	No	YES	YES	NO	YES	YES	YES	NO	8/12

Table 1 NIH Quality Assessment Tool For Before-After (Pre-Post) Studies With No Control Group

Selection criteria

The previously defined search strategy produced a total of n=340 studies. After removing duplicate articles, the total equalled n=281. The first stage of inclusion criteria refinement involved reviewing study titles and then abstracts. Study selection was based on the following inclusion criteria: articles must be written in English and variable versus constant power output during real-world or simulated time trials must be a primary focus of the study. Furthermore, studies had to define and give values for all of the variables that were used to create the mathematical model or simulation of the time trial including but not limited to: coefficient of drag area (Cda), Coefficient of rolling resistance (Crr) Power (w). The study also had to include a detailed description and or imagery of the course profile used for each time trial simulation. Another element of the criteria was that all included studies must present both baseline pacing strategies and optimised pacing strategies clearly either in a data table or graph. Studies were excluded if the time trial was completed on a velodrome or if all simulated courses were unlike real-world conditions such as completely flat and windless. Articles were only included in the full-text review if their title and abstract matched the fundamental demands of the inclusion criteria. After the final selection, the total number of included studies equalled n=11. All eligible papers were screened via analysing the full text and making a record in an excel spreadsheet of all the pivotal information and characteristics of the study.

Quality assessment

After analyzing all 340 identified studies through the search strategy and narrowing down the selection at each stage of the inclusion/exclusion criteria the total number of included studies was n=11. Using a modified version of the 11 step Pedro Scale (Costa Santos et al., 2007; Eriksen et al., 2018; Morton 2009), the studies were assessed for any possible risk of biases and overall quality.

Inclusion/exclusion criteria

Study design: Full-text articles of Repeated measure design, Randomised control trial and Mathematical modelling and simulation design studies which focused on constant versus variable power output pacing strategies implemented in both real-world outdoor time trials and simulated time trials with road gradient changes or wind speed changes. Studies were excluded if deemed to be review articles or conference abstracts. Studies were included if the time trials compared constant power output pacing strategies with variable power output pacing strategies for time trials with either variable gradients or variable wind conditions. Moreover, studies needed to provide a detailed report of course characteristics as well as baseline pacing strategy (constant) and the optimised pacing strategy (variable) and the differences between the two regarding potential effects on finish time, segment time mean power and normalised power.

Population: Men (n=43) age 27.7 ± 6.1 (years), system mass 75.125 ± 1.6 (KG), aerodynamic drag was modelled to be 0.246 (Cda), and rolling resistance equalled 0.00276 (Crr), who identified as either recreationally trained or simulated mathematically modelled cyclists.

Outcome measures

All the studies included in the meta-analysis were *Cangley et al., 2011; Atkinson et al., 2007a; Boswell 2012; Atkinson et al., 2007b; Wells and Marwood 2016; Atkinson and Brunskill 2000; Yamamoto 2018; Wells et al., 2013; Gordon 2005; Sundstorm et al., 2013 and Swain 1997.*

The outcomes of this meta-analysis were:

- Time trial (TT) finishing time (in seconds) data was split into different groups depending on TT distance (KM) either 10, 16.1 or 40 KM.
- Power output (w). For real-world time trials, average power and normalised power were reported for the whole TT duration as well as specific course segments. For mathematically modelled TTs a variety of power outputs were tested, commonly in steps of 100w.
- Level of power variability (reported as a percentage of baseline power) data was split into different groups depending on how much the power varied either by 5%, 10% or 15%.

Data extraction and statistical analysis

Fundamental information and critical study data were extracted into a standardised spreadsheet which included: Author name and year, study title, the database where the study was found, study type, sample size, the experience level of the participant, distance, intervention group characteristics, control group data, intervention method, outcome measures, performance test, statistical analysis and how can the data be compared to data found in other included studies.

Additionally, an enhanced data collection process occurred, the data fields for this included: course characteristics (including distance, net elevation and segment elevation), finish time data (the difference between the baseline, constant power, pacing strategy and variable power pacing). All raw data for segment timings and whole course timings were compiled to calculate effect sizes for 5%, 10% and 15% power variation to report the reduction in finish time for cycling time trials.

The meta-analysis was conducted by exporting all publicly accessible raw data for the selected outcome measures into a customised spreadsheet to calculate the difference between optimal pacing strategies compared to constant power output pacing strategies. Once the effect size for variable versus constant pacing for each subgroup had been calculated, the data was imported into the Meta-Essentials excel software package (Hak et al., 2018). Subsequently, calculated effect sizes were analysed using the effect sizes analysis package inside Meta-essentials. Data analysis was divided into different percentages of power variability, 5%, 10% and 15%, as well as different course distances 10, 16.1 and 40-km. The meta-analysis was presented by mean versus graphs created in excel. The graphs show different effect sizes and data points were colour coded and separated into different categories spending on power output or study type.

Heterogeneity: To evaluate heterogeneity in the 11 studies, the I² statistic (Borenstein et al., 2017) was used with values >50% demonstrating substantial heterogeneity (Higgins 2003). Additionally, the risk of publication bias was analysed by using the Egger plot. (Egger 1997) The effect of heterogeneity largely depends on the total number of studies included in the meta-analysis. In the case of this meta-analysis, the total included number of studies equalled 11. Consequently, the statistical power of the findings of this study may be limited. Therefore, a 95% confidence interval (CI) was chosen. (Huedo-Medina et al., 2006; Thompson 1999)

Study quality: Study quality and reporting were assessed using the previously validated TESTEX scale (Smart, 2015). The scale consists of a 15-point scale which evaluates the randomised control trial elements of a particular study (a total of 5 points is available for this section), and the quality of data and information reporting within the study (10 points in total for this section). An article with a TESTEX quality score of less than ten was deemed of low study quality.

	Cangley et al., 2011	Atkinson et al., 2007	Boswell 2012	Atkinson et al., 2007b	Wells and Marwood 2016	Atkinson and Brunskill 2000	Yamamoto 2018	Wells et al., 2013	Gordon 2005	Sundstorm et al., 2013	Swain 1997
Eligibility criteria specified	1	1	1	1	1	1	1	1	1	1	1
randomisation details specified	1	0	0	1	0	1	0	0	0	0	0
Allocation concealed	1	0	0	1	0	1	0	0	0	0	0
Groups similar at baseline	1	1	1	1	1	1	1	1	1	1	1
Assessors blinded	1	0	0	1	0	1	0	0	0	0	0
Outcome measures assessed >85% participants	3	3	3	3	3	3	3	3	3	3	3
Intention to treat analysis	1	1	1	1	1	1	1	1	1	1	1
Reporting between group statistical comparison	1	1	1	1	1	1	1	1	1	1	1
Point measures & measures of variability	1	1	1	1	1	1	1	1	1	1	1
Activity monitoring in control group	1	0	0	1	0	1	0	0	0	0	0
Relative exercise intensity constant	1	1	1	1	1	1	1	1	1	1	1
Exercise volume & energy expenditure	1	1	1	1	1	1	1	1	1	1	1
Overall TESTEX score (/15)	14	10	10	14	10	14	10	10	10	10	10

Table 2 TESTEX study quality (Smart, 2015)

Results:

Context

Two primary outcome measures were analysed, time trial finishing time and power output.

The primary outcome measure of time trial finishing time aimed to identify if adopting a variable pacing strategy (increase or decrease of power in parallel to wind and or gradient changes) reduced overall time trial finishing time when compared to a constant power pacing strategy.

Description:

The results from the meta-analysis indicate that for courses with changing environmental characteristics, a variable pacing strategy performed in parallel with the changes will always reduce time to complete the time trial course compared to constant pacing. (Atkinson et al., 2007a) The data shows that a variable pacing strategy will only reduce competition time if used in parallel with the change in wind conditions or gradient. The statistical findings report that a 15% variation in power resulted in the most significant time saving compared to constant pacing. However, the statistical findings demonstrate that a 15% variation in power approach only works for a short duration. (Smith et al., 1999) When the cyclist has to increase power output by 15% for long durations, increased physiological strain occurs from cycling above critical power (CP) for a prolonged time. If the power required from the pacing strategy is sufficiently above critical power then w'_{prime} becomes the main factor when determining if riding at that power is a feasible strategy. This is arguably the primary limitation of variable pacing strategies, if the cyclist spends too much time putting out power above critical power, then their power output and cycling performance for the rest of the race will be severely compromised.

Furthermore, if power is varied by distance (1-2-km segments where power increases to achieve a higher total average speed for the whole course) and not in relation to environmental conditions then time to complete the time trial course will always increase. (Wells et al., 2013)

There was only one previously published study which examined the effects of varying power based on distance and not in relation to environmental changes and for the results to be considered valid there should be multiple studies testing this approach.

A visual representation of a variable pacing strategy plotted against the elevation of a 4-km time trial course (Figure 1) (Cangley et al., 2011). Power is varied in parallel to changes in road gradient to reduce the time taken to complete the 4-km distance. The graph shows that power is increased just before reaching the end of downhill segments and then decreased just before the end of uphill segments. The variable pacing strategy also illustrates the ability to dramatically increase power during the final meters of the course. Subsequently, suggesting that the optimal way to vary power is in parallel to course characteristics (wind or gradient) rather than regarding distance irrespective of course characteristics.

Proposed time savings comparing variable pacing to constant pacing using a mean versus graph to illustrate effect sizes for 10-km cycling time trials (Fig. 2A). The results of the statistical analysis show that when power is varied in parallel to changes in environmental characteristics, a 15% variation in power will always provide the biggest time saving compared to a constant pacing strategy. The findings suggest that the most significant mechanical time savings are experienced by cyclists who have the largest difference in speed during uphill and downhill segments. For example for a 10-km course with 2x2.5km uphill/downhill segments at 6% and a normalised power of 300w, a 77kg cyclist will experience a more significant time saving compared to a 63kg cyclist when varying power out by any amount. This is because the 77kg cyclist is travelling slower uphill compared to the 63kg cyclist due to the added system mass. This suggests that cyclists with a higher mass will experience an increased benefit from using a variable pacing strategy over a course with steep gradients.

Figure 2A: Time-saving for a 10-km cycling time trial time when using a variable pacing strategy compared to constant pacing.

4 studies (110 subgroups) evaluated variable pacing compared to constant pacing using both real world data and computerised models. 90 subgroups reported that a variable pacing strategy significantly reduced time to complete a 10-km cycling time trial where environmental conditions varied. SMD 5% variation = -34.975 (s), 10% variation = -65.756 (s) and 15% variation = -77.682 (s) 95% CI p = 0.005. However, the findings suggest that when environmental conditions remain constant (e.g. road grade remained 0% or wind speed 0 m/s) a 5% variation in power resulted in the same time as constant pacing but, 10% variation increased finishing time by SMD 10(s) 15% variation increased finishing time by SMD 20 (s) 95% CI p = 0.005.

Comparison between variable and constant pacing strategies during a variety of modelled 16.1-km cycling time trials (Fig. 2B). Adopting a variable pacing strategy in parallel to changes in course characteristics (wind and gradient) always reduced the time to complete the course. However, when course conditions remained constant, (e.g. no change in wind speed or direction and no change in road gradient) variable pacing increased time to complete the course. Varying power in relation to distance and not course characteristics resulted in a small-time increase but was not enough to be considered statistically significant. This does suggest that power output should only be varied in parallel to changes in course or environmental characteristics and not solely by distance.

Figure 2B: An analysis of time savings for a 16.1-km time trial when comparing variable pacing to constant pacing strategies.

36 subgroups from 3 different studies reported data for 16.1-km distance. 18 subgroups demonstrated that by varying power out by 10% in parallel to wind or gradient changes time to complete the 16.1-km course was reduced by (SMD) -52.33(s) 95% CI $p = 0.005$. However, the 18 other subgroups reported that when power is varied in relation to distance and not in parallel to change in environmental conditions or gradient time to complete the course was increased by (SMD) 0.36(s). 95% CI $p = 0.005$. This increase was not considered big enough to be statistically significant. Another statistical finding was that the biggest time savings were achieved using the highest baseline power outputs. The subgroups from Atkinson et al., 2007a compared a 5% power variation for three different power outputs (164w, 289w and 394w) over the same course profile and environmental conditions. For all cases, the biggest time saving was achieved when using the 394w mean power output and then varying it 5%.

Determining the optimal power distribution for a variety of 40-km cycling time trial courses by comparing variable and constant pacing (Fig. 2C). The graph below shows that for all cases a variable pacing strategy performed in line with changes in course characteristics and conditions resulted in reduced time to complete the 40-km. However, when power was varied by distance and irrespective of course profile or conditions performance was negatively affected with an increased time to complete the 40-km course. This finding suggests that if cyclists are attempting to improve performance through pacing, they should vary power where possible by 15% regarding changes in course characteristics.

Figure 2C: Time savings for a 40-km time trial comparing variable pacing to constant pacing strategies.

Figure 2C shows changes in time to complete a 40-km cycling time trial when adopting a variable pacing strategy as opposed to constant pacing. five studies (155 subgroups) reported results for time savings over a 40-km time trial when comparing variable versus constant pacing strategies.

70 studies reported time-saving when using either 5%, 10% or 15% variable pacing when compared to using a constant pacing strategy. (SMD) 5% = -21.684(s) 10% = -44.052(s) 15% = -63.684(s) 95% CI p = 0.005. However, 85 subgroups reported either no time saving or an increase in time to complete the time trial course when using a variable pacing strategy. These 85 subgroups did not use a variable pacing strategy in parallel to environmental changes. Instead, power varied for a specific distance irrespective of gradient or wind changes to achieve an increase in average speed for that segment. (SMD 5% variation = 18.235(s) 95% CI p = 0.005.

A Comparison between variable and constant pacing strategies during a 4-km outdoor cycling time trial

Figure 3: Average times from Cangley et al., 2011 for constant versus variable pacing during an outdoor 4-km cycling time trial.

Time to complete the 4-km time trial was recorded for 20 cyclists, with 10 in each subgroup. The course used is shown in figure 1, the control group (constant pacing) was instructed to ride at an average power of 255w. Whilst the intervention group (variable pacing) was instructed to ride at a baseline power output of 255 but to vary power in parallel to course profile by 27% so that the normalised power was equal to the control group at 255w. The statistical findings report that a variable pacing strategy resulted in a reduction in time to complete the 4-km course of -15(s). The standard deviation (red bars) was also less for variable pacing, meaning that the results were more consistent for the whole intervention group.

Discussion

This systematic review and meta-analysis aimed to update previous reviews using only studies published between 1997-2020, regarding the possible effects of using a variable pacing strategy during a cycling time trial. The primary outcome measure of time trial finishing time was used to calculate the time difference between constant pacing and variable pacing and express this as a time saved when using the variable pacing strategy.

The results from the statistical analysis support the theories raised in previous research regarding the proposed time savings when using a variable pacing strategy in parallel to environmental changes (gradient and wind speed or direction). (Atkinson et al., 2007b and Atkinson and Brunskill 2000) The statistical findings equally uphold the theory that when there are no changes in environmental characteristics (similar to that of velodrome track cycling) variable pacing will either result in the same finish time as constant pacing or can even increase finish time and therefore may be detrimental to performance. Prior research has shown that variable pacing may reduce time trial event time, but it was unclear exactly how much power should be varied depending on course distance, baseline power output or course characteristics. This meta-analysis shows that the time saving between 5%, 10% and 15% are not directly proportional to each other. It was found that when a 15% variation in power is performed in parallel to environmental changes it will always result in the biggest time saving compared to 10% and 5% variable pacing strategies.

Time trial competition time

The results indicate that a variable pacing strategy has a statistically significant effect on reducing time to time trial finishing time (the time taken to complete a pre-specified course). For all studies and all subgroups, a variable pacing strategy performed in parallel with environmental changes always resulted in a reduction in time to complete the time trial course. Additionally, for all subgroups, a 15% variation in power resulted in the biggest time saving compared to a constant pacing strategy. One critical finding from the meta-analysis was that when a cyclist experiences a large variation in environmental characteristics (high wind speeds > 14 km/h or steep gradients > 6%) they should vary their power output in parallel to these conditions. (Boswell, 2012) Thus, the findings support the previously established theory that for outdoor cycling time trials, cyclists should increase their power output uphill or into headwind sections and then decrease their power for downhill or tailwind segments to decrease event time as much as possible. Previously the literature was unclear on exactly how much cyclists should vary their power by when utilizing a variable pacing strategy. (Jones et al., 2015) The statistical findings from this review propose that when physiologically possible, power should be varied by 15% to maximise the mechanical advantage of this pacing technique.

Two other aspects of the proposed mechanical advantage of variable pacing were explored within this meta-analysis. The first aspect that was explored was; does system mass (combined mass of the cyclist and their bike) have any effect on which type of pacing strategy should be used to minimize time to finish a 10-km course. Previous research has been unclear regarding if lighter cyclists should use constant or variable pacing when competing over steep (>6%) singular or repeated gradients. The statistical findings from Boswell 2012 report that cyclists weighing 63kg still benefited from using a variable pacing strategy when cycling on a course which included 2x5km segments at 15% (one up hill-one downhill segment) and 15% grade for 20x0.5km segments. The computer modelling reported a time saving for 2x5km at 15% of -142(s) when the 63kg cyclist adopted a 10% variable pacing strategy. Equally a time saving of -139(s) was reported for the 63kg cyclist on the course design 20x.05km at 15% grade. Therefore, the results suggest that cyclists with a low mass should still aim to implement a variable pacing strategy as they will experience a significant reduction in time to complete the time trial.

The second aspect of variable pacing strategy that was examined was the proposed theory riders with a high normalised power (the baseline power ridden at before any variation in power is considered) benefit less than cyclists with a proportionally lower normalised power. The evidence from previous studies suggests that because cyclists with a higher normalized power will be travelling at proportionally higher speeds when facing environmental resistance (wind or gradient) they would benefit less from varying that power output. Despite this theory, the statistics calculated during this meta-analysis suggest that cyclists with a high power output (> 390) still experience a significant benefit from a variable pacing strategy. The findings collected from Atkinson et al 2007a reported a 200% increase in time-saving from a power output of 164w compared to 394w. For the exact same course profile and conditions and weight 164w with 5% variability resulted in a time saving of -75(s), whilst 394w with 5% variability resulted in a time saving of -230(s). This result was not the only statistical finding regarding the performance advantage of using variable pacing with a high normalized power.

Perceptive

The statistical findings from this meta-analysis support the original findings of Cangle et al., 2011, Atkinson et al 2007b and others. The data suggest that cyclists competing in outdoor cycling time trials with changeable environmental conditions (wind or road gradient) will always benefit from adopting a variable pacing strategy in parallel with the changes in course characteristics when compared to maintaining a constant power output. The findings reported that when possible a 15% variation in power output resulted in the biggest time saving for all course configurations. For the 10, 16.1 and 40-km time

trials 5%, 10% and 15% power variation strategies were tested to identify which pacing strategy had the biggest effect on reducing finishing time. For courses with long or steep uphill segments, a 15% variation in power was not always possible and thus a 10% variation in power should be used. In addition, the findings presented in this study should be used by all cyclists aiming to maximise their physiological performance during outdoor cycling time trial races. By varying power by 15% for a 10-km time trial finish time was reduced by -77.682 (s) 95% CI $p = 0.005$. Equally, for the 40-km time trial, a 15% variation in power output resulted in a time saving of -63.684(s) 95% CI $p = 0.005$. However, variable pacing in relation to distance and irrespective of course characteristics was always detrimental to performance. Thus, this method of pacing should be avoided. The findings of this study are of particular relevance to endurance athletes and sports scientists seeking to develop power output strategies for outdoor cycling time trials such as the world championships or Tokyo 2021 Olympic and Paralympic games.

In regard to applying the results to outdoor cycling time trials, cyclists may wish to write out or print out data for specific course segments. One way of doing this may be to use modelling software such as best bike split to identify potential power outputs for uphill or downhill segments and then aim to maintain that specific power output depending on course segments within the actual event. Cyclists could then use the information provided in this meta-analysis and the predictions made by modelling software to identify if a 15% variation of power is achievable for their specific course characteristics.

Limitations

This meta-analysis has several limitations that need to be considered.

One of the major limitations of this study is that the results can not be applied to females. There were no females included in the studies with human participants. There were only two computerised models that used data that could be regarded as useful for female competitors. These were Boswell 2012 and Atkinson et al 2007a who examined 63kg weight and 164w variables respectively. It should, therefore, be stated that the results from this meta-analysis can not be fully generalised to the current general population.

Secondly, only two studies were repeated measure design in nature and there were no randomised control trials that met the inclusion criteria. Therefore, there needs to be several included randomised control trials and repeated measure design studies with large sample sizes to provide more definitive results. Finally, regarding the process of data collection, there were several subgroups from included studies where the data was reported for a unique distance not shared by any other subgroup, for instance, a time trial lasting 800kj. As a result, the results from these subgroups could not be compared to other subgroups because of the differences in course distance. In order to have a stronger statistical power, there should be more studies with the same course distance and similar course layout to strengthen the statistical findings. The analysis of Egger plots suggests a minimal chance of publication bias, indicating there may not be negative publicly available datasets in existence.

Conclusion

The findings from this meta-analysis support previous theories that variable pacing in parallel to course characters will reduce time trial finishing time compared to constant pacing. For the purpose of practical recommendations, it should be advised that cyclists should aim to vary their power output by 15% when experiencing environmental resistance (wind or gradient) in order to reduce time to complete the time trial course as much as possible. However, for courses with long climbs at steep gradients (> 6%) the findings suggest that varying power by 15% is sometimes not possible because it requires the cyclists to produce power well above critical power for extensive durations which can be detrimental to overall time trial performance. Thus, for courses with long climbs cyclists should instead vary power

output by only 10%.

Figure 1 presents a graphical representation of how power should be distributed to maximise the advantage of variable pacing. The other critical finding of this meta-analysis was that cyclists should not manipulate their power output in relation to distance irrespective of course characteristics as this always resulted in an increase in finishing time.

Recommendations for future research:

Using the conceptual framework originally created by Atkinson and Brunskill 2000, this meta-analysis has shown that utilising a variable pacing strategy in parallel with changes in course characteristics has a positive impact on reducing time to complete a time trial course. However, there are still several elements that are unclear regarding the optimal power distribution for outdoor cycling time trials. One recommendation for future research is to test variable versus constant pacing strategies in an outdoor time trial using either a randomised control trial method or a repeated measures design method. Only one study that met the inclusion criteria was a repeated measures design, but this study only tested the different pacing strategies over a 4-km distance. Thus, future studies may wish to test variable versus constant pacing strategies over longer time trial distances such as 16.1 and 40-km courses. Moreover, future studies may also want to explore variable pacing strategies over a variety of different real-world course configurations, such as flat courses with wind or courses with a single prominent uphill segment or multiple prominent uphill segments. Whilst the validated models provide great information to athletes, experiments using human participants in real-world conditions maintain a greater overall validity.

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Data and Supplementary Material Accessibility

All supplementary material is available from <https://osf.io/fxuph/>

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