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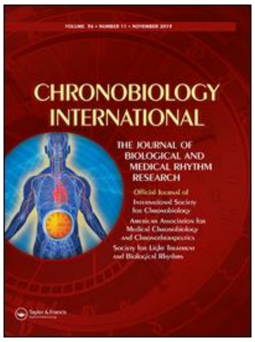

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Time-of-day variation on performance measures in repeated-sprint tests: a systematic review

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ABSTRACT

The lack of standardization of methods and procedures have hindered agreement in the literature related to time-of-day effects on repeated sprint performance and needs clarification. Therefore, the aim of the present study was to investigate and systematically review the evidence relating to time-of-day based on performance measures in repeated-sprints.

The entire content of PubMed (MEDLINE), Scopus, SPORTDiscus® (via EBSCOhost) and Web of Science was searched. Only experimental research studies conducted in male adult participants aged ≥18yrs, published in English before June 2019 were included. Studies assessing repeated-sprints between a minimum of two time-points during the day (morning versus evening) were deemed eligible.

The primary search revealed that a total of 10 out of 112 articles were considered eligible and subsequently included. Seven articles were deemed strong and three moderate quality. Eight studies found repeated-sprint performance across the first, first few, or all sprints, to increase in favor of the evening. The magnitude of difference is dependent on the modality and the exercise protocol used. The non-motorized treadmill established an average 3.5–8.5% difference in distance covered, average and peak velocity, and average power, across all sprints in three studies and in peak power in two studies. In cycling, power output differed across all sprints by 6.0% in one study and 8.0% for the first sprint only in five studies. All four studies measuring power decrement values (i.e. rate of fatigue) established differences up to 4.0% and two out of five studies established total work to be significantly higher by 8.0%.

Repeated-sprint performance is affected by time-of-day with greater performance in the late/early afternoon. The magnitude is dependent on the variable assessed and the mode of exercise. There is a clear demand for more rigorous investigations which control factors that specifically relate to investigations of time-of-day and are specific to the sport of individuals.

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Chronobiology; circadian rhythm; diurnal variation; RS performance; repeated accelerations; review

Introduction

Sporting related performance variables display a diurnal variation in a temperate environment (around 17–22°C) in humans (Drust et al. 2005; Reilly and Waterhouse 2009). Gross muscular tasks such as short-term, one-off maximal anaerobic performance (lasting < 6s), are greater (1.9–11.6%) in the mid-afternoon or early evening (14:00 to 19:00 h) compared to the early morning (07:00 to 10:00 h) (Racinais et al. 2004; Souissi et al. 2004). However, rather than singular sprint capacity, the ability to repeatedly perform maximal sprints (≤6 s) with limited recovery between bouts (≤60 s) carries more relevance for team-based sports (Aloui et al. 2013; Bangsbo et al. 2006).

Time-of-day differences in repeated-sprint performance have previously mainly been investigated using cycle-ergometry exercise (Aloui et al. 2013; Giacomoni et al. 2006; Lopes-Silva et al. 2019; Racinais et al. 2005, 2010; Zarrouk et al. 2012), and more recently the non-motorized treadmill (Pullinger et al. 2014, 2018a, 2018b). Studies using cycle-ergometry have consistently reported higher peak power values in the mid-afternoon for the first or first few sprints only (4.3–8.5%) (Racinais et al. 2005, 2010), or for all sprints performed (6%) (Lopes-Silva et al. 2019). In addition, measures of distance covered, peak and average power, peak and average speed found diurnal variation for all sprints (3.3–10.3%) on a non-

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Supplemental data for this article can be accessed here.

motorized treadmill (Pullinger et al. 2014, 2018a, 2018b).

However, there is a lack of agreement in the literature concerning the presence of a diurnal variation of fatigue index (FI), also known as decrement in power (%) over repeated-sprints, with diurnal variation observations affected by modality. In cycling ergometry diurnal differences are 1) apparent with higher decrements in the evening (4.0–13.1%) (Chtourou et al. 2012; Racinais et al. 2005, 2010; Zarrouk et al. 2012) or, 2) not apparent (Hammouda et al. 2012; Souissi et al. 2008). In contrast, all time-of-day studies performed on a non-motorized treadmill reported no diurnal variation for variables related to FI (Pullinger et al. 2014, 2018a, 2018b). Differences between exercise protocols and the use of cycle ergometry call into question not only the validity of repeated-sprint performance protocols and their relevance to team sports. Using non-motorized treadmill as the mode of exercise still enables research to be performed within a standardized laboratory environment and allows for rapid changes in running velocity, like sprints during game play, to be investigated (Pullinger et al. 2014) and provides greater accuracy for measurement of the mechanical power generated in each sprint (Lakomy 1987).

Observing significant changes in diurnal variation, may involve several contributing factors – such as type and intensity of the task, the motivation of subjects to perform the task, the time spent on the task and subject familiarization regarding the task to be performed (Bambaeichi et al. 2005; Giacomoni et al. 2006; Reilly et al. 1997). The chosen number of sprints, repetitions and training status of subjects differ between studies, making it difficult to compare findings. The amount of literature investigating a time-of-day variation on repeated sprint performance has increased over the last 10 years (Pullinger et al. 2014). However, the lack of standardization of methods and procedures have hindered agreement on the time-of-day effects on repeated sprint performance and needs clarification.

Therefore, the aim of the present paper was to examine the following question: “In healthy adolescent males, what is the magnitude of time-of-day differences in repeated-sprint performance outcomes between cycling and running in the evening (17:00 to 19:00 h) compared to the morning (06:00 to 09:00 h) during experimental trials? The specific repeated-sprint performance outcomes we assessed included FI, peak power, average power, peak velocity, average velocity, total work, time, distance covered, etc.

Methods

Protocol

This systematic review conforms to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al. 2015). The PRISMA checklist is presented in Appendix 1, indicating the page numbers where items of information are present in the current manuscript.

Eligibility criteria

The inclusion criteria were based on the Cochrane guidelines for conducting systematic reviews (Higgins 2017). The criteria for inclusion and exclusion were set and agreed by all eight authors. Following the initial selection process of studies, three authors (EV, SC and SP) independently completed the eligibility assessment in a blinded standardized way by screening the titles and abstracts. To be considered eligible, the manuscript had to meet the following inclusion criteria:

(1) Language – published in English.
(2) Population – healthy males (females were excluded so that menstrual implications did not need to be addressed) and adult participants (18+ years of age) only.
(3) Time-of-day – compared the effects of morning versus evening repeated sprint performance (a minimum of two time-points).
(4) Repeated sprints – a series of sprints (≤6 s) with minimal recovery intervals (≤60 s) were considered.
(5) Design – Randomized and/or counterbalanced trials.

Literature search strategy and information sources

A computerized English-language literature search of electronic databases: PubMed (MEDLINE), Scopus, SPORTDiscus® (via EBSCOhost) and Web of Science were conducted (June 2019). A search strategy is shown in online supplementary appendix 2 for PubMed (MEDLINE). A search for relevant content related to repeated sprint performance and time-of-day variation using the following search syntax was performed ("RSA" OR "repeated sprint ability" OR "repeated sprint activity" OR "RS performance" OR "repeated sprint performance" OR "repeated sprint" OR "repeated sprint exercise" OR "repeated sprint running" OR "repeated sprint cycling") AND ("time of day" OR "time-of-day" OR "daily variation" OR "daily fluctuation" OR "diurnal variation" OR "diurnal fluctuation" OR "circadian rhythm" OR "circadian variation"). The search syntax was combined with Boolean operators and the quotation marks were used for phrase searching (i.e., combinations of two or more words). The search was limited to papers published in the English language and research published since 1984, to focus on more modern methods of measurement of repeated sprint performance (since the creation of the non-motorized Woodway Force treadmill). In addition, the reference lists of articles retrieved were screened manually for additional relevant papers, as part of the secondary search to uncover any additional articles that met inclusion criteria (Greenhalgh and Peacock 2005). Two authors (SC and SP) independently carried out the searches for study selection to minimize potential selection bias. Figure 1 presents the flow of papers through the study selection process.

Study selection

Where both male and female participants took part in a research study, the article was included if the data from male participants could be independently identified. In instances where the title and abstract did not contain enough detail to indicate whether an article was relevant to the review, the complete article was obtained and read. This enabled the authors to determine whether the paper met the primary inclusion criteria. In instances where the primary purpose of the article was not an investigation looking at the effects of time-of-day, meaning a minimum of two

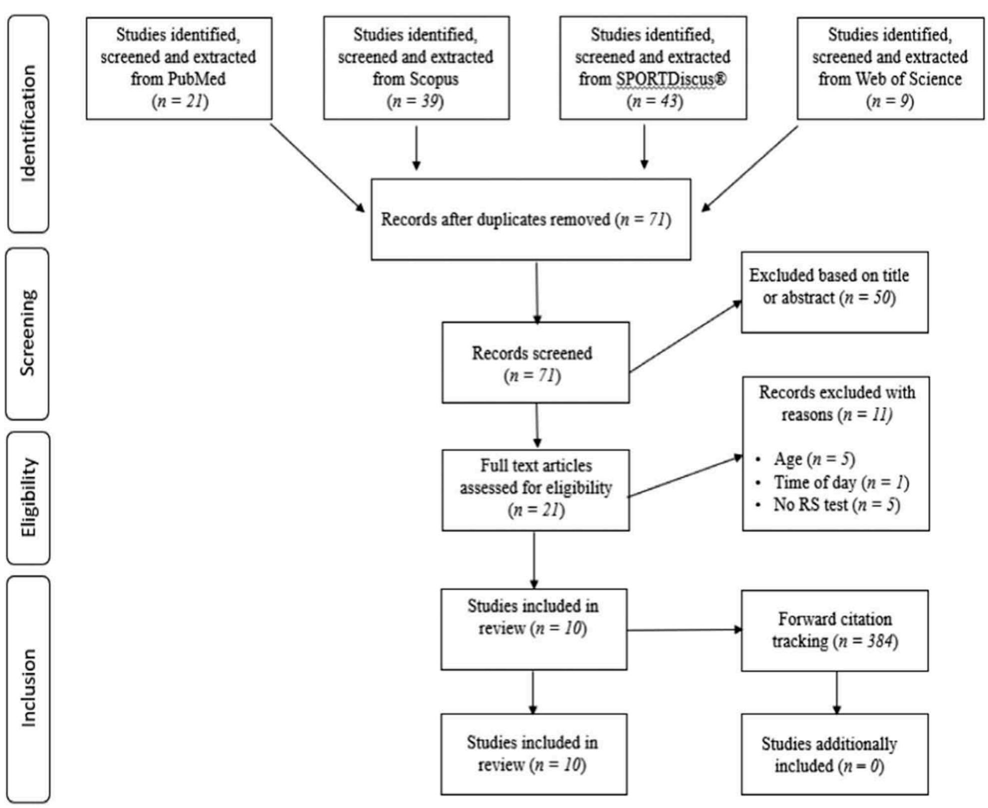

Figure 1. Flow diagram of the study selection process.

time-points were not assessed (morning and evening), the papers were excluded from the review. Letters to the editor, conference abstracts and literature reviews were excluded as these studies were not found to be methodologically-quality-assessable and/or critically appraisable.

Data extraction

Data extraction was performed by one author (SP) independently and a data check performed by a second author (SC) with the following data extracted from the included studies: 1) the study authors and date; 2) the number of participants and participant's characteristics; 3) the circadian chronotype questionnaire used to assess the participants (and their scores); 4) the time-of-day testing sessions took place; 5) repeated-sprint performance test used (sprint duration/distance, number of reps and duration of recovery and recovery mode); 6) mode of exercise used for the sprints; 7) performance variables which were assessed; 8) mean ± SD values for the repeated-sprint performance variables, % difference between testing time-points and information as to whether diurnal variation was established.

In addition, analysis regarding aspects relating to research design and factors deemed specifically important in investigations of chronobiological nature were quantified. The studies which met the inclusion criteria were summarized under the following headings: randomized; counterbalanced; controlled for light; controlled for meals; controlled for sleep; fitness. In most instances, a simple 'yes' or 'no' was recorded against each of the included studies, other than 'fitness' (when the studies were classified as having 'trained' or 'untrained' participants). Articles that made no specific reference to any of these primary areas were considered to indicate a negative response and 'no' was marked against the area in question.

Quality assessment

A modified 26-item methodological quality assessment checklist on each included article using the Downs and Black scale (Downs and Black 1998) was conducted. The checklist consisted of 26 "yes"-or- "no" questions which were scored totaling up to a possible 27 points. The questions were categorized under four sections: Reporting (10 items; 1–10), External validity (3 items; 11–13), Internal validity study bias (7 items; 14–20) and internal validity confounding selection bias (7 items; 21–26). The quality assessment of the articles was conducted by two reviewers (SC and SP) independently with 1.5% disagreement (4 questions). The observed differences were resolved by a third reviewer (EV). Studies scoring above 75% were deemed as strong quality, 50 – 75% were deemed as moderate quality and below 50% as weak quality. In addition, the total % of points lost for each checklist item over the 10 studies was also calculated.

Results

Search results

The literature search ended in June 2019 and the primary database search revealed 112 articles based on the search criteria. To reduce selection bias, each study was independently reviewed by two of the investigators (SP and SC), and the investigators mutually determined whether they met the basic inclusion criteria and found a 100% selection agreement. Once duplicates were removed, 71 titles remained in the reference manager (EndNote V.X.8). Following the examination of titles, abstracts and keywords of all these manuscripts, 21 academic studies were deemed potentially relevant to the topic and subsequently retained for full-text analysis. After additional full-text analysis, 10 studies were deemed eligible and included in the systematic review and met the inclusion criteria (Aloui et al. 2013; Chtourou et al. 2018; Giacomoni et al. 2006; Lopes-Silva et al. 2019; Pullinger et al. 2014, 2018a, 2018b; Racinais et al. 2005, 2010; Zarrouk et al. 2012). Upon further inspection of the 384 articles present in their bibliographical references, none of these studies met the inclusion criteria and hence were deemed ineligible. Figure 1 presents the number of articles found in each electronic database and a detailed flow chart of the literature search, including all the steps performed.

Study characteristics

The detailed participant characteristics are shown in Table 1. A total of 128 participants were included across the 10 studies (average number of participants per study = 13). Nine studies assessed circadian chronotype of participants using the morningness-eveningness questionnaire (Horne and Ostberg 1976) or a deviation of this (Barton et al. 1995). In total, 94 participants (73%) belonged to the intermediate chronotype, 16 to the moderately morning chronotype (13%) and 6 to the moderately evening chronotype (5%). No participants belonged to the extreme morning or evening chronotype (Table 1). Only one study (Giacomoni et al. 2006) failed to report any information related to chronotype for their participants. Two studies (Pullinger et al. 2014, 2018a) also performed the Sleep Flexibility/Rigidity [F/R] and Languid/Vigor [L/V] questionnaires (Smith et al. 1989). Both studies showed their participants to indicate more "rigidity" while one more "languidity" (Pullinger et al. 2014) and the other more "vigorous" (Pullinger et al. 2018a).

The time-of-day during which morning sessions took place were between 06:00 and 10:00 h and evening sessions between 17:00 and 19:00 h. No other time-points were used to assess time-of-day variation in repeated-sprints. The mode of exercise varied across studies, with six studies using cycling as the mode of exercise, while four used running. The studies that used cycling to assess repeated-sprint performance either used Monark (n = 4), SRM Training System, ergometer (n = 1) or Lode Excalibur (n = 1) ergometers. In the running studies, three used the Woodway Force 3.0 non-motorized treadmill to assess repeated-sprints, while one used an over ground indoor PVC running surface (Table 1). Further, three studies used sprint durations of 3-s (Pullinger et al. 2014, 2018a, 2018b), one study used sprint durations of approximately 5-s or 25-m distance (Chtourou et al. 2018), and six studies used sprint durations of 6-s (Aloui et al. 2013; Giacomoni et al. 2006; Lopes-Silva et al. 2019; Racinais et al. 2005, 2010; Zarrouk et al. 2012). The number of sprint repetitions varied from 5 to 10 and the duration of recoveries varied from ~20 to 30-s (Table 1), and were either passive (n = 5), active (n = 1) or not reported (n = 4).

Eight studies found several of their performance variables displayed time-of-day effects, with higher values in the morning than the evening. There was an average of 8.5% difference in distance covered, 8.8% in average power, 8.5% in average velocity and 3.5% in peak velocity, in favor of evening performance (Table 2), based on three studies using non-motorized treadmill as the mode of exercise and all of which were deemed high quality. However, only two of these studies established peak power to be significantly higher, with an average of 5.8% difference in favor of evening performance (Table 2). In the studies which used cycling as mode of exercise, there was an average 8.0% difference for the 1st sprint in (peak) power output during cycling observed in 5/6 studies in favor of evening performance (Table 2). Only one study found (peak) power output to be significantly higher across all sprints in the evening, with an average of 6.0% difference. All four studies which assessed power decrement found evening values to be significantly different to morning values for power decrement up to 4.0%. Only 2 out of 5 studies established values of total work to be significantly higher, with an average of 8.0% difference in favor of evening performance (Table 2). There was an average of 9.0% difference in anaerobic power reserve based on one study in favor of evening performance (Table 2), while pedaling rate peak torque did not establish differences. Only two studies found no time-of-day variation in any of the performance variables they assessed (Table 1) of which one used cycling and the other over-ground running as a mode of exercise.

The substantial differences in methodological and clinical heterogeneity among studies meant we were unable to conduct a meta-analysis and pool the observed data-sets to evaluate the evidence related to findings in repeated-sprint performance and therefore provided in-depth information related to unweighted results. Missing data information, differences in populations, metrics, outcomes and designs were the main reasons for a meta-analysis not to be pursued. Conducting a meta-analysis will simply

Table 1. Summary of the articles reviewed (n = 10) with an overview of the participants, the experimental protocols with the time-of-day, exercise mode, and repeated-sprint protocol design and variables examined, and the main findings related to time-of-day in relation to each variable. **Statistical significance ($p < .05$) is indicated in bold**. *Statistical "trend" or "marginal significance" in italic ($0.10 > p > .05$).*

Author and Date	Participants	Chronotype assessment and distribution	Testing time-of-day	Repeated-sprint test	Mode of exercise	Performance variables examined	Significance of main effects between condition	Main findings
Racinais et al. (2005)	9 male physical education students	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 07:00–09:00 h	5 x 6-s sprints	Cycle ergometer	Peak Power Output	**$F_{4,\ 32}$ = 45.89, P < .05**	Significantly higher in the E *vs.* M for sprint 1 only; 5.3%
	22 ± 4 yrs, 1.78 ± 0.07 m, and 73.5 ± 10.5 kg	2-MM types, 1-ME type and 6-N types	E = 17:00–19:00 h	24-s passive recovery	Monark 824E	Power Decrement	**$F_{1,\ 8}$ = 10.57, P < .05**	Significantly higher in the E *vs.* M; 4%
						Total Work	$F_{1,\ 8}$ = 0.01, P = .93	No significant difference between M and E
Giacomoni et al. (2006)	12 active males	Not assessed	M = 08:00–10:00 h	10 x 6-s sprints	Cycle ergometer	Peak Power Output	$F_{2,\ 22}$ = 16.8, P > .05	No significant difference between M and E
	23 ± 2 yrs, 1.80 ± 0.06 m, and 76.4 ± 4.2 kg		E = 17:00–19:00 h	30-s recovery	SRM	Total Mechanical Work	$F_{2,\ 22}$ = 5.9, P > .05	No significant difference between M and E
						Pedaling rate	$F_{2,\ 22}$ = 21.2, P > .05	No significant difference between M and E
Racinais et al. (2010)	8 active males	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 08:00–10:00 h	10 x 6-s sprints	Cycle ergometer	Power Output	**$F_{1,\ 7}$ = 12.15, P < .05**	Significantly higher in the E *vs.* M for sprints 1, 2, 3 and 5 only
	25 ± 1 yrs, 1.77 ± 0.02 m, and 68.7 ± 3.2 kg	2-MM types, 1-ME type and 5-N types	E = 17:00–19:00 h	30-s recovery	Monark 818E	Power Decrement	**$F_{9,\ 63}$ = 4.53, P < .05**	Significantly higher in the E *vs.* M
Zarrouk et al. (2012)	12 male physical education students	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 06:00 h	5 x 6-s sprints	Cycle ergometer	Power output	**P < .05**	Significantly higher in the E *vs.* M for sprints 1, 2 and 3 only
	21 ± 2 yrs, 1.78 ± 0.02 m, and 76.8 ± 3.7 kg	12-N types	E = 18:00 h	24-s recovery	Monark 894E	Power decrement	**t = 2.32, P = .041**	Significantly higher in the E *vs.* M
						Total work	**t = 4.15, P = .002**	Significantly higher in the E *vs.* M
Aloui et al. (2013)	12 male amateur soccer players	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 07:00–09:00 h	5 x 6-s sprints	Cycle ergometer	Peak Power	**F = 5.1, P = .045**	Significantly higher in the E *vs.* M for sprint 1 only
	20 ± 2 yrs, 1.74 ± 0.05 m, 72.5 ± 6.4 kg	8-MM types and 4-N types	E = 17:00–19:00 h	24-s passive recovery	Monark 894E	% Peak Decrement	**P = .012**	Significantly higher in the E *vs.* M
						Total Work	P > .05	No significant difference between M and E
Pullinger et al. (2014)	20 male field-based team-sport players	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 07:30 h	10 x 3-s sprints	NMT	Distance Covered	**$F_{1,\ 19}$ = 43.973, P < .0005**	Significantly higher in the E *vs.* M; 8.2%
	21 ± 2 yrs, 1.79 ± 0.07 m, 77.2 ± 10.5 kg and VO_2 max 60.8 ± 4.8 ml.kg.min^{-1}	20-N types	E = 17:30 h	30-s passive recovery	Woodway Force 3.0	Peak Power	*$F_{1,\ 19}$ = 4.067, P = .058*	Trend for DV with higher values in the E *vs.* M; 4.5%
						Average Power	**$F_{1,\ 19}$ = 14.926, P = .001**	Significantly higher in the E *vs.* M; 7.8%

(*Continued*)

Table 1. (Continued).

Author and Date	Participants	Chronotype assessment and distribution	Testing time-of-day	Repeated-sprint test	Mode of exercise	Performance variables examined	Significance of main effects between condition	Main findings
						Peak Velocity	**$F_{1,\ 19}$ = 8.161, *P*= .010**	Significantly higher in the E *vs*. M; 3.3%
						Average Velocity	**$F_{1,\ 19}$ = 44.065, *P* < .0005**	Significantly higher in the E *vs*. M; 8.3%
						% Decrement PP	$F_{1,\ 19}$ = 0.831, *P*= .373	No significant difference between M and E
						% Decrement PV	$F_{1,\ 19}$ = 0.235, *P*= .633	No significant difference between M and E
Chtourou et al. (2018)	14 male judokas	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 07:00 h	6 x ~ 5-s sprints	Overground Indoor	Mean Sprint Time	P > .05	No significant difference between M and E
	21 ± 1 yrs, 1.72 ± 0.07 m, and 70.0 ± 8.1 kg	14-N types	E = 17:00 h	~ 20s active rest	PVC running Surface	Ideal Sprint Time	*P*= .609	No significant difference between M and E
						Fatigue Index	*P*= .570	No significant difference between M and E
Pullinger et al. (2018a)	12 well-trained males	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 07:30 h	10 x 3-s sprints	NMT	Distance Covered	***P* < .0005**	Significantly higher in the E *vs*. M; 8.2%
	21 ± 2 yrs, 1.79 ± 0.06 m, 78.2 ± 11.8 kg and VO_2 max 60.0 ± 4.4 $ml.kg.min^{-1}$	12-N types	E = 17:30 h	30-s passive recovery	Woodway Force 3.0	Peak Power	***P* = .004**	Significantly higher in the E *vs*. M; 6.7%
						Average Power	***P* < .0005**	Significantly higher in the E *vs*. M; 8.3%
						Peak Velocity	***P* = .031**	Significantly higher in the E *vs*. M; 3.4%
						Average Velocity	***P* < .0005**	Significantly higher in the E *vs*. M; 7.8%
						% Decrement PP	*P*= .823	No significant difference between M and E
						% Decrement PV	*P*= .101	No significant difference between M and E
Pullinger et al. (2018b)	12 well-trained males	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 07:30 h	10 x 3-s sprints	NMT	Distance Covered	***P* < .0005**	Significantly higher in the E *vs*. M; 9%
	22 ± 3 yrs, 1.78 ± 0.07 m, 76.0 ± 6.3 kg and VO_2 max 60.6 ± 4.6 $ml.kg.min^{-1}$	12-N types	E = 17:30 h	30-s passive recovery	Woodway Force 3.0	Peak Power	***P* = .006**	Significantly higher in the E *vs*. M; 4.9%
						Average Power	***P* < .0005**	Significantly higher in the E *vs*. M; 10.2%
						Peak Velocity	***P* < .0005**	Significantly higher in the E *vs*. M; 3.7%

(*Continued*)

Table 1. (Continued).

Author and Date	Participants	Chronotype assessment and distribution	Testing time-of-day	Repeated-sprint test	Mode of exercise	Performance variables examined	Significance of main effects between condition	Main findings
						Average Velocity	***P*< .0005**	Significantly higher in the E *vs*. M; 9.4%
						% Decrement Peak Power	*P*= .765	No significant difference between M and E
						% Decrement PV	*P*= .343	No significant difference between M and E
Lopes-Silva et al. (2019)	13 physically active males	Morningness-eveningness questionnaire (Horne and Ostberg 1976)	M = 08:00 h	10 x 6-s sprints	Cycle ergometer	Total Work Done	**$F_{1,\ 22}$ = 21.35, *P*= .001**	Significantly higher in the E *vs*. M; 8%
	26 ± 4 yrs, 1.77 ± 0.07 m, 77.0 ± 12.6 kg and VO_2 peak 43.2 ± 6.9 ml.kg.min^{-1}	4-MM types, 4-ME types and 5-N types	E = 18:00 h	30-s recovery	Lode Excalibur	Relative Peak Power	**$F_{1,\ 23}$ = 4.40, *P*= .04**	Significantly higher in the E *vs*. M; 6%
						Anaerobic Power Reserve	**$F_{1,\ 22}$ = 13.67, *P*= .001**	Significantly higher in the E *vs*. M; 9%
						Total Anaerobic Power Reserve	**$F_{1,\ 23}$ = 4.40, *P*= .04**	Significantly higher in the E *vs*. M

M = Morning, E = Evening, N = Number, reps = repetitions, h = hours, s = seconds, yrs = years, m = meters, kg = kilogram, ml = milliliter, min = minute, MM = Moderately morning, ME = moderately evening, N = neither, DV = Diurnal variation, NMT = Non-motorized treadmill, PV = Peak velocity, PP = Peak power.

Table 2. Mean ± SD values for all repeated-sprint performance variables measured in the morning and the evening in each sprint. Papers by Zarrouk et al. (2012) and Lopes-Silva et al. (2019) failed to disclose any data within their manuscripts and were therefore not added to the Table. – *indicates missing data.*

Author and Date	Variable	1	2	3	4	5	6	7	8	9	10
Racinais et al. 2005	PP	915.0 ± 133.0	-	-	-	-	-				
	(W)	958.0 ± 112.0									
	PD	7.0 ± 3.0	-	-	-	-	-				
	(%)	11.0 ± 2.0									
Giacomoni et al. 2006	PPO	935.7 ± 110.1	-	-	-	898.3 ± 96.2	-	-	-	-	831.3 ± 68.9
	(W)	940.0 ± 155.7				914.1 ± 95.9					848.6 ± 96.8
	TMW	5.0 ± 1.3	-	-	-	4.7 ± 0.9	-	-	-	-	4.2 ± 1.1
	(kJ)	5.1 ± 0.8				5.1 ± 1.3					4.3 ± 0.9
	PR	80.6 ± 5.8	-	-	-	79.0 ± 5.8	-	-	-	-	74.0 ± 4.8
	($rev{\cdot}min^{-1}$)	83.4 ± 7.3				79.8 ± 6.8					77.3 ± 5.6
	PT	179.2 ± 17.9	-	-	-	180.9 ± 21.5	-	-	-	-	175.0 ± 16.3
	(Nm)	187.2 ± 19.8				184.6 ± 20.8					169.6 ± 26.9
Racinais et al. 2010	PO	21.2 ± 1.0	-	-	-	-	-	-	-	-	19.7 ± 1.0
	($W.kg^{-1}$)	23.3 ± 1.0									20.4 ± 1.0
Aloui et al. 2013	PW	652.6 ± 73.2	609.7 ± 73.0	586.8 ± 72.1	571.7 ± 73.7	557.0 ± 73.6					
	(W)	682.9 ± 5.3	617.2 ± 74.4	588.6 ± 77.7	570.5 ± 77.0	553.4 ± 71.1					
	TW	2977.9 ± 358.4	-	-	-	-					
	(W)	3012.6 ± 378.6									
Pullinger et al. 2014	DC	14.4 ± 1.8	14.2 ± 2.3	14.4 ± 1.6	14.0 ± 1.0	14.2 ± 1.7	14.1 ± 1.6	13.9 ± 1.7	13.9 ± 1.8	14.0 ± 1.7	13.5 ± 1.8
	(m)	15.6 ± 1.9	15.5 ± 2.0	15.4 ± 1.6	15.4 ± 1.8	15.1 ± 1.8	15.1 ± 1.8	15.1 ± 1.5	15.1 ± 1.4	14.8 ± 1.6	14.9 ± 1.5
	PP	3172.9 ± 337.9	3201.1 ± 403.5	3228.8 ± 405.6	3193.5 ± 401.1	3215.5 ± 456.3	3147.7 ± 366.9	3115.8 ± 419.8	3177.6 ± 391.9	3169.4 ± 429.6	3122.3 ± 366.5
	(W)	3397.9 ± 463.8	3397.2 ± 434.5	3408.9 ± 434.2	3316.2 ± 343.0	3278.5 ± 375.9	3331.9 ± 387.5	3275.6 ± 342.6	3262.8 ± 353.7	3230.2 ± 323.1	3262.5 ± 353.4
	AP	2411.5 ± 309.3	2382.1 ± 403.3	2409.3 ± 312.8	2349.4 ± 299.8	2383.2 ± 330.7	2356.0 ± 288.6	2335.5 ± 321.0	2309.4 ± 306.8	2339.3 ± 295.4	2258.6 ± 308.5
	(W)	2628.8 ± 369.0	2603.7 ± 374.8	2591.1 ± 312.6	2565.9 ± 305.5	2528.8 ± 309.6	2527.7 ± 311.8	2509.6 ± 255.1	2486.1 ± 242.2	2463.9 ± 2667.0	2467.2 ± 254.5
	PV	20.1 ± 1.6	20.0 ± 1.5	20.0 ± 1.3	19.9 ± 1.2	19.9 ± 1.3	19.8 ± 1.3	19.6 ± 1.3	19.7 ± 1.2	19.7 ± 1.2	19.4 ± 1.2
	($km{\cdot}h^{-1}$)	20.9 ± 1.8	20.9 ± 1.7	20.7 ± 1.7	20.6 ± 1.5	20.4 ± 1.3	20.4 ± 1.4	20.2 ± 1.2	20.2 ± 1.3	20.1 ± 1.2	20.1 ± 1.2
	AV	17.1 ± 2.1	16.8 ± 2.7	17.0 ± 1.9	16.6 ± 2.1	16.8 ± 2.1	16.7 ± 1.9	16.5 ± 2.0	16.4 ± 2.1	16.6 ± 2.0	16.0 ± 2.1
	($km{\cdot}h^{-1}$)	18.6 ± 2.3	18.4 ± 2.4	18.3 ± 2.0	18.2 ± 2.1	17.9 ± 2.2	17.9 ± 2.2	17.9 ± 1.9	17.9 ± 1.7	17.5 ± 1.9	17.6 ± 1.8
	% PP	6.2 ± 2.0									
		7.1 ± 3.5									
	% PV	3.1 ± 2.1									
		3.4 ± 2.0									
Chtourou et al. 2018	Time	5.3 ± 0.2	5.3 ± 0.2	5.4 ± 0.2	5.4 ± 0.3	5.5 ± 0.3	5.6 ± 0.2				
	(s)	5.2 ± 0.2	5.3 ± 0.2	5.4 ± 0.3	5.4 ± 0.3	5.5 ± 0.3	5.6 ± 0.2				
	Mean time	5.4 ± 0.2									
	(s)	5.4 ± 0.2									
	Ideal time	31.6 ± 1.3									
	(s)	31.4 ± 1.5									
	FI	1.0 ± 0.4									
		1.1 ± 0.5									
Pullinger et al. 2018a	DC	15.4 ± 1.3	15.2 ± 1.7	14.5 ± 2.7	14.8 ± 1.5	14.6 ± 1.9	14.8 ± 1.7	14.7 ± 1.7	14.8 ± 1.5	14.5 ± 1.9	14.2 ± 1.9
	(m)	16.4 ± 1.8	16.5 ± 1.6	16.1 ± 1.5	16.0 ± 1.5	16.0 ± 1.5	15.9 ± 1.3	15.8 ± 1.3	15.6 ± 1.4	15.3 ± 1.7	15.8 ± 1.1
	PP	1611.3 ± 176.4	1644.1 ± 198.4	1634.1 ± 205.9	1632.7 ± 184.3	1631.5 ± 180.6	1599.2 ± 172.5	1602.7 ± 215.6	1614.3 ± 184.8	1608.7 ± 232.4	1588.3 ± 195.2
	(W)	1782.9 ± 224.0	1799.2 ± 205.3	1786.7 ± 164.0	1750.0 ± 160.1	1729.9 ± 182.8	1740.9 ± 172.6	1710.0 ± 165.2	1700.3 ± 169.4	1668.8 ± 145.8	1690.4 ± 169.5

(Continued)

Table 2. (Continued).

Author and Date	Variable	1	2	3	4	5	6	7	8	9	10
	AP	1279.3 ± 143.8	1231.7 ± 234.1	1259.6 ± 147.3	1237.7 ± 147.6	1257.0 ± 158.0	1242.1 ± 147.6	1243.9 ± 140.5	1213.1 ± 162.4	1199.8 ± 155.5	1182.5 ± 174.5
	(W)	1392.8 ± 170.3	1391.3 ± 155.5	1364.4 ± 136.2	1352.1 ± 125.0	1340.6 ± 109.6	1341.6 ± 89.2	1314.8 ± 102.3	1299.1 ± 107.1	1284.1 ± 128.5	1310.7 ± 92.1
	PV	20.4 ± 1.7	20.2 ± 1.7	20.3 ± 1.5	20.2 ± 1.3	20.1 ± 1.4	120.0 ± 1.4	19.8 ± 1.4	19.8 ± 1.3	19.7 ± 1.3	19.5 ± 1.4
	(km·h^{-1})	21.4 ± 1.8	21.2 ± 1.6	21.0 ± 1.4	20.8 ± 1.4	20.6 ± 1.2	20.7 ± 1.2	20.4 ± 1.2	20.3 ± 1.3	20.2 ± 1.2	20.3 ± 1.1
	AV	18.0 ± 2.0	17.2 ± 3.1	17.6 ± 1.8	17.3 ± 2.2	17.6 ± 2.0	17.5 ± 2.0	17.5 ± 1.8	17.3 ± 2.3	16.9 ± 2.2	16.6 ± 2.3
	(km·h^{-1})	19.5 ± 2.2	19.5 ± 2.0	19.2 ± 1.9	19.0 ± 1.8	19.0 ± 1.8	18.9 ± 1.5	18.7 ± 1.6	18.5 ± 1.7	18.1 ± 2.0	18.7 ± 1.3
	% PP	6.5 ± 2.3									
		6.6 ± 3.0									
	% PV	4.0 ± 2.2									
		3.9 ± 2.4									
Pullinger et al. 2018b	DC	14.2 ± 1.8	14.1 ± 1.8	14.0 ± 1.6	13.8 ± 1.5	13.8 ± 1.4	13.8 ± 1.4	13.7 ± 1.4	13.5 ± 1.6	13.4 ± 1.6	12.9 ± 1.4
	(m)	15.4 ± 1.7	15.3 ± 1.8	15.3 ± 1.5	15.2 ± 1.7	15.1 ± 1.8	15.0 ± 1.6	15.0 ± 1.4	15.0 ± 1.3	14.7 ± 1.6	14.7 ± 1.5
	PP	1565.6 ± 173.5	1585.7 ± 201.9	1608.5 ± 224.0	1585.8 ± 228.2	1614.0 ± 264.9	1577.7 ± 218.3	1539.1 ± 240.9	1585.3 ± 225.2	1582.6 ± 241.5	1557.5 ± 194.1
	(W)	1678.2 ± 224.1	1680.6 ± 212.7	1709.7 ± 234.9	1663.4 ± 185.7	1641.2 ± 219.6	1667.9 ± 201.1	1663.5 ± 197.2	1654.9 ± 182.0	1629.7 ± 197.5	1624.8 ± 206.7
	AP	1177.3 ± 154.7	1164.0 ± 150.7	1154.8 ± 143.0	1135.1 ± 120.8	1149.6 ± 134.0	1136.9 ± 121.4	1146.9 ± 132.2	1105.3 ± 127.5	1144.9 ± 137.8	1077.7 ± 117.5
	(W)	1315.7 ± 157.0	1306.4 ± 146.9	1289.6 ± 144.7	1281.5 ± 139.1	1270.6 ± 141.2	1262.3 ± 135.4	1254.3 ± 132.6	1248.8 ± 107.5	1236.2 ± 110.0	1227.1 ± 117.7
	PV	19.8 ± 1.3	19.9 ± 1.1	19.8 ± 1.1	19.7 ± 1.1	19.8 ± 1.1	19.8 ± 1.3	19.5 ± 1.3	19.6 ± 1.2	19.5 ± 1.3	19.3 ± 1.2
	(km·h^{-1})	20.7 ± 1.7	20.7 ± 1.6	20.6 ± 1.6	20.6 ± 1.6	20.5 ± 1.4	20.3 ± 1.4	20.2 ± 1.3	20.1 ± 1.2	20.1 ± 1.3	20.1 ± 1.2
	AV	16.8 ± 2.1	16.6 ± 2.1	16.4 ± 1.9	16.3 ± 1.5	16.3 ± 1.7	16.2 ± 1.6	16.2 ± 1.8	15.8 ± 1.8	15.8 ± 1.6	15.5 ± 1.7
	(km·h^{-1})	18.1 ± 2.3	18.2 ± 2.3	18.1 ± 2.0	18.1 ± 2.1	17.9 ± 2.1	17.8 ± 1.9	17.8 ± 1.8	17.8 ± 1.6	17.4 ± 2.0	17.4 ± 1.9
	% PP	6.4 ± 2.2									
		6.4 ± 4.0									
	% PV	2.7 ± 1.8									
		2.4 ± 1.1									

AP = Average Power, AV = Average Velocity, DC = Distance Covered, FI = Fatigue Index, PO = Power Output, PP = Peak Power, PPO = Peak Power Output, PR = Pedaling Rate, PT = Peak Torque, PV = Peak Velocity, PD = Power Decrement, TMW = Total Mechanical Work TW = Total Work.

Table 3. Detailed information related to randomization, counterbalancing, record of light intensity, control of meals, control of room temperature, control of sleep and fitness for articles related to chronobiology (time-of-day).

Date	Author	Randomization	Counterbalancing	Record of light intensity	Control of meals	Control of room temperature	Control of sleep	Fitness
2019	Lopes-Silva et al.	Yes	No	No	Yes	No	No	Physically Active
2018a	Pullinger et al.	No	Yes	Yes	Yes	Yes	Yes	Well-trained
2018b	Pullinger et al.	No	Yes	Yes	Yes	Yes	Yes	Well-trained
2018	Chtourou et al.	Yes	Yes	No	Yes	No	Yes	Elite Athletes
2014	Pullinger et al.	No	Yes	Yes	Yes	Yes	Yes	Well-trained
2013	Aloui et al.	No	No	No	Yes	No	Yes	Amateur Soccer
2012	Zarrouk et al.	Yes	No	No	Yes	Yes	Yes	PE students
2010	Racinais et al.	Yes	Yes	No	No	No	Yes	Physically Active
2006	Giacomoni et al.	No	Yes	No	No	No	Yes	Active
2005	Racinais et al.	Yes	Yes	No	No	Yes	Yes	Physically Active

compound the errors and produce an inappropriate set of results and summary.

Quality of work

Table 3 provides detailed information related to randomization, counterbalancing, record of light intensity, control of meals, control of room temperature, control of sleep and fitness, to quantify for the control of aspects relating to research design deemed specifically important in investigations of a chronobiological nature. In total, half of the studies (50%) stated the design of their research had been randomized, while seven had clearly stated that their protocol had been counterbalanced in order of administration. Of these, only 30% of studies were counterbalanced and randomized in their design. Regarding specific control over matters which are deemed particularly important to investigations of a chronobiological nature, 90% of the studies controlled for sleep and stated that usual timing and quantities were deemed enough. A further 70% of the studies-controlled food intakes, and half the studies controlled for room temperature. Only 30% of studies recorded light intensity. However, all studies discussed specific reference to the amount and type of training or the current fitness of their participants. None of the studies provided information regarding the seven primary chronobiological areas (Table 3). Nevertheless, 60% of the studies met a minimum of 50% of factors deemed specifically important in investigations of chronobiological nature (Table 3). In addition, all studies were diurnal by nature, as all used two time points during waking hours of a normal day to assess repeated-sprint performance.

Methodological quality control and publication bias

Based on a modified 26-item Downs and Black (1998) checklist, the results of the methodological quality assessment of the included studies ranged from 19 to 24. Reporting (10 items; items 1–10) showed 6 items to be fully met by all studies, with four questions ranging from one to three studies not meeting the criteria. External validity (3 items; items 11–13) only displayed one item (item 13) to be fully met, with the other two items not met by four studies. Internal validity study bias (7 items; items 14–20) only reported 5 items out of 7 to be fully met with one item being met by no study (item 14) and another by three studies (item 13). Half of the internal validity confounding selection bias (7 items; items 21–26) met all criteria with one item being met by no studies (item 24) and the other two 1 study (item 22) and 6 studies (item 23), respectively. A total of seven studies reached a quality assessment score of ≥75% and were

Table 4. Results of the detailed methodological quality assessment scores based on a modified 26-item Downs and Black (1998) checklist.

															Internal validity															
		Reporting (Items 1–10)										External validity (Items 11–13)			Study bias (Items 14–20)							Confounding selection bias (Items 21–26)								
Date	Study Author	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Total S core	Rating	Quality
2019	Lopes-Silva et al.	1	1	1	1	1	1	0	0	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1	0	1	1	20	74	Moderate
2018a	Pullinger et al.	1	1	1	1	2	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	1	1	24	89	Strong
2018b	Pullinger et al.	1	1	1	1	2	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	0	0	1	1	22	81	Strong
2018	Chtourou et al.	1	1	1	1	2	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	24	89	Strong
2014	Pullinger et al.	1	1	1	1	2	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	0	1	1	23	85	Strong
2013	Aloui et al.	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0	0	1	1	22	81	Strong
2012	Zarrouk et al.	1	1	1	1	2	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1	1	23	85	Strong
2010	Racinais et al.	1	1	1	1	1	1	0	1	1	0	0	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1	19	70	Moderate
2006	Giacomoni et al.	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1	1	0	0	1	1	19	70	Moderate
2005	Racinais et al.	1	1	1	1	2	1	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	0	0	0	1	1	21	78	Strong
	Total	10	10	10	10	16	10	7	9	10	7	6	6	10	3	0	10	10	10	10	10	10	9	4	0	10	10	21.7	80.4	
	Maximum	10	10	10	10	20	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	27	100	
	% of lost points	0	0	0	0	20	0	30	10	0	30	40	40	0	70	100	0	0	0	0	0	0	10	60	100	0	0	19.6	19.6	

1 = criteria was met; 0 = criteria was not met.

deemed strong, while the other three studies were deemed moderate (50% to 75%). Detailed methodological quality assessment scores can be found in Table 4.

Discussion

The present study analyzed data from studies that compared the effects of diurnal variation on repeated-sprints performance and determined the quality of evidence that reports a “peak” time for performance. The main finding of this review was that most research papers (n = 8; 80%) established time-of-day differences related to repeated-sprint performances, with significantly greater values in the afternoon compared to the morning dependent on the variable assessed.

Repeated-sprint performance

Relatively few papers (n = 10) have investigated time-of-day effects on repeated-sprint performance. In agreement with a convincing body of previously established research that has shown many human performance variables to display diurnal variation, rhythms in repeated-sprint performance also display diurnal variation. Most repeated-sprint performance variables consistently peaked between 17:00 h and 19:00 h with lower values observed between 06:00 h and 10:00 h. Time-of-day differences ranged from 3.4% to 10.2% (Table 1) with the magnitude of difference highly dependent on aspects such as the performance variable measured, the mode of exercise, the sprint duration, the type of recovery, the number of sprint repetitions and the training status of subjects.

All studies (Pullinger et al. 2014, 2018a, 2018b) that investigated diurnal variation in repeated-sprint performance on a non-motorized treadmill found an average time-of-day difference between 8.5% and 8.8% for distance covered, average power and average velocity and 3.5% in peak velocity in favor of the evening for all sprints. Peak power displayed an average difference of 5.8% in two studies with the third study only displaying a “trend” or “marginal significance” (Pullinger et al. 2014). However, FI (% power decrement) for peak power and velocity was unaffected by time-of-day. Similarly, five studies found several repeated-sprint performance variables on a cycle ergometer to favor evening performance. Only one study (Lopes-Silva et al. 2019) found (peak) power outputs to display diurnal variation of 6.0% in favor of evening performance in all sprint repetitions, with all other studies observing improvements in only the first or the first few sprints only. Total work was also higher 8.0% on average in two studies and one study established 9.0% differences in anaerobic power reserve. However, unlike findings related to repeated-sprints on a non-motorized treadmill, significantly higher average FI (power decrement) of 4.0% were observed in favor of the evening. The different performance variables assessed and methodologies between cycling and running repeated sprint tasks, make comparisons difficult and likely contribute to the different observations presented in this review.

Considering most findings related to repeated-sprints have established diurnal variation, it has previously been suggested that superiority in repeated-sprint performance can be attributed to a causal link between performance and both rectal (Trec) and muscle temperatures (Tm). Research wherein temperature values have been reported for Trec and Tm (at 3 cm depth) are sparse, those that have report a diurnal variation, with lower values in the morning compared to the evening for both sites of measure. For several years, it was proposed that the increased temperature values in the evening effected performance by the mechanisms of a resultant increase in neural function (increase in speed contraction and/or reduction in twitch time-course) and the force-generating capacity of the muscle (Bernard et al. 1998; Coldwells et al. 1994; Melhim 1993). However, recent findings have established to the diurnal changes in Trec and Tm and the causal link between body temperature and repeated-sprint performance are not as simple as previously suggested and not the only determinants in diurnal variation – such that raising morning Trec to evening values by active warm-up does not increase repeated-sprint performance to levels observed in the evening as would be expected if the link was causal (Pullinger et al. 2014). Other factors have been suggested to account for diurnal variation in repeated-sprints such as determined by external (environmental) and endogenous (outputs from the body clock) components (Edwards et al. 2013; Zhang et al. 2009), such as motivational aspects, subjective arousal, sleepiness, ionic changes and hormonal fluctuations (cortisol ratio, thyroid secretion and testosterone ratio) (Zhang et al. 2009).

Two studies included in this review did not find any repeated-sprint performance variables to show a significant difference between the morning and evening conditions. The study performed by Chtourou et al. (2018) tested repeated-sprint performance of 14 elite male judokas in the morning vs. the afternoon. These authors suggested that the observed discrepancies between their findings and other studies were related to the training level of their participants and/or the differences in the involved muscle groups used in running compared to cycling (Atkinson et al. 1993; Glaister et al. 2008). However, time-of-day differences in repeated-sprints have been established in trained individuals and in running as the mode of exercise therefore questioning some of these suggestions (Table 2). Other suggestions such as regular training preference in the morning hours, which has previously shown to reduce the diurnal variation of short-term maximal performance (Chtourou et al. 2012) and the extended warm-up duration (15-min) could help explain why repeated-sprint performance did not display time-of-day differences. The only study to use an indoor repeated-sprint test consisting of six 2 × 12.5 m shuttle sprints with changes of direction of 180° with 25-s recovery performed by Giacomoni et al. (2006), also found no diurnal variation in repeated-sprint performance. Their results suggest that the occurrence of fatigue and recovery patterns from all-out intermittent exercise may be differentially affected time-of-day. These authors disagreed with previously observed findings that reported increases in peak power output on a cycle ergometer but did find mechanical indices related to power recorded during the first sprint to be 3.9% higher in the evening compared to the evening, although this was not significant. They stated that methodological differences between findings observed in the literature and their study affected the observation of time-of-day. The authors suggest that the accuracy of results is highly dependent on aspects such as motivation of subjects, warm-up conditions and the device/acquisition system used.

Methodological quality and control

With reference to methodological quality, the included studies all reached a quality assessment score of ≥70% (Table 3). However, from a chronobiological study design perspective, there is an apparent lack of control of important factors which specifically relate to investigations of chronobiological nature. Considering the periodicity of the body clock is affected by rhythmic cues which are derived from the external environment and which influence the continual adjustment of the body clock (zeitgebers), such as the light-dark cycle, the feeding-fasting cycle and the activity-inactivity cycle (Aschoff 1965; Aschoff and Wever 1980; Dunlap et al. 2004), it is important for these factors to be controlled. However, only three studies (Pullinger et al. 2014, 2018a, 2018b) reported consideration of light or dark exposure of subjects or recorded any information regarding light intensity. The control of meals (either calorific intake or timing) a factor which has previously been stressed to play an important role in studies of chronobiology (Bougard et al. 2009) was controlled by seven studies. Nine of the 10 studies also reported chronotype assessment with no studies reporting any of their participants belonging to extreme chronotypes.

Given the strength of evidence regarding a potential 4% to 6% increase in muscle force development through passive warming of the musculature (Asmussen and Bøje 1945; Ball et al. 1999) and with every 1°C increase in core temperature from resting values (Bergh and Ekblom 1979), it is surprising only 50% of studies reported or controlled for room temperature. Although the exact mechanisms for the observed diurnal variation in human performance are still, yet unknown, they have been attributed to several factors including the causal link of the temperature rhythm (Zhang et al. 2009). Therefore, the decision not to report on all factors relating to aspects of temperature (core and environmental) would seem to be more of an oversight rather than a choice.

Nine out of the 10 studies in this systematic review commented on measures of sleep such as; keeping standard sleeping habits with a minimum amount of sleep required, no staying up late and no experience of insomnia or sleep deprivation. However, of these only five studies quantified timings of retiring or rising, and/or how much sleep/rest was allowed during throughout the experimental procedure. A great extent of previous research has investigated the effect of sleep and its impact on performance and central fatigue (Edwards and Waterhouse 2009; Waterhouse et al. 2011; Winget et al. 1985). It has been established that gross muscular tasks that are repeated or have a time on task component are negatively affected by sleep loss. Therefore, the extent of this lack of control comes as a major surprise when reviewing articles concerned with time-of-day variation. The known restorative influence of sleep, and fatigue associated with time-since-sleep, would suggest that whilst muscle force output might be parallel to the rhythm of core temperature (see above), cognitive performance and central arousal will decline as time-awake increases (Ball et al. 1999). Given the weight of influence of this factor, although all studies bar one commented on measures of sleep, no studies provided detailed information on the timings of retiring and rising and the exact amount of sleep and/or rest was allowed. By failing and choosing not to control or report on sleep, it is impossible to determine whether sleep-loss had affected these aspects of repeated-sprint performance.

Regarding previous exercise history of the participants used in the studies, all the articles recruited people of a 'trained' classification. Choosing to recruit participants with such previous history of exercise should not present a problem with regards to interpretation of findings (Guette et al. 2005; Häkkinen 1989). However, training status is an aspect which has a large influence on repeated-sprint performance with elite team-sport athletes achieving far greater peak power than other trained individuals (Bishop and Spencer 2004). In addition, it has been suggested that the observation of a significant diurnal variation is somewhat dependent on subject familiarization regarding the task to be performed (Bambaeichi et al. 2005; Giacomoni et al. 2006; Reilly et al. 1997). The lack of control of familiarization and the number of sessions scheduled or the objective way of assessing when the participant was deemed as familiarized could have resulted in neuromuscular adaptations during the experimental sessions in un-familiarized individuals. If the sessions were not counterbalanced for order this learning effect could have biased the results, such that the interpretation of time-of-day changes in the observed peak power in several sprints could be argued as being simply due to acute neuromuscular adaptations associated with familiarization and the initial learning of motor recruitment pathways as opposed to any endogenously driven rhythm. Which is exactly why familiarization and counterbalancing are such important aspects of the research design, as it is precisely because of familiarization and counterbalancing that these effects are minimized or removed.

Finally, there is clearly a diurnal type bias of studies where participants live normally, and measures taken were typically within normal waking hours such as the early morning (05:00–-09:00 h) and evening (17:00–19:00 h). Rather than a circadian type study where 4–6 equally spaced times of day across the solar 24 h day are chosen (with cosinor analysis undertaken). Further, few authors stated that they had aligned their time-of-day data collection points to known (based on previous research findings) lows and highs of both the rhythm of core temperature and/or performance variables during the repeated-sprint test or been influenced by other factors such as opening times of the laboratories and potential effects of sleep restriction on morning performance.

Strength and weaknesses

The primary limitation of the present review is related to several methodological limitations. The substantial differences in methodological and clinical heterogeneity among studies meant we were unable to conduct a meta-analysis and pool the observed data-sets to evaluate the evidence related to findings in repeated-sprint performance (Borenstein et al. 2009). Our interpretation of findings implies that there is a considerable inconsistency in the methods and scientific rigor of the past research, in addition to the relationship between time-of-day and repeated-sprint performance. In addition, methodological differences between included research articles and the general lack of research related to time-of-day and repeated-sprint performance made comparisons between findings difficult. It is therefore important for future studies to consider strict protocols which take into account and control factors related to chronobiology as these significantly influence repeated-sprint performance.

The primary strength of the present systematic review is that it was performed using a structured analysis according to the PRISMA guidelines (Weir et al. 2016) and is the first to provide an excellent overview of all the literature considering time-of-day and repeated-sprint performance. Further, in-depth information relating chronobiological factors and how these affect findings has also been provided. Another strength of this systematic review is the diversity of databases used during the search strategy and the strong method created to incorporate search terms that are specific and important. Importantly, the current review focused solely on the repeated-sprint performance paradigm and only included studies designed to assess diurnal variation in repeated-sprint performance.

Conclusions

The present systematic review showed that repeated-sprint performance is affected by time-of-day in favor of evening performance around the peak of the rhythm of core and muscle temperature for the first, first few or all sprints. However, there is a clear demand for more rigorous investigations, which control factors that specifically relate to investigations related to chronobiology (time-of-day), such as appropriate familiarization of participants with the performance test, randomization, counterbalancing, record of light intensity, control of meals, control of room temperature, control of sleep and fitness. It is of great importance that participants taking part in time-of-day studies are fully familiarized with the procedures and that the repeated-sprint protocol and mode of exercise used are specific to the sport of the individuals. Therefore, to assess the magnitude of the daily variation in repeated-sprint performance the aforementioned factors must be taken into account, while choosing appropriate morning and evening times (as close to the time-points of the core body temperature minimum and maximum values as possible), whilst taking into account effects of sleep inertia and restriction.

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