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Heart rate recovery to assess fitness: comparison of different calculation methods in a large cross-sectional study

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Authors contribution

Design was performed by D.M. and D.S.C.. Measurements were performed by J.R.A.C. and J.G.R.. Analysis was conducted by D.M.. Writing of the manuscript and interpretation was conducted by D.M. and C.C.. All authors agreed to the final version of the manuscript.

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Abstract

We propose a cross-sectional study based on 980 maximal effort tests to quantify the effect of the calculation method of heart rate recovery (HRR) on its association with cardiorespiratory fitness (CRF). For five different time t_0 after exercise cessation, HRR has been calculated as:

- the difference and the ratio between maximal measured heart rate and heart rate (HR) at t_0
- HR at t_0
- the decay time of an exponential decay encompassing the first t_0 minutes of the HR recovery.

The associations between HRR indices and CRF were estimated from generalized estimating equations stratified by gender and adjusted for age and body mass index. For HRR indices based on exponential regression, no significant association with CRF was found, whereas the other HRR indices are associated with CRF when t_0 is at least one minute and is maximum for t_0 = 2 minutes for females and t_0 = 3 minutes for males.

Keywords: Exercise test, Heart rate recovery, cardiorespiratory fitness, vagal reactivity

Introduction

Heart rate during exercise is a common measurement to assess the cardiorespiratory fitness (CRF) of a person. Among the information contained in such measurement, heart rate recovery (HRR) is a central one. HRR is the result of the parasympathetic reactivation and sympathetic withdrawal balance (Borresen & Lambert, 2008) after exercise cessation. Additionally to its use in medicine as a predictor of cardiovascular disease or mortality (Ross Robert et al., 2016), HRR is widely used for the adjustment and prescription of training by professionals (Bellenger et al., 2016). It is indeed affected by training and physical fitness (Borresen & Lambert, 2008), with trained persons having faster HRR than untrained ones (Otsuki et al., 2007). In the general population, faster HRR is associated with higher physical activity (Carnethon et al., 2005).

The use of the term heart rate recovery covers a large variety of methods involved to quantify heart rate decay after exercise (Bosquet et al., 2008). As first proposed (Savin et al., 1982), HRR can be measured by the decay rate of a mono-exponential of the HR recovery (Buchheit et al., 2010), or as the slope of the logarithm transformed of HR between the 10th and the 40th first seconds of the recovery (T30) (Sugawara et al., 2001; Thomson et al., 2016). An important number of studies define HRR as the difference between the peak HR and HR at a given time t_0 after exercise cessation. This time is frequently 60 seconds (Lamberts et al., 2009), but is sometimes longer (120 seconds (Carnethon et al., 2005) or even longer (Shetler et al., 2001)) or shorter (30 seconds (Danieli et al., 2014) or even shorter (van de Vegte Yordi J. et al., n.d.)). Some studies use the ratio between maximum HR and HR at a given recovery time (Borresen & Lambert, 2007), while others prefer to use directly the value of the heart rate at a given time of recovery as a measure of HRR (Bosquet et al., 2008; Mahon et al., 2003). The studies using several of these indices indicate that these different definitions do not provide the same results (Buchheit et al., 2008; Danieli et al., 2014; Del Rosso et al., 2017; Thomson et al., 2016), and the research focusing on the reliability of the various HRR calculations find differing and relatively low reliability of HRR measurements (Bosquet et al., 2008), especially during maximal exercise testing. The results of studies using HRR as a measure of CRF could thus depend on the HRR calculation method employed.

The aim of this article is thus to compare the different ways of calculating HRR to provide guidelines to help researchers identify the most appropriate index. To reach that aim, we will test the association of 21 different HRR indices with indices CRF, using a collection of 980 treadmill maximal effort tests.

Methods

The collection of effort tests is obtained from all effort tests measured at Exercise Physiology and Human Performance Lab (Department of Human physiology, histology, pathological anatomy and sport physical education of University of Malaga) between 2005 and the end of 2018. The selection process is described in Appendix A, and the data used for this study is available (Mongin et al., 2021) in the physionet database (Goldberger et al., 2000).

Exercise test

The athletes performed a Graded Exercise Testing (GET) on a PowerJog J series treadmill connected to a CPX MedGraphics gas analyzer system (Medical Graphics) with breath-by-breath measurements of respiratory parameters -including VO_2, and HR- with a 12 lead ECG (Mortara). The stress test consisted of an 8-10 min warm-up period of walking at 5 km.h^{-1} followed by a continuous (ramping) or step by step incremental effort with a 1km.h^{-1}/min speed increase. When incremental, the step amplitudes range from 0.5 to 1 km/h. The participants were asked to go beyond exhaustion, and the test was considered maximal if there was an increase of less than 2.1 mL/kg/min in VO2 between two stages. The effort was then ceased, and to avoid vasovagal syncope, the treadmill speed was set back to the initial 5 km.h^{-1} speed, and the participant was asked to walk. This active recovery setting follows the recommendations of several official institutions (Medicine, 2013) and ensures reliable measurement of HRR (D. A. Boullosa et al., 2014). The recovery was recorded for 200 seconds after exercise cessation.

Two standard CRF indices (Ross Robert et al., 2016) were derived from the GET: the maximum oxygen consumption per kg (VO_2max), derived from the VO_2 measured at the end of the effort test averaged over 10 measurement points and normalized by the body mass, and the maximum aerobic speed (MAS), i.e. the maximum speed reached during the test.

Participants

Participants are athletes (student in sport, amateur or professional) followed by the laboratory or who participated in a study. Exercise testing was voluntary, and prior to its initiation, written informed consent was obtained from the participants and the legal guardians of those under 18 years of age. All effort tests have been performed under the supervision of a doctor in sport science, and their analysis carried out according to the principles of the Declaration of Helsinki. Because this retrospective study uses completely de-identified data that cannot be reidentified, it was exempted from ethics committee approval.

Heart rate recovery measurements

Let be t_0 a time after exercise cessation, and HRpeak the maximum of the HR averaged over 10 measurement points reached during exercise. The different HRR measurements compared in this study are:

- The difference between HRpeak and HR at t_0 = 10, 30, 60, 120 or 180 seconds (HRRΔ10, HRRΔ30, HRRΔ60, HRRΔ120 and HRRΔ180 respectively). The higher is this value, the faster is the HR recovery.
- The ratio between HR at t_0 = 10, 30, 60, 120 or 180 seconds and HRpeak, expressed as a percentage (HRR%10, HRR%30, HRR%60, HRR%120, HRR%180). The smaller the value, the faster is the HR recovery.
- The exponential decay times of a mono-exponential regression of the following three parameters model:

$$HR(t) = ae^{-\frac{t}{HRR\tau}} + b \qquad \text{Equation 1}$$

with t the time encompassing the first 30, 60, 120 or 180 seconds of the recovery. The decay times for each regression are respectively HRRτ30, HRRτ60, HRRτ120, HRRτ180. The smaller this value, the faster is the HR recovery.

- The raw HR at t_0 = 10, 30, 60, 120 or 180 seconds (HRrec10, HRrec30, HRrec60, HRrec120 and HRrec180 respectively). For a fixed HRpeak, the lower this value, the faster the HR recovery.
- The T30 as defined by Buchheit (Buchheit et al., 2007, 2008), calculated as the slope of the natural logarithm of HR between 10 and 40 seconds after exercise cessation. This slope is negative, and the smaller is its value (i.e. the higher its absolute value), the faster is the HR recovery.

A summary table of these indices is proposed in Appendix B.

Statistics

All the analyses performed were done with R 3.6.2 (R Core Team, 2019) using *data.table* and *ggplot2* packages for the data management. The exponential-based HRR indices ($HRR\tau$) were obtained by performing a nonlinear least square regression using the function nls and the model presented in equation 1. HRR indices were compared between sex using the Wilcoxon rank-sum test and the effect size of the difference was estimated with Cohen's d. The association of CRF indices with HRR was estimated using multivariable generalized estimating equations (GEE) with a gaussian distribution, an independent correlation structure and the individual as a cluster using the *geepack* package (Højsgaard et al., 2005). To compare the effects of HRR measures having different scales and units, regression coefficients were standardized. The outcome variables and predictors used were thus transformed with the following equation before the regression:

$$X_{standardized} = \frac{X - \bar{X}}{\sigma(X)}$$

where $\bar{X}$ is the mean of the variable X and $\sigma(X)$ its standard deviation. The regression was adjusted for confounders, namely age and BMI, and stratified by sex. Difference between standardized coefficients was tested by Monte Carlo simulation, consisting in performing 1000 estimation of the GEE regression on a random sample of 70% of the effort tests to calculate for each run the difference between the two standardized coefficients of interest. The difference was considered significative if it had the same sign for 950 over 1000 runs. As we tested for each fitness index the associations with 21 HRR indices, the p value threshold considered for the null hypothesis rejection was corrected using Bonferroni correction. The resulting significance threshold for the p-value is thus $\alpha = 0.0025$. To ensure and promote the reproducibility of this research, the code used for this study is openly available (*Denis Mongin / HRR_comparison*, 2021).

Results

The physiological characteristics of the participants are presented in table 1. A total of 980 effort tests were performed by 850 athletes (694 males and 129 females). The age of the athletes ranged from 10 to 62 years, with a mean age of 27 years. VO_2max indicates an overall high cardiovascular fitness (Sanders & Duncan, 2006). The females were significantly lighter, smaller, younger, with lower aerobic capacities, but similar maximum heart rate. The maximal heart rate estimated by Tanaka's formula (Tanaka et al., 2001) was 2 beats/min higher than HRpeak, consistent with recent findings (Berglund et al., 2019). The effort protocol (graded or ramping) did not induce significant change in HRpeak in a linear model predicting HRpeak as a function of Age, Sex, and the protocol type (p = 0.66)

Table 1: physiological characteristics of the population studied. The values given are the mean (standard deviation). Maximum HR is estimated with Tanaka's formula (Tanaka et al., 2001)

	Overall	Male	Female
Number of effort tests	980	832	148
Participants	848	718	130
Participant with at least			
1 effort test	848	718	130
2 effort tests	113 (13.3 %)	99 (13.7%)	14 (10.8%)
3 or more effort tests	19 (2.2%)	15 (2.1%)	4 (3.1%)
Age (year)	26.90 [21.00, 36.23]	27.60 [21.30, 36.62]	24.55 [18.70, 30.40]
Height (cm)	175.00 [170.00, 180.00]	176.00 [172.00, 181.00]	166.00 [160.97, 171.00]
Weight (kg)	73.00 [66.00, 80.12]	74.35 [68.33, 81.10]	61.50 [55.90, 67.00]
bmi ($\mathrm{kg.m^{-2}}$)	23.67 [22.15, 25.38]	23.93 [22.46, 25.56]	22.20 [20.89, 23.95]
Peak HR (HRpeak, beat.min^{-1})	187 [180, 194]	188 [180, 194]	187 [181, 194]
Maximum HR (HRmax, beat.min^{-1})	190 [184, 194]	190 [183, 194]	192 [188, 196]
Speed at VO_2max (MAS, km.h^{-1})	16.70 [15.00, 18.10]	17.00 [15.50, 18.20]	14.10 [12.38, 15.33]
Maximum VO_2 (VO_2max, mL.min^{-1})	3513 [2935, 3951]	3627 [3200, 4037]	2404 [2147, 2663]
Maximum VO_2 per kg (VO_2maxkg, mL.kg^{-1}.min^{-1})	47.64 [41.42, 53.62]	49.09 [43.04, 54.81]	40.45 [35.21, 43.63]
protocol type (% Ramping)	666 (68.0%)	556 (66.8%)	110 (74.3%)
Effort duration (s)	685 [581, 779]	716 [618, 791]	544 [430, 614]

To provide reference values for the different HRR indices derived from the maximum effort tests, we present in table 2 the mean values and standard deviations of these indices, both overall and by sex. Most of the HRR indices indicate a significantly faster recovery among males than females, except for HRrec10, HRRτ30, and HRRτ60. The effect size generally increased with the time t_0 between HRpeak and the HR considered during the recovery. The mono-exponential decays HRRτ have higher value and higher variability when estimated at the beginning of the recovery period. The mean coefficients b estimated from the nonlinear exponential regression (see equation 1) were -43, -32, 26, and 80 beat/min for HRRτ30, HRRτ60, HRRτ120, and HRRτ180 respectively.

Table2: Reference values of the HRR indices proposed. Median [Inter Quartile Range] values of the different HRR measurements for all effort tests and by sex category. P values of the differences between male and female, together with Cohen's d size effect measures are provided.

HRR measures	HRR values			p	Cohen's d
	Overall	Male	Female		
HRRΔ10 (beat/min)	4.0 [2.0, 7.7]	4.4 [2.0, 8.0]	3.1 [1.3, 5.7]	0.001	-0.24
HRRΔ30 (beat/min)	15.6 [11.1, 20.5]	16.2 [11.9, 21.0]	12.9 [9.8, 16.7]	<0.001	-0.42
HRRΔ60 (beat/min)	31.8 [25.0, 39.0]	32.6 [26.0, 39.9]	27.4 [21.5, 34.3]	<0.001	-0.51
HRRΔ120 (beat/min)	54.0 [47.0, 61.7]	54.8 [47.9, 62.2]	49.0 [42.0, 56.5]	<0.001	-0.53
HRRΔ180 (beat/min)	63.4 [56.5, 70.5]	64.0 [58.0, 71.0]	57.5 [51.0, 67.1]	<0.001	-0.57
HRR%10 (%)	97.8 [95.9, 98.9]	97.6 [95.7, 98.9]	98.3 [97.0, 99.3]	0.001	0.24
HRR%30 (%)	91.6 [89.0, 94.0]	91.2 [88.7, 93.7]	93.2 [91.2, 94.6]	<0.001	0.40
HRR%60 (%)	82.9 [78.9, 86.6]	82.5 [78.5, 86.1]	85.6 [81.6, 88.9]	<0.001	0.48
HRR%120 (%)	71.2 [66.7, 75.1]	70.5 [66.5, 74.6]	73.5 [69.2, 78.5]	<0.001	0.49
HRR%180 (%)	65.7 [62.0, 69.9]	65.3 [61.8, 69.3]	68.7 [64.4, 73.5]	<0.001	0.55
HRRτ30 (s)	406.8 [124.5, 622.6]	402.9 [123.7, 609.9]	418.3 [124.7, 704.7]	0.144	0.14
HRRτ60 (s)	386.9 [123.1, 542.3]	376.9 [118.1, 537.4]	409.1 [139.8, 587.4]	0.125	0.15
HRRτ120 (s)	190.0 [112.5, 513.8]	177.8 [107.6, 491.5]	349.5 [144.9, 694.7]	<0.001	0.53
HRRτ180 (s)	120.1 [89.4, 194.8]	115.2 [88.0, 184.7]	151.4 [109.6, 289.4]	<0.001	0.28
HRrec10 (beat/min)	182.0 [174.0, 189.0]	181.5 [174.0, 188.0]	183.0 [175.0, 190.0]	0.277	0.06
HRrec30 (beat/min)	170.0 [162.0, 179.0]	170.0 [162.0, 178.0]	174.0 [165.0, 181.0]	0.009	0.18
HRrec60 (beat/min)	155.0 [143.0, 164.0]	154.5 [142.0, 163.0]	159.0 [150.0, 168.0]	<0.001	0.29
HRrec120 (beat/min)	132.5 [121.0, 143.0]	132.0 [120.0, 142.0]	138.0 [128.0, 147.0]	<0.001	0.34
HRrec180 (beat/min)	123.0 [112.0, 133.0]	121.0 [112.0, 131.0]	129.0 [119.0, 137.0]	<0.001	0.43
T30 (ms^{-1})	-3.0 [-4.1, -2.3]	-3.1 [-4.2, -2.4]	-2.6 [-3.5, -1.9]	<0.001	0.35

The raw associations between the twenty HRR indices and the fitness indices are presented in Appendix C. To adjust these associations for age and bmi, we performed for each fitness index Fit_i (i.e. VO_2max or MAS) and each HRR measurement HRR_j the following GEE regression:

$$Fit_i \sim a_{ij} HRR_j + b_{ij} Age + c_{ij} BMI$$

The analysis was stratified by sex to assess the potential sex difference of these associations. The standardized marginal effects a_{ij} of the 21 different heart rate recovery indices (HRR_j) for males and females on both VO_2max and MAS are presented in table 3.

All significant associations with VO2max and MAS have a sign indicating a faster recovery for an improvement of aerobic capacities. For males, VO2max is significantly associated with all HRR indices based on raw HR recovery values (HRrec) or on difference and ratio between HR during recovery and HRpeak (HRRΔ and HRR%). For females, these associations are significant only when considering t0 equal or higher than 60 seconds. MAS is associated with HRrec, HRRΔ and

HRR% for t0 higher or equal than 120 seconds for males and for t_0 equal or higher than 60 seconds for females. The associations between HRR measurements and CRF measurements tend to increase with t0. HRR%180 and HRRΔ180 are more associated to VO2max and MAS than any other indices ($p < 0.001$) for males, whereas for females it is HRR%120 and HRRΔ120 ($p < 0.001$). None of the exponential-based HRR indices (HRRτ) yielded a significant association, except for HRRT30, which is slightly associated with VO2max only for males.

Table 3: Associations between HRR indices and aerobic performance indices. Standardized regression coefficients between performance indices (maximum oxygen consumption VO_2max and maximum aerobic speed MAS) and HRR measurements, when adjusting for age and bmi. Significance is indicated as follow: *: 0.0025>p>0.0005, **: 0.0005 >p>0.00005, ***: p<0.00005

HRR measures	Association with VO_2max	Association with MAS	Association with VO_2max	Association with MAS
	males		females	
HRRΔ10	0.096 *	-0.092	0.18	0.18
HRRΔ30	0.17 ***	-0.091	0.19	0.24
HRRΔ60	0.18 ***	0.032	0.22 **	0.31 ***
HRRΔ120	0.22 ***	0.16 ***	0.22 ***	0.34 ***
HRRΔ180	0.28 ***	0.24 ***	0.19 **	0.34 ***
HRR%10	-0.095 *	0.096	-0.18	-0.18
HRR%30	-0.17 ***	0.096	-0.19	-0.23
HRR%60	-0.18 ***	-0.03	-0.22 **	-0.3 **
HRR%120	-0.22 ***	-0.15 **	-0.22 ***	-0.32 ***
HRR%180	-0.28 ***	-0.24 ***	-0.18 *	-0.32 ***
HRRτ30	-0.065	0.045	-0.13	-0.14
HRRτ60	-0.089	0.019	0.024	-0.03
HRRτ120	-0.071	0.038	-0.14	-0.19
HRRτ180	-0.032	0.056	-0.094	-0.027
HRrec10	-0.071	0.093	-0.12	-0.1
HRrec30	-0.13 *	0.089	-0.15	-0.16
HRrec60	-0.14 ***	-0.0083	-0.19 *	-0.25 *
HRrec120	-0.19 ***	-0.12 *	-0.2 **	-0.28 **
HRrec180	-0.22 ***	-0.18 ***	-0.16 *	-0.29 **
HRRT30	-0.1 *	0.035	-0.16	-0.2

Discussion

The present exhaustive analysis of 21 different well-known measurement methods of heart rate recovery from 980 graded exercise testing allows us to compare the association between the measured HRR and the CRF measurements.
For athletes undergoing maximal effort tests, the HRR indices predicting the best VO_2max or the maximum speed are the difference or the ratio between the HRpeak and HR two minutes after exercise cessation for females, three minutes for males. An increase in VO_2max or maximal speed is associated with a faster heart rate recovery.
HRR measured by mono-exponential regressions did not yield a significant link with fitness indices once adjusted for age and BMI.

The absent association between CRF indices and HRR indices based on exponential regression may be a consequence of the higher cardiac stimulation during maximal effort tests. Although the HR dynamics after a submaximal effort test is known to have an exponential shape (Borresen & Lambert, 2008) mainly driven by parasympathetic reactivation, it has been shown that the higher sympathetic stimulation during maximal exercise causes a deviation from this exponential shape (Pierpont et al., 2000) due to a sustained sympathetic activity after exercise cessation. Exponential decay of HR is then an inadequate model producing no correlations with CRF indices. The sustained sympathetic activity during the first minutes of recovery hinders the link between CRF and parasympathetic activity (Machhada et al., 2017), thus causing the poor association between CRF indices and HRR indices based on HR at $t_0 \leq 1$.

The association we observe between CRF and HRR indices involving HR at $t_0 \geq 1$ minute would then be mainly due to the parasympathetic reactivation dynamics. This vagal reactivation has been shown to be delayed by the sustained sympathetic activity (Kannankeril et al., 2004), and occurs between one and four minutes after exercise cessation. When increasing t_0 (the delay between HRpeak and HR during the recovery), the association between HRR and cardiorespiratory fitness first increases, because the contribution of the initial sympathetic retention to the HRR index is reduced. It then diminishes back, because HR starts to be driven by other mechanisms influencing its long-term dynamics, such as hormonal regulation (Gordan et al., 2015) and blood lactate release after exercise cessation (Thimm et al., 1984). The link between performance indices and HRR is thus expected to reach a maximum for a given t_0. In the present work, it occurs two minutes after exercise cessation for females and at least three minutes after exercise cessation for males. The fact that females have a lower sympathetic activity associated with a faster parasympathetic reactivation after exercise cessation (Joyce M. et al., 2001) could explain why this maximum association occurs for shorter t_0 than for males. Their lower use of the anaerobic energetic pathway during exercise could be another reason for this difference with males, as high anaerobic capacities have been shown to be related to slower post-exercise heart rate kinetics (Del Rosso et al., 2017).

The correlations values between HRR and fitness reported in our cross-sectional appear rather low in comparison with what has been reported in other studies (Daniel A. Boullosa et al., 2009). This may be due to a dependence of the association between HRR and fitness with the level of fitness. The large range of fitness used in our study would then result in a lower averaged effect, whereas using a narrower range of high fitness would increase the observed correlations.

Nevertheless, we expect that the main effects of the HRR calculation methods on the association between HRR and fitness to stay valid across the fitness levels of our data.

Strength and weakness

The present study proposes to our knowledge the first extensive comparison of the associations between a broad range of HRR measures and fitness indices for a large population. The main strengths of this study are the important number of effort tests considered (n = 980), the broad population covered in terms of age and physical performances, and the extensive number of HRR measures included. The methodic computation of HRR indices, their statistical analysis using multivariate generalized estimating equations together with the Bonferroni correction is a solid asset to this research. This work provides useful guidelines to sport exercise professionals for choosing the best HRR calculation method to evaluate the fitness of their athletes during out-of-laboratory activities. All the data used for this research (Mongin et al., 2021), as well as the code used for the HRR calculation and analysis, are openly provided (*Denis Mongin / HRR_comparison*, 2021).

There are of course limitations to this work. The results presented here only apply to maximal effort tests on treadmills. Furthermore, our cross-sectional approach cannot be generalized for longitudinal changes. Although being the protocol recommended, the use of active recovery in our measurements can be a seen as a limitation. HRR during active recovery has been shown to be slightly slower than rest recovery (Barak et al., 2011)., which could reduce the t_0 for which the association between HRR and performance indices is maximum. Another limitation is that we considered only two performance indices, disregarding the potential link between HRR indices and ventilatory thresholds or explosive performance indices.

Finally, the last limitation is the absence of information about the sport type of the athletes in our data. Indeed, it has been shown (Ostojic et al., 2010) that intermittent sports athletes are likely to have a faster HRR during the first 20 seconds of recovery after maximal exercise than athletes trained for continuous exercise. This could potentially hinder the correlation between short time (< 30s) HRR and fitness if the proportion of sport type would significantly change across the fitness levels of our data.

Conclusion

Although HRR is in the literature mainly measured as the difference between heart rate at exercise cessation onset and heart rate 60 seconds after, or as the exponential decay time of the heart rate during recovery, our study seems to indicate that these measurements of the heart rate recovery are not optimal for maximal exercises. When aiming at using HRR as a proxy of cardiovascular fitness, physicians, researchers, and coaches should prefer indices base on the peak HR and HR 2 minutes after exercise cessation for females, 3 minutes after exercise cessation for males. The first minute of HR dynamics after exercise cessation seems to be less or not influenced by cardiovascular fitness, because of the maintained sympathetic activity and associated delayed parasympathetic reactivation. The use of exponential-based HRR indices should be restricted to submaximal exercises.

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Appendix A

Effort tests used for this study were selected from the ensemble of the effort tests measured at Exercise Physiology and Human Performance Lab (Department of Human physiology, histology, pathological anatomy and sport physical education of University of Malaga) between 2005 and end of 2018. The selection process is described in figure 1. From the 1714 effort test available, 1711 with complete information about the subjects were considered. We then selected maximum effort tests having similar protocol: lasting at least 5 minutes in total, having an incremental effort with a speed increase comprised between 0.8 and 1.2 km.h^{-1}/min and having a recovery period with a speed of 5 km.h^{-1}. All effort tests have a recorded warm up period of 5 km.h^{-1} before the incremental effort. From the resulting 1164 effort tests, we then removed effort test having part of the heart rate measurement damaged. To do so, we fitted a smooth spline to the heart rate measurements along the effort tests and calculated the variance of the difference between the experimental HR measure and the spline regression. The histogram of this variance displayed a clear bimodal distribution, with variance above 100 beat/min corresponding to damaged recording. Removing these effort tests resulted in 980 final effort tests. Spurious HR measurements having a relative variation between two successive points of more than 20% were removed. It corresponded to less than 1% of the experimental measures.

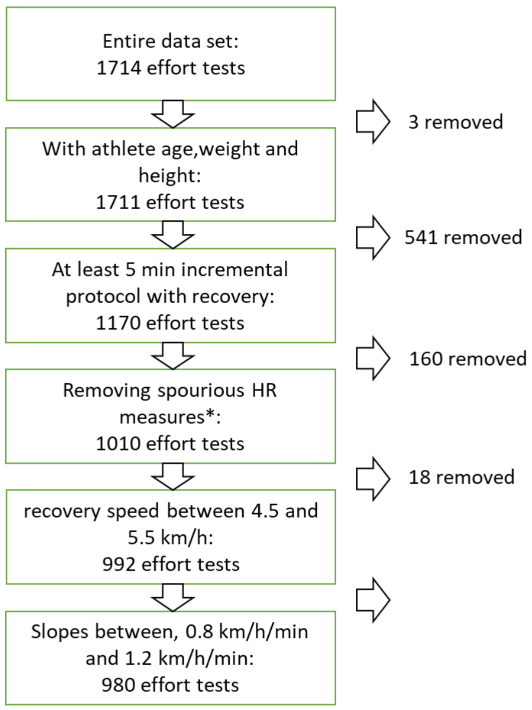

Figure 1: selection procedure of the effort tests included in this study

Appendix B

summary of the HRR indices considered in the study.

HRR index	For different recovery time considered	Variation with recovery
HRR∆	HRR∆10 = HRpeak – HR(t = 10s)	Increases for a faster recovery
	HRR∆30 = HRpeak – HR(t = 30s)	
	HRR∆60 = HRpeak – HR(t = 60s)	
	HRR∆120 = HRpeak – HR(t = 120s)	
	HRR∆180 = HRpeak – HR(t = 180s)	
HRR%	HRR%10 = HR(t = 10s)/HRpeak*100	Decreases for a faster recovery
	HRR%30 = HR(t = 30s) /HRpeak *100	
	HRR%60 = HR(t = 60s) /HRpeak *100	
	HRR%120 = HR(t = 120s) /HRpeak *100	
	HRR%180 = HR(t = 180s) /HRpeak *100	
HRrec	HRrec10 = HR(t = 10s)	Decreases for a faster recovery
	HRrec30 = HR(t = 30s)	
	HRrec60 = HR(t = 60s)	
	HRrec120 = HR(t = 120s)	
	HRrec180 = HR(t = 180s)	
HRRt	HRRt30: $HR(t) = ae^{-\frac{t}{HRR\tau 30}} + b$ for 0 < t < 30s	Decreases for a faster recovery
	HRRt60: $HR(t) = ae^{-\frac{t}{HRR\tau 60}} + b$ for 0 < t < 60s	
	HRRt120: $HR(t) = ae^{-\frac{t}{HRR\tau 120}} + b$ for 0 < t < 120s	
	HRRt180: $HR(t) = ae^{-\frac{t}{HRR\tau 180}} + b$ for 0 < t < 180s	

Appendix C

raw correlation coefficients between HRR indices and aerobic performance indices

HRR measures	Correlation with VO_2max	Correlation with MAS
HRRΔ10	0.18 ***	-0.0096
HRRΔ30	0.28 ***	0.039
HRRΔ60	0.32 ***	0.18 ***
HRRΔ120	0.36 ***	0.29 ***
HRRΔ180	0.4 ***	0.37 ***
HRR%10	-0.17 ***	0.016
HRR%30	-0.27 ***	-0.022
HRR%60	-0.3 ***	-0.15 ***
HRR%120	-0.33 ***	-0.25 ***
HRR%180	-0.36 ***	-0.32 ***
HRRτ30	-0.12 *	-0.042
HRRτ60	-0.096	-0.013
HRRτ120	-0.21 ***	-0.11 *
HRRτ180	-0.11 *	-0.013
HRrec10	-0.013	0.12 **
HRrec30	-0.082	0.082
HRrec60	-0.15 ***	-0.034
HRrec120	-0.2 ***	-0.13 ***
HRrec180	-0.24 ***	-0.19 ***
HRRT30	-0.19 ***	-0.047

Spearman rank correlation coefficient between HRR measures (left column) and VO_2max and the maximum speed MAS. Significance is indicated as follow: *: $0.0025 > p > 0.0005$, **: $0.0005 > p > 0.00005$, ***: $p < 0.00005$