



Optimal load for a torque-velocity relationship test during cycling

Renata L. Krüger¹ · Arthur Peyrard² · Hervé di Domenico² · Thomas Rupp² · Guillaume Y. Millet^{1,3,4} · Pierre Samozino²

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Abstract

Purpose Lower limbs' neuromuscular force capabilities can only be determined during single sprints if the test provides a good fit of the data in the torque-velocity (T - V) and power-velocity (P - V) relationships. This study compared the goodness of fit of single sprints performed against traditional (7.5% of the body mass) vs. optimal load (calculated based on the force production capacity and ergometer specificities), and examined if reducing the load in fatigued state enhances T - V and P - V relationship goodness of fit.

Methods Thirteen individuals performed sprints before (PRE) and after (POST) a fatiguing task against different loads: (1) TRAD: traditional, (2) OPT: optimal, and (3) LOW-OPT: optimal load reduced according to fatigue levels.

Results At PRE, OPT sprints presented a higher R^2 of the T - V relationship (0.92 ± 0.06) and lower time to reach maximal power (P_{\max}) ($48 \pm 9\%$) when compared with TRAD sprints (0.89 ± 0.06 and $66 \pm 22\%$, respectively, $p < 0.01$). At POST, the range of velocity spectrum was greater in the LOW-OPT ($33 \pm 4\%$) vs. TRAD ($24 \pm 3\%$) and OPT ($26 \pm 8\%$, $p < 0.007$). Similarly, the time to reach P_{\max} was lower in the LOW-OPT ($46 \pm 12\%$) vs. TRAD ($76 \pm 24\%$) and OPT ($70 \pm 24\%$, $p < 0.006$).

Conclusion Sprints performed against an OPT load and reducing the OPT load after fatigue improve the fit of data in the T - V and P - V curves. Sprints load assignment should consider force production capacities rather than body mass.

Keywords Maximal power output · Braking load · Neuromuscular fatigue · Force-velocity test

Abbreviations

BW	Body weight
ICC	Intraclass correlation coefficient
LOW-OPT	Optimal load reduced according to fatigue levels
OPT	Optimal load
P_{\max}	Maximal power output
P_{mean}	Mean power output

POST	After Wingate
PRE	Before Wingate
P - V	Power-velocity
R^2	Coefficient of determination
TEM	Typical error of measurement
TRAD	Traditional load
T - V	Torque-velocity
T_0	Maximal theoretical torque produced at null velocity
V_0	Maximal theoretical angular velocity produced under zero load

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✉ Pierre Samozino
pierre.samozino@univ-smb.fr

¹ Human Performance Laboratory, University of Calgary, 2500 University Drive NW, Calgary T2N 1N4, Canada

² Univ Savoie Mont Blanc, Inter-university Laboratory of Human Movement Biology, EA 7424, Bâtiment 8C-Chartreuse, Campus scientifique, F-73000, Chambéry, France

³ Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Étienne 73376, France

⁴ Institut Universitaire de France (IUF), Paris, France

Introduction

Lower limbs' dynamic force production capabilities can be well described using linear and polynomial relationships that are obtained between torque and velocity (torque-velocity relationship, T - V) and between power output and velocity (power-velocity relationship, P - V), respectively (Samozino et al. 2007). From the two extremums of the T - V relationship, the force production capacities at high and low

velocities are represented by the maximal theoretical angular velocity until which torque can be produced (V_0) and the maximal theoretical torque produced at null velocity (T_0), respectively (Samozino et al. 2007). The apex of the P – V relationship refers to the maximal power output (P_{\max}) that the limbs can produce (Samozino et al. 2007). Among the different tests often used to assess lower limbs T – V and P – V relationships—squat jumps (Rahmani et al. 2001), leg press exercises (Yamauchi and Ishii 2007), and sprint running (Cross et al. 2017)—the T – V test performed on a stationary cycle ergometer has gained a lot of attention in the past years (Driss and Vandewalle 2013). The advantage of using this testing protocol resides in the fact that: (1) it assesses lower limbs neuromuscular force production capacities in a safe, accessible, and reliable way; (2) cycling is considered a “common” task that everyone can perform; and (3) it can specifically examine cycling performance while it is still a typical movement to explore more generally muscle concentric contractions (McCartney et al. 1983; Arsac et al. 1996; Driss et al. 2002; Dorel et al. 2005; Samozino et al. 2007; Driss and Vandewalle 2013; Dorel 2018; Rudsits et al. 2018).

The T – V relationship test performed on a cycle ergometer consists of performing multiple sprints for a very short period (< 7 s) against different braking loads to obtain experimental points on the most of parts of the regression models (Arsac et al. 1996; Dorel et al. 2005). Although the T – V relationship test has a very short duration, the performance of multiple sprints can be a disadvantage in some circumstances, such as when investigating the effects of neuromuscular fatigue induced by exercise (Dorel 2018). In particular, it has been shown that fatigue can already occur after 3 s for high pedaling rates (Dorel 2018). The execution of several sprints to assess neuromuscular force production capacities before and immediately after a fatiguing task will likely cause substantial levels of fatigue and, thus, can lead to equivocal interpretations of the neuromuscular fatigue induced by exercise. The fatigue-induced reduction in neuromuscular capabilities decreases the ability to rapidly overcome the flywheel inertia and resistance (Krüger et al. 2019). This shifts the spectrum of velocities over force production to the left-side of T – V and P – V relationship curves and prevents the achievement of P_{\max} . In this situation, the individual should perform a single and brief (i.e., short acceleration time) sprint to minimize the residual effects of fatigue.

In the single sprint method, the individual cycles against only one braking load. Because of that, the determination of the load during a single cycling sprint is crucial to precisely compute the neuromuscular capabilities (Jaafar et al. 2016). It was originally suggested that cycling sprints should be performed against a load equivalent to 7.5% of the body-weight (BW) when using a Monark cycle ergometer (Bar-Or

1978). This braking load was assumed to be suitable to measure force production capabilities for a wide spectrum of intermediate velocities in young, untrained individuals (Bar-Or 1978). A few years later, however, the same group of authors proposed that braking load optimization depends on the anaerobic fitness and body composition of the individual and, therefore, these variables should be taken into account when assigning the load (Dotan and Bar-Or 1983). Accordingly, the traditional (TRAD) load of 7.5% BW may be either too high for obese (Duché et al. 2002) and non-obese young individuals (Dotan and Bar-Or 1983; Duché et al. 2002) or too low for active, athlete males (Evans and Quinney 1981; Dotan and Bar-Or 1983; Patton et al. 1985; Jaafar et al. 2016). It is important to consider that these observations were made for cycling sprints performed on a Monark cycle ergometer.

Despite several pieces of evidences suggesting that the load assignment should account for interindividual differences (e.g., anthropometric measurements and force levels) and ergometer specificities (e.g., gear ratio, flywheel velocity, and diameter) (Dotan and Bar-Or 1983; Driss et al. 2002; Duché et al. 2002; Jaafar et al. 2016; Valenzuela et al. 2018), the majority of studies still conduct cycling sprints using the TRAD load of 7.5% BW, independent of the population or ergometer tested (Glaister et al. 2005; Jacobs and Goldstein 2010; Hureau et al. 2014, 2016; Phillips et al. 2014; Ikutomo et al. 2018). The use of a non-optimal load can lead to a narrow, scattered, and uncentered distribution of velocities in the T – V and P – V spectrum, which increases the error of the neuromuscular capabilities' variables estimation (P_{\max} , T_0 , and V_0). To overcome these limitations, this study proposes a biomechanical model to determine an individualized optimal (OPT) load that accurately elicits dynamic force production capacities during single cycling sprints and considers both the specificities of the ergometer used (Monark) and the neuromuscular capabilities of the individual. In this study, we considered P_{\max} as the apex of the P – V relationship (Samozino et al. 2007). The OPT braking load should allow a wide, unscattered, and centered distribution of velocities in the T – V and P – V relationship curves. Our biomechanical model calculates the OPT braking load that allows P_{\max} to be reached at 50% of the acceleration time, i.e., $\sim 50\%$ of the total velocity range covered by the points on the left (high torque, low velocity) or the right side (low torque, high velocity) of the T – V and P – V spectrum.

The first aim of this study was to test if using the individualized OPT load method increases the P – V and T – V relationships goodness of fit compared to the TRAD load. It was hypothesized that our new model to calculate individualized OPT load would present a better reliability and goodness of fit when compared with the TRAD load. The second aim of this study was to examine if reducing the load after a fatiguing exercise, according to the decrease

in neuromuscular capabilities, enhances T – V and P – V relationships goodness of fit when compared with sprints performed against the same load used in a non-fatigued state. It was expected that reducing the load after fatigue would provide a better fit of the data in the T – V and P – V relationship curves and, consequently, a more accurate estimation of the neuromuscular capabilities. It was hypothesized that the difference in the goodness of fit between the different loads would be attenuated as the neuromuscular recovers following the fatiguing task.

Materials and methods

Participants

Thirteen young individuals (10 males and 3 females) were recruited to participate in this study (age, 26 ± 4 years; height, 174 ± 8 cm; BW, 67 ± 8 kg). All participants were classified as physically active (exercise duration > 150 min/week of moderate- to vigorous-intensity exercise) according to the Canadian Society for Exercise Physiology recommendations (CSEP 2011) and familiar with cycling sprints. The participants were instructed to abstain from consuming caffeine and alcohol for at least 12 h prior to experimental exercise conditions and from participating in any intense exercise for 24 h before testing. Informed consent was received from all subjects and all procedures were in accordance with the principles of the Declaration of Helsinki and met the international standards in sport and exercise science research.

Study protocol

Participants visited the laboratory in three different days (interspersed by at least 48 h) to perform similar experimental procedures on a Monark cycle ergometer (Monark type 818 E, Stockholm, Sweden). The cycle ergometer was instrumented with a strain gauge that measures the frictional force applied by the belt to the flywheel and with an optical encoder that assesses flywheel displacement. In the first visit, body mass (kg), height (cm), and physical fitness status were assessed. The seat and handlebar heights were determined and recorded for reproduction in the subsequent tests.

Prior to each test, individuals performed a 5-min active warm-up at ~ 100 W. After 3 min of rest, two 7-s sprints at 4 and 8% BW were performed in a randomized order. The sprints were interspaced by a 3-min passive recovery interval. The data from these two sprints were combined to determine individual T – V relationships from which OPT load was computed using a biomechanical model. Following 5 min of rest, participants performed the PRE-assessments that consisted of two sprints (PRE 1 and 2) against the TRAD

load (7.5% BW) or an OPT load (see below). After 5 min of recovery, the fatiguing exercise, which consisted of a Wingate test against a load of 7.5% BW, was performed. The single sprints were repeated 30 s after (POST) the fatiguing task as well as 1, 2, and 4 min during the recovery period (POST 1, POST 2, and POST 4). Sprints and Wingate tests were preceded by a 3 s countdown followed by the command “Go!”. The individuals were instructed to remain seated and were verbally motivated to maintain maximal cadence during the sprints. The Wingate test was chosen to induce fatigue since we have previously demonstrated that this exercise induces a great decrease in P_{\max} ($\sim -42\%$), which recovers quickly ($\sim -24\%$ after 4 min) (Krüger et al. 2019).

The three different experimental procedures were: (1) TRAD: PRE and POST sprints were performed against the TRAD load (7.5% BW); (2) OPT: PRE and POST sprints were performed against an OPT load calculated based on the individual neuromuscular capabilities; and (3) LOW-OPT: PRE sprints were performed against an OPT load calculated based on the individual neuromuscular capabilities, and POST sprints were performed at an OPT load reduced to the fatigue-induced reduction in neuromuscular capabilities. The load was diminished according to the decrease in the mean power (P_{mean}) previously recorded across the different sprints performed at POST in the OPT exercise condition. For example, if the OPT load of the individual at PRE was 7% BW and P_{mean} decreased by 30% at POST in the OPT exercise condition, the load would be reduced by 30% at POST in the LOW-OPT exercise condition (4.9% BW). This session aimed to test if reducing the load to the neuromuscular fatigue level enhances T – V and P – V relationship curves goodness of fit when compared with sprints performed against the same load used in a non-fatigued state.

The order of the sessions was pseudo-randomized in the first visit to the laboratory. At first, TRAD and OPT exercise conditions were randomized. This is because the LOW-OPT condition had to be conducted after the OPT exercise trial. If the OPT exercise condition was performed on the first day, then the TRAD and LOW-OPT exercise conditions were randomized to be conducted either at the second or third visits. If the TRAD experimental protocol was performed on the first day, then the OPT and LOW-OPT exercise conditions were conducted at the second and third visits, respectively.

Procedures

Torque-velocity relationship test

Instantaneous friction force and displacement signals were sampled at 200 Hz in a custom LabVIEW program (National Instruments Corporation, Austin, TX). First- and second-order derivatives of the flywheel displacement were

calculated to obtain flywheel velocity and acceleration, respectively. The instantaneous inertial force applied to the flywheel was computed from the acceleration signal and flywheel inertia. Instantaneous crank angular velocity and torque applied to the crank were computed from frictional and inertial forces applied to the flywheel, flywheel velocity, gear ratio (52×14) and flywheel diameter (0.514 m). Instantaneous power output (in W) was computed as the product of instantaneous crank angular velocity and torque. Crank torque, angular velocity, and power output were averaged from each pedal downstroke of the acceleration time phase and plotted into T – V and P – V relationships using least-square linear and second-order polynomial regression, respectively (Samozino, Horvais, and Hintzy 2007). T_0 was determined as the intercept of the T – V relationship in the force axis and V_0 as the intercept of the T – V relationship in the velocity axis. P_{\max} was defined as the apex of the P – V relationship (Samozino et al. 2007). The mean power output (P_{mean}) of every single sprint and Wingate was also computed.

Calculation of the optimal load

A biomechanical model based on an exponential shape of the velocity–time curve during the acceleration time of the sprint was used to compute the individual OPT load. This model assumes that maximal velocity and time constant change according to the change in the braking load (Driss and Vandewalle 2013). Individual T_0 and V_0 values were obtained from pooled data originated from the two single sprints performed against 4 and 8% BW at PRE. From these parameters, the load that allows P_{\max} to be reached at 50% of the acceleration time was determined for each individual to optimize—in terms of the number of points and velocity range covered—the distribution of the experimental points along with the T – V and P – V relationship curves.

Goodness of fit

The quality of the T – V and P – V relationship models to accurately estimate P_{\max} , T_0 , and V_0 depend on several criteria, such as the number of experimental points, the capacity to obtain points on a large range of angular velocities below and above P_{\max} (i.e., a great area covered by velocities), and the coefficient of determination (R^2) (Dorel 2018). Based on these assumptions, the following dependent variables were considered for the assessment of the T – V and P – V relationship goodness of fit:

1. T – V and P – V relationship coefficient of determination (R^2): quantifies the dispersion of experimental points around the model.
2. The range of velocities covered by the experimental points in the T – V and P – V relationship curves (range of the spectrum, expressed in percentage): expressed relatively to the entire range covered by the T – V and P – V relationship (relatively to V_0). The greater the area covered, the higher the accuracy of the extrapolations (T_0 , V_0 , and P_{\max}) (Dorel 2018).
3. The time spent to reach maximal experimental velocity (acceleration time, expressed in seconds): the shorter the acceleration time is, the lower the potential development of fatigue will be. This can lead to underestimation of P_{\max} and V_0 .
4. The distribution of the range covered by the experimental points on both sides (i.e., lower or higher than the OPT velocity associated to P_{\max}) of the T – V and P – V curve (expressed in percentage of the entire range of velocity spectrum covered by all the experimental points): a well-balanced distribution of points can be characterized by 50% of the total velocity range covered by the points on the left (high torque, low velocity) or the right side (low torque, high velocity) of the T – V and P – V relationship.
5. The relative time of the acceleration time spent to achieve P_{\max} (time to reach P_{\max} , expressed in percentage): in the OPT exercise condition, the OPT load was computed so that the time to P_{\max} is 50% of the acceleration time. This variable was computed to confirm whether the biomechanical model and the OPT load determination work.

Statistical analyses

Data were described as mean and standard deviation (mean \pm SD). Mauchly's test was used to assess the sphericity assumption. Greenhouse–Geisser correction factor was applied if the sphericity was not assumed. A 95% level of confidence was pre-determined as the minimum criterion to denote a statistical difference ($p \leq 0.05$). The data were analyzed using the Statistical Package for Social Sciences (SPSS) version 24 (SPSS Inc., Chicago, IL).

Intra-day and inter-day sprints reliability

To test the first aim of this study, intra-day reliability of the sprints performed against the TRAD and OPT load was tested to compare P_{mean} , P_{\max} , T_0 , and V_0 responses between the two trials (PRE 1 and PRE 2). Inter-day reliability of the sprints performed against an OPT load in different days (OPT and LOW-OPT exercise conditions at PRE) was assessed to compare the calculated OPT load (% BW), P_{mean} , P_{\max} , T_0 , and V_0 responses. Reliability was assessed through a change in the mean, the typical error of measurement (TEM, expressed in raw units and percentage,

and standardized to inter-individual standard deviation), and intraclass correlation coefficients (ICC). Paired *t*-tests were conducted to compare the difference of the variables between the trials.

Differences at PRE: goodness of fit

Paired *t* tests were performed to compare the goodness of fit— R^2 , range of the spectrum (%), acceleration time (s), range of points to the left (%), and time to achieve P_{\max} (%)—between the TRAD and OPT load sprints at PRE. Effect sizes were reported as Cohen's *D* (Cohen 1988). For the additional paired *t* tests, the PRE trial in which the highest P_{mean} was achieved was considered.

Differences at POST: fatigue effect

To test the second aim of this study, a one-way ANOVA was performed to compare the P_{mean} during the Wingate across the exercise conditions to assure there was no difference in performance during the exercise between the testing days. A two-way repeated measure ANOVA considering the three different exercise conditions (TRAD, OPT, and LOW-OPT) and time (PRE and POST) was performed for each force production capacity outcome (P_{mean} , P_{\max} , T_0 , and V_0) to test the effect of fatigue induced by the Wingate (i.e., significant decrements in the outcomes).

Differences at POST: neuromuscular capabilities

A two-way repeated measure ANOVA was conducted for P_{mean} , P_{\max} , T_0 , and V_0 to compare the responses of these variables across the three experimental conditions (TRAD, OPT, and LOW-OPT) and four recovery time-points (POST, POST 1, POST 2, and POST 4).

Differences at POST: goodness of fit

A two-way repeated measure ANOVA was conducted for each dependent variable— R^2 , range of the spectrum (%), acceleration time (s), range of points to the left (%), and time to achieve P_{\max} (%)—to test the goodness of fit across the three exercise conditions (TRAD, OPT, and LOW-OPT) and four time-points representing four different levels of neuromuscular capabilities during the recovery period (POST, POST 1, POST 2, and POST 4).

For the ANOVAs, Bonferroni post-hoc tests were applied when the main effect of condition or time was observed. If there were an exercise condition \times recovery interaction, multiple paired *t*-tests would be performed followed by Bonferroni-Holm correction for multiple comparisons (the difference between exercise conditions at each recovery time-point). Effect sizes for the two-way ANOVAs were reported

as partial eta-squared (ηp^2) with interpretation thresholds fixed at 0.02, 0.13, 0.26 for small, medium and large, respectively (Cohen 1988). For paired *t* test and Bonferroni post-hoc test, effect sizes were reported as Cohen's *D* with interpretation thresholds fixed at 0.2, 0.6, 1.2, and 2.0 for small, moderate, large, and very large, respectively (Cohen 1988).

Results

Differences at PRE

Intra-day and inter-day sprints reliability

The intra-day reliability of the sprints performed against TRAD vs. OPT load is presented in Table 1. There was no significant difference between the two trials (PRE 1 and PRE 2) for P_{mean} , P_{\max} , T_0 , and V_0 . The inter-day reliability of the sprints performed at an OPT resistance is shown in Table 2. The calculated OPT resistance was $7.3 \pm 0.7\%$ BW (95% CI: [6.9, 7.6]; Min: 6.0; Max: 8.5). A high degree of inter-day reliability was found for all the force production capacity outcomes (all ICC > 0.75).

Goodness of fit

The sprints performed against an OPT load presented an overall better goodness of fit according to the pre-established criteria (Fig. 1). The R^2 of the T - V relationship was greater in the OPT than with the TRAD load sprints (0.92 ± 0.06 vs. 0.89 ± 0.06 , respectively, $t(12) = -3.138$, $p = 0.009$, $d = 0.50$, Fig. 1a), but there was no difference between the loads for the R^2 of the P - V relationship (Fig. 1b). No difference was observed in the range of the spectrum (Fig. 1c) and acceleration time (Fig. 1d) between the sprints performed at different loads. The range of points to the left was lower and closer to 50% in the OPT when compared with the TRAD load sprints ($67 \pm 11\%$ vs. $83 \pm 13\%$, respectively, $t(12) = 3.559$, $p = 0.004$, $d = 1.33$, Fig. 1e). Likewise, the time to reach P_{\max} was lower and proximal to 50% in the OPT in comparison with the TRAD load sprints ($48 \pm 9\%$ vs. $66 \pm 22\%$, respectively, $t(12) = 2.989$, $p = 0.011$, $d = 1.07$, Fig. 1f).

Differences at POST

Fatigue effect

P_{mean} values were not different during Wingate tests across the three exercise conditions. An interaction between exercise condition \times time (fatigue) was found for P_{mean} ($F(1,12) = 49.832$, $p < 0.001$, $\eta p^2 = 0.806$, Fig. 2a), P_{\max} ($F(1,12) = 44.225$, $p < 0.001$, $\eta p^2 = 0.787$, Fig. 2b), T_0 ($F(1,12) = 20.822$, $p = 0.001$, $\eta p^2 = 0.634$, Fig. 2c), and V_0

Table 1 Intra-day reliability of the sprints performed against traditional (TRAD) vs. optimal (OPT) load

	Trials		Mean	t value	p value	Change in mean	TEM (95% CI) raw	TEM (95% CI) %	Stand TEM (95% CI)	ICC (95% CI)
	PRE 1	PRE 2								
TRAD load										
P_{mean} (W)	723 ± 211	708 ± 191	715 ± 201	1.757	0.104	- 15.0	21.6 (15.5–35.6)	3.0 (2.1–5.0)	0.11 (0.08–0.18)	0.99 (0.97–1.00)
P_{max} (W)	818 ± 234	804 ± 206	811 ± 219	1.038	0.320	- 13.8	34.2 (24.5–56.5)	4.2 (3.0–7.0)	0.16 (0.11–0.26)	0.98 (0.94–0.99)
T_0 (N·m)	28 ± 5	27 ± 4	28 ± 4	0.372	0.716	- 0.5	2.2 (1.6–3.6)	7.9 (5.7–12.9)	0.51 (0.36–0.84)	0.78 (0.41–0.93)
V_0 (rad/s)	117 ± 25	117 ± 24	117 ± 24	0.214	0.834	- 0.3	4.6 (3.3–7.6)	3.9 (2.8–6.5)	0.19 (0.14–0.31)	0.97 (0.91–0.99)
OPT load										
P_{mean} (W)	726 ± 197	723 ± 182	724 ± 189	0.256	0.802	- 3.3	30.5 (21.9–50.4)	4.2 (3.0–7.0)	0.16 (0.12–0.27)	0.98 (0.93–0.99)
P_{max} (W)	825 ± 217	817 ± 206	821 ± 210	0.527	0.608	- 7.5	35.2 (25.3–58.2)	4.3 (3.1–7.1)	0.17 (0.12–0.28)	0.98 (0.93–0.99)
T_0 (N·m)	28 ± 5	27 ± 4	27 ± 4	0.354	0.730	- 1.0	1.2 (0.9–2.0)	4.4 (3.3–7.4)	0.41 (0.29–0.67)	0.86 (0.60–0.95)
V_0 (rad/s)	118 ± 24	119 ± 21	119 ± 22	- 0.427	0.667	0.9	5.4 (3.9–8.9)	4.5 (3.3–7.5)	0.24 (0.17–0.39)	0.95 (0.86–0.99)

P_{mean} , mean power; P_{max} , maximal power output; T_0 , maximal dynamic torque; V_0 , maximal angular velocity; mean diff, difference in mean; CV, coefficient of variation; TEM, typical error of measurement; stand TEM, standardized typical error of measurement; ICC, intraclass correlation

($F(1,12) = 24.572$, $p < 0.001$, $\eta^2 = 0.672$, Fig. 2d). With exception of T_0 in the TRAD condition, all the force production capacity variables were significantly lower at POST Wingate, when compared with PRE, in all the exercise conditions (all $p < 0.05$, $d > 0.69$).

Neuromuscular capabilities

No exercise condition and no exercise condition × recovery interaction were observed for P_{mean} , P_{max} , T_0 , and V_0 (Fig. 2). Interestingly, P_{mean} levels decreased during the recovery period ($F(3,30) = 57.375$, $p < 0.001$, $\eta^2 = 0.852$, Fig. 2a), while P_{max} and V_0 levels recovered after fatigue ($F(3,30) = 28.318$, $p < 0.001$, $\eta^2 = 0.739$, Fig. 2b and $F(3,30) = 10.054$, $p < 0.001$, $\eta^2 = 0.501$, Fig. 2d, respectively).

Goodness of fit

There was no exercise condition × recovery interaction for any dependent variable (Fig. 3). A main exercise condition effect was observed for R^2 of the P – V relationship ($F(2,20) = 9.086$, $p = 0.002$, $\eta^2 = 0.476$, Fig. 3b), range of the spectrum ($F(2,18) = 19.617$, $p < 0.001$, $\eta^2 = 0.686$, Fig. 3c), range of points to the left ($F(2,20) = 13.730$, $p < 0.001$, $\eta^2 = 0.579$, Fig. 3d), and time to reach P_{max} ($F(2,18) = 13.766$, $p < 0.001$, $\eta^2 = 0.605$, Fig. 3e). The R^2 of the P – V relationship was higher in the TRAD when compared with the LOW-OPT exercise condition ($p = 0.006$, $d = 1.72$, Fig. 3b). The range of spectrum was greater in the LOW-OPT than in the TRAD ($p < 0.001$, $d = 2.22$) and OPT exercise conditions ($p = 0.007$, $d = 1.33$, Fig. 3c). The range of points to the left was closer to 50% in the LOW-OPT protocol in comparison with both TRAD ($p < 0.001$, $d = 1.59$) and OPT exercise conditions ($p = 0.013$, $d = 1.26$, FIG. 3d). Similarly, the time to reach P_{max} was lower and closer to 50% in the LOW-OPT when compared with TRAD ($p < 0.001$, $d = 1.55$) and OPT exercise conditions ($p = 0.006$, $d = 1.02$, Fig. 3e). A main effect of recovery was also observed for a range of the spectrum ($F(3,27) = 5.991$, $p = 0.003$, $\eta^2 = 0.400$, Fig. 3c); however, the post-hoc test showed no difference between the recovery time-points. There was neither a main effect of exercise condition nor recovery for acceleration time.

Discussion

The main findings of this study were: (1) the use of an OPT load during single sprints provides an overall better fit of data in the T – V and P – V curves when compared with the TRAD load at PRE, and (2) single sprints performed in the LOW-OPT exercise condition present an overall greater T – V

Table 2 Inter-day reliability of the sprints performed against the optimal load (OPT) and LOW-OPT exercise conditions at PRE)

	Condition		Mean	t value	p value	Change in mean	TEM (95% CI) raw	TEM (95% CI) %	Stand TEM (95% CI)	ICC (95% CI)
	OPT	LOW-OPT								
Load (% BM)	7.3±0.8	7.2±0.7	7.3±0.7	0.826	0.425	-0.1	0.3 (0.2-0.4)	4.1 (2.7-5.5)	0.36 (0.26-0.60)	0.90 (0.71-0.97)
P_{mean} (W)	597±129	620±171	609±140	-0.741	0.473	23.5	80.9 (58.0-133.5)	13.3 (9.5-21.9)	0.53 (0.38-0.88)	0.75 (0.36-0.92)
P_{max} (W)	828±210	817±221	823±213	0.677	0.511	-11.4	42.5 (30.5-70.2)	5.2 (3.7-8.5)	0.20 (0.14-0.33)	0.97 (0.90-0.99)
T_0 (N·m)	120±20	123±26	122±23	-0.939	0.366	2.4	6.9 (4.9-11.4)	5.7 (4.0-9.3)	0.30 (0.21-0.49)	0.93 (0.78-0.98)
V_0 (rad/s)	27±4	26±4	27±4	1.877	0.850	-0.8	1.0 (0.8-1.7)	3.7 (3.0-6.3)	0.27 (0.20-0.45)	0.94 (0.81-0.98)

BM, body mass; P_{mean} , mean power; P_{max} , maximal power output; T_0 , maximal dynamic torque; V_0 , maximal angular velocity; mean diff, difference in mean; CV, coefficient of variation; TEM, typical error of measurement; stand TEM, standardized typical error of measurement; ICC, intraclass correlation

and $P-V$ relationship goodness of fit when compared with the sprints performed in the TRAD and OPT exercise conditions at POST. These results suggest that the assignment of the load during a single cycling sprint test should consider the inter-individual (force and power output production capacities levels at rest) and intra-individual differences (non-fatigued vs. fatigued state) rather than BW.

Differences at PRE

Although the intra-day reliability was high for both sprints loads, the reliability was overall higher in P_{mean} , P_{max} , and T_0 assessments between the two trials (PRE 1 and 2) when the sprints were performed against the OPT load. Firstly, while the changes in the mean between the two trials (PRE 1 and 2) for P_{mean} and P_{max} were not significantly different, they were greater when the sprints were conducted against the TRAD (-15.0 and -13.8 W, respectively) vs. OPT load (-3.3 and -7.5 W, respectively). Secondly, T_0 reliability was much lower in the TRAD when compared with the OPT load (ICC: 0.78 vs. 0.86, respectively); therefore, sprints performed against an OPT load provided more reproducible data. Although the high ICC values can be partly explained by the heterogeneous sample of individuals included in this study, the high reliability was confirmed by the absolute indexes as TEM in raw units and in % (TEM < 7.9% in TRAD and TEM < 4.5% in OPT for intra-day reliability).

The use of an individualized OPT load during single sprints also presented a better $T-V$ and $P-V$ relationship curve goodness of fit. The R^2 of the $T-V$ relationship was significantly higher when cycling against an OPT load. Similarly, the distribution of the range of velocities covered by the experimental points was more centered, which allows a better mathematical extrapolation of T_0 and V_0 . This was associated with the fact that, as aimed by the biomechanical model, P_{max} was achieved closer to 50% of the acceleration duration in the OPT load sprint when compared with the TRAD load. These findings suggest that our method to calculate individualized OPT load works. The model was designed to achieve P_{max} in the middle of the acceleration time (48±9% in the OPT vs. 66±22% in the TRAD load) and to obtain a well-balanced distribution of points to the left and right side of the $P-V$ relationship curve. These results also show that the experimental data fit very well in the $T-V$ and $P-V$ relationship when the sprints are performed against an OPT load.

A good fit of the data in the $T-V$ and $P-V$ relationships is extremely important to accurately determine the neuromuscular force production capabilities during dynamic movements (P_{max} , T_0 , and V_0) (Rudsits et al. 2018). For example, in Fig. 4, the use of the TRAD load (7.5% BW) for a less powerful individual prevented the participant to achieve higher velocities and, consequently, P_{max} during the sprint

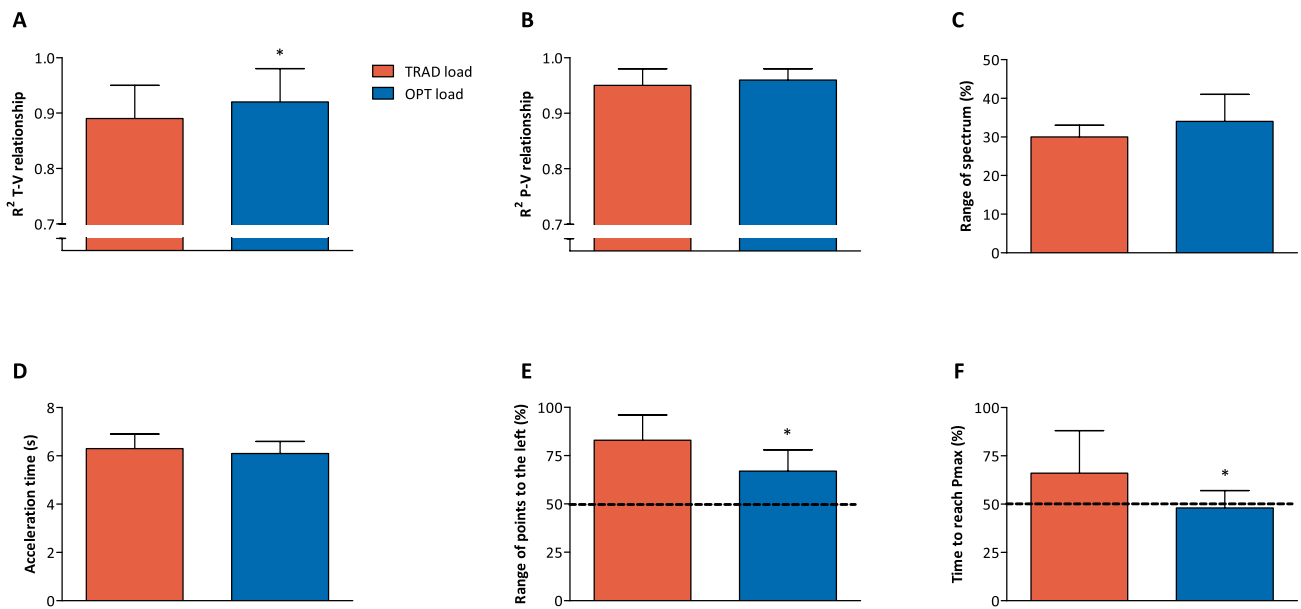


Fig. 1 Torque-velocity and power-velocity goodness of fit when cycling against the TRAD load vs. an OPT load. **a** R^2 T - V relationship; **b** R^2 P - V relationship; **c** range of spectrum; **d** acceleration time;

e range of points do the left; and **f** time to reach P_{\max} . Red bars, traditional (TRAD) load; blue bars, optimal (OPT) load. *, difference between TRAD and OPT load ($p < 0.05$)

(time to reach P_{\max} was 100% of the acceleration time). On the contrary, the use of an OPT load (6.4% BW) allowed a better distribution of the velocities in the T - V and P - V relationship curves (range of spectrum: 40%). The greater range of velocities covered by the experimental data in the T - V relationship increases the accuracy of V_0 and T_0 extrapolation (Fig. 4). In addition, the use of an OPT load allowed for a shorter acceleration time (2.4 s) and time to reach P_{\max} (42%), which are extremely important to avoid the effect of fatigue in the last downstrokes performed at the end of the acceleration time (Dorel 2018). Despite a few exceptions (as presented in Fig. 4), most participants of this study achieved P_{\max} during the 7-s sprint independent of the load assigned. This is because the TRAD load was firstly proposed for a young, untrained population (Bar-Or 1978), which was the population included in this study.

Together, our findings suggest our novel method to determine a single cycling sprint load is accurate and reliable. Our method stands out from previously published sprint determination methods as it requires the performance of one single sprint instead of two or more sprints (Arsac et al. 1996; Dorel et al. 2005; García-Ramos et al. 2018a, b). Based on our findings, we recommend the use of our model to determine OPT load when T - V properties need to be assessed from one single sprint (e.g., after a fatiguing exercise). When it is possible to perform several sprints, drawing T - V relationships from several (or at least two) sprints against different loads is recommended as this approach could include lighter loads that provide more points close to V_0 .

Differences at POST

The sprints performed at POST in the LOW-OPT exercise condition presented a greater goodness of fit when compared with the other exercise conditions (TRAD and OPT). Time to reach P_{\max} and acceleration time were significantly shorter in this exercise condition. These findings suggest that lower limbs' dynamic force production capabilities can be estimated with greater accuracy when the braking load is reduced according to the decrease in neuromuscular capabilities at a fatigued state. As previously discussed, the first downstrokes performed at the beginning of the sprint can already induce some significant levels of neuromuscular fatigue (Dorel 2018). The longer the acceleration time is, the greater the fatigue induced by the first downstrokes performed during the cycling sprint test will be. This could result in a potential underestimation of the neuromuscular capabilities during the last downstrokes and, consequently, reduce the accuracy of the estimation of V_0 , T_0 , and P_{\max} . It should be considered that, contrary to the other indexes of quality of T - V relationship determination, the acceleration time was greater in TRAD than in OPT condition since TRAD load was higher than OPT load in average, and not due to the fact that OPT is 'optimal' and TRAD 'non-optimal'. For other populations in which the TRAD load is lower than OPT load (e.g., trained athletes), the result of acceleration time can be the opposite, while the other results remain the same. This was the case for 4 individuals with an optimal load greater than 7.5% BW. The limitation of having an OPT load higher than the TRAD load is the greater

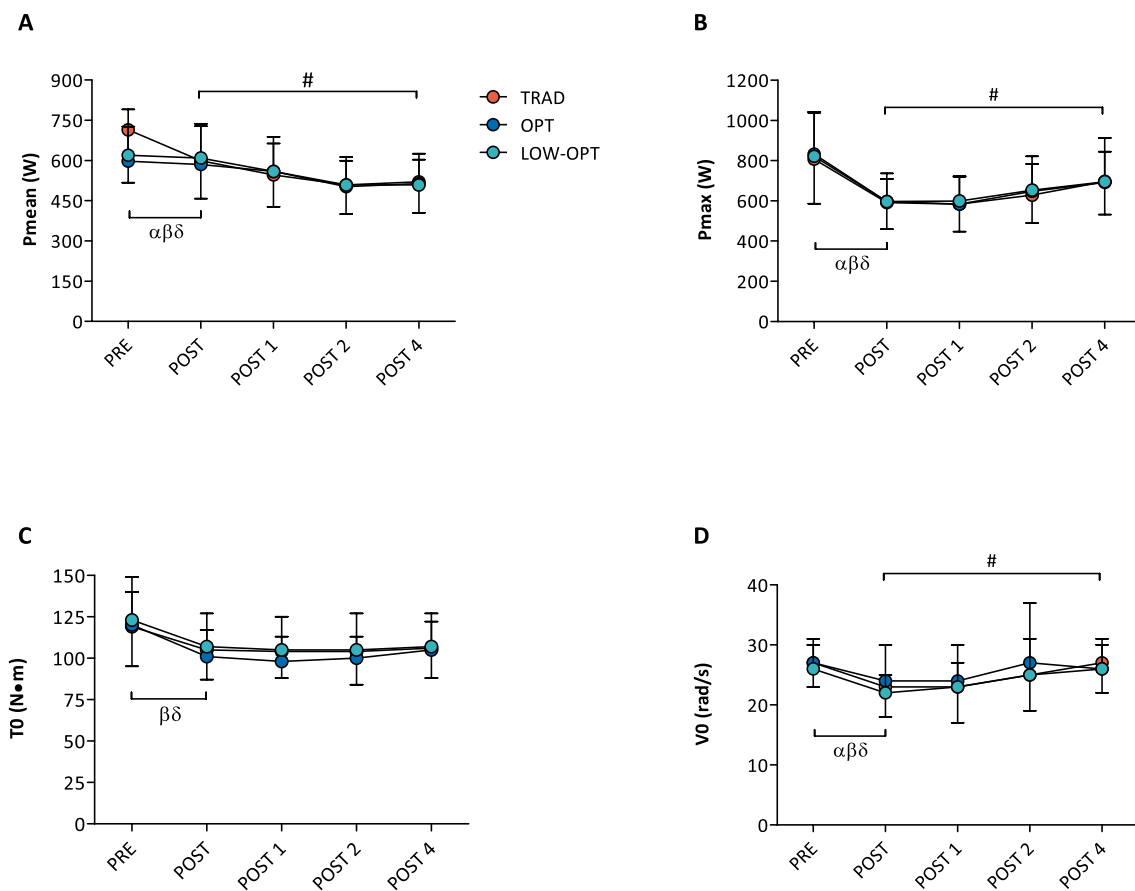


Fig. 2 Neuromuscular capabilities responses across the experimental conditions at PRE, POST, POST 1, POST 2, and POST 4. **a** Mean power (P_{mean}); **b** maximal power (P_{max}); **c** maximal torque (T_0); and **d** maximal angular velocity (V_0). Red circle, traditional condition

(TRAD); blue circle, optimal condition (OPT); green circle, low-optimal condition (LOW-OPT). α , fatigue effect for TRAD ($p < 0.05$). β , fatigue effect for OPT ($p < 0.05$). δ , fatigue effect for LOW-OPT ($p < 0.05$). #, recovery effect ($p < 0.05$)

levels of fatigue induced by the longer sprint acceleration time. The benefits of sprinting against an OPT load should, however, compensate for its limitation due to improvements in T - V and P - V relationship goodness of fit (well-balanced distribution of points on the left and right sides and range of velocities covered by the experimental points). Interestingly, although R^2 of the P - V relationship was overall higher in the TRAD exercise condition, sprints performed at the LOW-OPT exercise condition presented a better distribution of the points on both sides of the P - V relationship curve and a greater area of the T - V relationship spectrum covered by experimental points. These last results suggest a greater area of the T - V and P - V relationship curves covered by experimental points in the LOW-OPT condition, which provide a more precise extrapolation of T_0 , V_0 , and P_{max} .

It is important to note that individuals with low muscle force capacity might not achieve P_{max} during a 7-s cycling sprint performed at high loads ($\geq 7.5\%$ BM). The TRAD load has been shown to be too high, for example, for obese individuals (Duché et al. 2002). In the scenario

in which P_{max} is not achieved during the sprint, it needs to be extrapolated from the P - V relationship curve. There is an error associated with extrapolations as they estimate P_{max} by considering a data set that goes beyond the collected data. We have recently shown this when assessing neuromuscular fatigue using T - V and P - V relationships plotted during cycling sprints in elderly individuals (Krüger et al. 2020). In this study, we observed that three older individuals were not able to achieve P_{max} during the 7-s cycling sprint, which was performed at the same load of pre-fatigue sprints, immediately after the fatiguing exercise (Krüger et al. 2020). Because of that, V_0 was highly extrapolated from the T - V relationship curve, which increased the inaccuracy of V_0 and P_{max} computations and led to irrelevant values (Krüger et al. 2020). For this reason, sprints in which P_{max} is achieved in the middle of the sprint (i.e., at an OPT load), should provide a better estimation of the muscle capacities measured at fresh and fatigued state.

Another aspect that should be considered is the specificity of the cycle ergometer used. Although the mean OPT

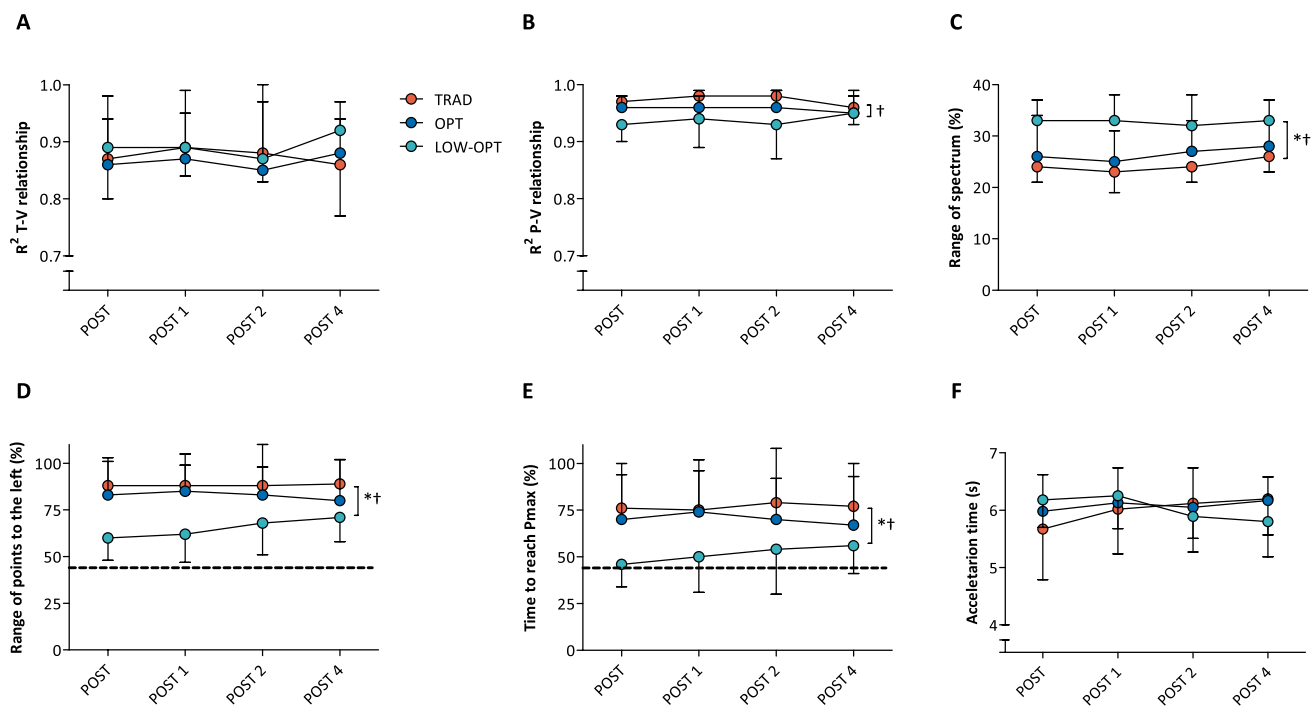


Fig. 3 Goodness of fit of the torque-velocity and power-velocity relationship across the experimental conditions at POST, POST 1, POST 2, and POST 4. **a** R^2 T - V relationship; **b** R^2 P - V relationship; **c** range of spectrum; **d** acceleration time; **e** range of points do the left; and **f** time to reach P_{max} . Red circle, traditional condition (TRAD); blue

circle, optimal condition (OPT); green circle, low-optimal condition (LOW-OPT). *, exercise condition effect: difference between TRAD and OPT ($p < 0.05$). †, exercise condition effect: difference between TRAD and LOW-OPT ($p < 0.05$)

load assigned was remarkably close to 7.5% BM in young, physically active males when the sprints were performed on a Monark cycle ergometer, this load is too high for sprints conducted on a recumbent bike. In a previous study from our research team, young active participants performed cycling sprints at either 5 or 7% BM on a recumbent cycle ergometer as our pilot study showed that 7.5% BM would not provide a good fit of the data in the T - V and P - V relationship curves (Krüger et al. 2019). Collectively, results from this study suggest that the accuracy of these extrapolations depends on the inter-individual (force and power output production levels at rest), intra-individual differences (non-fatigued vs. fatigued state), and cycle ergometer specificities (e.g., gear ratio, flywheel velocity, and diameter). Importantly, the mean magnitude of the variable measured (T_0 , V_0 , and P_{max}) obtained from T - V and P - V relationships is quite independent of the assigned load in young, physically active individuals when using a Monark cycle ergometer.

In summary, single sprints performed in a non-fatigue condition against an OPT load provide an overall better fit of data in the T - V and P - V relationship curves when compared with sprints conducted against the TRAD load. This knowledge is extremely important to situations in which several sprints cannot be conducted, and single

sprint evaluations are required (e.g., when assessing the effect of fatigue and recovery). Results from this study have also shown that reducing the sprint load for tests occurring at a fatigued state improves the fit of the data in the T - V and P - V relationship curves. It should be noted that the proposed method to compute OPT braking load is based on a simple biomechanical model. The model considers the ergometer characteristics (gear ratio, flywheel inertia, and radius) and the neuromuscular force capacities of the individual (T_0 and V_0), which can be obtained at rest by combining the data from two cycling sprints performed at 4 and 8% BW. Our results support that our new methodological approach to determine cycling sprint braking load is accurate, reliable, and improves the goodness of fit of the T - V and P - V relationship. We recommend future experimental studies to individualize the load when assessing neuromuscular force capacities using single sprints based on the individual neuromuscular capabilities, and so the neuromuscular fatigue level and considering the design of the cycle ergometer. It should be noted that the population included in this study presented, in average, a TRAD load very close to the OPT load. These results may underestimate the actual positive effect of performing cycling sprints against an optimal load on the quality of T - V relationship determination in populations that present

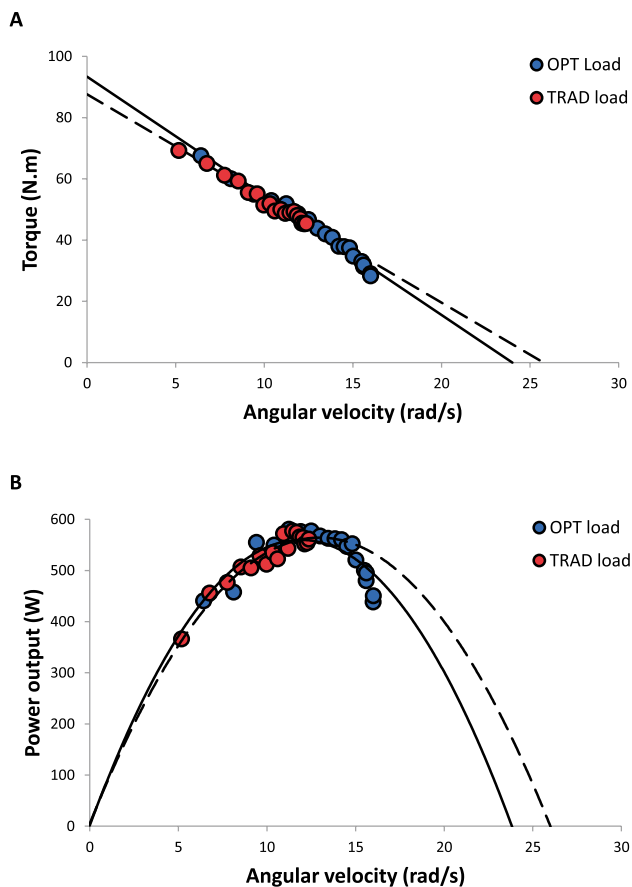


Fig. 4 Differences in the fit of the T - V and P - V relationship when the sprint is performed against the traditional [TRAD (7.5% of the bodyweight)] vs. optimal [OPT (6.4% of the bodyweight)] load for one individual. Red circle, TRAD load; blue circle, OPT load

either much higher (e.g., trained athletes) or lower (e.g., children and seniors) strength capabilities. Future studies testing individuals with higher and lower force capabilities should be performed to support the results presented in this study.

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Author contributions Design of the study: RLK, AP, HD, TR, GYM, and PS. Data collection: RLK, AP, and HD. Data analysis and interpretation: RLK, AP, HD, and PS. Draft the paper and critical review: RLK, AP, HD, TR, GYM, and PS. All persons designated as authors qualify for authorship and all authors have approved the final version of the manuscript.

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Compliance with ethical standards

Conflicts of interest The authors have no conflict of interest in relation to the present scientific paper.

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