



Suitability of jumps as a form of high-intensity interval training: effect of rest duration on oxygen uptake, heart rate and blood lactate

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Abstract

Purpose High-intensity interval training (HIT) has been shown to be an effective endurance training method. However, most HIT research has been conducted on running and cycling. The aim of this study was to assess the suitability of intermittent exercises such as jumps as a type of HIT.

Methods Respiratory gases, heart rate and ground reaction forces were recorded for 21 participants (age 25 ± 4 years, mass 73 ± 12 kg, 13 male) during 5 distinct jump sessions on different days that varied with respect to the rest durations in between series (0, 15 or 30 s) and in between jumps (0, 1 or 2 s). Blood lactate was determined 3 min after the last series. Prior to the first session, maximal jump height as well as $\dot{V}O_{2\max}$ during cycling was recorded.

Results Peak oxygen uptake and heart rate were nearly maximal during all five jump sessions (87–99% of $\dot{V}O_{2\max}$, 96–98% of maximal heart rate). The time spent at more than 90% of $\dot{V}O_{2\max}$ (1–43% of the total session duration), average jump height (34–82% of maximal jump height) and lactate accumulation (4–9 mmol/l) differed between jump sessions, mainly depending on the rest interval between jumps ($p < 0.001$, rmANOVA between sessions with different rest intervals between jumps).

Conclusion With short rest intervals, jumping elicited comparable acute responses as reported for running or cycling HIT. Thus, training programs using intermittent exercises should elicit similar adaptations as other forms of HIT, provided the rest intervals are sufficiently short. Heart rate might be of limited value when comparing different types of HIT.

Keywords HIT · Plyometrics · Cardiovascular · Jump training

Abbreviations

| | |
|--------------------|----------------------------------|
| CMJ | Countermovement jump |
| GRF | Ground reaction force |
| HIT | High-intensity interval training |
| HR | Heart rate |
| RPE | Rated perceived exertion |
| $\dot{V}O_{2\max}$ | Maximal oxygen uptake |

Background

High-intensity interval training (HIT) has become an increasingly popular type of training in the last years. It has been shown to elicit similar adaptations as high-volume moderate-intensity endurance training, but with considerably reduced training time (Gibala and McGee 2008). However, most HIT research has been conducted on running and cycling, even though training types using other intermittent types of exercises such as squats, push-ups or jumps in crossfit or freeletics are quite widespread in recreational athletes. In addition to improving endurance, these exercise modes can increase strength and power (Saez-Saez de Villarreal et al. 2010), muscle endurance (McRae et al. 2012), and in case of impact exercises such as jumps also bone mass and density (Kramer et al. 2017a; Multanen et al. 2014). For athletes, using exercise modes that are close to the ones required in competition will yield more specific effects, increasing its usefulness for targeted training (Giboin et al. 2015; Morrissey et al. 1995; Roberts and Alspaugh 1972). For non-athletes aiming to improve their overall fitness,

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or for sedentary or elderly populations trying to keep the deteriorating effects of aging or a predominantly sedentary lifestyle at a minimum, an exercise mode that targets bone, muscle and the cardiovascular system at the same time and does not require much time and equipment would be ideal.

Recently, it has been demonstrated that a short, intensive jump training program is able to prevent the large musculoskeletal deconditioning effects caused by 2 months of physical inactivity during bed rest; furthermore, it can also prevent most cardiovascular deconditioning (Kramer et al. 2017a, b, 2018). It is not clear though how an optimal jump training program should be programmed to maximize its effect on the cardiovascular system. It is known that for HIT, the time spent above 90% of the maximal oxygen uptake ($\dot{V}O_{2\max}$), exercise modality, work interval intensity, relief interval duration and between-series recovery duration are important variables that determine the efficacy of the training (Buchheit and Laursen 2013).

Thus, the aim of this study was to assess the suitability of jumps as a type of intermittent HIT as well as the effect of manipulating the rest duration in between repetition and series. We hypothesized that heart rate, oxygen uptake and rated perceived exertion would be near maximal during jump HIT sessions and that the rest duration in between repetitions as well as in between series would significantly affect the physiological responses.

Methods

Study design

In this cross-sectional study, participants completed five different jump protocols on five different days, separated by at least 2 days of rest, see Fig. 1. During each of these sessions, oxygen uptake, heart rate and ground reaction forces (GRF) were continuously recorded; additionally, rated perceived

exertion and blood lactate were assessed after each series and after the last series, respectively. Prior to these jump sessions, $\dot{V}O_{2\max}$ was determined in a ramp test on a cycle ergometer, and maximal jump height on a force plate.

Subjects

Of the 22 healthy subjects that were enrolled in the study, 1 subject discontinued the study for medical reasons unrelated to the study. All 21 subjects that completed the study were healthy with no injuries of the lower leg. Mean age of the 13 male and 8 female participants was 25 ± 4 years, height 174 ± 9 cm, body mass 73 ± 12 kg and relative $\dot{V}O_{2\max}$ 47 ± 8 ml/min/kg. Subjects were active, with 5 ± 5 h of exercise per week on average. Before taking part in the study, all participants gave written informed consent to the experimental procedures, which were approved by the ethics committee of the University of Konstanz and conducted according to the latest revision of the Declaration of Helsinki.

$\dot{V}O_{2\max}$ testing

$\dot{V}O_{2\max}$ was measured using a cycle ergometer (Ergoselect 200, Ergoline, Bitz, Germany). After an initial 30 s of seated rest and a 3 min warm-up phase (30–50 W, depending on the ramp slope), subjects were instructed to start and maintain a constant cadence between 75 and 90 rpm while the load was continuously increased. To keep the test duration between 8 and 12 min, the ramp slope was set to 15 W/min, 20 W/min, 25 W/min or 30 W/min, based on gender, body weight and weekly exercise duration. The load was increased and strong verbal encouragement was given until volitional exhaustion. Breath-by-breath oxygen uptake and carbon dioxide emission was monitored using the Ergostik system (Geratherm Respiratory GmbH, Bad Kissingen, Germany; calibrated before each session using a 3-l calibration pump and a calibration gas with 15%

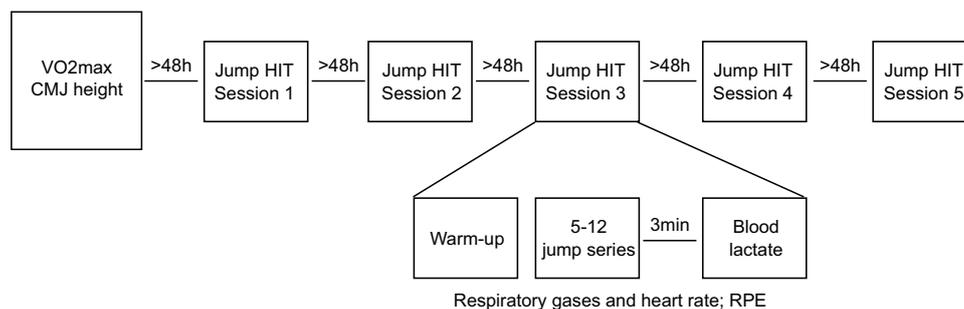


Fig. 1 Study overview. During the first session, $\dot{V}O_{2\max}$ was determined in a ramp test on a cycle ergometer, and maximal counter-movement jump height on a force plate. Afterwards, participants completed the five different jump HIT sessions in counterbalanced

order, with at least 48 h of rest in between sessions. Metabolic load during each of these sessions was assessed via spirometry, heart rate and rated perceived exertion, with a blood lactate measurement 3 min after the end of the last jump series

oxygen and 5% carbon dioxide content), heart rate was continuously monitored via a chest belt (Polar Bluetooth Wearlink, Polar, Kempele, Finland). The spiroergometry data were filtered by taking a moving average over 30 s. Afterwards the maximal values for the following parameters were extracted: oxygen uptake, heart rate, respiratory exchange rate, and ergometer power. If the respiratory exchange rate right before test termination was below 1.1, the trial was deemed not exhaustive and not considered for further analyses.

CMJ height

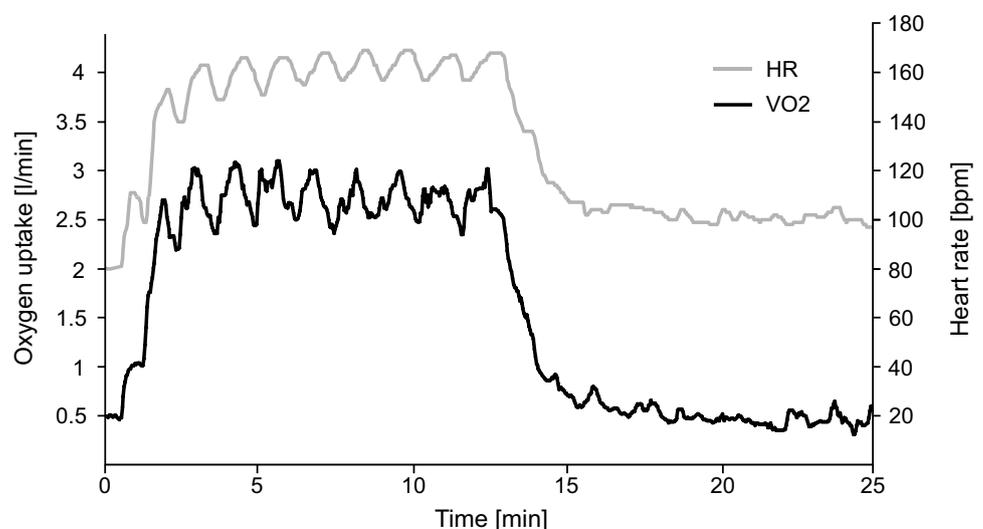
For the CMJs, the jump height was calculated based on the velocity at takeoff, which was calculated from the GRF ($jh = v^2/2g$). For the first session, the highest one of the three CMJs was taken as a reference for the five jump sessions.

Table 1 Characteristics of the five different jump sessions

| Jump session | Rest between series | Rest between jumps | #Series | Total duration |
|--------------|---------------------|--------------------|---------|----------------|
| 0-0 | None | None | 5 | 3 min 20 s |
| 30-0 | 30 s | None | 5 | 5 min 20 s |
| 15-1 | 15 s | 1 s | 9 | 8 min |
| 30-1 | 30 s | 1 s | 9 | 10 min |
| 30-2 | 30 s | 2 s | 12 | 13 min 30 s |

Rest duration was varied between sessions, whereas the work duration of each series was kept constant (40 s). The number of series was based on the inter-series rest duration to match the average number of jumps between the 5 jump sessions (180 jumps). The total duration includes the work and rest intervals

Fig. 2 Exemplary data. One participant's exemplary data recorded during a 30-1 session, i.e., nine jump series with a duration of 40 s each and 30 s of rest in between series. The black line represents the oxygen uptake, the grey line the heart rate



Jump HIT sessions

Each of the five jump HIT sessions was completed on a force plate (Leonardo GRFP, Novotec medical GmbH, Pforzheim, Germany). The order of the five sessions was counterbalanced between subjects. Prior to the first test, all participants were shown and practiced the correct execution of the countermovement jumps: hands were placed on the hips and subjects were instructed to jump with maximal effort. The instruction was to “Quickly drop to a squat and then immediately jump as high as possible”. After the warm-up—consisting of three squats, ten submaximal hops and three submaximal countermovement jumps—one of five jump HIT sessions was performed, see Table 1. Rest duration between series and between jumps was varied between sessions, whereas the work duration of each series was kept constant (40 s). The number of series was based on the inter-series rest duration to match the average number of jumps between the five jump sessions (180 jumps). Heart rate and respiratory gases were continuously recorded during each jump session, starting with a 30 s rest period before the warm-up and ending 15 min after the end of the last series of jumps. For exemplary data, see Fig. 2. Directly after each series of jumps, rated perceived exertion (RPE) was noted on a 6–20 BORG scale. Three minutes after the end of the last series of jumps, a blood droplet was taken from the ear lobe, and blood lactate was measured using a LactatePro2 [Arkray Factory Inc, Japan; for data on reliability and accuracy, see (Bonaventura et al. 2015)].

Statistics

The main goal of the study was to quantify the metabolic demand of the jump HIT by providing absolute values. In addition, we compared sessions with the same rest duration

in between jumps but different rest duration between series (0-0 vs. 30-0, 15-1 vs. 30-1), as well as sessions with the same rest duration in between series but different rest duration in between jumps (30-0 vs. 30-1 vs. 30-2) using paired two-tailed student's *t* tests. The overall effect of the rest duration in between jumps was assessed with repeated measure analyses of variance. Group data are presented as means and

standard deviations (SD). The analyses were executed with JASP 0.8.4 (University of Amsterdam).

Results

The five different jump sessions elicited values for peak heart rate, peak oxygen uptake and RPE that were close to the maximal values observed during a $\dot{V}O_{2max}$ ramp cycle test, especially the sessions with shorter rest durations or no rest, see Table 2 and Fig. 3.

When analyzing the oxygen uptake, there were pronounced differences between sessions, mostly between sessions with different rest intervals in between jumps, see Table 1 and Fig. 4. Regarding the time spent below 80%, between 80 and 90% and above 90% of $\dot{V}O_{2max}$, both the absolute values and the time-normalized values—the times in percent of the session duration from the start of the first series of jumps until the end of the last series of jumps—showed significant differences between sessions, and both the rest in between series and the rest duration in between jumps had an impact: there was no significant difference in absolute time between the 30-0 and the 30-1 sessions, but all the other comparisons yielded significant differences, see Table 2.

Blood lactate accumulation 3 min after the end of the last jump series reached values between 4 and 9 mmol/l, depending mostly on the rest duration in between jumps, see Fig. 5 and Table 1. There were no significant differences when varying the rest duration in between series (0-0 vs. 30-0 and 15-1 vs. 30-1), but significant differences when varying the rest duration in between jumps (30-0 vs. 30-1 vs. 30-2).

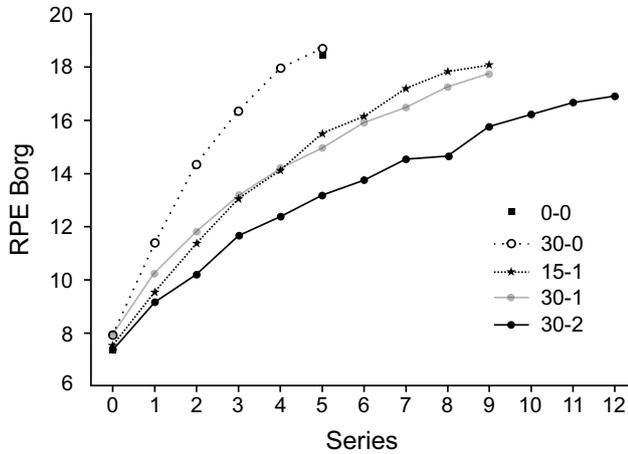


Fig. 3 Mean of all participants' rated perceived exertion (RPE) on a 6–20 point Borg scale for the five different jump sessions, measured directly after the end of every series of jumps. The 0 data point refers to RPE before the start of the jump session. There are only two data points for the 0-0 session (0 and 5) as there was no rest in between series. There are little differences in between sessions with similar rest duration in between jumps (0-0 vs. 30-0 and 15-1 vs. 30-1) compared to the differences in between sessions with different rest duration in between jumps (30-0 vs. 30-1 vs. 30-2)

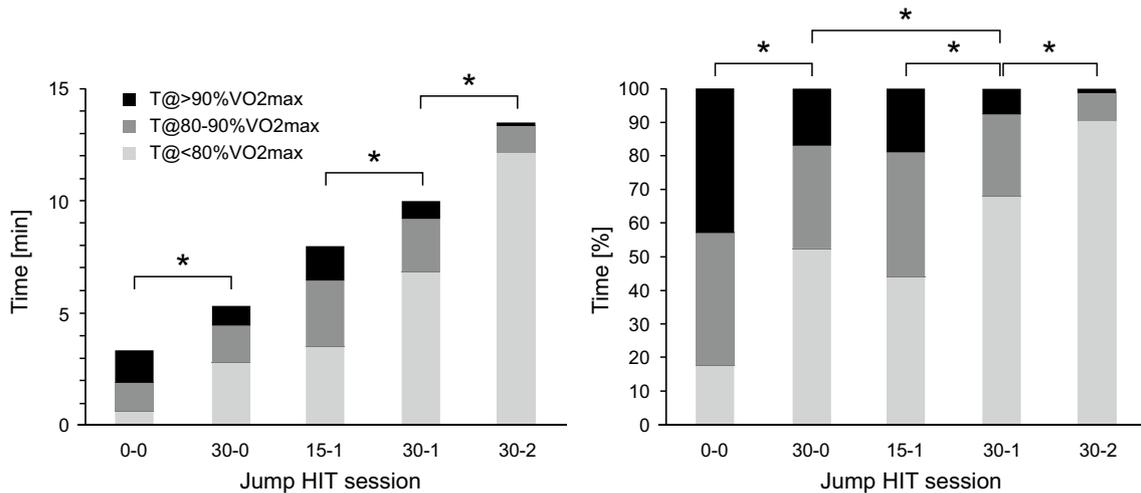


Fig. 4 Mean values of the time spent above 90% of $\dot{V}O_{2max}$ (black bars), between 80 and 90% of $\dot{V}O_{2max}$ (dark grey bars) and below 80% of $\dot{V}O_{2max}$ (light grey bars). The left part of the figure refers to the absolute times and the right part of the figure refers to the times

relative to the duration of the respective session. An asterisk symbol denotes a significant difference between sessions (four comparisons were made, 0-0 vs. 30-0, 15-1 vs. 30-1, 30-0 vs. 30-1 and 30-1 vs. 30-2)

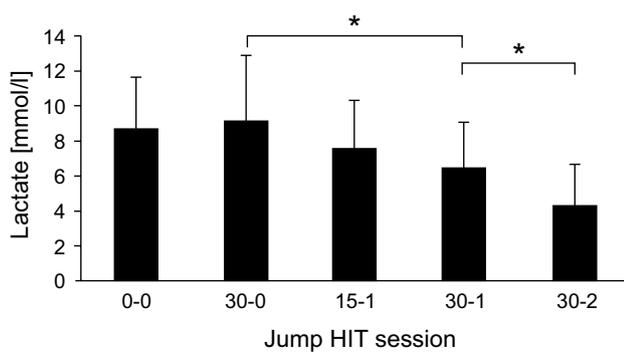


Fig. 5 Mean and standard deviations of the blood lactate measurements for the five different jump HIT sessions. An asterisk symbol denotes a significant difference between sessions (four comparisons were made, 0-0 vs. 30-0, 15-1 vs. 30-1, 30-0 vs. 30-1 and 30-1 vs. 30-2)

Except for two comparisons, heart rate did not show significant differences as a result of the variation in rest intervals, neither for peak nor for average values during exercise or recovery, see Table 2.

RPE after the end of the last series and RPE after five series (i.e., not matched for the number of jumps but for the number of series) both showed a clear effect of varying the rest interval in between jumps, but exhibited no significant differences when the rest interval in between series was varied.

Discussion

All the five jump sessions elicited a high-peak heart rate, oxygen consumption and perceived exertion, making jumps a suitable type of HIT exercise. The variation of the rest duration in between series had mostly small effects, whereas the variation of the rest duration in between repetitions had a pronounced influence, among others on lactate accumulation and the time spent above 90% of $\dot{V}O_{2max}$. Rest duration, both in between repetitions and in between series, also had a pronounced effect on performance, in this case jump height. It is noteworthy that there was little influence of the rest durations on heart rate, neither during exercise nor during recovery, suggesting that heart rate monitoring might be of limited use when comparing variations of high-intensity exercise protocols.

These results add to the existing literature on the metabolic demand of different types of HIT, as most research has been done on continuous types of exercise such as cycling or running that do not allow a manipulation of the rest duration in between repetitions, in contrast to intermittent types of exercise such as jumps or other forms of bodyweight exercises that are widely used in crossfit or freeletics. It appears

that the rest duration in between repetitions is the main factor that determines both aerobic and anaerobic demands in intermittent types of HIT. The two jump HIT sessions with no rest in between repetitions induced both the highest lactate accumulation (9 mmol/l), and the longest time spent above 90% of $\dot{V}O_{2max}$. In addition, when keeping a constant inter-series rest duration of 30 s and increasing the inter-repetition rest duration from 0 to 1 to 2 s, there was a clear decrease in lactate accumulation, RER and time spent above 90% $\dot{V}O_{2max}$. The rest duration in between series also affected some of the recorded factors of aerobic and anaerobic demand, but to a lesser extent, with differences mainly in average oxygen uptake and time spent above 90% of $\dot{V}O_{2max}$. These results can be used to program exercise types that use bodyweight exercises with the aim to increase aerobic capacity. The advantage of using these intermittent types of exercises—compared to classical continuous HIT modalities such as running or cycling—is that they can be adapted to be more specific to the demands of different sports, and in addition to the aerobic benefits they can elicit improvements in strength, power or bone mineral density. Indeed, the high-aerobic demand of the jump sessions examined in this study support the results of a previous study that showed that a short jump training program was able to counteract the severe deteriorating effects of physical inactivity during 2 months of bed rest, prompting the authors to conclude that the jump sessions with short rest intervals acted as a type of HIT (Kramer et al. 2017a, b).

Directly comparing the physiologic responses, the jump sessions used in the present study to the ones reported for HIT using running or cycling as exercise modalities is not an easy task, as variations of a HIT protocol elicit distinct acute responses in lactate levels, oxygen uptake and heart rate (Nicolo et al. 2014), just as it can be observed with the variations of the jump protocol used in the present study. Nevertheless, the lactate level of 9 mmol/l observed for the most demanding jump HIT protocol used in our study is comparable to the lactate levels reported in other HIT studies, for instance an all-out cycling protocol that used 30 s of work and a rest duration of 30 s (Nicolo et al. 2014), or a similar running HIT protocol (Billat et al. 2000). Cycling protocols that use even shorter rest intervals, such as the Tabata protocol with 20 s of all-out cycling followed by 10 s of rest, tend to elicit higher lactate levels of approximately 12 mmol/l (Foster et al. 2015). Peak and average oxygen consumption was also comparable to the aforementioned cycling study using a 30:30 protocol (Nicolo et al. 2014), but a bit lower than for running HIT (Billat et al. 2000). However, the time spent at more than 90% of $\dot{V}O_{2max}$ was lower for the jump exercise than most of the values reported in the literature. In our study, participants spent about one to one and a half minutes above 90%, whereas during cycling HIT—albeit until exhaustion—4–7 min were

Table 2 Mean and standard deviations of the five different jump sessions (0-0, 30-0, 15-1, 30-1 and 30-2) for all subjects

| | 0-0 | 30-0 | 0-0 vs. 30-0 | 15-1 | 30-1 | 15-1 vs. 30-1 | 30-2 | 30-0 vs. 30-1 vs. 30-2 |
|----------------------------------|-----------|-----------|--------------|-----------|-----------|---------------|-----------|----------------------------------|
| Peak $\dot{V}O_2$ (ml/min/kg) | 46±6 | 46±7 | $p=0.27$ | 46±7 | 44±6 | $p=0.03$ | 41±6 | $p<0.001$ $p=0.047$ $p<0.001$ |
| Peak $\dot{V}O_2$ (%) | 98±8 | 99±5 | | 99±8 | 96±8 | | 87±9 | |
| Average $\dot{V}O_2$ (ml/min/kg) | 39±5 | 36±5 | $p<0.001$ | 37±4 | 34±4 | $p<0.001$ | 31±4 | $p<0.001$ $p=0.006$ $p<0.001$ |
| Average $\dot{V}O_2$ (%) | 84±7 | 77±6 | | 80±7 | 74±7 | | 67±7 | |
| Time >90% $\dot{V}O_{2max}$ (s) | 86±70 | 54±46 | $p<0.001$ | 91±88 | 47±63 | $p<0.001$ | 7±17 | $p=0.002$ $p=0.94$ $p=0.002$ |
| Time >90% $\dot{V}O_{2max}$ (%) | 43±35 | 17±14 | $p<0.001$ | 19±18 | 8±10 | $p<0.001$ | 1±2 | $p=0.02$ $p=0.002$ $p<0.001$ |
| Average RER () | 1.17±0.08 | 1.16±0.08 | $p=0.24$ | 1.04±0.07 | 1.03±0.06 | $p=0.18$ | 0.98±0.04 | $p<0.001$ $p<0.001$ $p<0.001$ |
| Lactate (mmol/l) | 8.7±3.0 | 9.2±2.7 | $p=0.27$ | 7.6±3.7 | 6.5±2.6 | $p=0.13$ | 4.3±2.4 | $p<0.001$ $p<0.001$ $p<0.001$ |
| Peak HR (bpm) | 182±10 | 183±11 | $p=0.50$ | 186±11 | 182±13 | $p=0.05$ | 182±13 | $p=0.73$ $p=0.49$ $p=0.88$ |
| Peak HR (%) | 96±3 | 97±3 | | 98±3 | 96±4 | | 96±4 | |
| Average HR (bpm) | 170±11 | 169±13 | $p=0.83$ | 173±11 | 166±13 | $p<0.001$ | 166±13 | $p=0.12$ $p=0.13$ $p=0.92$ |
| Average HR (%) | 89±4 | 89±4 | | 91±3 | 87±5 | | 87±5 | |
| RPE _{last} (BORG) | 18.4±1.7 | 18.7±1.4 | $p=0.33$ | 18.1±1.8 | 17.7±2.0 | $p=0.25$ | 16.9±2.3 | $p<0.001$ $p=0.005$ $p=0.047$ |
| RPE _{five} (BORG) | 18.4±1.7 | 18.7±1.4 | $p=0.33$ | 15.5±1.8 | 15.0±2.2 | $p=0.11$ | 13.2±2.3 | $p<0.001$ $p<0.001$ $p=0.007$ |
| Mean jump height (%) | 34±8 | 48±9 | $p<0.001$ | 66±12 | 72±11 | $p=0.007$ | 82±9 | $p<0.001$ $p<0.001$ $p<0.001$ |
| Recovery | | | | | | | | |
| $\dot{V}O_2$ average (ml/min/kg) | 11±2 | 12±2 | $p=0.10$ | 11±2 | 11±2 | $p=0.61$ | 10±2 | $p<0.001$ $p<0.001$ $p=0.003$ |
| HR average (bpm) | 123±13 | 126±16 | $p=0.14$ | 125±16 | 122±16 | $p=0.08$ | 122±15 | $p=0.04$ $p=0.07$ $p=0.96$ |

Peak oxygen uptake ($\dot{V}O_2$)—absolute as well as normalized to $\dot{V}O_{2max}$ during the ramp test—average absolute and relative oxygen uptake, time spent at more than 90% of $\dot{V}O_{2max}$ (absolute as well as relative to session duration), average respiratory exchange rate (RER), lactate accumulation 3 min after the last jump series, continuously monitored heart rate (HR), both as absolute values and normalized to maximal heart rate during the ramp test, average absolute and relative heart rate, and rated perceived exertion (RPE) after the last jump series as well as after the fifth series. Mean jump height refers to the average jump height of all the jumps in one session, normalized to maximal jump height. The recovery values refer to the 15 min of recovery that was monitored after the end of the last series of jumps. The statistical results refer to the paired t tests between sessions with different rest duration in between series (0-0 vs. 30-0 and 15-1 vs. 30-1), and the last column contains the comparison between the sessions with different rest duration in between repetitions (30-0 vs. 30-1 vs. 30-2), with the first value being the result of the ANOVA, the second one to the t test between 30-0 and 30-1, and the third one to the t test between 30-1 and 30-2

reported (Nicolo et al. 2014) and recommended (Buchheit and Laursen 2013). It should be noted though that only few studies actually measured this parameter, and even fewer studies comparing the effectiveness of different protocols with different amounts of time spent in that zone (Midgley and Mc Naughton 2006).

An important outcome of the present study is that the manipulation of both rest intervals had a pronounced effect on power output, i.e., average jump height. During the most demanding session (0-0, no rest in between repetitions or series), the average jump height amounted to only 34% of the individual maximal jump height, whereas for the least demanding session (30-2, with 30 s of rest in between series and 2 s of rest in between jumps), the average jump height amounted to 82% of the maximal jump height. This has two

important implications: first, if increasing maximal power is a primary focus, then the rest intervals should be longer, most likely at the expense of aerobic adaptations. Second, with shorter breaks, not only performance but also technique and movement quality might suffer. Therefore, care should be taken when using exercises that rely on the correct execution of the movement to prevent injuries, for instance loaded squats.

As it is virtually impossible to examine the myriads of different possible combinations of rest and work intervals, it is important to understand the underlying mechanisms that determine the aerobic and anaerobic demand of an intermittent HIT session. One major limiting factor for sustained performance is energy metabolism, i.e., the resynthesis of ATP via phosphocreatine (PCr) degradation, anaerobic

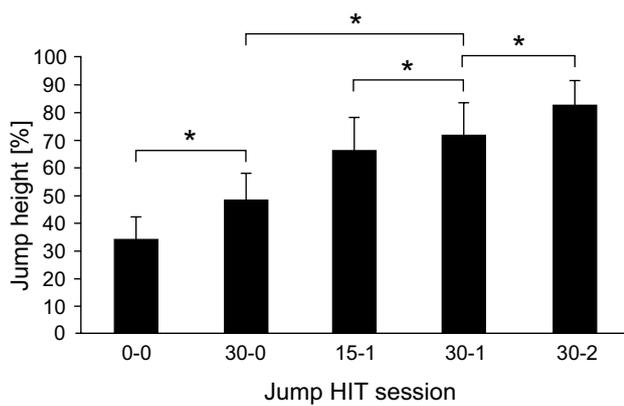


Fig. 6 Mean and standard deviations of the average jump height (normalized to each participant's maximal jump height) of all the jumps in one session. An asterisk symbol denotes a significant difference between sessions (four comparisons were made, 0-0 vs. 30-0, 15-1 vs. 30-1, 30-0 vs. 30-1 and 30-1 vs. 30-2)

glycolysis, aerobic glycolysis and fat oxidation. For repeated sprints and other types of maximal intensity exercise, it has been suggested that replenishing the PCr stores is an important factor of the recovery process in between bouts of exercise (Balsom et al. 1992; Bogdanis et al. 1996). It is hard to quantify exactly how long the PCr stores will last until largely depleted, as it will depend on the type of exercise and the initial level of PCr stores, but 10–15 s seem to be a reasonable estimate (Walter et al. 1997). For the first 5–6 s of exercise, the phosphagen energy system seems to dominate the ATP regeneration (Greenhaff and Timmons 1998), and is then superseded by glycolysis (Hultman et al. 1991). Thus, intermittent maximal power output depends on PCr stores and their replenishment (Sahlin et al. 1998), and the rest intervals between repetitions as well as during series will considerably influence power output as well as the contribution of the different energy systems. The time course of PCr replenishment has been suggested to have a rapid initial phase with a half time of 21 s and a much slower second phase with a half time of more than 3 min (Harris et al. 1976). The decreasing power output with decreasing rest duration observed in the present study (see Fig. 6) can, therefore, at least partly be explained by the depletion and replenishment of PCr stores, with 2 s of rest in between repetitions resulting in hardly any depletion of PCr stores, and the continuous jumps resulting in a fast depletion in the first third of each series and an incomplete replenishment in the 30 s of rest. With decreasing rest durations, glycolysis and fat oxidation will increase to offset the decreased contribution of the phosphagen system. Indeed, the aerobic contribution in short-duration HIT has been estimated to be 25–30%, increasing with more series and shorter rest intervals (Sloth et al. 2013), which is consistent with the high values for oxygen uptake measured in the present study. The high lactate

levels observed specifically for the sessions with no rest in between repetitions also indicate that anaerobic glycolysis was increased when rest durations were too short to allow for an adequate PCr replenishment. Thus, intermittent HIT seems to put high demands on all energy systems if the rest intervals—especially those in between repetitions—are sufficiently short.

The results of this study can be very helpful to program intermittent types of HIT, selecting the right kind of rest intervals depending on the training goals. However, one has to keep in mind that it is not entirely clear yet what is mainly driving the aerobic HIT adaptations, for instance if the accumulated time spent at more than 90% of $\dot{V}O_{2max}$ is indeed the most important factor (Laursen and Jenkins 2002; Midgley et al. 2006), or if other factors such as maintaining the heart rate in a near-maximal range for as long as possible are primarily responsible for the adaptations observed after HIT (Seiler et al. 2013). Ideally, the influence of the various HIT variables on the mechanisms causing the adaptations should be elucidated, i.e., changes in mitochondrial content and function, capillary density, stroke volume, cardiac output and blood volume. Therefore, our results can be used as a starting point, but training studies should be used to confirm which combination of rest intervals elicits the highest aerobic adaptations. Moreover, even though the session without any rest elicited the highest aerobic and anaerobic responses, it has to be tested whether a training program that uses only this strenuous type of exercise is really feasible over a longer training period, or if compliance and adherence would quickly drop, which tends to be the case when enjoyment is low (Kramer et al. 2014; Hickson et al. 1977).

Conclusion

Peak heart rate and oxygen uptake reached near-maximal values during the intermittent jump HIT sessions, similar to the ones reported for HIT protocols using running or cycling as exercise modality. The duration of the rest intervals—in particular the rest in between jumps—had a pronounced effect on the aerobic and anaerobic demand, measured via oxygen uptake and lactate accumulation. Selecting short rest intervals increased important parameters such as the time spent at more than 90% of $\dot{V}O_{2max}$, but also significantly decreased power output. There was little influence of the rest durations on heart rate, suggesting that heart rate monitoring is of limited use when comparing different types of HIT. The results of this study can provide valuable information to program intermittent HIT that uses bodyweight exercises instead of cycling or running.

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Author contributions AK contributed to study preparation and execution, data analysis, figure preparation and manuscript draft. TP contributed to study execution, data analysis and manuscript revision, MG contributed to study preparation and manuscript revision. All the authors read and approved the manuscripts.

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