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Effect of the Intrasession Exercise Order of Flywheel Resistance and High-Intensity Interval Training on Maximal Strength and Power Performance in Elite Team-Sport Athletes

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Abstract

Petré, H, Ovendal, A, Westblad, N, Ten Siethoff, L, Rosdahl, H, and Psilander, N. Effect of the intrasession exercise order of flywheel resistance and high-intensity interval training on maximal strength and power performance in elite team-sport athletes. *J Strength Cond Res* XX(X): 000–000, 2023—This study aimed to investigate the effect of intrasession *exercise* order of maximal effort flywheel resistance training (RT; 4 × 6 repetitions [rep]) and high-intensity interval training (HIIT, 2–4 × 8 rep of 20 second at 130% of Watt at $\dot{V}O_2$max [w$\dot{V}O_2$max]), on the development of maximal strength and power in elite team-sport athletes. A 7-week training intervention involving 2 training sessions per week of either HIIT followed by RT (HIIT + RT, $n = 8$), RT followed by HIIT (RT + HIIT, $n = 8$), or RT alone (RT, $n = 7$) was conducted in 23 elite male bandy players (24.7 ± 4.3 years). Power and work were continuously measured during the flywheel RT. Isometric squat strength (ISq), countermovement jump, squat jump, and $\dot{V}O_2$max were measured before and after the training period. Power output during training differed between the groups ($p = 0.013$, $\eta_p^2 = 0.365$) with RT producing more power than HIIT + RT ($p = 0.005$). ISq improved following RT + HIIT (~80%, $d = 2.10$, $p = 0.001$) and following HIIT + RT (~40%, $d = 1.64$, $p = 0.005$), and RT alone (~70%, $d = 1.67$, $p = 0.004$). $\dot{V}O_2$max increased following RT + HIIT and HIIT + RT (~10%, $d = 1.98$, $p = 0.001$ resp. $d = 2.08$, $p = 0.001$). HIIT before RT reduced power output during RT in elite team-sport athletes but did not lead to blunted development of maximal strength or power after a 7-week training period. During longer training periods (>7-weeks), it may be advantageous to schedule RT before HIIT because the negative effect of HIIT + RT on training quality increased during the final weeks of training. In addition, the largest training effect on maximal strength was observed following RT + HIIT.

Key Words: divergent training, interference effect, flywheel training, concurrent training sequence, concurrent training order

Introduction

Several team sports include repetitive high-intensity sprints (maximal effort actions lasting 2–10 seconds) and thus require well-developed anaerobic and aerobic fitness. One such sport is bandy, a winter sport similar to ice hockey in equipment and playing surface yet also similar to soccer in field size and rules. The active playing time of bandy is 90 minutes of which more than 20 minutes are spent above 90% of maximal heart rate (MHR) (3). The total skating distance normally exceeds 20 km, including frequent sprints with velocities up to 37 km·h^{-1} (3,30). To handle the demands of the game, the players must have a well-developed overall fitness, including maximal strength and aerobic power. However, during the competitive season, bandy and other team-sport athletes typically demonstrate no change or slight decreases in their maximal strength and aerobic power (11,16,17). Therefore, during the off-season team-sport athletes need to focus on training these abilities to improve performance over time. However, this off-season period is often relatively short because of the long competitive season, making concurrent training a necessity. Concurrent training can be defined as including both resistance and aerobic-based exercises in the same training session or at different occasions within the training program, to simultaneously improve both biomotor abilities (22). Concurrent training has been associated with attenuated maximal strength and power development, a phenomenon known as "the interference effect" (19). Nevertheless, this effect is not universal, given that several studies have reported similar improvements in strength (14,18,21,24,42) and power (14,18,24) during concurrent resistance and endurance training compared with resistance training (RT) alone.

A possible reason for these conflicting results could be differences in the order in which resistance and aerobic training were performed (31). It has been proposed that RT should be conducted before aerobic training if the main purpose is to maximize dynamic strength development (9,27). A likely reason is that the addition of aerobic training before RT may interfere with the quality of the performed RT, through either reduced training volume (i.e., reduced number of performed repetitions [rep]) (8,29,34,39) or reduced intensity (i.e., reduced power or velocity output) (34). This situation has been primarily demonstrated when aerobic training is performed as high-intensity interval training (HIIT) (8,29,34), which is commonly performed in team

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sports. However, so far, no study has examined this in elite athletes and few studies have continuously monitored power and work during RT in a concurrent training program.

Another explanation for the conflicting results could be differences in the training status of subjects (31). Training status has recently been identified as an important factor for the development of strength during concurrent training, especially when resistance and aerobic training are performed within the same session (31). Aerobic training seems to have a more negative effect on maximal strength development in trained individuals compared with less trained individuals (31). Most concurrent training studies have been performed on moderately trained and trained individuals, and there are still extremely few studies on highly trained athletes (31). It is of outmost importance to examine populations with different training statuses because of existing differences in anthropometric, physiological, and biomechanical parameters. Therefore, further studies are warranted to examine the effects of concurrent HIIT and RT in highly trained individuals.

A challenge that is encountered when designing training programs for elite team-sport athletes is their well adaptation to both resistance and endurance training, and hence, further improvement in strength, power, and endurance is difficult. In this regard, flywheel RT has been demonstrated as an effective RT method for developing maximal strength, power, and functional performance in team-sport athletes (1,2,4). A likely reason for its effectiveness is that flywheel RT allows variable resistance, wherein load is dependent upon the effort exerted by the athlete, thereby enabling individual progression based on the readiness of the athlete. Another benefit with flywheel RT is the potential to emphasize and overload the eccentric part of the movement, which has been shown to be important for maximal strength and power development in athletes (26). HIIT using short, very intense intervals (20-second work and 10-second rest) has been shown to be efficient to improve aerobic performance in both moderately trained and trained individuals (32,41). We have previously shown that such a HIIT protocol can induce large improvements in highly trained athletes during concurrent training after only 6 weeks (32). Therefore, combining a very intense HIIT protocol with flywheel RT, should have the potential to induce significant improvements in maximal strength, power, and aerobic power in elite team-sport athletes. Thus, enabling the detection of possible interference effects.

This study primarily aims to investigate how intrasession exercise sequence of HIIT and flywheel RT affects the work and power output during 7 weeks of training by measuring these variables during each flywheel RT session. Moreover, it aims to investigate how intrasession sequence of flywheel RT and HIIT affects strength and power performance tested before and after the 7-week training period. We hypothesized that HIIT before flywheel RT would reduce work (39) and power (34) during RT sessions. We also hypothesized that this reduction in training quality would translate into blunted maximal strength and power development (12,19).

Methods

Experimental Approach to the Problem

A randomized controlled study was performed by randomly (simple random sample, names were drawn from a bowl including all volunteered subjects) dividing the subjects into 3 groups; 1 group ($n = 8$) performed RT followed by HIIT, 1 group ($n = 8$) performed HIIT followed by RT, and 1 control group ($n = 7$) who performed RT alone. All subjects completed 14 sessions, 2 sessions per week for 7 weeks during the off-season. Although the subjects were elite athletes and familiar with flywheel RT and cycling, the RT and HIIT protocols were extremely physically demanding, and 2 sessions per week alongside free upper-body training and 1 session with light-intensity running were considered sufficient for an adaptive response. The subjects who trained both HIIT and strength were allowed 10-minute rest between the 2 exercises. Body mass, maximal strength, vertical jump height, and aerobic power were assessed before and after the intervention (Figure 1). The training intervention started approximately 48 hours after the pretests, and the posttests were performed 72–96 hours after the final training session. A standardized warm-up initiated each testing and training session. All players were familiarized with the tests and the training procedure on 3 separate occasions.

Subjects

In total, 23 elite male bandy players (age, 24.7 ± 4.3, 18–33 years; body height, 181.9 ± 5.6 cm; body mass, 81.0 ± 9.0 kg) volunteered to participate in the intervention. The subjects played in the Swedish "Elitserien," 1 of the highest-ranked leagues in the world. They were only recruited if they underwent regular structured strength training for more than 2 sessions per week alongside their sport-specific on-ice training for at least 2 years. The total number of training sessions per week was 8–10. All subjects performed squats and cycling as a part of their weekly training routine and were well accustomed to flywheel RT. The subjects were fully informed regarding the study's risks and benefits and were required to fill in a health declaration and sign an informed consent document before participation. They were asked to maintain their regular diet throughout the intervention, replicate it before the pretest and posttest, and refrain from training for >48 hours before the pretest. The study followed the principles outlined in the Declaration of Helsinki and was approved by the Regional Ethical Review Board in Stockholm (Dnr 2018/1357-31/1).

Procedures

Testing

Maximal Strength. Lower-body maximal strength was determined with an isometric squat strength (ISq) test from a standing position on a platform with the knees at a 90° angle and hip at a 110° angle while wearing a harness (Figure 2). A single axial load cell (Bofors KRG-4 T10; Nobel Elektronik, Karlskoga, Sweden; range 0–4 kN) was attached between the harness and platform at the midfoot with a chain that was adjusted to achieve the correct knee and hip position. This resulted in a setup in which the subjects could not move in the vertical direction. Then, the subjects were instructed to apply a small amount of pretension to avoid soft tissue compression affecting the joint angle before pushing against the ground as hard as possible, applying maximal force for at least 3 seconds. To ensure a standardized force trace in terms of body mass and steadiness, the athletes' correct body position was verified during the test with a goniometer. To stabilize the posture during the test, the subjects placed their hands against the wall in front of them. After the completion of 2 submaximal efforts, each subject was allowed 3 attempts.

To ensure the reliability of the measurements, for inclusion, a difference of <250 N was allowed between the 2 best trials (6), and the final analysis was based on the best trial. A 2-minute rest

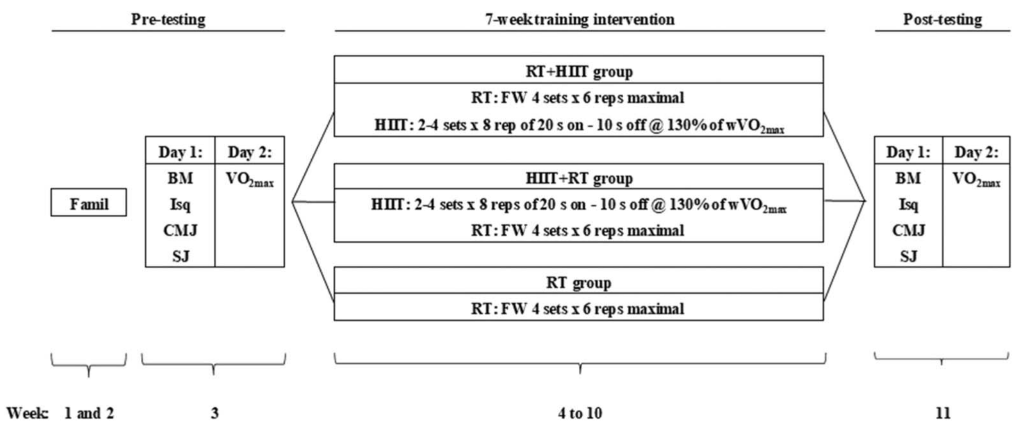

Figure 1. Experimental overview. Famil = familiarization; BM = body mass; Isq = isometric squat; CMJ = countermovement jump; SJ = squat jump; RT = resistance training; $\dot{V}O_{2}max$ = maximal oxygen uptake; HIIT = high-intensity interval training; wVo_{2max} = watt at maximal oxygen uptake; FW = flywheel training.

was provided between each test, and all the subjects were verbally encouraged during each trial. The maximal isometric force was calculated at the position on the force curve that displayed the highest mean force value over a 1-second period. A display unit (BKI-5; Nobel Electronic, Karlskrona, Sweden) was employed for axial load cell power supply and analog output signal gain. The 0–5-V output signal was converted from analog to digital and displayed at a sampling frequency of 1,500 Hz with a 12-bit resolution through Spike2 software (Cambridge Electronic design 1988–2012) and hardware (CED2501; CED Limited, Cambridge, United Kingdom). Data were exported from Spike2 to Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA) for further data processing. The coefficient of variation (CV) for ISq was 3.8% (n = 22).

Vertical Jump Height. Maximal jump height in countermovement jump (CMJ) and squat jump (SJ) was assessed using an optical measurement system (Optojump; Microgate, Bolzano, Italy). The Optojump optical measurement system has shown high validity and test-retest reliability for estimating vertical jump height (13). The warm-up before each test included 2 submaximal jumps. In total, the subjects completed 3 maximal CMJ and 3 maximal SJ. Each jump was performed at an interval of 60 seconds of rest. During both the sets of jumps, the arms were placed on the hip to minimize arm swing. Jump depth during the CMJ was self-selected, and during the SJ, it was set to 90° knee angle using a goniometer. The average of the 2 highest jumps was used as the maximal jump height. Countermovement jump power was calculated using the Sayers equation as previously described (37):

Figure 2. Representation of the isometric squat test.

power (W) = 51.9 × jump height (cm) + 48.9 × body mass (kg) − 2007. For the CMJ, CV was 1.3% ($n = 23$).

Aerobic Power. Maximal oxygen consumption ($\dot{V}O_2max$) was determined during a graded exercise test (GET) on a cycle ergometer (Monark LC6, Monark Exercise AB, Vansbro, Sweden) performed to volitional exhaustion. Oxygen consumption was obtained using a stationary automated metabolic system, the Oxycon Pro with a mixing chamber (Vyaire Medical; GmbH, Hoechberg, Germany). The Oxycon Pro system exhibits a high validity and reliability (10). After an initial warm-up involving four 4-minute intervals starting at 140 W and ending at 260 W (40-W increase/interval), a 4-minute rest was allowed before starting the GET. The test was initiated at 260 W (90 rpm), and the resistance was increased by 20 W every minute until the subject was unable to maintain a 70-rpm cadence. The heart rate of the subjects was monitored throughout the test using a pulse sensor (Polar RS400; Polar Electro Oy, Kempele, Finland). $\dot{V}O_2max$ was calculated as the highest 60-second average sample obtained during the test. Criteria for attaining $\dot{V}O_2max$ were as follows: heart rate ±5 beats from MHR, rate of perceived exertion >17, respiratory exchange ratio >1.1, and a $\dot{V}O_2$ plateau despite an increased workload. A $\dot{V}O_2$ increase of <2.5 ml·kg^{-1}·min^{-1} between two 60-second measurements (separated by 30 seconds) was considered a plateau.

Training

Squat RT was performed on a flywheel device (kBox; Exxentric AB, Stockholm, Sweden) with a resistance of 0.025 kg·m^2. Peak power (concentric and eccentric power merged) and total work during the training were derived from the flywheel device. During the training, the subjects were instructed to perform the concentric phase as fast as possible and to fully extend their hips and knees and then to deaccelerate as late as possible during the eccentric phase to facilitate eccentric loading. The squatting depth was set to a knee angle of 90°, manually inspected with a goniometer by the test leaders. A 3-minute rest period was allowed between the sets. Each set was initiated by 2 submaximal prerepetitions at low intensity to activate the rotational force of the flywheel. The next 6 rep in each set (4 sets) were measured and used for the final analysis.

Aerobic training was performed as HIIT on a cycle ergometer (Monark 894, Monark Exercise AB, Vansbro, Sweden) comprising 2–4 sets of 8 × 20-second intervals separated by 10 seconds of rest and sets by 4 minutes of rest (Table 1). The first interval intensity was set to 130% of w$\dot{V}O_2max$ from the $\dot{V}O_2max$ test, and the subjects were instructed to maintain the cadence at 90 rpm. If the subjects were able to complete all the intervals, the braking weight was increased by 0.1 kg in the following session. If the subjects were unable to maintain 90 rpm during a set, the resistance was reduced by 0.1 kg in the following set. Workload (W) was calculated as braking weight × cadence (90 rpm). Moreover, all subjects completed 1 aerobic training session per week on their own, including 40 minutes of running at light intensity (60–70% of MHR). No other training was allowed for the lower body during the intervention.

Statistical Analyses

The descriptive data were processed in Microsoft Excel (version 2102), and the statistical analyses were performed in SPSS (version 27; IBM Corporation, Armonk, NY). Data were checked for normal distributions using the Shapiro-Wilk test and by visual inspection of the histograms (authors H.P. and L.T.). To detect pre-to-post changes of body mass and physical tests, a repeated-measures multivariate analysis of variance (MANOVA) was performed. In this analysis, 7 dependent variables (body mass, ISq, CMJ [cm], CMJ [W], SJ, $\dot{V}O_2max$, and w$\dot{V}O_2max$) and 3 independent variables (RT + HIIT, HIIT + RT, and RT) were used. The within-group effect for the change from pre to post measurements was taken from the MANOVA by splitting the files by group in SPSS. Training data were first analyzed with a repeated-measures ANOVA. However, because body mass was identified as a significant predictor for total work and peak power, we also performed an ANCOVA. In these analyzes, we used time (14 training sessions) and group (RT + HIIT, HIIT + RT, and RT) as factors and peak power or total work as the dependent variables. When a significant difference was observed, a least-significant different post hoc test was applied for both the training data and the pre-to-post measurements. To control for differences in bike resistance progression between the 2 HIIT groups (RT + HIIT and HIIT + RT), an independent-sample t test was conducted. Effect size for the differences between pretest and posttest data were presented as Cohen's d (d) and were classified as trivial (<0.20), small (0.20–0.60), moderate (0.60–1.20), large (1.20–2.00), and very large (2.0–4.0) (20). When a significant interaction was observed for repeated-measures ANOVA or MANOVA, the magnitude of the effect was presented as partial eta squared (η_p^2). Descriptive data are presented as mean ± SD and uncertainty of the estimate as 95% confidence intervals. The significance level was set at a p value of ≤0.05.

Results

Work and Power Output during Flywheel Training

No main effect of time ($p = 0.167$) or interaction between time and group ($p = 0.179$) was found for total work per session. Body mass was a significant main predictor for total work ($p < 0.001$, $\eta_p^2 = 0.539$). When data were adjusted for body mass, there was a trend toward a group difference ($p = 0.085$) in total work between RT and HIIT + RT (Figure 3).

A significant main effect of time ($p = 0.030$) was found for peak power per session (concentric and eccentric power merged), but there was no significant interaction effect of time and group ($p = 0.737$). Body mass was a significant main predictor of peak power ($p < 0.001$, $\eta_p^2 = 0.595$). When data were adjusted for

Table 1

Progression of aerobic training throughout the 7-wk training intervention.

		HIIT	
Week	Session	Number of 20-second intervals	Intensity (% of w$\dot{V}O_2max$)
1	1	16	130
	2	16	IP
2	3	24	IP
	4	24	IP
3	5	24	IP
	6	24	IP
4	7	24	IP
	8	24	IP
5	9	32	IP
	10	32	IP
6	11	32	IP
	12	32	IP
7	13	32	IP
	14	32	IP

HIIT = high-intensity interval training; w$\dot{V}O_2max$ = wattage at $\dot{V}O_2max$; IP = individual progression.

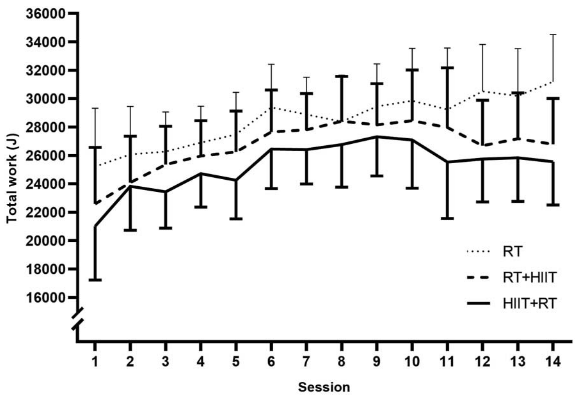

Figure 3. Total work per session measured with the flywheel device during the 7-week intervention in the RT, RT + HIIT, and HIIT + RT groups. RT = resistance training; HIIT = high-intensity interval training; J = Joules.

body mass, there was a significant interaction between time and group ($p = 0.013$, $\eta_p^2 = 0.365$) in peak power produced during flywheel RT. RT produced higher peak power during training compared with HIIT + RT ($p = 0.005$), and there was a trend toward a statistically significant higher peak power production also for RT + HIIT compared with HIIT + RT ($p = 0.057$; Figure 4).

Effect of the Intervention on Body Mass, Isometric Squat Strength, Countermovement Jump, Squat Jump, $\dot{V}O_2max$, and $w\dot{V}O_2max$

The results from the premeasurements and postmeasurements are presented in Table 2. The MANOVA main analysis showed a significant effect of time ($p < 0.001$) and interaction between time and group ($p < 0.001$) but no effect of group ($p = 0.454$). The intervention had a significant effect (main effect of time) on body mass, Isq, $\dot{V}O_2max$, and $w\dot{V}O_2max$ and trended toward a significant effect for CMJ. For $\dot{V}O_2max$ and for wVO_2max, the increase over time differed between the groups (interaction between time and group). More specific information for each of the dependent variables are presented in the following 2 sections.

For body mass, there was a significant main effect of time ($p = 0.001$), but no interaction was observed between time and group ($p = 0.355$). The subjects of the RT and RT + HIIT groups showed an increase in body mass (moderate Cohen's *d*). The body mass of the HIIT + RT group did not significantly change during the intervention. For ISq, there was a significant main effect of time ($p < 0.001$), but no interaction was observed between time and group ($p = 0.141$); ISq increased for all groups (RT and E + ET large Cohen's *d* and RT + E very large Cohen's *d*). For CMJ height, there was a trend for a significant main effect of time ($p = 0.054$), but no interaction was observed between time and group ($p = 0.148$). CMJ height decreased slightly in the HIIT + RT group (medium Cohen's *d*) and tended to decrease in the RT + HIIT group (medium Cohen's *d*) but remained unchanged in the RT group. For CMJ power, there was no significant main effect of time ($p = 0.548$) or interaction between time and group ($p = 0.212$). CMJ power did not change in the RT + HIIT or HIIT + RT group but tended to increase in the RT group (medium Cohen's *d*). For SJ height, there was no significant main effect of time ($p = 0.603$) or interaction between time and group ($p = 0.406$); SJ height did not change for any of the groups.

For $\dot{V}O_2max$ and $w\dot{V}O_2max$, there was a significant main effect of time ($p < 0.001$ respectively $p < 0.001$) and interaction between time and group ($p = 0.019$, $\eta_p^2 = 0.355$ respectively $p = 0.001$, $\eta_p^2 = 0.520$). Moreover, $\dot{V}O_2max$ increased more in the RT + HIIT group compared with the RT group ($p = 0.030$) and tended to increase more in the HIIT + RT group compared with the RT group ($p = 0.093$). There was a trend for a higher increase in $w\dot{V}O_2max$ for the RT + HIIT group compared with the RT group ($p = 0.082$) and for the HIIT + RT group compared with the RT group ($p = 0.060$). Thus, $\dot{V}O_2max$ and $w\dot{V}O_2max$ increased only for the HIIT + RT and the RT + HIIT group (large to very large Cohen's *d*).

The mean progression in training load during the HIIT sessions were 25.9 ± 19.5 W for RT + HIIT and 21.4 ± 12.7 W for HIIT + RT, with no difference between the groups ($p = 0.594$).

Discussion

To the best of our knowledge, this is the first study that continuously measured power and work during a concurrent training program and examined the effects of concurrent flywheel RT and HIIT on the strength and power development of elite team-sport athletes. The primary finding was that HIIT before RT reduced power output during RT; however, this reduction in training intensity did not affect strength or power development during a 7-week training period. This finding disagreed with our hypothesis, which stated that a reduction in training quality would engender blunted strength and power development. However, the largest training effect on strength was observed following RT + HIIT. Therefore, it is possible that this intrasession exercise order is more beneficial for long-term adaptations.

Previous studies have reported that a single session of HIIT before traditional RT with free weights could negatively affect subsequent performance during RT in untrained and moderately trained individuals (8,29,34,39). The findings of this study showed that this negative effect also exists in highly trained individuals during multiple training sessions, given that the HIIT + RT group showed lower peak power during RT compared with the other 2 groups. Furthermore, there was a trend toward a difference in the total work between the HIIT + RT and RT groups. An explanation for reduced training quality might be that the cycling intervals were performed at a very high intensity, almost to maximal exhaustion, and likely recruited some of the

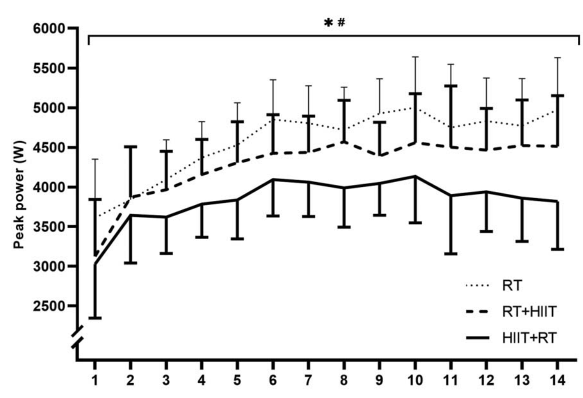

Figure 4. Peak power per session measured with the flywheel device during the 7-week intervention in the RT, RT + HIIT, and HIIT + RT groups. Significant effect ($p < 0.05$): * = time. # = time × group. RT = resistance training; HIIT = high-intensity interval training; W = Watts.

Table 2

Premeasurement and postmeasurements of body mass, Isq, CMJ, SJ, $\dot{V}O_2$max, and $w\dot{V}O_{2max}$.

Group	Pretest Mean ± *SD*	Posttest Mean ± *SD*	% Change (95% CI)	Cohen's *d* (95% CI)	*p*
Body mass (kg)					
RT + HIIT	85.1 ± 8.4	86.7 ± 8.6	1.81 (0.37 to 3.24)	1.05 (0.15 to 1.91)	0.021†
HIIT + RT	82.2 ± 9.3	82.7 ± 8.1	0.67 (−1.38 to 2.72)	0.27 (−0.44 to 0.97)	0.466
RT	74.9 ± 6.8	76.6 ± 6.4	2.23 (0.91 to 3.55)	0.74 (0.43 to 2.68)	0.006†
ISq (N)					
RT + HIIT	1,069.8 ± 253.4	1,910.4 ± 256.0	78.58 (46.26 to 110.89)	2.10 (0.80 to 3.37)	0.001†
HIIT + RT	1,106.6 ± 256.1	1,564.9 ± 449.2	41.41 (18.05 to 64.78)	1.64 (0.45 to 2.78)	0.005†
RT	883.7 ± 192.9	1,513.5 ± 293.0	69.87 (31.21 to 108.54)	1.67 (0.45 to 2.83)	0.004†
CMJ (cm)					
RT + HIIT	40.2 ± 5.3	38.3 ± 4.7	−4.74 (−10.48 to 1.00)	−0.69 (−1.45 to 0.11)	0.092
HIIT + RT	38.7 ± 2.2	37.7 ± 2.5	−2.41 (−4.78 to −0.04)	−0.85 (−1.65 to −0.01)	0.047†
RT	39.7 ± 2.5	40.0 ± 3.3	0.61 (−3.66 to 4.88)	0.13 (−0.62 to 0.87)	0.738
CMJ (W)					
RT + HIIT	4,243.3 ± 503.5	4,219.5 ± 463.1	−0.56 (−3.72 to 2.60)	−0.15 (−0.84 to 0.55)	0.688
HIIT + RT	4,018.6 ± 492.6	3,997.1 ± 415.5	−0.53 (−3.36 to 2.29)	−0.16 (−0.85 to 0.55)	0.669
RT	3,718.3 ± 402.9	3,812.6 ± 364.6	2.54 (−0.45 to 3.24)	0.78 (−0.10 to 1.16)	0.083
SJ (cm)					
RT + HIIT	35.5 ± 4.3	34.6 ± 3.9	−3.38 (−9.50 to 2.74)	−0.46 (−1.18 to 0.29)	0.233
HIIT + RT	35.6 ± 2.3	34.5 ± 2.5	−1.11 (−6.16 to 3.94)	−0.18 (−0.88 to 0.52)	0.619
RT	35.8 ± 3.0	36.8 ± 2.8	1.96 (−6.54 to 10.46)	0.21 (−0.55 to 0.95)	0.594
$\dot{V}O_2$max (L·minute^{-1})					
RT + HIIT	4.48 ± 0.36	4.93 ± 0.39	10.13 (5.86 to 14.40)	1.98 (0.73 to 3.19)	0.001†
HIIT + RT	4.42 ± 0.48	4.84 ± 0.57	10.15 (6.07 to 14.23)	2.08 (0.73 to 3.33)	0.001†
RT	4.14 ± 0.19	4.27 ± 0.20	3.14 (−3.12 to 9.40)	0.57 (−0.41 to 1.15)	0.273
$w\dot{V}O_2$max (W)					
RT + HIIT	379.0 ± 15.9	423.8 ± 23.9	11.8 (7.7 to 15.9)	2.43 (0.99 to 3.83)	0.001†
HIIT + RT	390.0 ± 53.8	418.9 ± 48.7	7.28 (4.89 to 9.67)	2.55 (1.05 to 4.00)	0.001†
RT	360.9 ± 17.6	369.5 ± 14.5	2.36 (−1.48 to 6.20)	0.76 (−0.28 to 1.75)	0.163

ISq = isometric squat test; CMJ = countermovement jump; SJ = squat jump; $\dot{V}O_2$max = maximal oxygen uptake; $w\dot{V}O_{2max}$ = Watt at $\dot{V}O_2$max; CI = confidence intervals; RT = resistance training; HIIT = high-intensity interval training.
†$p < 0.05$ between pretest and posttest.

high-threshold motor units that were also recruited during the subsequent RT (15). Hence, if the same motor units were fatigued by the previous cycling, this would have a negative effect on the muscle's ability to generate force and thereby reduce power output during RT.

Previously, flywheel RT was depicted as an efficient form of training to develop maximal strength in both untrained and trained individuals (1,7,33). This study supports these findings because maximal isometric strength increased between approximately 40 and 80% in the 3 groups, which is a large improvement compared with what is normally observed following traditional dynamic RT during concurrent training (31). This increase may be explained by the variable resistance and the eccentric emphasis provided by the flywheel training allowing multiple maximal rep, eccentric overload at specific joint angles, and individual progression during the intervention. Variable resistance and eccentric training have proven to be effective training methods to increase maximal strength (40). The RT + HIIT group exhibited the largest improvement (~80%), whereas the HIIT + RT group exhibited the smallest improvement (~40%). However, no significant difference was observed between the groups. This might be a consequence of the relatively short training period because our results indicate that the reduction in training quality (power) seems to be more prominent after 5 weeks (Figure 3). This is in line with previous studies showing a reduced strength development after approximately 5 weeks of concurrent training (12,19).

Surprisingly, the largest increase in strength and effect size was observed following RT + HIIT and not RT (~80%, Cohen's d = 2.10, vs. ~70%, Cohen's d = 1.67). This indicates that HIIT might have provided an extra "boost" of neuromuscular stimuli when performed after RT or, at least, demonstrated no negative effect on the maximal strength. Spiliopoulou et al. (38) observed similar findings after a 6-week concurrent training intervention that included HIIT cycling following RT. Herein, the concurrent training group improved maximal strength with an effect size that was twice as large as that observed in the RT group (Cohen's d = 2.21 vs. Cohen's d = 1.05). However, it is important to point out that, in both this study and the study by Spiliopoulou et al. (38), the HIIT protocols were very intense and probably demanded more neuromuscular activity than the HIIT training used in other concurrent training studies. The HIIT protocol might by itself stimulate strength development and thereby "boost" the overall development of strength when executed after RT.

Previous studies have shown that vertical jump performance and power development during concurrent training are not affected by the intrasession order of the endurance and RT (5,25). Instead, endurance training seems to have a similar negative impact on power performance, regardless of whether it is performed before or after RT (5). It is difficult to draw any conclusions from this study because no group showed an increase in CMJ height or power; therefore, flywheel training alone does not seem to be an efficient training method to improve power performance as measured by vertical jump in our population. However, there was a trend toward an increase in CMJ power in the RT group, which is in line with previous findings suggesting that HIIT might blunt power development regardless of the intrasession order (5,21).

Notably, the HIIT protocol in this study was highly effective in increasing aerobic power because $\dot{V}O_2max$ increased by approximately 10% after only 14 training sessions. For comparison, a 2–6% improvement in $\dot{V}O_2max$ was observed following 14 sessions of concurrent training, including HIIT in ice hockey players (36); a 4–9% increase was observed in amateur rugby players, including the same amount of sessions (35). Previously, our research group demonstrated an approximately 4% increase in $\dot{V}O_2max$ in team-sport athletes under a similar HIIT protocol as in this study during concurrent training (32). In that study, the training frequency was higher (3 vs. 2 sessions per week); however, the training volume per session was lower (8–24 vs. 16–32 intervals) (32). Therefore, it might be favorable to reduce the number of sessions per week and increase the number of intervals per session when using this protocol to improve $\dot{V}O_2max$.

Despite the novelty of the findings, this study has some limitations. The training period was relatively short (7 weeks). Thus, it is possible that a longer training period would have resulted in differences between the groups, given that the interference effect seems to be more prominent after 5 weeks in the present and previous studies (12,19). Nevertheless, a general preparation subphase of 6–8 weeks is common for elite-level team-sport athletes and is therefore of practical relevance. Previous studies have shown that flywheel training is an efficient method to improve jump performance in team-sport athletes (23,28), but this was not the case in this study. Therefore, it is difficult to draw any conclusions from our SJ and CMJ measurements. A possible explanation for this result could be the lack of specific training as the subjects were not allowed to perform any plyometrics or other power exercises during the intervention. It is well known that movement-specific training increases the transfer to power performance, especially in trained individuals (43). Therefore, we recommend future studies to combine flywheel training with some type of plyometric or ballistic jump training if the aim is to examine the effect of concurrent training on jump performance.

In conclusion, the findings from this study suggest that elite team-sport athletes can obtain large improvements in maximal strength and $\dot{V}O_2max$ when flywheel RT is combined with HIIT, regardless of the intrasession order. However, in the long term (>7 weeks), it might be more beneficial to schedule HIIT after RT because the largest effect was observed when concurrent training was performed in that intrasession order.

Practical Applications

This study shows that HIIT before flywheel RT reduces power output and potentially also work during RT in elite team-sport athletes. This reduction in training quality does not blunt strength development during a 7-week training period. Therefore, team-sport athletes seeking to improve both maximal strength and aerobic power during a short training period can schedule the intrasession order on personal preferences. However, during longer training periods, we recommend RT to be performed before HIIT because the reduction in training quality (power) seems to be more prominent for HIIT + RT during the final weeks of this training intervention (approximately after the fifth week). Moreover, short and very intense HIIT might provide an extra stimulus for strength development when performed after RT because the largest effect on strength development was observed after RT + HIIT.

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