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Human Kinetics
ORIGINAL INVESTIGATION

Effects of High-Intensity Interval Training in Hypoxia on Taekwondo Performance

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Purpose: To evaluate the effects of a 6-week taekwondo-specific high-intensity interval training (HIIT) in simulated normobaric hypoxia on physical fitness and performance in taekwondoists. ***Methods:*** Eighteen male and female black-belt taekwondoists trained twice a week for 6 weeks in normoxia or in hypoxia ($FiO_2 = 0.143\ O_2$). The HIIT was composed of specific taekwondo movements and simulated fights. Body composition analyses and a frequency speed of kick test during 10 seconds (FSKT10s) and 5 × 10 seconds (FSKTmult), countermovement jump (CMJ) test, Wingate test, and an incremental treadmill test were performed before and after training. Blood lactate concentrations were measured after the FSKTmult and Wingate tests, and a fatigue index during the tests was calculated. ***Results:*** A training effect was found for FSKT10s (+35%, $P < .001$), FSKTmult (+32%, $P < .001$), and fatigue index (–48%, $P = .002$). A training effect was found for CMJ height (+5%, $P = .003$) during the CMJ test. After training, CMJ height increased in hypoxia only (+7%, $P = .005$). No effect was found for the parameters measured during Wingate test. For the incremental treadmill test, a training effect was found for peak oxygen consumption ($P = .002$), the latter being 10% lower after than before training in normoxia only ($P = .002$). ***Conclusions:*** In black-belt taekwondoists, hypoxic HIIT twice a week for 6 weeks provides tiny additional gains on key performance parameters compared with normoxic HIIT. Whether the trivial effects reported here might be of physiological relevance to improve performance remains debatable and should be tested individually.

Keywords: VO_2peak, martial art, frequency speed of kick test, RSH, Wingate test

Taekwondo is a martial art that requires a good combination of specific technical skills, tactical experience, and physical fitness to score against one's opponent by kicking or punching the opponent on permitted scoring areas or by achieving a technical knockout. In its official form, taekwondo matches are constituted by 3 rounds of 2 minutes interspersed by 1-minute recovery periods. It can be considered as a high-intensity intermittent discipline. The fights comprise a succession of 1- to 5-second high-intensity efforts interspersed by nonfighting periods.[1] The activity-to-rest ratio ranges between 1:2 and 1:7.[2]

Based on the previously mentioned characteristics of the discipline, taekwondoists should be able to develop a high ability to repeat high-intensity activities.[3,4] One efficient training strategy to reach this ability is through high-intensity interval training (HIIT). It is now widely supported that HIIT induces the required molecular and muscular adaptations to improve intermittent sports performance.[5,6]

During the fight, to cope with the energetic demand of the bursts of exercise, both aerobic and anaerobic pathways are widely solicited. On the one hand, the anaerobic pathways contribute to a suitable adenosine triphosphate (ATP) resynthesis for the high-intensity part of exercise.[7] A good muscle buffer capacity is also required to cope with the number of repetitions and the ability to maintain a high intensity.[7] On the other hand, the aerobic system provides sufficient energy to sustain the effort for the duration of the fight and to recover during the lower intensity phases. HIIT seems particularly interesting as it is known to stimulate mitochondrial biogenesis[8] and increase oxidative ATP production.[9] A drawback is that HIIT seems to decrease anaerobic ATP production.[9] In that perspective, high-intensity training in hypoxia (HYP) seems of particular interest as it increases the use of the anaerobic pathways,[10] which could potentially limit the reduction in ATP production by those pathways induced by HIIT in normoxia (NOR).

Whether HIIT in HYP is more efficient at improving performance in taekwondo compared with HIIT in NOR has never been tested before. Therefore, based on the previously mentioned literature, the main hypothesis of our research study was that HIIT performed in HYP condition would induce larger muscle stimuli/adaptations than the same training performed in NOR in a population of black-belt taekwondoists.

Methods

Participants

A total number of 18 trained male and female taekwondoists were recruited from the Association Francophone de Taekwondo and Federation ITF Belgium. All subjects were black belt, practicing 4-hour taekwondo per week on average. They were randomly divided into 2 groups: NOR (sea level 20.9% O_2; n = 9; age 28.6 ± 1.4 y, height 175.4 ± 0.5 cm) or HYP (normobaric-simulated HYP; 14.3% O_2 corresponding to 3000-m altitude; n = 9; age 26.3 ± 1.0 y, height 174.2 ± 0.7 cm). The randomization was based on peak oxygen consumption (VO_2peak) values to avoid differences in fitness levels between the 2 groups. In addition, 2 women were put in each group. All participants signed an informed consent before the start of the study. The study was approved by the ethical committee of the Université catholique de Louvain (Belgium) and conducted in accordance with the Declaration of Helsinki.

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Experimental Design

In total, the study lasted for 8 weeks including 1 week of pretests, 6 weeks of training, and 1 week of posttests. The whole study was planned outside any competition phase. At day 0, the subjects got familiarized with the performance tests, which are detailed in specific sections hereafter and have been chosen as they have been related to taekwondo performance.[1] At day 1, anthropometric measurements were performed as follows: height; body weight; and skinfold thickness in 8 locations (triceps, subscapular, axillary, supraspinal, pectoral, umbilical, front thigh, and medial calf) and circumferences in 6 locations (waist, hip, chest, arm relaxed and contracted, calf, and thigh). The skinfold thickness measurements were carried out in triplicate with a Harpenden caliper and averaged to ensure good reproducibility. Fat mass (FM) and fat-free mass were calculated from Jackson and Pollock[11] body density equation for men and Siri[12] FM equation. After the anthropometric measurements, a countermovement jump (CMJ) test and a frequency speed of kick test (FSKT) performance coupled to blood lactate analyses were performed. At day 2, a graded exercise test on a treadmill (incremental treadmill test) was followed 1 hour after by a Wingate test (WNT) that was coupled to blood lactate analyses. During all tests, the temperature and relative humidity were maintained at 18°C and 55%, respectively. After the pretests, the training period began for 6 weeks with 2 training sessions per week. During this period, the athletes continued their usual training (in average 4 h/wk taekwondo + 1.5 h/wk physical preparation). Each session lasted for 1.5 hours and consisted of a 20-minute warming up, 3 sets of highly specific taekwondo exercises[2,13] interspersed by 3 minutes of passive recovery, 3 repetitions of a simulated fight, and a 20-minute cooling down (see Supplementary Table 1 [available online] for more details). The highly specific taekwondo exercises and the simulated fights were realized at maximal intensity. The training load was progressively increased to cope with the adaptations to training and maximize training gains (see Supplementary Table 2 [available online] for more details). Both groups trained in the same room (b-Cat Hoogtetraining, Tiel, the Netherlands) except that when the HYP group trained, the ambient air was enriched in nitrogen to reduce the percentage of oxygen to 14.3%. During each training session, the temperature and relative humidity were maintained at 18°C and 55%, respectively. At the end of the 6-week training period, measurements made at day 1 and day 2 were repeated at day 3 and day 4. Day 3 and day 4 were planned between 4 and 6 days posttraining, during which no physical activity other than the tests was performed. The tests were performed between 6 and 8 PM. Food and water intake was not controlled, but it was advised to the participants to ingest a light meal or a snack 2 to 3 hours before the tests. The participants were instructed not to take any supplement or alcohol the day before and the day of the tests.

Frequency Speed of Kick Test

Three parameters are usually recorded or calculated during an FSKT. The first is the FSKT during 10 seconds (FSKT10s) commonly used to demonstrate the speed at which the athlete can kick. The test consists in performing semicircular kicks, alternating right, and left legs, during the 10-second test period.[1,14] During the test, the athlete stood in front of a body opponent bag (Century BOB XL, Brussels, Belgium) at a comfortable distance to kick at the height of his belly button. The athlete was instructed to kick and hit up the black belt or above the opponent bag. Any kick below the black belt was not counted. Before the start, the athlete had to be in the fighting position, with his dominant leg put back. From this starting position, driven by an automated sound, the athlete began to kick by alternating his legs, from right to left or from left to right, for 10 seconds. The second is the FSKT multiple (FSKTmult), which is usually taken as a measure of performance and consists of executing 5 consecutive FSKT10s with 10-second rest in between. The purpose is to perform the highest amount of kicks possible within the 5 FSKT10s.[13] The third parameter is the kick fatigue index, which indicates the performance decrease during the FSKTmult.[13] The following equation was used to calculate the fatigue index percentage[13]: kick fatigue index (in percentage) = (1 − [no. of kicks during FSKT1 + FSKT2 + FSKT3 + FSKT4 + FSKT5]/[best FSKT × number of sets]) × 100.

The test was filmed and recorded using 3 different cameras getting both video and audio data. A computer was programmed to automatically give a bip every 10 seconds, which was loud enough to guide the athlete and to be recorded by the cameras. Kinovea software (version 0.8.15) was used to pool the signal from the 3 cameras and get an accurate follow-up of the trajectory of the movement. Any kick below the black belt was not counted. In addition, the video of 1 camera placed in front of the athlete was analyzed with the software Adobe Premiere CC (version 13.1; San Jose, CA) to accurately determine when the 10 seconds started and ended.

For lactate determination, capillary blood samples (5 μL at the fingertip) were taken just before the test, immediately at the end of the test, at minute 3 and minute 6 afterward. Blood lactate concentrations were determined by using an automated device (Lactate Pro 2 LT-1730; ARKRAY Inc, Kyoto, Japan).

Countermovement Jump

The CMJ test allows the determination of the explosive lower body power.[1,15] The athlete starts from an upright standing position, makes a preliminary downward movement by flexing the knees and hips, and immediately extends the knees and hips to jump vertically up off the ground. Flight time was recorded using an Optojump optical measurement system and analyzed with the software Optojump Next (version 1.12; Microgate, Bolzano, Italy). Height[16] was calculated by the software Optojump Next.

The position of the feet was guided by a cross drawn on the floor. The athletes were asked to put the hands on the hips and to bend the legs to an angle of 90°. During the whole flight phase, the legs and trunk had to be kept stretched. For the reception, it was asked to absorb the shock with the ankles first, keeping the legs stretched, and then with the knees and hips. The warm-up consisted of the repetition of 3 jumps. Then, the athlete performed 3 jumps, and the best of the 3 jumps was kept for the analyses.

Wingate Test

The WNT is a maximal cycling (Cyclus2, Melle, Belgium) test, which allows the determination of the anaerobic leg power over 30 seconds.[17] The athlete is asked to cycle as fast as possible against a resistance equals to 75 g/kg body weight. The following parameters were determined or calculated: peak and mean power output over the whole duration of the test, relative peak power per kilogram body weight, and a fatigue index calculated from the decline in power following the equation: (peak power output − end power output)/peak power output × 100.[17] Lactate concentrations were measured as described for the FSKT.

Incremental Treadmill Test

Aerobic capacity was assessed by determining the VO_2peak.[18] The latter was measured during incremental treadmill test, using a static breath-by-breath gas analyzer (Ergocard; Medisoft, Sorinnes, Belgium). The incremental test began at 9 km/h with a 0.5% grade and was incremented by 1 km/h every 2 minutes until exhaustion. VO_2peak was considered as the mean VO_2 during the last 30 seconds before exhaustion.

Statistics

Statistical analyses were performed using GraphPad (San Diego, CA) Prism 8. A 2-way ANOVA for repeated measures was used to test the main effect of environmental conditions (NOR, HYP) and time (PRE, POST), as well as the interaction between these 2 factors. When a significant main effect was found, Sidak multiple-comparison post hoc tests were performed to test potential differences between NOR and HYP at the same time point and differences between the 2 time points within the same environmental conditions. For lactate measurements, a 2-way ANOVA for repeated measures was used at each time point (0, 3, and 6 min) to test the main effect of environmental conditions (NOR, HYP) and time (PRE, POST), as well as the interaction between these 2 factors. When a significant main effect was found, Sidak multiple-comparison post hoc tests were performed. Effect sizes were calculated according to Cohen d and interpreted using the following classification[19]: $d < 0.01$, very small; $0.01 < d < 0.2$, small; $0.2 < d < 0.5$, medium; $0.5 < d < 0.8$, large; $0.8 < d < 1.2$, very large; and $1.2 < d < 2.0$, huge. Effect sizes (Cohen d values) are reported in Table 1 and in the figures for each environmental condition. Data are reported as mean ± SEM. Statistical significance was set at $P < .05$.

Results

Body Composition

A main interaction effect was found in the evolution of body weight and body mass index between NOR and HYP from PRE to POST ($P = .037$, Table 1). The effect was mainly due to a trend to a decrease in body weight (−1.5%, $P = .067$, $d = 0.123$) and body mass index (−1.5%, $P = .069$, $d = 0.119$) in NOR at the end of the training protocol. A main time effect was found for lean and FM ($P < .001$), with lean mass increasing and FM decreasing between PRE and POST in both groups. Lean mass increased by 2% in NOR ($d = 0.498$) and by 3% in HYP ($d = 0.734$) ($P < .001$). FM decreased by 14% in NOR ($d = 0.498$) and by 18% in HYP ($d = 0.734$) ($P < .001$).

Frequency Speed of Kick Test

A main time effect was found for FSKT10s ($P < .001$; Figure 1A), FSKTmult ($P < .001$; Figure 1B), the fatigue index ($P = .002$; Figure 1C), and lactate concentrations at 0 minute ($P = .040$, data not shown). A tendency toward a main time effect was found for lactate concentrations at 3 minutes ($P = .061$) and 6 minutes ($P = .059$, data not shown). The number of kicks during 10 seconds increased by 50% in NOR ($P = .004$, $d = 1.183$) and tended to increase in HYP ($P = .064$, $d = 0.941$) after training. The number of kicks during the FSKTmult increased by 38% in NOR ($P = .002$, $d = 1.372$) and by 25% in HYP ($P = .008$, $d = 0.961$) after training. The fatigue index decreased from 15% to 6% in NOR ($P = .023$, $d = 1.660$) and from 16% to 6% in HYP ($P = .013$, $d = 1.372$) after training.

CMJ, Wingate, and Incremental Treadmill Tests

A main time effect was found for CMJ height ($P = .003$; Figure 2). After training, CMJ height increased in HYP only (+7%, $P = .005$, $d = 0.418$). No main effect was found for the parameters measured or calculated during the WNT: mean power (Figure 3A), peak power (Figure 3B), fatigue index (Figure 3C), total work (Figure 3D), and blood lactate concentrations immediately, 3 and 6 minutes posttest (data not shown). For the incremental treadmill test, a main time effect ($P = .002$) and a tendency to interaction was found ($P = .057$) for VO_2peak (Figure 4). VO_2peak was 10% lower after compared with before training in NOR only ($P = .002$, $d = 0.442$).

Discussion

For the first time, the effects of HIIT in HYP have been tested in high-level taekwondoists. The main finding of the present study is that HIIT in HYP, performed twice a week for 6 weeks, does not provide frank additional gains on key performance parameters compared with HIIT in NOR. Contrary to previous studies in endurance and team-sport athletes,[20] we failed to find clear additional effects of HYP on high-intensity training. Several explanations may be put forward, among which the type of exercise performed. In the studies having found a frank additive effect of HYP, cycling, running, or double-poling exercise was used.[20] Here, for the first time, taekwondo-specific movements were

Table 1 Changes in Body Composition

	Normoxia			Hypoxia			Analysis of variance		
	PRE	POST	Cohen *d*	PRE	POST	Cohen *d*	Time main effect	Condition main effect	Time-by-condition interaction
Weight, kg	74.0 ± 1.4	72.7 ± 1.3	0.123	73.0 ± 1.0	73.5 ± 1.1	0.051	0.331	0.983	0.037
Body mass index, kg/m^2	24.0 ± 0.7	23.6 ± 0.6	0.119	23.9 ± 0.3	24.1 ± 0.3	0.144	0.332	0.853	0.038
Lean mass, %	86.3 ± 0.4	88.2 ± 0.4*	0.498	87.8 ± 0.3	90.0 ± 0.3*	0.734	<0.001	0.310	0.671
Fat mass, %	13.7 ± 1.3	11.8 ± 1.4*	0.498	12.2 ± 0.8	10.0 ± 0.8*	0.734	<0.001	0.310	0.671

Note: Results are presented as mean ± SEM.
*$P < .001$ versus PRE.

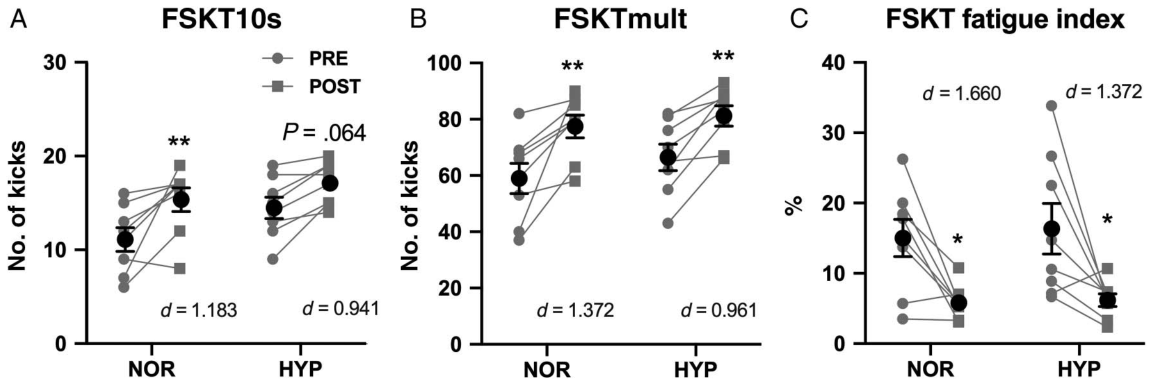

Figure 1 — Effects of high-intensity interval training on the FSKT. (A) Number of kicks during 10 seconds, (B) number of kicks during 5 × 10 seconds, and (C) fatigue index before (PRE) and after (POST) high-intensity interval training for 6 weeks in NOR or in HYP in taekwondoists. FSKT indicates frequency speed of kick test; FSKT10s, FSKT during 10 seconds; FSKTmult, FSKT during 5 × 10 seconds; HYP, hypoxia; NOR, normoxia. Values are mean ± SEM. Effect size (Cohen *d* value) is reported for each environmental condition. $^*P < .05$. $^{**}P < .01$.

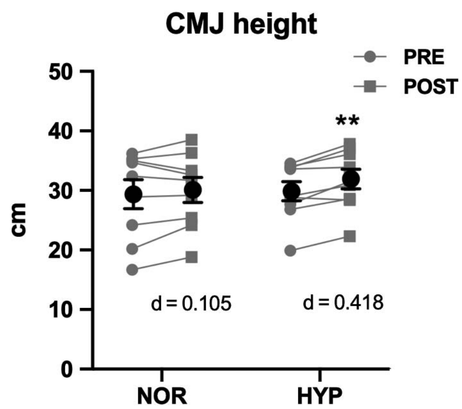

Figure 2 — Effects of high-intensity interval training on the CMJ test. Jump height before (PRE) and after (POST) high-intensity interval training for 6 weeks in NOR or in HYP in taekwondoists. CMJ indicates countermovement jump; HYP, hypoxia; NOR, normoxia. Values are mean ± SEM. Effect size (Cohen *d* value) is reported for each environmental condition. $^{**}P < .01$ versus PRE same environmental conditions.

performed at maximal intensity. As in both cases, the intensity was all out; it might be hypothesized that the lack of effect was due to the more technical feature of the exercises. However, it should be mentioned that similarly to the present study, others found no additional effect of repeated sprint in hypoxia (RSH) over repeated sprint in NOR on repeated-sprint ability at sea level in endurance-trained males,[21] young footballers,[22] and team-sport athletes.[23] In summary, while high-intensity training in HYP has shown some beneficial effects on sprint performance at sea level, those effects are far from being straightforward and systematic.

The purpose of the present study was to add 2 sessions per week of HIIT to the usual training load of the taekwondoists for 6 weeks. Our results indicate that 12 sessions of HIIT were sufficient to improve some parameters related to performance in taekwondo but that there was no clear added value of performing the training in HYP. This is of particular importance as the taekwondoists who participated to the present study were all black belt, meaning that they had a certain experience in training. We could have expected that the NOR trained group would not have improved its performance in the FSKT, but it did. Those results suggest that even black-belt taekwondoists have some space for improvement in a very short term, that is, 6 weeks. It is likely that the intensity of their usual training sessions was not high enough to optimize adaptations. The high-intensity training induced a 50% higher amount of kicks during the FSKT. As there was a familiarization phase before the pretests and the movement performed in the FSKT is very common in taekwondo, it is quite unlikely that this increase in performance was due to habituation to the test between before and after the training period. Whatever the explanation, those results underline the importance of adding HIIT to the usual training in taekwondoists.

While less specific than the FSKT, the CMJ test allows the determination of the explosive lower body power,[15] a determinant physiological parameter for the performance in taekwondo.[1] Contrary to Brocherie et al[24] who did not detect any change after RSH for 2 weeks, CMJ height increased by about 7% after HIIT in HYP. No improvement was found in the NOR group. The increase in CMJ height in the HYP group indicates a more favorable adaptation of the explosive power and thereby a more favorable adaptation for the performance in taekwondo, in that group compared with the NOR group. It has been shown that 74% of the CMJ height variation could be explained by 3 parameters: peak knee power, take-off shoulder angle, and peak ankle power.[25] Whether the higher CMJ height observed after HYP training was due to an improvement in one, or several, of those parameters, has not been tested here.

Hypoxic training, whether including continuous exercise of moderate intensity[26,27] or intervals of high intensity,[28] has previously been shown to improve at least one parameter of the performance measured during a WNT. Here, neither the peak power, nor the mean power, nor the lactate values postexercise were changed by HYP training. This is quite surprising as the WNT measures the anaerobic power, and the glycolytic activity is usually improved by HYP training.[10,20] Of note, none of the parameters measured during the WNT was modified by our training protocol in NOR, suggesting that the content of the training was not efficient at improving anaerobic power or that this improvement, if any, could not be translated into the specific cycling movement of a WNT. Finally, we cannot exclude that glycolytic activity and anaerobic power were already optimized in the sample of taekwondoists we studied before the start of the study. However, as those 2 physiological parameters are also determinant in the FSKT, which was improved after training, the latter option is highly unlikely.

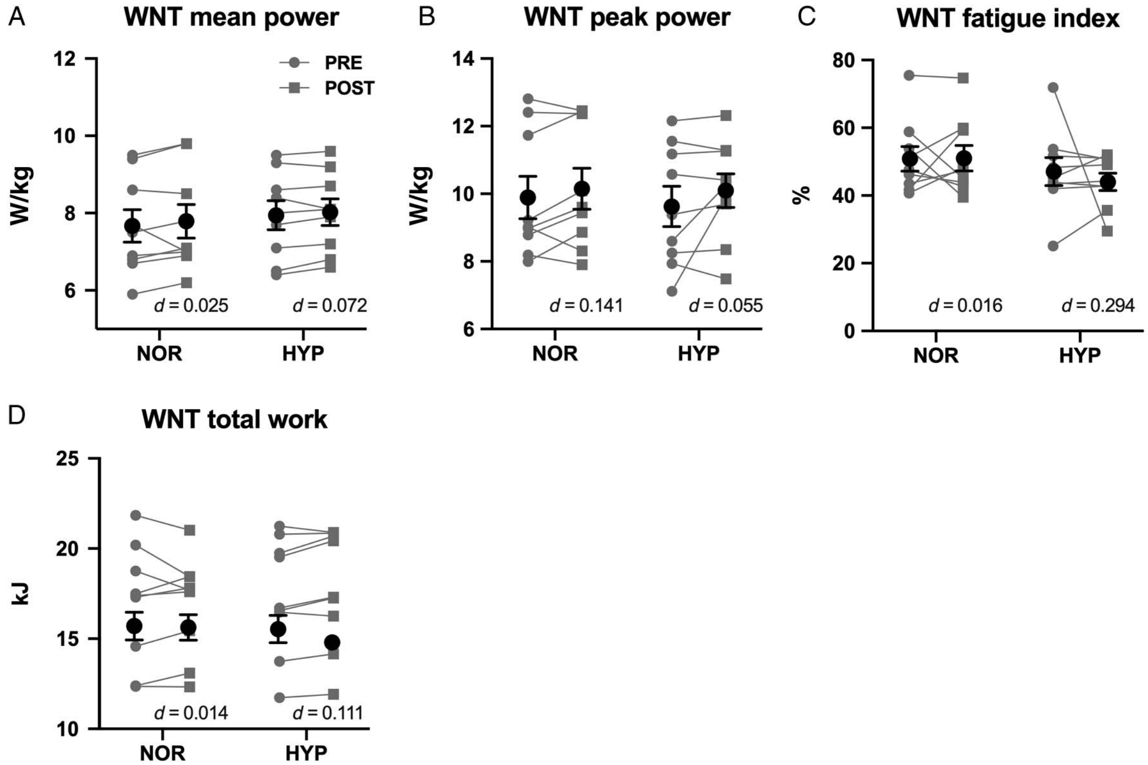

Figure 3 — Effects of high-intensity interval training on the WNT. (A) Mean power, (B) peak power, (C) fatigue index, and (D) total work before (PRE) and after (POST) high-intensity interval training for 6 weeks in NOR or in HYP in taekwondoists. HYP indicates hypoxia; NOR, normoxia; WNT, Wingate test. Values are mean ± SEM. Effect size (Cohen *d* value) is reported for each environmental condition.

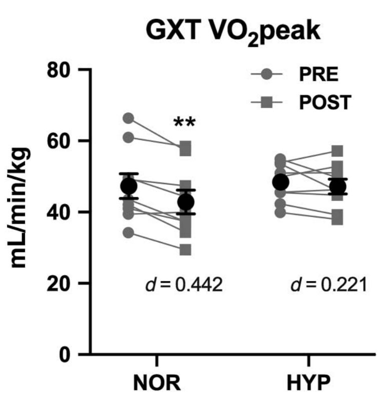

Figure 4 — Effects of high-intensity interval training on a GXT. Peak oxygen consumption (VO_2peak) before (PRE) and after (POST) high-intensity interval training for 6 weeks in NOR or in HYP in taekwondoists. GXT indicates incremental treadmill test; HYP, hypoxia; NOR, normoxia. Values are mean ± SEM. Effect size (Cohen *d* value) is reported for each environmental condition. $^{**}P < .01$ versus PRE same environmental conditions.

Finally, we assessed the effects of HIIT in HYP on the aerobic capacity using an incremental treadmill test. Indeed, a trivial beneficial effect of RSH on aerobic capacity compared with repeated sprint in normoxia has been reported recently.[20] Even if the increase was trivial, a higher aerobic capacity could be of importance in taekwondo, which requires a good ability to repeat technical movements for minutes. Only the HYP group could maintain its VO_2peak, not the NOR group. Knowing that VO_2peak reflects the aerobic capacity of a subject, the HYP group might possibly have taken a tiny advantage over the NOR group by ameliorating its performance in the FSKT and CMJ tests, reflecting anaerobic performance, while maintaining its aerobic capacity. Anyway, if there is any effect, the latter is tiny, but in high-level sport, any little improvement can make the difference. We have to acknowledge that the decrease in VO_2peak by 10% in the NOR group was unexpected, and no compelling explanation can be put forward. As no scientific data exist about the error of measurement of the device used here, we cannot exclude that this decrease was due to technical issues, although this should have been observed in the HYP group as well.

One limitation of the study is the moment at which the posttraining tests were carried out, namely 4 to 6 days posttraining. It is possible that after a longer recovery period, the added value of HYP versus NOR training could have been fully expressed, as previously shown after 10 versus 2 days.[27] Hypoxic training, certainly as the intensity was maximal, is a very stressful stimulus, and it is possible that a longer recovery period than for NOR training is warranted to be translated into performance. On the other hand, positive adaptations to RSH have already been shown to appear 2 to 3 days after the end of the training period and to be maintained over at least 3 weeks.[24] Based on the present design, it is difficult to determine whether HIIT in HYP had no effect on taekwondo performance or whether the timing of evaluation was not appropriate. In addition, we only quantified the number of kicks as a measure of performance during the FSKT while the power output and the speed of movement could have been valuable parameters to determine as well. Finally, we did not record heart rate nor blood oxygenation.

Practical Implications

Based on the present results, we could recommend taekwondoists to add HIIT twice a week to their regular training. Even in black-belt taekwondoists, an improvement in the FSKT, a highly specific test in that discipline, was found after HIIT, whatever the environmental conditions. It is of note that we only found very tiny additive responses of HYP to HIIT in NOR. This said, in high-level sport, any little improvement can make the difference. As no dampening of the improvement in performance was noticed in the HYP compared with the NOR group after training, and as some athletes respond better to HYP than others,[29] it could be worth to test HYP HIIT in athletes who are looking the little extra to their usual training to optimize the adaptations toward performance.

Conclusions

In black-belt taekwondoists, HIIT in HYP twice a week for 6 weeks provides tiny additional gains on key performance parameters compared with HIIT in NOR. Whether the trivial effects reported here might be of physiological relevance to improve performance remains debatable and should be tested individually.

Acknowledgments

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