Article

Cold-Water Immersion Promotes Antioxidant Enzyme Activation in Elite Taekwondo Athletes

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Abstract: The aim of this study was to investigate the effect of cold-water immersion (CWI) on lipid peroxides and antioxidant enzymes in adult Taekwondo athletes after a match. A cross-sectional study was performed. After a Taekwondo match, the control group remained seated passively, while the treatment group immersed their legs below the knee joint in cold water at 10 °C. Blood samples were taken at pre-match, post-match, post-treatment, and post-rest, and changes in malondialdehyde (MDA), superoxide dismutase (SOD), and glutathione peroxidase (GPx) concentrations were analyzed. The results showed that there was a significant difference in MDA between the two groups, and while the CWI group had 19% lower SOD concentration compared to the control group, and the difference was not significant. However, in case of interaction for GPx concentration (p < 0.001), a statistically significant difference was found between the two groups (p < 0.05). In conclusion, CWI after a Taekwondo match elevates the concentration of antioxidant enzymes.

Keywords: cold-water immersion; malondialdehyde; antioxidant enzyme; Taekwondo athletes; recovery

1. Introduction

It is well known that free radicals and reactive oxygen species (ROS) produced in the human body cause cellular damage as well as aging and various chronic disease [1]. However, from a physiological perspective, enzymatic and non-enzymatic systems (antioxidant system) neutralize the harmful effects of ROS [2].

Unlike normal oxygen, ROS are free radicals containing oxygen that are highly reactive. They contain an unpaired electron and have a strong tendency to achieve a stable state, by either taking or giving up an electron. Therefore, when ROS is produced in the body, they easily react with lipids, proteins and DNA, and can cause functional impairments. When ROS attacks cellular membranes, they oxidize unsaturated fatty acids and form lipid peroxides; furthermore, malondialdehyde (MDA) is used as a marker of lipid peroxide [3]. However, ROS are suppressed by antioxidant enzymes, such as superoxide dismutase (SOD), glutathione peroxidase (GPX), and catalase (CAT) [4].

Antioxidant enzymes play an important role in defending cells against oxidative damage caused by free radicals [5] that are generated through physical activity through various pathways [6]. Regular and appropriate exercise promotes metabolism, prevents disease, helps with weight management, and strengthens immune function. However, strenuous exercise, such as that performed by well-trained athletes, rapidly increases oxygen consumption and consequently increases oxygen supply by 10–15 times, which induces the production of free radicals [7]. Furthermore, oxygen consumption by muscles during exercise is increased by 10–20 times than at rest [8]. Moreover, it activates ROS that attacks cells, which leads to damages to carbohydrates, fats, proteins, and nucleic acids [9]. In particular, hypoxia or local hypoxia causes transferrin to release iron and exacerbates hemolysis. This alters the metabolism, and these responses increase stress or weaken athletic performance [10].
To minimize such adverse physiological responses, many studies have utilized various approaches to examine methods to reduce exercise-induced fatigue and promote recovery [11–15]. In particular, cryotherapy or cold-water immersion (CWI), which involves immersion of a part of the body or the whole body, has been researched in various exercise conditions and treatment durations [11–15]. However, although CWI has more recently been researched in various exercise methods and sports [16,17], past studies on antioxidant activity-CWI involved swimming [18], kayaking [19], and cryotherapy using a chamber; there were no studies investigating the effects of antioxidant-CWI after an actual match involving electronic protective gear, such as a Taekwondo match.

Taekwondo, a combat sport, was introduced as a demonstration sport at the 1988 Summer Olympics at Seoul and the 1992 Summer Olympics at Barcelona. It was confirmed as an official sport at the 2000 Summer Olympics at Sydney. During a Taekwondo match, successful torso punches or kicks and successful head kicks are awarded more points. Thus, a Taekwondo match can result in significant fatigue due to the physical effort involved [20–24].

An appropriate intensity of training is expected to not only reduce the harmful effects of free radicals but also trigger health benefits by stimulating the immune system [25]. However, free radical production and subsequent lipid peroxidation increase proportionate to oxygen consumption, depending on the intensity of exercise, and are known to be positively correlated with skeletal muscle injury [26]. In other words, vigorous exercise at 80–90% of HRmax [27] induces oxidative stress one way or the other, thereby affecting lipid peroxidation and antioxidant enzymes.

Although studies have investigated injuries based on athletic proficiency, sex, body weight, age, mechanism, involving body part, situation, and years or experience [28,29], only a handful of studies were conducted on martial arts athletes. Furthermore, due to the presence of several variables in a Taekwondo competition, including different weight divisions [30], this randomized crossover study aimed to investigate changes in heart rate (HR) during a Taekwondo match and changes in MDA, SOD, and GPX in response to CWI treatment immediately after a match.

Furthermore, although Taekwondo is a well-known sport and an official Olympic sport that is actively researched, antioxidant activity-CWI after a Taekwondo match has never been researched previously. We hypothesized that CWI would have more positive impacts on HR and enzyme activity compared to that only passive resting after a Taekwondo match. Therefore, the aim of this study was to examine the effects of CWI on lipid peroxide and antioxidant enzyme activity in the distal knee after a match in elite male Taekwondo athletes.

2. Materials and Methods

2.1. Participants

Twelve college Taekwondo athletes, with a minimum of 10-year-long careers in the game and who had won a Korean or foreign competition in the past two years, were enrolled. The participants were fully informed about the purpose and method of the study prior to beginning the experiment and signed a written consent form. During the study period, the participants were subjected to an identical experimental condition (exercise, diet, and sleep) at the college dormitory of the place where our study was conducted (Taekwondo Center). In addition, the participants were requested to refrain from the consumption of alcoholic and caffeinated drinks and the use of specific drugs such as anti-inflammatory agents. Moreover, they had to maintain their normal diet until the end of the study. However, the amount of food intake was not controlled. Participant demographics are as follows: (mean age: 20.4 ± 0.8 years; mean height: 181.6 ± 3.2 cm; mean body weight: 71.6 ± 7.9 kg; body mass index: 21.7 ± 2.50 kg/m²; fat mass: 8.1 ± 2.0 kg; V̇O₂max: 57.7 ± 4.2 mL/kg/min; HRmax: 201.3 ± 0.8 beats/min).
2.2. Experimental Design

This study was conducted at a college Taekwondo center. The indoor temperature was set to 18–20 °C during the experiment. The participants’ Olympic weight classes were evenly distributed (−58 kg to +80 kg), and their body compositions were measured prior to beginning the experiment (Inbody230 Body Composition Analyzer; Inbody Co., Ltd., Seoul, Korea). A graded maximal exercise test to exhaustion using the Bruce protocol was used to measure maximal oxygen consumption (Vo$_{2\text{max}}$), maximum heart rate (HR$_{\text{max}}$), and time to exhaustion (Quark b2, Cosmed, USA). Prior to testing, we explained rating perceived exertion (RPE) to the participants; they were instructed to provide the RPE every minute during the testing. In addition, their coaches encouraged them to perform maximally. According to the Bruce protocol, the treadmill is started at 2.74 km/h at a gradient of 10%. The incline of the treadmill increases by 2% at 3 min. intervals and the speed increases with each stage. Vo$_{2\text{max}}$ was recorded when HR ceased to increase, despite the workload increasing when the RPE reached 17 on the Borg Scale, or when the respiratory exchange ratio was >0.15. The study progression is shown in Figure 1.

![Study progression](image)

2.3. Taekwondo Competition

The rules of the Taekwondo competition in this study adhered to the 2019 World Taekwondo Federation (WTF) rules. Electronic equipment approved by the WTF and utilized in international competitions was used in this study (electronic body protection, electronic headgear, and electronic socks; KP&P, Seoul, Korea). The duration of each match was 8 min (2 min each for 3 rounds with a 1-min break), similar to that in actual competition. Two coaches cooperated in the study by giving the athletes strategic advice during the match. Further, HR was measured during and after each round (Polar FT1; T31, Polar®, Bethpage, NY, USA).

2.4. Treatment Methods-CWI

A crossover design was used with a control group (CONG) and a cold-water immersion group (CWIG). was measured on visit 1; the second visit was conducted seven days later. A 10-min leisure walk would have had little metabolic impact on elite athletes.
The participants walked from their dorms to the Taekwondo Center on the day of the experiment (10-min walk), and arrived at the center by 8 AM in preparation for the experiment. The participants rested for 30-min before the first blood sampling. After fully preparing for the experiment with the help of research assistants and coaches, the Taekwondo competitions were performed at 10 AM. The second blood sampling was performed immediately after each 2-min match, with 1-min rests between each match. The CONG comfortably sat on the competition mat and rested for 20 min, while the CWIG sat on a chair and underwent CWI of the distal knee area. A research assistant was assigned to each participant to conduct the experiment, and CWIG assisted with supplying ice cubes during CWI to control the temperature of the water (10 °C) (TP-101, Xuzhou Sanhe Automatic Control Equipment Co., Ltd.; Jiangsu, China; RoHS Certification). The duration of treatment (20 min) and water temperature (10 °C) used in this study were determined based on those in previous studies [31–33], as well as our pilot study related to CWI. However, the outcomes varied despite the equal treatment durations [31–33]; hence, the treatment duration used in this study cannot be considered the optimal condition. However, the benefits of this treatment duration and immersion temperature are that they can easily be applied in many sports at a low cost. Both groups underwent a third blood sampling after 20 min of rest and treatment, respectively. Then, both groups comfortably sat on the floor and rested for another 10 min for the final blood sampling. The participants were instructed to limit their water intake to a minimum throughout the experiment, although this was not controlled.

2.5. Blood Analysis

Four blood samples were taken from a vein in the forearm using a disposable syringe after the participants rested. Blood samples were collected in a non-EDTA-treated serum tube and an EDTA-treated plasma tube, centrifuged at 2500 rpm for 15 min, diluted using the assay kit according to the manual, and analyzed for each item using an enzyme-linked immunosorbent assay. Blood analysis was performed at the Green Cross LabCell laboratory in Yong-in, Korea, certified by the Korean Board for Accreditation and Conformity assessment.

2.6. Statistical Analysis

All data were analyzed using SPSS version 24 (SPSS Inc., Chicago, IL, USA) software and presented as mean and standard deviation (SD). Differences in time between groups were analyzed using independent t-tests, and differences in groups, time, and group × time were analyzed using repeated measures analysis of variance (ANOVA). Differences between groups were analyzed with one-way ANOVA followed by Bonferroni correction. Significant differences of \( p \) values after testing were presented and explained in the tables using an alphabet. Statistical significance was considered when \( p < 0.05 \).

3. Results

3.1. Intensity during Taekwondo Competition

HR measured during the Taekwondo match is summarized in Table 1 and Figure 2. The mean pre-Taekwondo match HR was 74.6 ± 6.50 bpm, while mean HR during and post-match were 177.0 ± 13.52 bpm and 183.4 ± 13.52 bpm, respectively. With mean HR\(_{\text{max}}\) of 201.3 ± 0.75 bpm, intensity during the Taekwondo match represented by mean HR during the match and post-match were 88% and 91% HR\(_{\text{max}}\), respectively.

3.2. Change in MDA Concentration

Changes in MDA concentration following CWI are described in Table 2 and Figure 3; they were analyzed using repeated measures ANOVA. Significant differences according to the time of measurement were observed (\( F = 8.864; p < 0.001 \)). However, there were no significant differences in MDA concentration between the two groups and no interaction effect. Regarding differences based on time of measurement, the CONG showed a 9%
reduction in MDA concentration after CWI from that immediately after a match, while the CWIG showed a 2% increase in the same period. In addition, the CONG showed a 10% reduction of MDA concentration from immediately after a match until CWI and after rest, while the CWIG showed no changes.

Table 1. Heart rate (HR) during a Taekwondo match.

|                  | t  | p   |
|------------------|----|-----|
| Before           | 0.370 | 0.715 |
| Between round 1  | 1.786 | 0.088 |
| After round 1    | 1.108 | 0.320 |
| Between round 2  | 0.362 | 0.720 |
| After round 2    | 0.502 | 0.621 |
| Between round 3  | 0.167 | 0.869 |
| After round 3    | 0.413 | 0.684 |

Mean ± standard deviation.

Figure 2. Heart rate during a Taekwondo match.

Table 2. Change in malondialdehyde (MDA) concentration after cold-water immersion (CWI) (unit/µmol).

| Time            | Group   | CONG     | CWIG    | F      |
|-----------------|---------|----------|---------|--------|
| Pre-match       | CONG    | 102.5 ± 23.00 | 119.2 ± 27.61 | Group 3.040 |
|                 | CWIG    | 89.3 ± 17.05 | 93.9 ± 31.04 |       |
| Post-match      | CONG    | 81.0 ± 16.40 | 95.3 ± 26.59 | Time 8.864 *** |
|                 | CWIG    | 80.7 ± 19.77 | 93.5 ± 19.88 |       |

Mean ± standard deviation; *** p < 0.001; no significant interaction effect was observed for group by time in MDA concentration.

3.3. Change in SOD Concentration

Changes in SOD concentration after CWI are described in Table 3 and Figure 4 and were analyzed using repeated measures ANOVA. Significant differences according to time of measurement were observed (F = 8.496; p < 0.001). However, there were no significant differences in SOD concentration between the two groups with no interaction effect. Regarding the differences based on time of measurement, the CONG showed a 33% reduction of SOD concentration after CWI from that immediately after a match, while the CWIG showed a 24% reduction in the same period. However, the CONG showed a 10% reduction of SOD from after CWI to after rest, while the CWIG showed a 5% increase in
the same period. Furthermore, the CONG showed a 19% increase in SOD concentration after treatment from that before a match compared to the CWIG, but the difference was not statistically significant.

Table 2. Change in malondialdehyde (MDA) concentration after cold-water immersion (CWI) (unit/µ mol).

| Group   | Time                  | CONG       | CWIG       | F      |
|---------|-----------------------|------------|------------|--------|
|         | Pre-match             | 102.5 ± 23.00 | 119.2 ± 27.61 |        |
|         | Post-match            | 89.3 ± 17.05  | 93.9 ± 31.04   |        |
|         | Post-treatment        | 81.0 ± 16.40  | 95.3 ± 26.59   |        |
|         | Post-rest             | 80.7 ± 19.77  | 93.5 ± 19.88   |        |

Mean ± standard deviation; *** p < 0.001; no significant interaction effect was observed for group by time in MDA concentration.

Figure 3. Change in MDA concentration after CWI. (Data are expressed as mean ± standard deviation. A main effect was evident by time p < 0.001. CWI: cold-water immersion).

Table 3. Change in SOD concentration after CWI (unit/mL).

| Time          | Group   | CONG       | CWIG       | F      |
|---------------|---------|------------|------------|--------|
| Pre-match     | Group   | 1.7 ± 0.90  | 1.6 ± 1.02  | 0.158  |
| Post-match    | Time    | 3.0 ± 1.64  | 2.5 ± 1.52  | 8.496 ***|
| Post-treatment| Group × Time | 2.0 ± 0.96  | 1.9 ± 1.08  | 0.945  |
| Post-rest     |         | 1.8 ± 1.04  | 2.0 ± 1.31  |        |

Mean ± standard deviation; *** p < 0.001; no significant interaction effect was observed for group by time in MDA concentration.

Figure 4. Change in SOD concentration after CWI. (Data are expressed as mean ± standard deviation. A main effect was evident with respect to time—p < 0.001. CWI: cold-water immersion).
3.4. Change in GPX Concentration

Changes in GPX concentration following CWI are described in Table 4 and Figure 5 and were analyzed using repeated measures ANOVA. Significant differences according to the time of measurement were observed ($F = 13.317; p < 0.001$). Moreover, there were highly significant differences in interaction ($F = 26.588; p < 0.001$). The CONG showed a 2% reduction of GPX concentration after CWI compared to immediately after a match, while the CWIG showed an 8% increase in the same period. Furthermore, the CWIG showed an 89% increase in GPX concentration after rest from the level immediately after a match compared to the CONG ($F = 6.778; p < 0.05$).

Table 4. Change in glutathione peroxidase (GPX) concentration after CWI (unit/µ mol).

| Time          | Group  | CONG     | CWIG     | $F$  |
|---------------|--------|----------|----------|------|
| a Pre-match   |        | 112.4 ± 14.37 cd | 99.2 ± 37.30 bcd | Group 6.778 * |
| b Post-match  |        | 119.1 ± 15.84 cd | 65.7 ± 14.35 ad | Time 13.317 *** |
| c Post-treatment |    | 94.3 ± 14.38 ab | 70.8 ± 9.78 ad | Group × Time 26.588 *** |
| d Post-rest   |        | 93.4 ± 13.74 ab | 134.7 ± 24.98 abc |      |

Mean ± standard deviation, *: Pre-match, **: Post-match, ***: Post-treatment, ****: Post-rest; * $p < 0.05$, ** $p < 0.001$; significant differences in p-values of the Bonferroni post hoc test are indicated with letters.

Figure 5. Change in GPX concentration after CWI. (Data are expressed as mean ± SD; A main effect was evident for time and group × time—$p < 0.001$; differences between each group were statistically significant—$p < 0.05$: difference from before, * $p < 0.5$, ** $p < 0.5$; difference from after game, *** $p < 0.01$, **** $p < 0.001$; difference from before, † $p < 0.05$, †† $p < 0.01$; difference from before, ‡ $p < 0.05$, ‡‡ $p < 0.01$, ‡‡‡ $p < 0.001$. CWI: cold-water immersion.).

4. Discussion

This study was conducted on 12 male elite Taekwondo athletes with the aim to assist with the recovery of the athletes, who need to compete in all their respective matches of a tournament within a single day. To this end, the athletes’ HR was measured to investigate the intensity of a Taekwondo match, and CWI was applied to the below-knee area after a match to investigate its effects on the athletes’ lipid peroxide and antioxidant enzymes.
levels. Our study’s findings regarding recovery after a match of elite Taekwondo athletes showed that the mean HR after a match was about 91% HR\textsubscript{max}. CWI treatment after a match neither decreased lipid peroxide concentrations, nor did it confer positive effects on the concentration of SOD. However, it did improve GPX concentrations (Group × Time, \( p < 0.001; \) Group, \( p < 0.05 \)).

### 4.1. Athletic Intensity of the Taekwondo Competition

Since being confirmed as an official sport at the 2000 Summer Olympics at Sydney, Taekwondo has been recognized for its values at the Olympics and has advanced as a martial sport [21]. Taekwondo requires players to move quickly and powerfully [34]; thus, the players must have power, muscle strength, muscle endurance, agility, and flexibility [35,36]. In particular, muscle functions, such as muscle strength and endurance of the lower extremities, are important for performing strong and accurate kicks [37,38]. During the three two-min rounds of a Taekwondo competition, athletes employ various techniques and strategies, demanding a substantial amount of energy.

According to a study by Butios (2007) on the intensity of Taekwondo matches in 24 male college Taekwondo athletes, the mean HR of athletes who train for five days per week for an average of 25 h a week was 86% HR\textsubscript{max} [39]. In seven recreational Taekwondo students, the mean HR was about 80–90% HR\textsubscript{max} during Taekwondo-combined exercise [27]. Both studies showed a lower HR\textsubscript{max} than that found in our study, where actual Taekwondo matches were performed.

However, in a study investigating HR responses based on a type and technique combination of Taekwondo in seven elite female Taekwondo athletes, the HR was 186.6 ± 2.5 bpm during a Taekwondo match, with an intensity of 92% HR\textsubscript{max} [36]. This was consistent with the results of our study, where actual Taekwondo matches were performed with tactical strategies as opposed to previous studies that used Taekwondo as a type of exercise [27,39]. Furthermore, the mean HR of male Taekwondo athletes with an average career of nine years (age: 22 ± 4 years; height 182 ± 0.10 cm; body mass 69.4 ± 3.4 kg) during an international Taekwondo competition was 187 ± 8 bpm after a three-round match at 96% HR\textsubscript{max} [40]. This shows that HR is higher during a program similar to an actual match than that during Taekwondo performed as an exercise, and that HR is even higher during an actual match, as performed in our study.

### 4.2. Variation of MDA Concentration after CWI for Taekwondo Athletes

In general, ROS are released from the electron transport chain in the mitochondria, even at rest [3], and they eventually attack the cell membrane and nucleus and form lipid peroxides. Moreover, secondary ROS, produced as a result of ROS activation surpassing the defense system with antioxidant enzymes, stimulate the peroxidation of lipids containing unsaturated fatty acids in cell membranes, thereby elevating the concentration of MDA, the final metabolite of lipid peroxide, and induce injuries [41]. After exercise, ROS concentration can increase so much as to induce acute injuries of muscle fibers and connective tissues, leading to muscle ache, delayed recovery, and diminished exercise performance [42]. Previous studies have examined the effects of types of cryotherapy on such lipid peroxides produced through exercise and antioxidant enzymes [43,44].

Cryotherapies are used for therapeutic purposes in sports, and their effects differ according to the method, duration, treatment site, and the individual’s level of physical activity. Among various cryotherapies, crushed ice pack, ice massage, and CWI are the most effective [45]. In a study examining changes of MDA concentration after cold treatment, no change in MDA was found after performing high-intensity jump exercises between the untrained group and the group trained in the exercise; although the levels of lipid peroxidase in muscles, as measured by changes in MDA concentration, varied widely, there were no differences between the two groups [46]. These results seem to be attributable to excellent physical defense regulation in the athletes as a result of prolonged chronic training. These results are consistent with our findings. In this study, MDA
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concentration immediately after the match was lower than that before the match, but reduced MDA concentration did not differ between after CWI and after rest. However, another study reported that ice-water immersion after 30 min of cycling lowered lipid peroxide concentration \[44\], which contradicts the results of our study and that of the previously mentioned study \[47\].

In 2003, Krishnan et al. reported that MDA production is influenced more by exercise intensity or duration, as opposed to the type of exercise performed \[47\]. Thus, it seems that MDA concentration after jump exercises or a competition that can be performed in a short time \[47\], and that after a Taekwondo competition, are not markedly influenced by cold treatment or CWI. The reduction of MDA concentration after 30 min of cycling exercise, as reported in a prior study \[43\], seems to have been a result of the longer duration of the exercise.

There are various study findings regarding long-term chronic training, where some studies report that it bolsters an individual’s physical defense mechanisms and decreases MDA even if they engage in exhaustive exercise \[48\], while other studies report that ROS as well as antioxidant enzymes are produced after exhaustive exercise \[49\]. This suggests that the gap in the changes of MDA caused by exercise may be attributable to various factors, including study design. Furthermore, the most crucial factor is speculated to be the level of proficiency of participants for the particular type of exercise or perceived exercise intensity; in athletes who underwent prolonged professional training, local CWI seems to have been inadequate to reduce intracellular-intravascular flow to promote recovery from cellular or membrane injuries from free radical production triggered by increased oxygen consumption in the active muscles during a game.

4.3. Variation of Antioxidant Enzyme Concentration According to CWI for Elite Taekwondo Athletes

Taekwondo is a sport in which a player must be nimble enough to exploit the opponent’s weak points with explosive kicks; thus, active muscles are utilized alternately at a high intensity. Furthermore, players must compete in at least 5–7 matches in a single day \[50,51\], during which there is the accumulation of hydrogen ions, phosphorus, ammonia, and lactate. This accumulation has an impact on muscle metabolism, local muscle fatigue, and neuromuscular activities \[52,53\]. Moreover, high-intensity training, excessive training, and strenuous training without appropriate rest periods also induce fatigue, undermine athletic performance, and can cause sport-related injuries \[54\]. In addition, they cause muscle contraction and structural damages to cell membranes and muscles, thereby disturbing muscle fiber homeostasis and leading to oxidative stress.

However, lowering ROS levels after exercise can also have the opposite effect \[55\]. This is attributable to the fact that ROS is needed for appropriate muscle contraction during rest and physical activity \[42\]. In 1996, Swenson et al. suggested that CWI is a classic method of alleviating muscle injury. Furthermore, they reported that CWI treats muscle injuries by lowering local vascular permeability and edema by inducing vasocontraction while increasing the pain threshold \[56\]. Another study reported that CWI can regulate the physiological effects of exercise and can be used for treating exercise-induced injuries \[57\]. Regarding prior research on cold treatment, one study reported that a single session using ice increased antioxidant enzyme activity in untrained volunteers \[19\]. However, our findings showed that a single CWI session partially increased antioxidant enzyme activity. That is, there were no significant differences in SOD levels between groups, but there was an interaction effect. Moreover, CWI treatment increased GPX concentration, and there were interactions between groups. Thus, a single CWI session can be applied in different ways according to the study methodology. In another similar study, low-temperature stimulation once per day increased SOD activity \[58\], showing that the outcomes varied, even with the same cold treatment.

However, ice-cold water treatment did not increase antioxidant enzyme activation \[43\], which is in line with our findings, but inconsistent with the findings of other studies \[44,58\].
Elevated antioxidant enzyme activity attests to increased ROS concentration. However, such ROS production could be beneficial, as it may cause stimulating changes, and does not damage the body [18,59]. Therefore, as an oxidant, ice-water immersion stimulates and enhances antioxidant capacity [43]. In another study utilizing cold treatment, a whole-body cryotherapy (WBC) session used as a pre-training stimulation in a multiday training camp had adverse effects on elite athletes by diminishing both lipid peroxide level and antioxidant enzyme activities [60,61]. Nevertheless, WBC and CWI are increasingly used in professional sports to facilitate rehabilitation following an injury, as they lower oxidative stress, inflammatory reactions, and pain from vigorous exercise [19,57,60,61]. In particular, CWI continues to be researched using various study designs, which help support the claim that it is an effective method to delay or prevent physical fatigue, muscle fatigue, and diminished athletic performance suffered by athletes who undergo high-intensity training or compete in multiple games.

Therefore, the inconsistent effects of CWI on the oxidant/antioxidant balance in the human body would probably be helpful in maintaining an ROS concentration that is the most appropriate for both rest and exercise [43].

Inconsistent results pertaining to the effects of CWI on lipid peroxide and antioxidant enzymes were shown in previous studies [43,44,60,61]. Our study clarifies the tasks to be addressed by researchers in the future using new methodologies for the type of participant, duration of exercise, method of exercise, and CWI treatment duration and site. Furthermore, the exact mechanism of the antioxidant system and cold treatment must be researched.

4.4. Limitations of the Study

We acknowledge the following limitations of this study. First, we only enrolled adult men and analyzed three blood samples. Second, while all athletes were in the same Taekwondo weight category and were trained in the same training program prior to the study, we could not control for the amount of continuous training. Therefore, it may be difficult to draw definitive conclusions due to individual athletes’ physical responses to continuous training, including free radical production, cell injury, and antioxidant enzymatic system. However, the significance of this study is that we tackled a novel area of research involving antioxidant activity-CWI after an actual Taekwondo game.

Therefore, our findings highlight the need to restrict continued physical training, amount of food intake, and drug use for a certain period and to expand the scope of study parameters.

5. Conclusions

Regarding the exercise intensity of a Taekwondo match, the mean HR during the match was 88% \(HR_{\text{max}}\) and post-match was 91% of \(HR_{\text{max}}\). CWI treatment after the Taekwondo match had no effect on the reduction of MDA concentration in elite Taekwondo athletes. SOD concentration in the CWIG was 19% higher than that in the CONG, suggesting that CWI effectively increases SOD concentration. Further CWI after the Taekwondo match effectively increased GPX concentration.

In conclusion, although CWI at 10 \(^\circ\)C for 20 min after a Taekwondo match did not alter lipid peroxide levels, it may promote antioxidant enzyme activation in elite Taekwondo players. However, the theoretical grounds for the effects of CWI on antioxidant enzymes have not yet been established. Additional studies employing diverse methods are needed to examine post-match treatment for sports that use protective devices on the head, trunk, hands, and feet, such as Taekwondo.

We found that CWI, which can be readily applied after a high-intensity Taekwondo match, may promote the more rapid recovery of Taekwondo athletes who are required to play multiple matches in one day from their qualifications to the finals.

Author Contributions: E.-H.P. was the main researcher and writer, contributed to the study design, collected data, and took part in manuscript preparation. S.-W.C. and Y.-K.Y. helped conceptualize
the study, participated in its design and statistical analysis. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors would like to express their gratitude to the people who supported this study and the participants who joined the program voluntarily.

**Conflicts of Interest:** The authors declare no conflict of interest.

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