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ORIGINAL INVESTIGATION

Does Cold-Water Immersion After Strength Training Attenuate Training Adaptation?

Wigand Poppendieck, Melissa Wegmann, Anne Hecksteden, Alexander Darup, Jan Schimpchen, Sabrina Skorski, Alexander Ferrauti, Michael Kellmann, Mark Pfeiffer, and Tim Meyer

Purpose: Cold-water immersion is increasingly used by athletes to support performance recovery. Recently, however, indications have emerged suggesting that the regular use of cold-water immersion might be detrimental to strength training adaptation. ***Methods:*** In a randomized crossover design, 11 participants performed two 8-week training periods including 3 leg training sessions per week, separated by an 8-week "wash out" period. After each session, participants performed 10 minutes of either whole-body cold-water immersion (cooling) or passive sitting (control). Leg press 1-repetition maximum and countermovement jump performance were determined before (pre), after (post) and 3 weeks after (follow-up) both training periods. Before and after training periods, leg circumference and muscle thickness (vastus medialis) were measured. ***Results:*** No significant effects were found for strength or jump performance. Comparing training adaptations (pre vs post), small and negligible negative effects of cooling were found for 1-repetition maximum ($g = 0.42$; 95% confidence interval [CI], −0.42 to 1.26) and countermovement jump ($g = 0.02$; 95% CI, −0.82 to 0.86). Comparing pre versus follow-up, moderate negative effects of cooling were found for 1-repetition maximum ($g = 0.71$; 95% CI, −0.30 to 1.72) and countermovement jump ($g = 0.64$; 95% CI, −0.36 to 1.64). A significant condition × time effect ($P = .01$, $F = 10.00$) and a large negative effect of cooling ($g = 1.20$; 95% CI, −0.65 to 1.20) were observed for muscle thickness. ***Conclusions:*** The present investigation suggests small negative effects of regular cooling on strength training adaptations.

Keywords: cooling, recovery, performance, maximal strength, countermovement jump

Cold-water immersion (CWI) has emerged as a popular recovery intervention among athletes. While the actual mechanisms of cooling to support recovery are not understood in all mechanistic details, it has been suggested that a reduction in muscle temperature may lead to lesser extents of muscle damage and postexercise inflammation. Other potentially beneficial effects include a reduction in heart rate and cardiac output, peripheral vasoconstriction, reduction in peripheral edema formation, and analgesic effects.[1]

Studies investigating acute effects of cooling after strenuous exercise were summarized in several meta-analyses.[2,3] On a short-term basis, cooling appears to have positive effects on performance recovery. For instance, an average increase in performance of 2.4% associated with an average effect size of $g = 0.28$ for cooling was observed; however, effects depended strongly on the specific study protocol.[2]

Fast recovery is important not only during competition, but also during training periods. Athletes recovering faster from strenuous training are able to tolerate higher training loads, and may thus perform better in competition.[4] With such a scenario in mind, a possible chronic effect of CWI (eg, after each training session) might be interesting to athletes as well. Physiologically, it appears plausible that frequent CWI after exercise may have detrimental effects on the magnitude of training adaptations. This theory implies that postexercise fatigue and inflammation are necessary prerequisites for training adaptation. CWI after training might interfere with these processes and thus attenuate rather than enhance training adaptation.[5]

The long-term effects of CWI can be expected to depend on the specific type of exercise, for instance, strength or endurance training.[6] For strength training adaptations, Yamane et al[5,7] found detrimental effects of regular cooling after 4 to 6 weeks of forearm training. Fröhlich et al[8] observed reduced adaptations after 5 weeks of leg strength training for cooling compared with control. Those studies used a within-subject design with 1 side of the body being cooled, and the other serving as control. Roberts et al[9] divided subjects into 2 groups and found smaller strength training adaptations for cooling after a 3-month strength training program, compared with active recovery. The results of these studies were recently summarized in a review article.[10] None of the presently available studies on strength training used a randomized crossover design, which is considered the optimal approach because the influence of confounding covariates is reduced. For example, dividing the subjects into 2 groups has the consequence of less statistical power due to the use of unpaired samples. Using a within-subject design with 1 cooled leg and 1 control leg introduces a potential confounder as cooling-induced humoral effects may be present in the whole-body, even if only 1 leg is cooled.[11]

The aim of this study was to analyze the chronic effects of regular CWI on strength training adaptations. We hypothesized that regular CWI would lead to reduced adaptations of leg press

Poppendieck, Wegmann, Hecksteden, Darup, Schimpchen, Skorski, and Meyer are with the Inst of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany. Poppendieck is also with the Dept of Information Technology, Mannheim University of Applied Sciences, Mannheim, Germany. Ferrauti is with the Unit of Training and Exercise Science, Ruhr University Bochum, Bochum, Germany. Kellmann is with the Unit of Sport Psychology, Ruhr University Bochum, Bochum, Germany, and the School of Human Movement and Nutrition Sciences, University of Queensland, Brisbane, QLD, Australia. Pfeiffer is with the Inst of Sports Science, Johannes Gutenberg University, Mainz, Germany. Poppendieck (w.poppendieck@hs-mannheim.de) is corresponding author.

1-repetition maximum (1RM) and countermovement jump (CMJ) height.

Methods

General Design

The study was designed as a randomized crossover training trial (see Figure 1, trial registry: www.clinicaltrials.gov; ID: NCT03332446). It was carried out in accordance with the Declaration of Helsinki and approved by the local ethics committee (Ärztekammer des Saarlandes, Saarbrücken, Germany, approval number: 83/14). All participants provided written informed consent prior to participation.

Participants

A total of 11 participants (9 male and 2 female) with at least 6 months of strength training experience (1–2 training sessions per week) completed the study. Participants were recruited at local gyms, by advertisement on the university information screens, and social media. Out of the 126 candidates initially recruited, 91 decided not to take part in the study, mainly for personal reasons (too much effort and study duration too long). The remaining 35 candidates received an initial health check. After the health check, another 16 candidates dropped out due to medical (n = 7) or personal (n = 9) reasons. Finally, 19 participants took part in the study, out of which 8 were not able to complete the training due to medical (n = 4) or personal (n = 4) reasons. The medical withdrawals were not related to the study.

Anthropometric data included age, body mass index, and body fat (see Table 1). For body mass index determination, body height and weight were measured using a standard scale (M304040-01; ADE Germany GmbH & Co. KG, Hamburg, Germany). Body fat was determined by a skinfold thickness measurement using the 10-point method.[12] Table 1 includes participants' maximal aerobic capacity determined on the treadmill (detailed method described by Scharhag-Rosenberger et al[13]).

Performance Measurement

Prior to training, participants underwent a run-in phase of 8 weeks without any leg training. The investigation consisted of two 8-week strength training periods separated by a washout phase of 8 weeks. The run-in and washout phases were chosen to ensure that baseline training states were comparable before each of the training phases.[14] Therefore, study duration for each participant was 32 weeks. During washout phases, no leg strength training was allowed. In each training period, participants trained 3 times a week, summing up to 24 training sessions.

Participants were familiarized with all procedures prior to testing. This included 2 familiarization sessions with 1RM measurement and CMJ (methods described below). Participants were required to record their nutrition 24 hours prior to the first test, and to replicate this nutritional intake before all subsequent tests.

One week before each training period, 1RM and CMJ height were determined (pretest). Following a 10-minute warm-up phase on a cycle ergometer (Life Fitness, Rosemont, IL), participants performed 10 repetitions on a leg press (Gym80 International GmbH, Gelsenkirchen, Germany) at 50% of the estimated 1RM load. After a 2-minute break, 3 repetitions at 80% of the estimated 1RM load were performed, followed by a 3-minute break. Then, participants were asked to carry out 1 complete repetition at an estimated 1RM load, and this load was then adjusted until the 1RM load was found (3-min break between repetitions). An attempt was defined as valid if the participant was able to move the weight from the starting position (knee angle 85°) to the end position (knee angle 175°). The 1RM load was estimated for each participant

Table 1 Baseline Participant Characteristics

Participants	Age, y	BMI, kg/m^2	Body fat, %	VO_2max, mL/min/kg
N = 11	25.3 (3.6)	24.5 (2.4)	15.1 (4.9)	52.9 (4.5)

Abbreviations: BMI, body mass index; VO_2max, maximal aerobic capacity. Note: All results are presented as mean (SD).

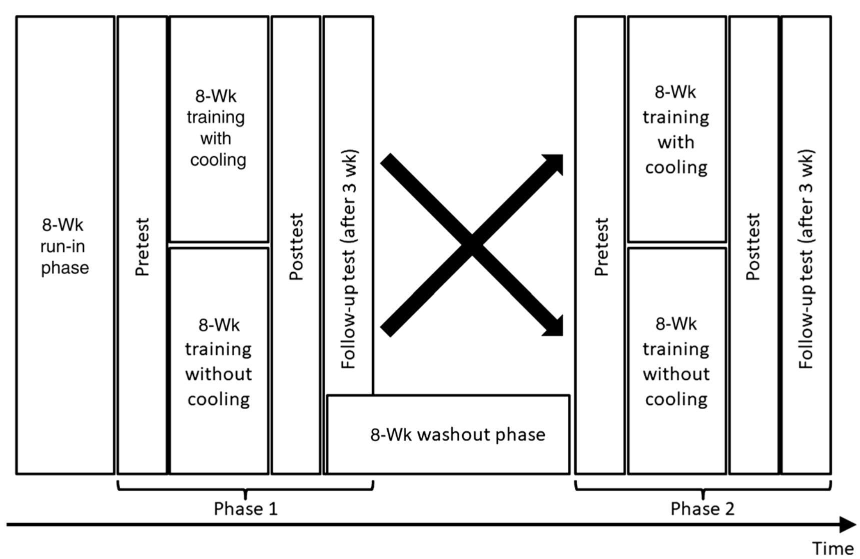

Figure 1 — Design of the randomized crossover training study.

based on the familiarization tests and (if available) preceding test results, thereby a determination using no more than 3 to 4 repetitions was possible in each case.

After a 15-minute break, a jump test was conducted. Participants stood on a force plate (Quattro Jump; Kistler Group, Sindelfingen, Germany) and performed 5 maximal CMJs with the arms placed at the hips. The best result was chosen as the test result. Due to technical problems with the force plate, only 8 out of the 11 participants could be tested for jump performance.

Strength and jump tests were repeated 1 week (posttest), and 3 weeks (follow-up test) after the end of each training period.

After the pretest and the posttest, leg circumference was measured using a measuring tape. Thickness of the M. Vastus medialis was determined using ultrasound (Vivid S6; GE Medical Systems, Freiburg, Germany). This method has been shown to provide valid results[15]; all measurements were executed by the same person. The measurement position was marked with a waterproof pen to ensure a consistent measurement, and participants were requested to repeatedly renew the mark to maintain it throughout the 6-month study duration. However, 2 participants lost their mark over the course of the study and could therefore not be reevaluated.

To evaluate the influence of cooling on sleep quality and perceived recovery and stress, participants completed a questionnaire assessing fatigue and sleep, as well as the Short Recovery and Stress Scale (SRSS).[16–18] The sleep questionnaire included the questions shown in Table 2, questionnaires were completed in the evening (question 1) and in the morning (questions 2–4). The SRSS is a standardized self-assessment procedure and includes the items *Physical Performance Capability*, *Mental Performance Capability*, *Emotional Balance*, and *Overall Recovery* in the *Short Recovery Scale*; and *Muscular Stress*, *Lack of Activation*, *Negative Emotional State*, and *Overall Stress* in the *Short Stress Scale*. Questionnaires were completed daily for a period of 2 weeks (weeks 3 and 4) during each training phase.

Training

Training sessions were carried out at the Saarland University gym. Each session started with a 10-minute warm-up phase at a self-chosen load on a cycle ergometer (95C Lifecycle; Life Fitness); participants used the same load for each warm-up. Training consisted of 3 machine-based exercises (leg press, leg curl, leg extension [Gym80 International GmbH]). The order was chosen such that multiple-joint exercises were performed before single-joint exercises.[19] Prior to the first exercise (leg press), a warm-up set of 10 repetitions at 50% of the 10-RM was performed. In each exercise, 3 sets were performed at the 10-repetition maximum until fatigue, separated by a 3-minute break. The 10-repetition maximum was determined during the first session, and was adjusted during the 13th session. All training sessions were supervised, and recorded by the gym's software system (aktivSystem Training; aktivKONZEPTE AG, St. Ingbert, Germany), to ensure compliance and proper training conduction.

Intervention

In the cooling condition, each training session was immediately followed by 10 minutes of CWI. Participants sat in a tub and were immersed up to the neck with water cooled down to 14°C to 15°C using crushed ice and cool packs. This protocol was chosen as it was shown to be effective in both reducing body temperature[20] and improving recovery,[2] and was tested for tolerability in a prior, unpublished pilot study. In the control condition, participants passively sat on a couch for 10 minutes.

Statistical Analysis

Outcome measures were strength and jump performance, as well as leg circumference and muscle thickness. Data are presented as mean (SD). Statistical analysis was performed using Microsoft Excel and Statistica (version 13; StatSoft, Tulsa, OK). Data were checked for normality (Shapiro–Wilk), and for sphericity (Mauchly W). All outcome measures were normally distributed, sphericity was not violated. Reliability of 1RM and CMJ tests was estimated by calculating the coefficient of variation (CV) between the second familiarization session and the first pretest.[21] Paired *t* tests were used to compare baseline values of outcome parameters for phase 1 and 2 (see Figure 1). A 2-factor repeated-measures analysis of variance (factor condition: cooling, control; factor time: pre, post, and follow-up) was performed on the outcome parameters. In case of significance, paired *t* tests were done post hoc to compare differences for the outcome parameters. SRSS and ratings on fatigue and sleep were evaluated using paired *t* tests. A value of $P \leq .05$ for the α-error was accepted as statistically significant. Effect sizes (Hedge g) were calculated to analyze differences in training adaptations (pre vs post and pre vs follow-up) between cooling and control. The magnitude of g was classified as follows: 0 to 0.19 = negligible effect, 0.20 to 0.49 = small effect, 0.50 to 0.79 = moderate effect, ≥0.80 = large effect.[22] Positive effect sizes correspond to effects in favor of the control condition, negative effect sizes are in favor of the cooling condition. The 95% confidence intervals (CIs) were calculated for the effect sizes.

Results

For 1RM and CMJ performance measurement, a typical error (CV) of 2.6 kg (1.5%) and 1.2 cm (2.9%) was calculated. Comparing the baseline values of phase 1 and 2, nonsignificantly higher values were found for the pretests of phase 2 (strength = +4.0 [12.3] kg [g = 0.12, P = .30], jump = +2.9 [4.1] cm [g = 0.35, P = .09]). Baseline values for leg circumference (53.2 [5.2] cm vs 51.7 [4.3] cm,

Table 2 Results of the Questionnaire on Fatigue and Sleep, Mean (SD)

Item	Cooling	Control	*P*
Did you feel tired today? (0: no, 3: very much)	0.5 (0.3)	0.8 (0.5)	.08
How restful was your sleep? (0: not at all, 4: very restful)	3.2 (0.8)	3.0 (0.6)	.18
How long did it take you to fall asleep? (min)	27 (28)	21 (16)	.50
Sleep duration (h)	9.6 (1.0)	9.0 (0.7)	.18

$P = .29$) and muscle thickness (19.4 [2.7] mm vs 19.1 [3.7] mm, $P = .74$) were not significantly different either.

Figures 2 and 3 show the development of strength and jump performance during the 2 training phases.

No significant effects were found for strength performance (condition: $F = 0.18$, $P = .86$; time: $F = 1.15$, $P = .34$; condition × time: $F = 2.66$, $P = .09$) or jump performance (condition: $F = 2.07$, $P = .19$; time: $F = 1.19$, $P = .33$; condition × time: $F = 1.52$, $P = .25$).

Small and negligible effect sizes were observed when comparing training adaptations between pretest and posttest. In the cooling condition the 1RM increased by 2.4 (7.1) kg, and in the control condition by 5.4 (7.1) kg ($g = 0.42$; 95% CI, −0.42 to 1.26). For CMJ, increases of 0.8 (2.1) and 0.9 (5.0) cm were found between pretest and posttest for the cooling and the control condition, respectively ($g = 0.02$; 95% CI, −0.82 to 0.86). Between the pretest and the follow-up test, cooling yielded a decrease of the 1RM by 1.7 (13.2) kg, while in the control condition the 1RM rose further to a total increase of 7.3 (12.3) kg ($g = 0.71$; 95% CI, −0.30 to 1.72). CMJ height increased by 0.3 (1.9) cm in the cooling condition and by 2.5 (4.5) cm in the control condition ($g = 0.64$, 95% CI, −0.36 to 1.64).

For leg circumference, a significant time effect ($F = 12.83$, $P < .01$), but no significant condition ($F = 1.78$, $P = .21$) or condition × time ($F = 1.37$, $P = .27$) effects were observed. No significant condition effect ($F = 0.62$, $P = .45$), but significant time ($F = 7.05$, $P = .02$) and condition × time ($F = 10.00$, $P = .01$) effects were observed for muscle thickness. Post hoc tests revealed a significant difference between pretest and posttest values for the control condition for both leg circumference ($P < .01$) and muscle thickness ($P = .02$). No other significant differences were found. Small and large effect sizes in favor of the control condition were calculated for training adaptations of leg circumference ($g = 0.27$, 95% CI, −0.65 to 1.20) and muscle thickness ($g = 1.20$, 95% CI, 0.19 to 2.20).

Tables 2 and 3 show the results for the sleep questionnaire and the SRSS. No significant differences were found for any of the investigated items ($P > .08$).

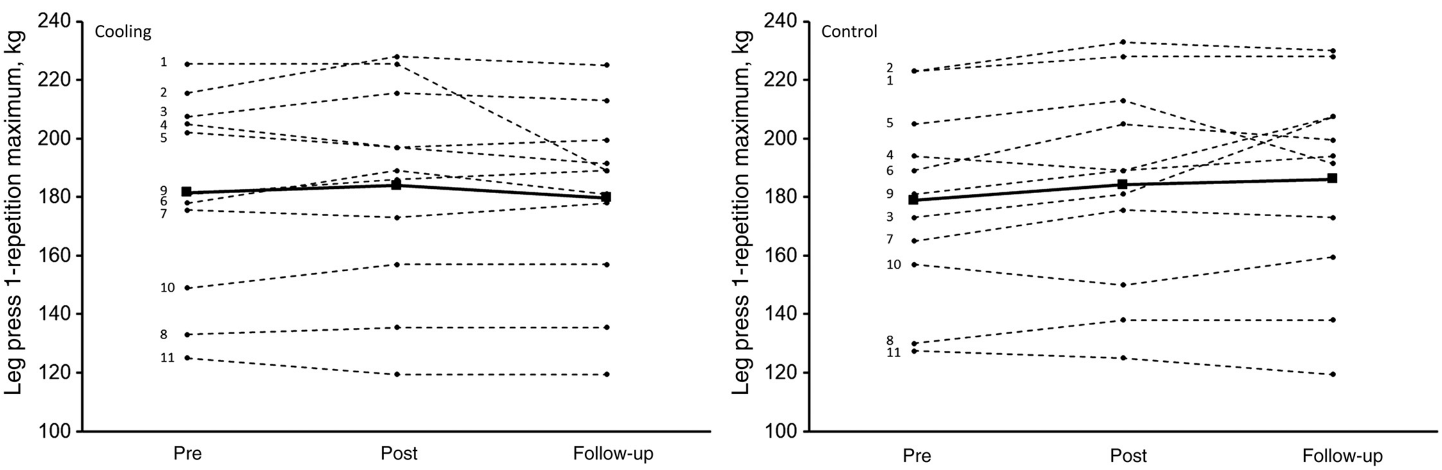

Figure 2 — Results of the strength performance tests (leg press 1-repetition maximum) for the cooling and the control condition before the training phase (pre), after the training phase (post), and 3 weeks after the training phase (follow-up). The thick line shows the mean value over all subjects; the dotted lines show the results for the individual subjects (numbers are given for assignment).

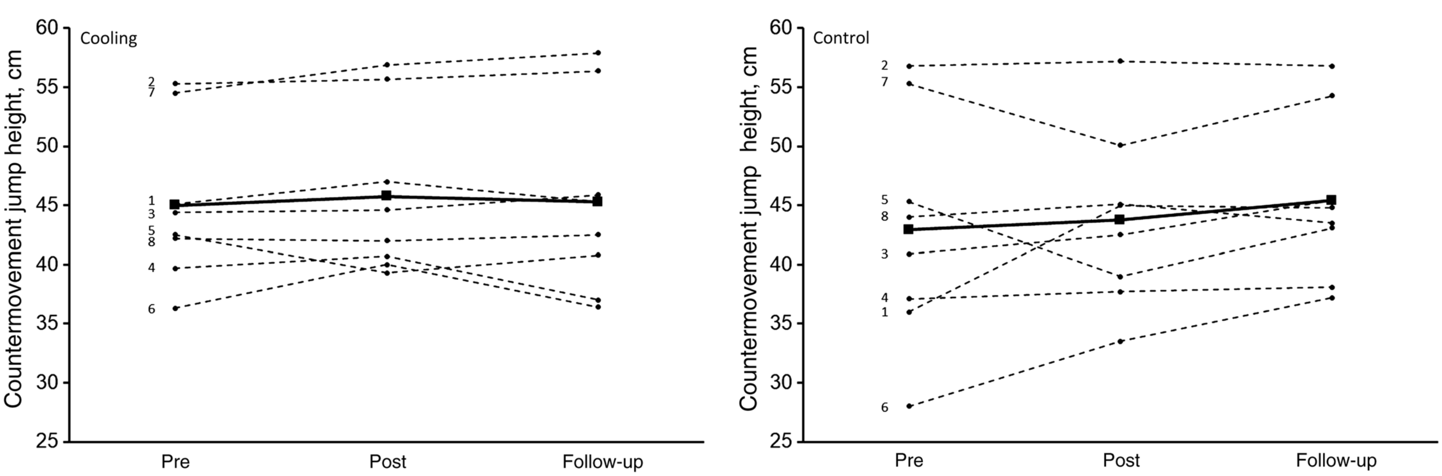

Figure 3 — Results of the jump performance tests (countermovement jump) for the cooling and the control condition before the training phase (pre), after the training phase (post), and 3 weeks after the training phase (follow-up). The thick line shows the mean value over all subjects; the dotted lines show the results for the individual subjects (numbers are given for assignment).

Table 3 Results of the Short Recovery and Stress Scale, Mean (SD)

Item	Cooling	Control	P
Physical performance capability (0: does not apply at all, 6: fully applies)	4.2 (1.2)	4.0 (1.0)	.46
Mental performance capability (0: does not apply at all, 6: fully applies)	4.3 (1.5)	4.2 (1.2)	.57
Emotional balance (0: does not apply at all, 6: fully applies)	4.2 (1.7)	4.3 (1.3)	.83
Overall recovery (0: does not apply at all, 6: fully applies)	4.1 (1.2)	4.2 (1.2)	.59
Muscular stress (0: does not apply at all, 6: fully applies)	1.7 (1.2)	1.0 (0.9)	.18
Lack of activation (0: does not apply at all, 6: fully applies)	1.6 (1.7)	1.6 (1.1)	.90
Negative emotional state (0: does not apply at all, 6: fully applies)	1.5 (1.8)	1.0 (1.0)	.32
Overall stress (0: does not apply at all, 6: fully applies)	1.6 (1.3)	1.2 (1.0)	.17

Discussion

This study focused on the chronic effects of cooling on training adaptation over a period of 2 months leg strength training. Between the pretest and posttest measures, a small and a negligible negative effect of cooling were found for training adaptations in strength and jump performance, respectively. Comparing pretest and follow-up test, moderate negative effects of cooling were found for both strength and jump performance. As CIs were overlapping with the 0 line, evidence for negative effects of cooling was not clear. This is in-line with the fact that the observed effects were not significant. However, a large negative effect of cooling for vastus medialis thickness was found. This could be a sign of reduced training adaptation due to cooling.

Between the second familiarization session and the first pretest, we observed a CV of 1.5% and 2.9% for 1RM and CMJ performance. As the primary aim of the familiarization sessions was to familiarize the participants with the tests, it is possible that the participants' lacking experience have influenced the results in these sessions. In previous studies, larger CV values of 3.3%[23] and 5.0%[24] were found for leg press 1RM and CMJ height, respectively. Between pretest and posttest, a 1RM increase (decrease) by more than 3.3% was observed in 4 (1) participants in the cooling condition and 7 (1) participants in the control condition. Between pretest and follow-up test, 3 (3) participants in the cooling condition and 6 (2) participants in the control condition increased (decreased) their 1RM by more than 3.3%. For CMJ, numbers were less clear. Between pretest and posttest, 1 (1) participant in the cooling condition and 2 (2) participants showed an increase (decrease) of CMJ height by more than 5.0%. Between pretest and follow-up test, 1 (1) participant in the cooling condition and 3 (0) participants had a corresponding increase (decrease). If such participant-specific effects turn out to be individually reproducible in subsequent investigations, this would support athletes in deciding if CWI is a suitable recovery protocol on an individual level. It is important to note that the present study was focused on strength training adaptations. To clarify if these results can be transferred to for example, endurance training, further research is necessary.

No significant differences between conditions were found in the *Short Stress Scale* and regarding sleep duration and quality. This is in-line with Robey et al,[25] who did not find any influence of CWI on sleep quality. As overall recovery did not differ significantly between groups, it can be suggested that cooling did not have any beneficial effects on recovery, at least on a subjective level.

The present results suggest that at least for some athletes, regular CWI may have detrimental effects on strength training adaptations. This confirms the results of Fröhlich et al,[8] who applied a training period of 5 weeks, and a within-subject design with a cooled leg and a control leg. They observed moderately larger strength increases in the control leg, compared with the cooled leg. We have shown that such effects can also be expected with longer training periods of 8 weeks. In contrast to Fröhlich et al,[8] our randomized crossover design allowed us to use a whole-body CWI protocol, instead of cooling only a single limb. This is of particular interest as, on a short-term basis, whole-body CWI appears to be more effective in speeding up recovery than part-body CWI.[2] From a scientific point of view, another disadvantage of using a within-subject design with 1 leg cooled is the possibility of (humorally mediated) systemic effects when cooling only 1 leg, affecting also the contralateral leg serving as control. For instance, Allan et al[11] have reported that cooling of 1 leg also enhanced PCG-1alpha expression in the nonimmersed leg. Independent of the fact that this result would indicate rather positive than negative effects of cooling on performance, it shows that systemic effects on nonimmersed limbs are possible.

Our results are also similar to those of Yamane et al[5,7] investigating the chronic effects of cooling after 4 and 6 weeks of forearm flexor strength training. Similar to Fröhlich et al,[8] they used a within-subject design, and training adaptation was reduced when the forearm was immersed in cold water after each training session.

Roberts et al[9] used a strength training protocol consisting of 24 training sessions. However, they did not compare cooling to a passive control condition, but to an active recovery condition consisting of 10-minute low-intensity cycling. Similar to our study, they found smaller training adaptations for the cooling group. To elucidate the responsible mechanisms, they took muscle biopsies and found that resistance exercise caused a sustained activity of signaling pathways involved in ribosome biogenesis, and that this activity was suppressed by cooling.[26] Ribosome biogenesis is considered to be a prerequisite for muscle hypertrophy.[27] Fuchs et al[28] had their participants undergo 2 weeks of leg press and knee extension training, and observed that CWI resulted in significantly lower postexercise myofibrillar protein synthesis rates. These studies would be in-line with our results showing reduced muscle hypertrophy (vastus medialis) in the cooling condition.

Training phases were separated by a 2-month washout phase. This duration was chosen based on a study showing that 40 days of detraining were sufficient to reverse the effects of a 60-day period of leg training.[14] It is possible that this phase was too short to eliminate the training effects of phase 1 and thus to ensure that the participants' baseline training state was equal for both training phases. Although not significant (strength: $P = .30$, jump: $P = .09$), the pretest differences for strength performance were in the same range as the observed differences between cooling and control; for jump performance, they were even higher. This suggests that to reach equal pretraining states for both phases, a longer washout phase would have been beneficial. For the present study, the influence of different baseline values before the 2 phases on the results was partly eliminated by using a randomized crossover design with almost the same number of participants starting with cooling ($n = 5$) as with control ($n = 6$). Moreover, the study did not focus on absolute training effects, but on the differences between the 2 interventions. However, a limitation of the study was a relatively small sample size ($n = 11$). Due to the extensive crossover design, completing the study took a long time (8 mo) and required a lot of effort for the participants. Therefore, we suffered from a very high dropout rate (91% of the initially recruited candidates) due to injuries, personal reasons, or insufficient compliance. However, the dropouts can be classified as "missing completely at random."[29] Thus, while the dropouts may have caused larger standard errors and a loss of power in significance tests, it is unlikely that there was any influence on the average outcome.

Practical Applications

While the observed potential negative effects of repeated cooling on strength training adaptation appear rather small, they are in a range that can be relevant to competitive athletes. For sports based on explosive strength, Malcata and Hopkins[30] have calculated a value of 0.3 of the CV as the smallest important change in performance. Taking the CV of 3.3% determined by Levinger et al,[23] this yields a value of 1.0%. In the present study, average 1RM increase was 1.3% in the cooling condition and 3.0% in the control condition. Looking at the individual cases, there were more participants who increased their 1RM by more than the CV in the control condition than in the cooling condition. Therefore, regular cooling after strength training should be regarded with caution by athletes and coaches, as it appears that at least in some subjects negative effects are possible.

Conclusions

The present study does not support the regular use of CWI after resistance training. Compared with control at least some participants showed smaller training adaptations after cooling. Therefore, while CWI may be a useful strategy to enhance recovery, for example, during important competitions, repeated application after training can have detrimental effects on training adaptation. Future research is warranted using crossover studies preferably with elite athletes, to gain further insight into the mechanisms and effects of regular cooling on training adaptation.

Acknowledgments

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