WRÓBLEWSKI, Wiktor, ZALEWSKI, Paweł, GRUCA, Dariusz, RAABE, Adam and WAIS, Marcin. How does cold water impact on human physiology? Recent research discoveries. Journal of Education, Health and Sport. 2024;57:95-109. eISSN 2391-8306.
https://dx.doi.org/10.12775/JEHS.2024.57.007
https://apcz.umk.pl/JEHS/article/view/48008
https://zenodo.org/records/10627715

The journal has had 40 points in Minister of Science and Higher Education of Poland parametric evaluation. Annex to the announcement of the Minister of Education and Science of 05.01.2024 No. 32318. Has a Journal's Unique Identifier: 201159. Scientific disciplines assigned: Physical culture sciences (Field of medical and health sciences); Health Sciences (Field of medical and health sciences).
Punkty Ministerialne 40 punktów. Załącznik do komunikatu Ministra Nauki i Szkolnictwa Wyższego z dnia 05.01.2024 Lp. 32318. Posiada Unikatowy Identyfikator Czasopisma: 201159. Przypisane dyscypliny naukowe: Nauki o kulturze fizycznej (Dziedzina nauk medycznych i nauk o zdrowiu); Nauki o zdrowiu (Dziedzina nauk medycznych i nauk o zdrowiu).© The Authors 2024;
This article is published with open access at Licensee Open Journal Systems of Nicolaus Copernicus University in Torun, Poland
Open Access. This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author (s) and source are credited. This is an open access article licensed under the terms of the Creative Commons Attribution Non commercial license Share alike.
(http://creativecommons.org/licenses/by-nc-sa/4.0/) which permits unrestricted, non commercial use, distribution and reproduction in any medium, provided the work is properly cited.
The authors declare that there is no conflict of interests regarding the publication of this paper.
Received: 12.01.2024. Revised: 06.02.2024. Accepted: 07.02.2024. Published: 07.02.2024.

How does cold water impact on human physiology? Recent research discoveries

Wiktor Wróblewski[1], Paweł Zalewski[2], Dariusz Gruca[1], Adam Raabe[1], Marcin Wais[1]

[1] 1 Military Clinical Hospital in Lublin, al. Racławickie 23, 20-049 Lublin, Poland,

[2] Stefan Wyszyński Regional Specialist Hospital in Lublin, al. Krasnicka 100, 20-718 Lublin, Poland

Wiktor Wróblewski; wiktorwroblewski10@gmail.com; ORCID: 0000-0003-4740-9455;

Paweł Zalewski; pawel-zalewski@wp.pl; ORCID: 0009-0007-2384-554X;

Dariusz Gruca; dariusz.gruca1@gmail.com; ORCID: 0000-0002-5583-1229;

Adam Raabe; adam.a.raabe@gmail.com; ORCID: 0000-0001-9574-4501;

Marcin Wais; marcin.wais0805@gmail.com; ORCID: 0000-0003-4757-8582;

Abstract

Introduction: New trends in social media relevant to cold water showers and immersion forced medical professionals to cover the subject in conversation with patients. We aimed to give professionals evidence-based conclusions from recent studies to favour their daily work.

We analysed the newest research conducted from 2019 to 2023. The study was searched in the online databases, especially in PubMed.

Results: The newest studies are not consistent with the impact of cold water after training sessions on muscle performance and regeneration. Further studies need to be conducted to evidence the positive impact of CWI. There are also no coherent results of the impact on biochemical immunological and hormonal parameters. The subject needs to be examined by the next research. Research showed that cold water has a good impact on heart recovery after strain. CWI can remove the positive effect of hypotension after exercise. The subsequent examination with a large number of participants needs to be conducted. Studies show no impact of CWI on PCG1-α in muscles with a depletion level of glycogen but there is a need for consideration that CWI can benefit when muscle glycogen is at a higher level. There is a need to confirm that thesis by further studies. It seems that CWI has a more efficient effect of vasoconstriction than PBC. There is a need to confirm that assumption through further studies with a larger amount of participants. There are suggestions that CWI can increase insulin sensitivity and better glucose tolerance after fasting sessions. There is a need for further research to confirm that data. There are suggestions that 18-degree water can cause an acute decrease in cognitive function. Researchers linked changes in cognitive function with heart rate changes. A number of 10 contestants require repeating that study with a larger number of participants.

Immersion in cold water which is defined in that study as 20-25℃ can benefit RLS among pregnant women. There is a need for further research to have clear evidence of the beneficial impact of CWI on RLS.

Conclusions: On the grounds of the newest studies, it is hard to come to a clear conclusion about the impact of cold water on the human body. There is a need for further studies with large and diverse groups of contestants. Results from studies analysed in that article can help design the next studies. At that moment there was no undisputed evidence of the beneficial impact of cold water on human physiology.

Keywords: cold water, recovery, restless leg syndrome, glucose metabolism, PGC-1a, cognitive function, cardiovascular regulation

Introduction

There is a keen demand for knowledge of cold water's impact on the human body. Many Internet fitness and health gurus advise cold water immersion or showering as a part of a healthy lifestyle. Many medical workers are asked to have conversations on that topic, because of that new trend. Ethical and professional demands answers based on scientific evidence from doctors and other health specialists. That is why we started work on that topic. We believe that our work can clear view of that subject and help many health specialists in their daily work.

Review method

We analysed the newest research conducted from 2019 to 2023. The study was searched in the online databases, especially in PubMed. We focused on muscle performance but we also broadened our commentary on other aspects, even the impact on restless leg syndrome was included.

Impact of cold water on muscle performance compared to other recovery strategies

The first research studied the impact of the strategy of recovery on muscle contractile properties[1]. The study included 28 healthy men. Three resting strategies were examined: hot water immersion, cold water immersion (CWI) and passively resting. The cold water temperature was 10°C while the hot water was 42°C. Every recovery strategy lasted 15 minutes. The results of rest were measured on the vastus medialis of the dominant leg by tensiomyography. The study shows the best results of muscle properties after the hot water immersion strategy. Cold water immersion group performance was at some points worse even than in the control group (changes in muscle displacement relativized in 15 min post recovery). The limitation of that study is that only the male population was examined.

Another investigation[2] examined 12 (7 men and 5 women) short-track speed skaters from the national team. The parameters of immersion were similar to the above (time of immersion, water temperature in hot and cold groups). In that study participants first exercised on ice by study protocol, then they rested depending on the group by hot or cold water immersion or performed active recovery on ergocycle. The results of recovery were measured 1 hour after recovery by the repeated sprint ability test conducted on the ergocycle. The results showed that active recovery and hot water immersion were correlated with better performance in repeated sprint ability tests compared to the cold water immersion recovery protocol.

The limitation of the two mentioned research is that performance is studied right after the rest- and it does not follow a long-term impact on muscle performance to the recovery strategy.

The next examination does not contain the previously mentioned limitation. That research follows 2 weeks of exercise sessions after which examined group recovery with cold water (11◦C, 11 minutes)[3]. The control group was sitting at room temperature. Bettering muscle performance was not observed in the CWI group versus the control group. Another examination conducted on hockey players during tournaments confirms that repeated cold water immersions (5-8 °C 5 minutes each through 5 days) have any beneficial impact on recovery[4].

Two similar studies confirmed the beneficial effect of CWI on rugby players. First suggests that CWI (10°C, 10 min) can have a good impact on neuromuscular fatigue (jump height, peak power output, and rate of force development from countermovement jump), but has no effects on sprint speed or perceptual recovery[5]. The second one shows that CWI (10°C, 10 min) has a good influence on countermovement jumps, wellness score and muscle soreness[6]. That study was conducted for over 3 weeks which ensures that the result does not ignore tardive changes in muscle performance

Research conducted among jiu-jitsu competitors (21 male) showed that cold water (10°C) immersion attenuated the decrease of muscle strength after 10 minutes of jiu-jitsu match[7]. That conclusion is similar to another study which suggests that CWI (8 or 15°C) slow down performance decrease compared to passive rest group[8]. What is worth pointing out is that only forearms were immersed[7][8]. That suggests that CWI can benefit from forearm muscle performance. There were also other protocols of immersion than in the study above: 3 times of 3 min of immersion with a 30-second break between or 3 sessions of 4 minutes of immerging forearms with 2 2-minute breaks after each immersion[8]. Another study with a short time of immersion (2,5 min and 5 min) in cold water (8°C) show benefits in the CWI group versus the control group[9]. We can speculate that a shorter time of immersion can have a beneficial effect. There is a need for further studies which conclude if CWI benefit on forearms or if the time of immersion played a role in the studies.

Any of the above research did not exclude the hydrostatic effect of immersion, so the consecutive study is worth taking into consideration. The impact of cold water on the body was conducted on 10-kilometre runners [10]. 30 trained recreational street runners were diverted into three groups due to rest strategy after a 10 km run. The first group was control and the intervention ended with 10 minutes of rest. Other groups after running immersed their body to the level of the anterior superior iliac spine in cold (10°C) or neutral (29.8°C) water for 10 min. Results show that cold water immersion is not beneficial compared to neutral water immersion and passive rest.

In another experiment[11] 12 volleyball players were examined during 5 days of training. Rest intervention was conducted 15 min after the last training of the day. What is revelatory besides the CWI group (14°C, 15 min) there was a control group where an "LED apparatus" (which did not emit light energy) was used to level the placebo effect among both conditions. Results show that CWI reduces thigh oedema compared to the control group. Performance in the contra movement jump test performance was also better in the CWI group but only on day 2. There was no significant difference in squat jump and agility test among groups.

All the above studies have their limitations. The number of participants (10-30) is one of them. There is also a limitation in group diversity. The majority of the studies examined exclusively male and only two research contain both male and female[2][8]. It is worth pointing out that except in one study, which explored moderately active males [3], sport-active contestants exclusively were observed. In five researches only elite sportsmen were included[2][4][5][6][11]. Only one study emphasizes diversity in primary sports done by contestants[9].

Differences in the impact of cold water immersion on male and female

The previously mentioned study takes into consideration differences in the impact on recovery in the male and female groups [8]. 15 males and 14 females undertake three different strategies of recovery (passive rest, 8°C CWI, 15°C CWI) between 3 sessions of intermittent handgrip contractions to failure. Cold water immersion was conducted in 3 sessions of 4 minutes of immerging forearms with 2 2-minute breaks after each immersion. Results suggest that CWI slow down performance decrease compared to the passive rest group[8]. That study also showed that male benefit of the 15-degree water immersion recovery strategy was more significant than the female. That suggests that sex differences may have an impact on the results of recovery strategies What is more 15-degree water is more tolerable by constantans and has a better impact on recovery than 8-degree water.

Cold water immersion impact on biochemical, immunological, and hormonal parameters

Creatine kinase (CK) is an enzyme which increases after intensive muscle training[12] and may suggest muscle damage. That is why the impact of cold water on that rate was observed. One study shows that the increase of CK was lower 24h post-recovery in the CWI group than in the control group[10]. That study also shows the same impact of neutral temperature water immersion on CK. That may suggest that hydrostatic impact and not cold water can play a role in those changes. Another study confirms any benefits of CWI on CK[11].

Lactates come into being during anaerobic glycolysis which is induced by high muscular labour. It is also considered that lactate level can cause muscle fatigue because of the impact of an acid environment on muscle contraction[13]. Recent research shows no consistent results on the impact of CWI on lactate levels. Some of them suggest no impact[14][15][16] when another shows benefits[7].

There was also an observed impact of CWI on immune response induced by excessive training. Changes in interleukin 6 (IL-6) and tumour necrosis factor α (TNF-α) were tested as a proinflammatory indicator. Studies show lowering levels of TNF-α[5][15] and IL-6[6][15] after CWI.

The impact of cold water on cortisol levels was also observed. Results are not consensual. Both the no effect of cold water shower (15 min 15°C)[17] and the beneficial impact of CWI[11] on decreasing levels of cortisol after training cortisol level were shown.

There were attempts to show an increase in the anabolic environment development. Testosterone and insulin-like growth factor 1 (IGF-1) were observed because of strong anabolic activity. After analysing recent studies conclusions are not clear. One study shows an increase in anabolic environment by increasing levels of IGF-1 and testosterone/cortisol ratio[11]. On the other hand second study suggests decreasing the anabolic effect of cold water by lowering the level of testosterone[15].

Cold water changes in the cardiovascular system and temperature regulation.

The newest research also tested the impact of cold water on the cardiovascular system. There is evidence that cold water can benefit heart recovery after strain[14][17] and CWI improves autonomic cardiac modulation[3] by affecting heart rate. In contrast to the beneficial impact on the heart, there are suggestions that cold water can suppress the hypotensive effect of exercises[14].

The effect of cold water on body temperature was examined. There were no[17][16] or some[9] impacts of decreasing core temperature. There are some suggestions that cold water after training can provide subjective thermal comfort[17]

CWI impact on PGC-1α overexpression

The subject of another study was whether CWI after endurance training can increase the expression of the peroxisome proliferator-activated receptor coactivator (PGC-1α). PGC-1α is a transcriptional coactivator whose overexpression boosts oxidative enzyme activity [18], improves insulin sensitivity [19], protects against sarcopenia[20] and also improves exercise capacity[21]. That metabolic environment is propitious to muscle development.

Researchers presume that stressors like low levels of glycogen and CWI can induce increasing levels of PGC-1α mRNA in muscles[16]. They included 9 healthy males to cross over the study. They induced low (<300 mmol/kg dw) glycogen concentration in one leg of each participant and very low (<150 mmol/kg dw) in another. Then constantans undertake one of two recovery strategy:10 min of CWI (8°C) or seated rest. Results showed that PGC-1α mRNA increased after exercises in both groups. Low glycogen levels carried a higher level of PGC-1α mRNA versus very low. There was no difference between CWI and control groups. Researchers compared the results to earlier study[22] and concluded that CWI can benefit in the activation of PGC-1α when muscle glycogen level is not near maximal depletion.

Impact of CWI on pain relief

Researchers depended on previous studies which indicated that cold application on the skin indicates vasoconstriction which reduces the analgetic effect[23][24]. They compared vasoconstriction after two procedures: partial-body cryotherapy (−60°C for 30 seconds, −135°C for 2 minutes) and CWI (10 min 10°C). CWI had a more expressed impact on vasoconstriction than partial-body cryotherapy(PBC)[25]. That may suggest that it also can be more beneficial in analgesia but it confirms that further studies need to be conducted.

Impact of cold water on glucose metabolism

Another team examined the impact of cold water on glucose metabolism[26]. Researchers based on previous discoveries that 2 days or more fasting can worsen glucose tolerance and decrease insulin sensitivity[27][28][29][30][31]. Researchers postulate that brown adipose tissue responds metabolically to temperature changes. They rely on the fact that the group with the largest amount and metabolic activity of brown adipose tissue are young women[32][33]. Therefore, the examination group was 12 young healthy women. That decision may give visible results of cold water impact but is also a limitation of this study. The goal of the study was to catch the impact of 10 minutes of body immersion in the cold (14-degree) water on glucose intolerance and insulin insensitivity induced by 2 days of fasting. That study proves that cold water immersion can increase glucose tolerance and maintain insulin sensitivity during fasting[26]. Results are promising and pioneering. Specific participants and small examination group involves need for further research exanimating the impact of cold water on metabolism.

Cool water impact on cognitive function linked with cardiorespiratory response

Other researchers examined the impact of cold water on cognitive function and the cardiorespiratory system. The cross-over study included 10 healthy males [34]. They examined cognitive function, heart rate, minute ventilation, and oxygen consumption[34]. The studied group was examined during immersion in an 18-degree portable pool in a seating position which excluded the impact of strain of buoying on organism response. It is worth pointing out that the temperature of the water was higher than in another study on cold water immersion previously mentioned. The control group was examined in a dry environment (25◦C)[34]. The limitation of that research what is marked by researchers is that the study does not count hydrostatic impact on organisms because of the environment of the control group. Another limitation is the small number and diversity of included participants. Results show that 18-degree water immersion decreases cognitive function in 2 minutes after immersion. Heart rate was higher in the examination group and averaged out with the control group in circa 1 minute although the results in the examination group were more variable. Minute ventilation and oxygen consumption elevated after immersion and stayed elevated to the end of measurement compared to the control group. Statistical analyses show a strong correlation between elevation of heart rate and decrease in cognitive function. There was no as strong correlation between ventilation parameters and cognitive functions. Despite multiple limitations, the study suggests that cold water immersion produces changes in the cardiorespiratory system and cognitive functioning during the first minutes after immersion. They suggest that loss of cognitive function should be connotated with heart rate changes and not with respiratory changes. The results should be confirmed by further study with larger and more variably participants group

Cold water can benefit pregnant women with restless leg syndrome

Researchers included 77 pregnant women with restless leg syndrome (RLS) to observe the effect of cold and hot water immersion on symptoms[35]. Participants were asked to immerse their legs from the toe to 10 centimetres above the knee for 10 minutes in hot (40−45◦C) or cold (20−25°C) water due to randomisation. Studies show that there was a decrease in symptoms of restless leg syndrome in both hot and cold water groups but the bettering was more expressed in the cold water group[35]. RLS can be oppressive and pharmacotherapy in pregnancy is limited. This study shows that there is a method which is not as risky as pharmacotherapy in pregnancy and can help in decreasing symptoms. Bettering in both groups can suggest that not only temperature has an impact on decreasing symptoms but also the hydrostatic effect of water can be beneficial. To confirm that thesis there is a need for further research.

Discussion

Interest in cold water's impact on organism function has echoed in recent studies.

Unfortunately, the newest studies are not consistent with the impact of cold water after training sessions on muscle performance and regeneration. Some of them suggest better performance while another even worse results than passive rest. There are some presumptions that cold water can improve the recovery of forearm muscles[7][8]. We can speculate if the time of immersion like 2,5-5 minutes or immersion in sessions with a break between can be beneficial[7][8][9]. Some research suggests no improvement after excluding hydrostatic and placebo effects[10][11]. There is a need to take into consideration if they could play a role in results which show CWI's superiority over other recovery strategies. All the above results can be only considered as a basis for planning the next studies and not as evidence findings because of plentiful limitations like the small number of participants and small group diversity. There are also some distinctions between male and female muscle recovery after CWI[8]. Those differences should indicate sex diversity in the planning examined group.

There are also no coherent results of the impact on biochemical immunological and hormonal parameters. There are some suggestions that CWI plays no role in decreasing CK[10][11]. There is also some evidence that CWI can reduce levels of TNF-a and IL-6[5][6][15]. But to have an evident conclusion, further studies need to be conducted whilst these results can be only considered as a basis for planning the next research.

Research showed that cold water has a good impact on heart recovery after strain[3][14][17]. In contrast, CWI can remove the positive effect of hypotension after exercise[14]. We can presume that it can be beneficial for people with cardiac problems but there is a need to control blood pressure. To confirm that thesis next studies are needed.

Studies show no impact of CWI on PCG1-α in muscles with a depletion level of glycogen[16]. When those results were compared to earlier studies[22] it needs to be taken into consideration that CWI can benefit when muscle glycogen is at a higher level. There is a need to confirm that thesis by further studies.

It seems that CWI has a more efficient effect of vasoconstriction than PBC[25]. There is a need to confirm that assumption through further studies with a larger amount of participants. Researchers presume based on earlier studies[23][24] that it could also benefit pain relief but that thesis was not confirmed in that study. To examine the role of CWI in pain relief there is a need for more research.

There are suggestions that CWI can increase insulin sensitivity and better glucose tolerance after fasting sessions [26]. Specific participants and small examination groups are limitations of that study. There is a need for further research to confirm that data.

There are suggestions that even 18-degree water can cause an acute decrease in cognitive function[34]. That is crucial because it escalates the risk of drowning. Researchers linked changes in cognitive function with heart rate[34] and not with respiratory changes as was presumed. That study was conducted on active males which may suggest that changes in overall populations can be higher. A number of 10 contestants require repeating that study with a larger number of participants.

The biggest of the analysed studies contains 77 participants which may suggest more certain results. It showed that immersion in cold water which is defined in that study as 20-25℃ can benefit RLS among pregnant women[35]. There are also suggestions that water immersion per se can reduce symptoms. It is crucial because some drugs should be avoided during pregnancy because of their impact on the fetus. Water immersion seems to be safe for pregnancy. The low cost of therapy can also lead to the prevalence of that method. After all, there is a need for further research to have clear evidence of the beneficial impact of CWI on RLS.

Conclusions

On the grounds of the newest studies, it is hard to come to a clear conclusion about the impact of cold water on the human body. There is a need for further studies with large and diverse groups of contestants. Results from studies analysed in that article can help design the next studies. At that moment there was no undisputed evidence of the beneficial impact of cold water on human physiology.

Author Contributions

Conceptualization: W.W., M.W.; Methodology: W.W.; Investigation: P.Z., W.W., D.G., M.W., A.R.; Resources: W.W., D.G., M.W., A.R., P.Z.; Writing - rough preparation: W.W., P.Z., M.W., A.R., D.G.; Writing - review and editing: A.R., D.G.; Supervision: W.W.; Project administration; W.W., D.G.

All authors have read and agreed with the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Statement of Informed Consent

Not applicable.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Bibliography:

[1] E. Mur-Gimeno, R. Sebio-Garcia, J. Solé, A. Lleida, and G. Moras, "Short-term effects of two different recovery strategies on muscle contractile properties in healthy active men: A randomised cross-over study," *J. Sports Sci.*, vol. 40, no. 6, pp. 646–654, 2022, doi: 10.1080/02640414.2021.2010978.

[2] R. Solsona *et al.*, "Active recovery vs hot- or cold-water immersion for repeated sprint ability after a strenuous exercise training session in elite skaters," *J. Sports Sci.*, vol. 41,

no. 11, pp. 1126–1135, 2023, doi: 10.1080/02640414.2023.2259267.

[3] E. S. Malta, V. H. F. Lopes, M. R. Esco, and A. M. Zagatto, "Repeated cold-water immersion improves autonomic cardiac modulation following five sessions of high-intensity interval exercise," *Eur. J. Appl. Physiol.*, vol. 123, no. 9, pp. 1939–1948, Sep. 2023, doi: 10.1007/s00421-023-05205-4.

[4] M. Krueger, J. T. Costello, M. Stenzel, J. Mester, and P. Wahl, "The physiological effects of daily cold-water immersion on 5-day tournament performance in international standard youth field-hockey players," *Eur. J. Appl. Physiol.*, vol. 120, no. 1, pp. 295–305, Jan. 2020, doi: 10.1007/s00421-019-04274-8.

[5] R. F. H. Nunes *et al.*, "Recovery following rugby union matches: Effects of cold water immersion on markers of fatigue and damage," *Appl. Physiol. Nutr. Metab.*, vol. 44, no. 5, pp. 546–556, 2019, doi: 10.1139/apnm-2018-0542.

[6] F. Tavares *et al.*, "Effects of chronic cold-water immersion in elite rugby players," *Int. J. Sports Physiol. Perform.*, vol. 14, no. 2, pp. 156–162, Feb. 2019, doi: 10.1123/ijspp.2018-0313.

[7] E. P. César, C. S. R. Júnior, and R. N. Francisco, "Effects of 2 intersection strategies for physical recovery in jiu-jitsu athletes," *Int. J. Sports Physiol. Perform.*, vol. 16, no. 4, pp. 585–590, Apr. 2021, doi: 10.1123/IJSPP.2019-0701.

[8] J. Baláš, J. Kodejška, D. Krupková, and D. Giles, "Males benefit more from cold water immersion during repeated handgrip contractions than females despite similar oxygen kinetics," *J. Physiol. Sci.*, vol. 70, no. 1, Mar. 2020, doi: 10.1186/s12576-020-00742-5.

[9] M. Egaña, L. Jordan, and T. Moriarty, "A 2.5 min cold water immersion improves prolonged intermittent sprint performance," *J. Sci. Med. Sport*, vol. 22, no. 12, pp. 1349–1354, Dec. 2019, doi: 10.1016/j.jsams.2019.07.002.

[10] G. Dantas *et al.*, "Cold-Water Immersion Does Not Accelerate Performance Recovery After 10-km Street Run: Randomized Controlled Clinical Trial," *Res. Q. Exerc. Sport*, vol. 91, no. 2, pp. 228–238, Apr. 2020, doi: 10.1080/02701367.2019.1659477.

[11] V. H. De Freitas *et al.*, "Effect of cold water immersion performed on successive days on physical performance, muscle damage, and inflammatory, hormonal, and oxidative stress markers in volleyball players," *J. Strength Cond. Res.*, vol. 33, no. 2, pp. 502–

513, Feb. 2019, doi: 10.1519/JSC.0000000000001884.

[12] V. H. Freitas, F. Y. Nakamura, B. Miloski, D. Samulski, and M. G. Bara-Filho, "Sensitivity of Physiological and Psychological Markers to Training Load Intensification in Volleyball Players," *J. Sports Sci. Med.*, vol. 13, no. 3, p. 571, 2014, Accessed: Jan. 08, 2024. [Online]. Available: /pmc/articles/PMC4126294/.

[13] D. Roberts and D. J. Smith, "Biochemical aspects of peripheral muscle fatigue. A review," *Sports Med.*, vol. 7, no. 2, pp. 125–138, 1989, doi: 10.2165/00007256-198907020-00004.

[14] Y. Yang, S. C. Chen, W. T. Yang, J. T. Kuo, and K. Y. Chien, "Cold water immersion recovery strategy increases blood pressure levels after high-intensity intermittent exercise," *J. Sports Med. Phys. Fitness*, vol. 59, no. 11, pp. 1925–1933, 2019, doi: 10.23736/S0022-4707.19.09771-8.

[15] J. E. Earp, D. L. Hatfield, A. Sherman, E. C. Lee, and W. J. Kraemer, "Cold-water immersion blunts and delays increases in circulating testosterone and cytokines post-resistance exercise," *Eur. J. Appl. Physiol.*, vol. 119, no. 8, pp. 1901–1907, Aug. 2019, doi: 10.1007/s00421-019-04178-7.

[16] R. Allan *et al.*, "Low pre-exercise muscle glycogen availability offsets the effect of post-exercise cold water immersion in augmenting PGC-1α gene expression," *Physiol. Rep.*, vol. 7, no. 11, Jun. 2019, doi: 10.14814/phy2.14082.

[17] A. Ajjimaporn, R. Chaunchaiyakul, S. Pitsamai, and W. Widjaja, "EFFECT OF COLD SHOWER ON RECOVERY FROM HIGHINTENSITY CYCLING IN THE HEAT," *J. Strength Cond. Res.*, vol. 33, no. 8, pp. 2233–2240, Aug. 2019, doi: 10.1519/JSC.0000000000003017.

[18] J. Lin *et al.*, "Transcriptional co-activator PGC-1α drives the formation of slow-twitch muscle fibres," *Nat. 2002 4186899*, vol. 418, no. 6899, pp. 797–801, Aug. 2002, doi: 10.1038/nature00904.

[19] C. R. Benton, D. C. Wright, and A. Bonen, "PGC-1alpha-mediated regulation of gene expression and metabolism: implications for nutrition and exercise prescriptions," *Appl. Physiol. Nutr. Metab.*, vol. 33, no. 5, pp. 843–862, Oct. 2008, doi: 10.1139/H08-074.

[20] T. Wenz, S. G. Rossi, R. L. Rotundo, B. M. Spiegelman, and C. T. Moraes, "Increased

muscle PGC-1alpha expression protects from sarcopenia and metabolic disease during aging," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 106, no. 48, pp. 20405–20410, Dec. 2009, doi: 10.1073/PNAS.0911570106.

[21] J. A. Calvo *et al.*, "Muscle-specific expression of PPARgamma coactivator-1alpha improves exercise performance and increases peak oxygen uptake," *J. Appl. Physiol.*, vol. 104, no. 5, pp. 1304–1312, May 2008, doi: 10.1152/JAPPLPHYSIOL.01231.2007.

[22] R. Allan *et al.*, "Postexercise cold water immersion modulates skeletal muscle PGC-1α mRNA expression in immersed and nonimmersed limbs: evidence of systemic regulation," *J. Appl. Physiol.*, vol. 123, no. 2, pp. 451–459, Aug. 2017, doi: 10.1152/JAPPLPHYSIOL.00096.2017.

[23] G. E. White and G. D. Wells, "Cold-water immersion and other forms of cryotherapy: physiological changes potentially affecting recovery from high-intensity exercise," *Extrem. Physiol. Med.*, vol. 2, no. 1, p. 26, Sep. 2013, doi: 10.1186/2046-7648-2-26.

[24] S. Khoshnevis, N. K. Craik, and K. R. Diller, "Cold-induced vasoconstriction may persist long after cooling ends: an evaluation of multiple cryotherapy units," *Knee Surg. Sports Traumatol. Arthrosc.*, vol. 23, no. 9, pp. 2475–2483, Sep. 2015, doi: 10.1007/S00167-014-2911-Y.

[25] E. Hohenauer, T. Deliens, P. Clarys, and R. Clijsen, "Perfusion of the skin's microcirculation after cold-water immersion (10°C) and partial-body cryotherapy (−135°C)," *Ski. Res. Technol.*, vol. 25, no. 5, pp. 677–682, Sep. 2019, doi: 10.1111/srt.12703.

[26] R. Solianik, K. Židonienė, and M. Brazaitis, "Short-duration cold exposure decreases fasting-induced glucose intolerance but has no effect on resting energy expenditure," *Cryobiology*, vol. 113, Dec. 2023, doi: 10.1016/j.cryobiol.2023.104564.

[27] I. W. Gallen, I. A. Macdonald, and P. I. Mansell, "The effect of a 48 h fast on the physiological responses to food ingestion in normal-weight women," *Br. J. Nutr.*, vol. 63, no. 1, pp. 53–64, Jan. 1990, doi: 10.1079/BJN19900091.

[28] P. Frank, A. Katz, E. Andersson, and K. Sahlin, "Acute exercise reverses starvation-mediated insulin resistance in humans," *Am. J. Physiol. - Endocrinol. Metab.*, vol. 304, no. 4, pp. 436–443, Feb. 2013, doi: 10.1152/AJPENDO.00416.2012/ASSET/IMAGES/LARGE/ZH10041367650005.JPE

G.

[29] J. W. Anderson and R. H. Herman, "Effect of fasting, caloric restriction, and refeeding on glucose tolerance of normal men," *Am. J. Clin. Nutr.*, vol. 25, no. 1, pp. 41–52, Jan. 1972, doi: 10.1093/AJCN/25.1.41.

[30] R. Solianik, K. Židonienė, N. Eimantas, and M. Brazaitis, "Prolonged fasting outperforms short-term fasting in terms of glucose tolerance and insulin release: a randomised controlled trial," *Br. J. Nutr.*, vol. 130, no. 9, pp. 1500–1509, Nov. 2023, doi: 10.1017/S0007114523000557.

[31] L. Norton, T. Parr, R. G. Bardsley, H. Ye, and K. Tsintzas, "Characterization of GLUT4 and calpain expression in healthy human skeletal muscle during fasting and refeeding," *Acta Physiol.*, vol. 189, no. 3, pp. 233–240, Mar. 2007, doi: 10.1111/J.1748-1716.2006.01639.X.

[32] J. M. Hoffman and T. G. Valencak, "Sex differences and aging: Is there a role of brown adipose tissue?," *Mol. Cell. Endocrinol.*, vol. 531, p. 111310, Jul. 2021, doi: 10.1016/J.MCE.2021.111310.

[33] C. Pfannenberg *et al.*, "Impact of Age on the Relationships of Brown Adipose Tissue With Sex and Adiposity in Humans," *Diabetes*, vol. 59, no. 7, pp. 1789–1793, Jul. 2010, doi: 10.2337/DB10-0004.

[34] A. B. Stella and S. A. Morrison, "Marine Survival in the Mediterranean: A Pilot Study on the Cognitive and Cardiorespiratory Response to Sudden Cool Water Immersion," *Int. J. Environ. Res. Public Health*, vol. 19, no. 3, Feb. 2022, doi: 10.3390/ijerph19031601.

[35] H. Jafarimanesh, K. Vakilian, and S. Mobasseri, "Thermo-therapy and cryotherapy to decrease the symptoms of restless leg syndrome during the pregnancy: A randomized clinical trial," *Complement. Ther. Med.*, vol. 50, May 2020, doi: 10.1016/j.ctim.2020.102409.