Journal of Thermal Biology 136 (2026) 104401

Contents lists available at ScienceDirect

Journal of Thermal Biology

journal homepage: www.elsevier.com/locate/jtherbio

The influence of cold temperature exposure on markers of bone health in humans: A scoping review

R. Allan [a,*], H.T. Hurst [a], B. Akin [a], N. Liles [a], J. Dickson [a], J. Knill-Jones [a], J. Sinclair [a], S. Dillon [a], S.J. Hesketh [b], C. Mawhinney [c]

[a] School of Health, Social Work and Sport, UK
[b] School of Medicine and Dentistry, University of Lancashire, Preston, UK
[c] College of Sport Science and Technology, Mahidol University, Nakhon Pathom, Thailand

ARTICLE INFO

Keywords:
Bone
Cold
Cooling
Cryotherapy
CWI
Cold application
Temperature
Osteoporosis
Bone mineral density
Bone health

ABSTRACT

Background: Studies of cold-dwelling humans show lower bone mineral density (BMD) and greater age-related bone loss. While cold exposure is regularly used for analgesic purposes, prolonged use may unintentionally exacerbate symptoms it aims to treat.
Objective: To evaluate human evidence on the effects of cold exposure upon markers of bone health.
Methods: This scoping review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. OVID (MEDLINE, EMBASE), Elsevier (ScienceDirect, Scopus), and PubMED databases were searched using the terms ("Cold temperature" OR "cryotherapy" OR "Hydrotherapy" OR "Cold stress") AND ("Bone Matrix" OR "Bone mineral density" OR "bone formation" OR "bone remodelling" OR Osteogenesis). Inclusion criteria were: (1) cold exposure or application in humans; (2) measurement of bone health or turnover markers; and (3) original research or case reports.
Results: Searches resulted in 2372 articles, yielding a final pool of 13 articles for inclusion after screening. Several cooling methods were used, predominantly cold air (n = 6), cooling vests (n = 4), sleeping in cold rooms (n = 1), β3 agonist coupled with cooling pads (n = 1) and ice water swimming (n = 3). Markers of bone health were assessed, with BMD shown to increase following cryotherapy, and having a positive correlation with brown adipose tissue. Papers returned suggest a neutral or positive response in factors that enhance osteoblast differentiation (irisin, insulin-like growth factor-1 [IGF-1], meteorin-like protein [METRNL]), which fails to translate directly into improved bone formation (procollagen 1 N-terminal propeptide [P1NP], osteocalcin).
Conclusion: Cold exposure might dampen bone resorption mechanisms (beta isomerised C terminal telopeptide of type 1 collagen [β-CTX]) but not others (receptor activator of nuclear factor κ B [RANK], RANK ligand [RANKL], interleukin-6 [IL-6]). Hormonal markers of bone remodelling (thyroid stimulating hormone [TSH], parathyroid hormone [PTH], triiodothyronine [T3]) also showed contrasting effects. As such, the limited data does not allow for clear conclusions.

1. Introduction

Chronic metabolic bone diseases, such as osteoporosis, are characterized by low bone mass, deterioration of bone tissue, and disruption of bone microarchitecture. These changes can compromise bone strength and increase risk of fractures (Sözen et al., 2017), and are associated with increased morbidity and mortality, reduced quality of life, and an increased disability-adjusted life span. In addition to clinical consequences, bone disease and frailty impose a substantial economic burden on global healthcare systems (Reginster and Burlet, 2006). Within the European Union alone, the economic cost of osteoporosis has been estimated at €37 billion (Hernlund et al., 2013).

Given the chronic pain and functional limitations often associated with these conditions, non-pharmacological strategies for symptom management are frequently employed. Among these, cold exposure has long been used for its analgesic properties, including its ability to reduce neural conductance velocity in sensory neurons ahead of motor neurons (Herrera et al., 2010, 2011). Cold water immersion, in particular,

* Corresponding author.
E-mail address: rallan1@lancashire.ac.uk (R. Allan).

https://doi.org/10.1016/j.jtherbio.2026.104401
Received 28 October 2025; Received in revised form 12 January 2026; Accepted 21 January 2026
Available online 22 January 2026

appears more effective than ice-pack application or ice massage in reducing sensory pain (Herrera et al., 2011). Public health resources such as the National Health Service and Royal Osteoporosis Society also suggest cold may assist in relieving pain associated with osteoporosis.

Despite recommendations promoting cold exposure for pain relief, emerging evidence suggests it may have adverse effects on bone health. Studies of cold-dwelling humans have reported reduced cortical thickness and bone mineral density (BMD), along with accelerated age-related bone loss (Robbins et al., 2018), implicating chronic cold exposure as a potential contributor to poor bone outcomes. Complementary findings from animal models support this notion, with rodents raised in cold environments exhibiting significantly and permanently shorter length limbs compared to those raised in warmer conditions (Serrat, 2013). Cold temperatures have also been linked to reductions in Serum 25 (OH) D (Śliwicka et al., 2020). Declines in vitamin D status can impair intestinal absorption of calcium, leading to increased calcium mobilisation from bone and subsequent decrease in BMD (Xue and Fleet, 2009). This suggests that cold exposure could further exacerbate symptoms of bone diseases such as osteoporosis through this altered calcium-vitamin D homeostasis. Additionally, data from animal models has demonstrated that chronic activation of the sympathetic nervous system (SNS) promotes bone loss via β2-adrenergic receptors on osteoblasts, whilst mice lacking β2-adrenergic receptors are protected from these effects (Bonnet et al., 2008; Kajimura et al., 2011). Accordingly, it has been proposed that cold exposure may induce bone loss in humans through SNS-mediated pathways (Robbins et al., 2018).

We have previously shown in humans that post-exercise cold-water immersion increases systemic SNS activity, as indicated by elevated normetanephrine levels and a slower return to baseline compared to a non-immersed control condition (Allan et al., 2017, 2019). However, the impact of this heightened SNS response on indices of bone health and density has not yet been established. Although cold exposure is regularly employed for its analgesic properties in managing chronic pain associated with bone-related conditions, it is not yet known if chronic use of this technique may inadvertently exacerbate the very symptoms it aims to alleviate. Given the global prevalence of bone diseases such as osteoporosis, and their associated clinical and socioeconomic burdens, evaluating the efficacy of cold exposure on indices of bone health is both clinically, and practically important.

Therefore, the aim of this scoping review is to evaluate the existing human evidence on the influence of cold exposure on markers of bone health, with the goal of identifying gaps in the literature and informing future research priorities.

2. Methods

A systematic search was conducted according to Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping for Reviews (PRISMA-ScR) guidelines in accordance with Tricco et al. (2018) and was registered with the Open Science Framework on September 9, 2024 (https://doi.org/10.17605/OSF.IO/EGCB2). A comprehensive search of online databases (OVID (MEDLINE, EMBASE), Elsevier (Science direct, Scopus), PubMed (central & PUBMED) took place in September 2024 for relevant articles. The keyword search string included ("Cold temperature" OR "cryotherapy" OR "Hydrotherapy" OR "Cold stress") AND ("Bone Matrix" OR "Bone mineral density" OR "bone formation" OR "bone remodelling" OR Osteogenesis). Inclusion criteria included 1) mention of cold temperatures and/or application within a human population, 2) measurement of markers associated with bone health and/or bone turnover; with primary outcomes being, but not limited to, bone mineral density, bone architecture, markers of bone health/turnover [osteoprotogerin (OPG), receptor activator of nuclear factor κ B ligand (RANKL), receptor activator of nuclear factor κ B (RANK), total procollagen 1 N-terminal propeptide (P1NP), beta cross-laps (β CTX), Osteocalcin], and 3) original articles and case reports that included mention of points 1 & 2. Exclusion criteria included non-English language articles, reviews and animal populations.

Studies identified through the database search were exported to Rayyan software, an online tool to screen articles in systematic reviews (Ouzzani et al., 2016). Duplicate articles were removed before two authors (RA, CM) independently screened article titles and abstracts in a blinded fashion. Studies were categorized using a simple traffic light system of green (meets inclusion criteria), amber (possibly meets inclusion criteria) and red (does not meet inclusion criteria). Upon completion blinding was removed, and any disagreement on study inclusion resolved through discussion and consensus between the two authors. The search and screening process is illustrated in the PRISMA flow diagram (Fig. 1).

The authors independently extracted data for pre-specified outcomes from the studies included in the scoping review. Study characteristics were entered into a standardized data charting collection form and cross-checked through discussion. Any inconsistencies were addressed through consensus between two authors (RA and CM). The extracted information included the authors names, year of publication, country of origin, study objectives, participant number, methodological approach, type of intervention (cooling stimulus) and comparator, and intervention duration (Table 1). No attempts were made to contact study authors for additional information.

After completion of data charting, a narrative synthesis was performed with data summarised by numerical representation, such as count and percentages. Key information from each study was extracted and categorized based on common themes and characteristics, such as cooling strategy used, and markers assessed. These categories were then used to identify patterns, consistencies and variations across the final pool of literature. The geographical location of the included studies is illustrated in Fig. 2. It should be noted the authors acknowledge the plethora of data previously published focussing on a causal relationship for people living in cold, high latitude regions appearing to have relatively shorter arms and legs (a summary of which is outlined in Betti et al., 2015). Whilst this information is important to the background of the current research question, these articles fall outside the scope and inclusion criteria of the search conducted herein.

3. Results

A total of 2372 search articles were assessed for suitability. Following title and abstract screening duplicates were removed (n = 314) and 2058 articles were eligible for screening, of which 30 were selected for full text-text review based on their potential relevance. The full text of these 30 articles was assessed for suitability according to the inclusion criteria and in line with the research question. Nineteen articles were excluded by not meeting the inclusion criteria, resulting in 11 articles being included in the initial pool. The reference lists of these 11 articles were then manually screened for additional eligible articles, resulting in the identification of 2 more studies. This yielded a final pool of 13 articles for inclusion in the review.

3.1. Characteristics of included studies

Characteristics of the included studies are displayed in Table 1. The studies included in this scoping review were published between 2012 and 2023 and assessed the impact of cooling on markers of bone health and remodelling. All but one study employed non-randomized observational or longitudinal pre-post designs, with a single randomised controlled trial included. As per Table 1, data were collected at different data points depending on the nature and design of the study, for example, acute or chronic responses. Studies were completed across 8 different countries, with the majority being conducted in USA ($n = 4$) and Poland ($n = 3$). Meanwhile studies were also conducted in China ($n = 2$), Egypt, Italy, Slovakia, Austria and Spain ($n = 1$ each).

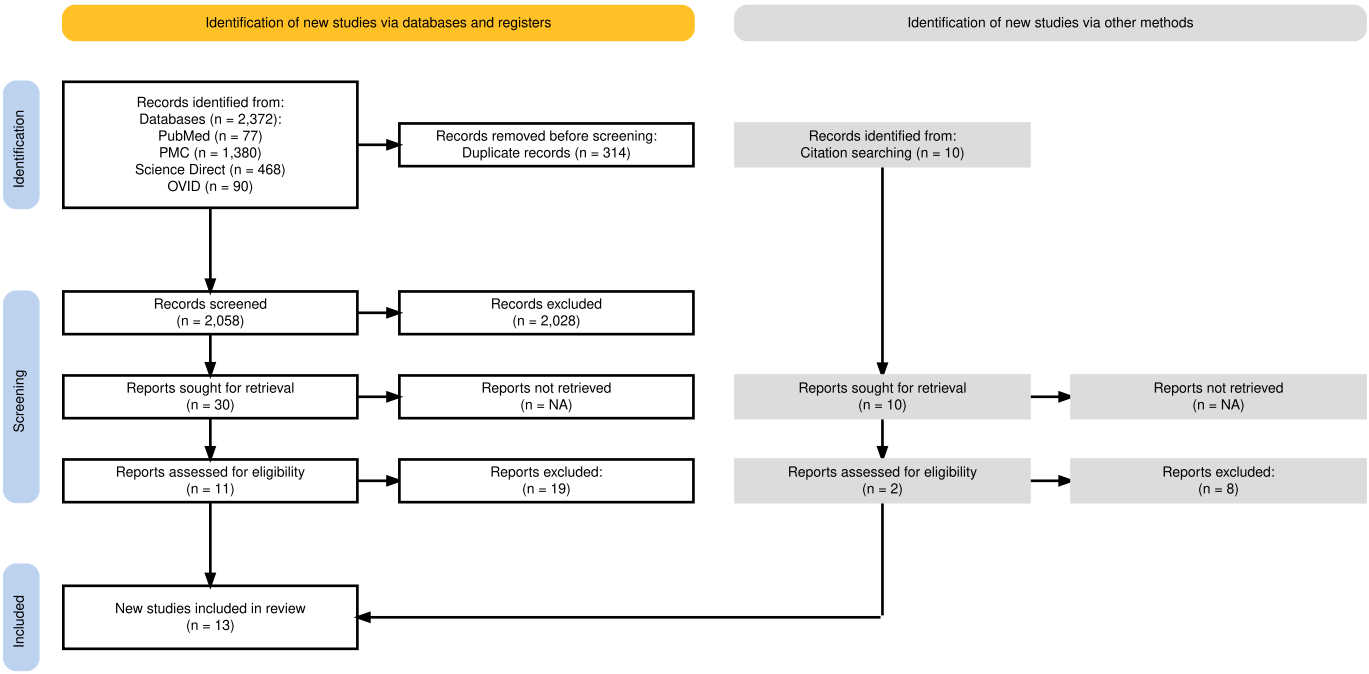

Fig. 1. PRISMA flow diagram for the scoping review process.

3.2. Cooling stimulus applied

The majority of studies ($n = 6$) utilised cold air as a cooling intervention, predominantly whole-body cryotherapy (WBC) at −110 °C ($n = 4$; Dulian et al., 2015; Galliera et al., 2013, Śliwicka et al., 2020; Straburzyńska-Lupa et al., 2021) or less extreme cool temperatures (cool air 16°C Abdo et al., 2020; cool air 21°C Wherry et al., 2019). A number of studies utilised cold temperature in an effort to stimulate and identify cold-activated brown adipose tissue (BAT) ($n = 5$; Bredella et al., 2012, 2013, Kovaničová et al., 2020; Lee et al., 2013, Sanchez-Delgado et al., 2019). Of these, some used extended rest in a cold room supplemented with a cooling vest ($n = 4$; Bredella et al., 2012, 2013, Kovaničová et al., 2020; Sanchez-Delgado et al., 2019), others utilised sleeping in a cold room (Lee et al., 2013) or β3 agonist followed by 120 min cooling pads at 10 °C (Kovaničová et al., 2020). The final studies utilised ice swimming in water <5 °C ($n = 3$; Kovaničová et al., 2020; Mu et al., 2021, 2023). It should be noted that the experimental design of Kovaničová et al. (2020) utilised 4 different cohorts and therefore 4 different cooling stimuli.

3.3. Body composition and BMD

Of the 13 studies identified 10 studies assessed body composition, bone mineral density, or both (Abdo et al., 2020; Bredella et al., 2012, 2013; Dulian et al., 2015; Lee et al., 2013; Mu et al., 2021, 2023; Sanchez-Delgado et al., 2019; Śliwicka et al., 2020; Straburzyńska-Lupa et al., 2021).

Studies assessing the impact of cooling upon BMD directly were few, with Abdo et al. (2020) showing cryotherapy (16 °C) 3x a week for 4 weeks increased BMD by 10 %. Often, a relationship was found between cold activated BAT and BMD, with Bredella et al. (2012) showing a strong positive correlation ($r \geq 0.76$, $P \leq 0.05$), and BAT being a positive predictor of BMD (Bredella et al., 2013). This relationship was further seen to be independent of fat mass and lean body mass in females (Lee et al., 2013). In contrast, Sanchez-Delgado et al. (2019) observed that cold induced BAT (volume and activity) was not related to total body and lumbar spine BMD, this time in young healthy adults and independent of sex, height, body composition and physical activity status.

Some studies measured BMD but did not report the direct change in response to the cooling stimulus applied (ice swimming: Mu et al., 2021, 2023). Instead, BMD data was used to examine for relationships in/with bone biomarkers. Also, some studies measured body composition without reporting the direct change in response to the cooling stimulus but used it largely to assess for differences between groups (high vs low activity status; Śliwicka et al., 2020; Straburzyńska-Lupa et al., 2021).

3.4. Biomarkers of bone health and remodelling

A summary of the responses of biomarkers measured by the 13 included articles is shown in Table 2. Narrative grouping of the markers allowed for separation into groups where previous research suggests promotion of or assisting in bone formation [P1NP, Osteocalcin, OPG, meteorin-like protein (METRNL), Irisin, insulin-like growth factor-1 (IGF-1), 25(OH)D], promotion of or assisting in bone resorption [RANK, RANKL, β-CTX, Sclerostin, insulin-like growth factor binding protein-2 (IGFBP-2), interleukin 6 (IL-6), C-reactive protein (CRP)], or markers involved in bone turnover homeostasis or maintaining some sort of balance (thyroid stimulating hormone (TSH), parathyroid hormone (PTH), thyroid hormones (T3 & T4).

3.5. Biomarkers promoting or assisting in formation

Markers associated with osteoblast activity and/or bone formation showed contrasting responses. P1NP following ice swimming was decreased whilst N-terminal osteocalcin and METRNL were unchanged (Mu et al., 2021, 2023, respectively). However, following WBC for 10 days increases in osteocalcin were seen 24h after the tenth exposure (Straburzyńska-Lupa et al., 2021), with increases in irisin seen in obese men (Dulian et al., 2015) and low fitness groups (vs high fitness comparator; Śliwicka et al., 2020). Also following WBC, this time daily for 5 days, increases were seen in OPG, a decoy receptor for RANKL that protects against excessive resorption, with parallel increases seen for the OPG/RANKL ratio (Galliera et al., 2013). However, in contrast, Straburzyńska-Lupa et al. (2021) showed no change in OPG following 10 days of WBC. Only one study assessed 25(OH)D, thought to be important in calcium absorption and bone mineralisation, again with contrasting results. Concentrations were decreased after 1 and 10 sessions of WBC in a low active group but increased after 10 WBC sessions in a highly active group (Śliwicka et al., 2020). Overall, markers associated with

Table 1
Summary of studies included in qualitative synthesis. β-CTX, beta crosslaps; BAT, brown adipose tissue; BMD, bone mineral density; Ca2+, calcium; CRP, C-reactive protein; CTX, d c-terminal telopeptide of type I collagen; DEXA dual-energy x-ray absorptiometry; iCa, ionized calcium; ICT, inferential current therapy; IGF-1, insulin-like growth factor −1; IGFBP-2, insulin-like growth factor binding protein 2; IL-6, interleukin-6; Mg2+, magnesium; METRNL, meteorin-like protein; N-MID, N-terminal osteocalcin; OC, osteocalcin; OPG, osteoprotogerin; PTH, parathyroid hormone; PET/CT, positron emission tomography and computed tomography; P1NP, total procollagen 1 N-terminal propetide; Pi, inorganic phosphate; PTH, parathyroid hormone; RANK, receptor activator of nuclear factor κ B; RANKL, receptor activator of nuclear factor κ B ligand; T3, triiodothyronine; TSH, thyroid stimulating hormone; UCP-1, uncoupling protein-1; 25(OH)D, 25-hydroxyvitamin D; WBC, whole body cryotherapy.

Authors, location, Article type	Aims & Objectives	Sample population:	Cooling methods	Outcome measures: Focus on bone health, turnover, architecture	Results: Applicable to described outcomes	Notes: Conclusions
Abdo et al. (2020). Egypt. Original article.	Interferential current therapy vs. cryotherapy on knee pain in osteoporotic postmenopausal women.	30 postmenopausal women. Randomly assigned to two equal independent groups.	Cryotherapy (16 °C cold air) vs. ICT. 3x wk. for 4 wks.	Femoral neck BMD via DEXA.	↑BMD in ICT (+12.32 %) and Cryotherapy (+10.14 %) ($P < 0.01$).	ICT and Cryotherapy both ↑BMD similarly; no diff between groups.
Bredella et al. (2012). USA, Original article.	BAT in AN and AN-recovered patients, vs control. Relationship between cold activated BAT, BMD and body composition.	15 women: 5 AN, 5 AN-recovered, 5 control.	2h in 19 °C room with cooling vest at 17 °C prior to PET scan.	Body composition, BAT, BMD, hormones.	BAT detection greater in healthy controls. Positive correlation between cold induced BAT and BMD (femoral neck, total hip, total lumbar spine) ($r \geq 0.76$, $P \leq 0.05$). Women with cold induced BAT also showed higher T3 lower Pref-1, vs women without BAT.	T3 influences bone remodelling. Pref1 inhibits osteoblast differentiation.
Bredella et al., 2013. USA. Rapid Communication.	IGFBP-2 and IGF-1 in regulation of brown adipogenesis and osteoblasogenesis.	15 women: 5 AN, 5 AN-recovered, 5 control.	2h in 19 °C room with cooling vest at 17 °C prior to PET scan.	Body composition, BAT, BMD, IGFBP-2, IGF-1.	7 out of 15 positive for cold activated BAT. IGFBP-2 negative predictor of BAT and BMD (independent of IGF-1 levels). BAT positive predictor of BMD. No association between IGF-1 and BAT.	IGFBP-2 possibly involved in regulation of BAT-mediated osteoblastogenesis.
Dulian et al. (2015). Poland. Original article.	Assess the impact of cryostimulation upon irisin in obese men of different activity levels.	12 obese men of high physical fitness or low physical fitness (VO2max above or below 35 ml kg.BM/min).	10 sessions (once per day) of WBC. 3 min at −110 °C	Body composition, Blood: IL-6, hsCRP, irisin, hepcidin, ferritin.	↑ irisin in low fitness obese men only, correlating with amount of fat tissue. ↓ CRP 24h post 1st and 10th cryo exposure. ↔ IL-6	Previous work suggests Irisin can enhance osteoblast differentiation.
Galliera et al. (2013). Italy. Original article.	Effect of WBC on musculoskeletal system of the athlete.	20 International level Rugby players. Males. Control group vs. WBC group.	Daily WBC (−60 °C for 30s, −110 °C for 2min) for 5 days vs. no WBC.	OPG, RANKL, RANK	WBC No change in RANK & RANKL. WBC ↑ OPG ($p < 0.05$). WBC ↑ OPG/RANKL ratio (2.53 ± 0.98 and 3.51 ± 0.83 before and after WBC, respectively, $p < 0.05$).	WBC does not influence markers of osteoclastogenesis & bone resorption (RANK & RANKL), but does influence bone formation marker OPG.
Kovaničová et al. (2020). Slovakia & Austria. Original article.	Cold exposure response of thyroid and parathyroid hormones in non-/cold acclimated humans	**Cohort 1**–15 middle aged ice swimmers, regularly ice swimming for 6 months. Cold acclimatised. **Cohort 2**–6 ice swimmers. Cold acclimatised. **Cohort 3**–11 healthy young men. Non acclimatised. **Cohort 4**–36 patients undergoing elective neck surgery. Non acclimatised.	**Cohort 1-** Swimming 15 min at 2.6 °C in winter and summer **Cohort 2–**150 min water perfused cooling vest kept slightly above shivering temperature (6.5 °C) **Cohort 3 –** β3 agonist followed by 120min cooling pads at 10 °C. **Cohort 4 –** n/a	**Cohort 1 -** Blood pre and post **Cohort 2 –** PET/CT for cold activated BAT **Cohort 3 –** Maximal induction of Nonshivering thermogenesis **Cohort 4 –** Tissue analysis BAT UCP1 gene expression, serum free thyroxine, T3, TSH.	**Cohort 1 –** ↓ serum free T3 and serum and total T4, but not total T3. Greater frequency of ice swimming associated with larger decrease in fT4. - ↑ TSH, sCa2+, sPhosphorus - ↑ PTH (78 %) - PTH high in winter, 25-OHVitD increased in summer - ↑serum glycaemia, ↓ serum insulinemia - ↑lactate, succinate **Cohort 2 & 3 –** Cold exposure aimed at inducing nonshivering thermogenesis ↓TSH in	Regulation of PTH and thyroid hormones during cold exposure varies by acclimatisation status and cold stimulus intensity.

(*continued on next page*)

Table 1 (*continued*)

Authors, location, Article type	Aims & Objectives	Sample population:	Cooling methods	Outcome measures: Focus on bone health, turnover, architecture	Results: Applicable to described outcomes	Notes: Conclusions
					acclimatised and non-acclimatised pop-ulations, and fT3 in acclimatised only. No change in PTH in accli-matised (cohort 2). **Cohort 4-** plasma PTH levels positively corre-lated with BAT UCP1 (gene expression and protein content).	
Lee et al. (2013). USA. Original article.	Examine the relationship between BAT and BMD in healthy adults.	1) 24 participants (10 female, 14 male)	12h sleep in 19 °C room	BMD, Body Composition, Cold activated BAT,	BAT correlated positively with FM, but not LBM. Positive correlation between BAT volume with total and spine BMD in women, independent of FM and LBM.	Healthy women with more abundant BAT to have higher BMD, independent of age and other body compositional parameters. These positive correlations are absent in men
Mu et al. (2021). China. Original article.	Investigate variations in circulating bone metabolism markers after ice swimming.	87 ice swimmers	Ice swimming <5 °C (time and distance not mandated)	BMD, Pre vs. post ice swimming bloods for serum PTH, total Ca2+, Pi, Mg2+, N-terminal osteocalcin (N-MID), TP1NP, β-CTX.	↑PTH, Ca2+, Pi ($P < 0.01$) ↓TP1NP, β-CTX ($P \leq 0.001$) ↔ N-MID	Bone turnover (anabolism and catabolism) was inhibited after ice swimming. No change in osteocalcin.
Mu et al. (2023). China. Original article.	Changes in sclerostin and meteorin-like (METRNL) protein before and after ice swimming.	56 ice swimmers	Ice swimming <5 °C (time and distance not mandated)	Body Composition, BMD, pre and post swim bloods for sclerostin and METRNL.	↓sclerostin after ice swimming ($P < 0.001$) ↔ METRNL ($P = 0.861$) Baseline serum sclerostin level before Ice swimming was significantly and positively correlated with METRNL, and the decrease in sclerostin caused by ice swimming was also significantly and positively correlated with METRNL fluctuations	Sclerostin – an osteokine secreted by osteocytes. Sclerostin inhibition potentially related to PTH increases seen in Mu et al., (2021). METRNL – adipomyokine involved in WAT conversion to BAT.
Sanchez-Delgado et al. (2019). Spain. Original article.	Association between cold induced BAT and BMD in healthy adults.	98 healthy participants (68 female)	2h water perfused vest set to 4 °C above their individual shivering threshold.	Body composition, BMD, cold activated BAT	Cold induced BAT volume and activity not related to total body and lumbar spine BMD in young healthy adults, independent of sex, height, body composition and physical activity.	Contrasts to Bredella et al., (2012), Lee et al., (2013).
Śliwicka et al. (2020). Poland. Original article.	Effects of repeated exposure to systemic cryotherapy at −110 °C in physically active volunteers with different physical fitness levels.	22 healthy males (age: 21 ± 1.17 years). Split into high-physical fitness vs. low physical fitness groups.	WBC, 1x per day for 10 days. WBC = 30s at −60 °C followed by 3min at −110 °C.	Body composition, VO2max, biochemical analyses (CRP, myoglobin, IL-6, irisin, Mst, 25(OH) D. Biochemical analyses measured at before, 30min and 24h after both the first and tenth WBC session.	**Following 10 days of WBC:** 25(OH)D ↑ in the high physical fitness level (HPhL) group ($p = 0.002$) and ↓ in the low physical fitness level (LPhL) group ($p = 0.020$). After 24 h returned to normal in both groups. Only Myostatin was different between groups after 10 days WBC; ↓ in low physical fitness group. **Following a single WBC session:** HPhL IL-6 ↑ at 30min, returned to baseline by 24h after first treatment. LPhL 25(OH)D ↓ at	

(*continued on next page*)

Table 1 (*continued*)

Authors, location, Article type	Aims & Objectives	Sample population:	Cooling methods	Outcome measures: Focus on bone health, turnover, architecture	Results: Applicable to described outcomes	Notes: Conclusions
					30min, irisin and Mst increased at 24h following the tenth treatment.	
Straburzyńska-Lupa et al. (2021). Poland. Original article.	Sclerostin and bone remodelling biomarkers response to WBC in men with different physical fitness.	22 males. 2 groups. 1) **Highly active** VO 2 max ≥43 ml min^{-1} kg^{-1} (n = 11), physically active ≥5 h/ week. 2) **Low active** VO 2 max <43 ml min^{-1} kg^{-1} (n = 11), physically active ≤4 h/ week.	WBC, 1x per day for 10 days. 3min at −110 °C. 15 min cycling 100w following WBC to prevent shivering.	Body composition, BMD, Blood: OPG, sRANKL, sclerostin, CTx-1, OC.	**After 1 exposure:** ↔ OPG, sRANKL ↑ Sclerostin CTx-1 & OC ↓ 30 min post-WBC, then ↑ at 24h post-WBC, in both groups. CTx-1 increases of 20 % highly active and 25 % low active group 24h post-WBC. OC increases of 9 % highly active and 6 % low active 24h post WBC **After 10**th **exposure:** OC/CTx-1 ↓ 30 min post-WBC, then ↑ at 24h post-WBC, in highly active groups (P < 0.05). WBC led to positive correlations between sclerostin and RANKL, CTx-1, OC, OPG/ sRANKL. OPG/RANKL transient diff between Highly and Low active groups suggest adverse effect of WBC on Low active subjects.	WBC increases bone resorption markers CTx-1 and formation marker OC. Modified turnover. Low active subjects might be more susceptible to RANKL activated resorption. Sclerostin ↑ contrasts with Mu et al. (2023).
Wherry et al. (2019). USA, Original article.	Does exercise in warm environment exaggerate the decrease in serum iCa and increases in PTH and CTX compared to a cool environment?	Older males (n = 7) and females (n-5) accustomed to brisk walking.	RM design: 60 min of treadmill walking at 70–80 % HRmax at 21 °C and 28 °C, separated by 4 weeks.	Blood sampled (Pre (−15, 0min), during (15, 30, 45, 60min) & post (75, 90, 105, 120min) & analysed for PTH, CTX, iCa, haematocrit. Urine sampled (20min before & immediately after exercise) assessed for urine Calcium loss.	No between condition differences in iCa, PTH, CTX.	

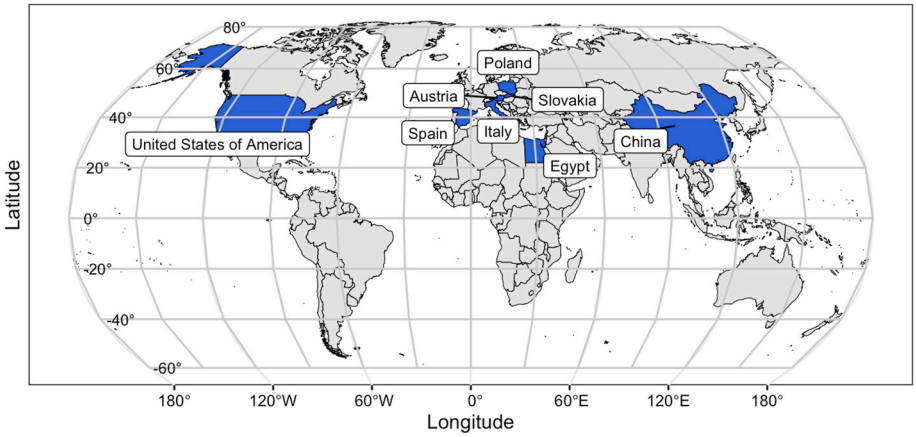

Fig. 2. Geographical distribution of included studies. The shaded area represents the countries from which eligible studies originated, all located in the Northern Hemisphere, with none from south of the equator.

Table 2
Summary of biomarker responses to cold stimuli from the included studies. Grey rows are markers of resorption; white rows are markers of formation. Blue rows are hormones linked to bone turnover/homeostasis. β-CTX, beta crosslaps; BAT, brown adipose tissue; BMD, bone mineral density; CRP, C-reactive protein; CTX, d c-terminal telopeptide of type I collagen; IGF-1, insulin-like growth factor −1; IGFBP-2, insulin-like growth factor binding protein 2; IL-6, interleukin-6; Mg2+, magnesium; METRNL, meteorin-like protein; N-MID, N-terminal osteocalcin; OC, osteocalcin; OPG, osteoprotogerin; PTH, parathyroid hormone; P1NP, total procollagen 1 N-terminal propetide; PTH, parathyroid hormone; RANK, receptor activator of nuclear factor κ B; RANKL, receptor activator of nuclear factor κ B ligand; T3, triiodothyronine; TSH, thyroid stimulating hormone; 25(OH)D, 25-hydroxyvitamin D; WBC, whole body cryotherapy.

Marker	Proposed effect on bone remodelling or health	Measured change	Cold stimulus	Reference
P1NP	Marker of bone formation. Reflects osteoblast activity.	↓P1NP	Ice swimming <5 °C (time and distance not mandated)	Mu et al. (2021)
Osteocalcin (N-MID)	Marker of bone formation and mineralisation. Produced by osteoblasts.	↔ N-MID	Ice swimming <5 °C (time and distance not mandated)	Mu et al. (2021)
		↓ 30 min post-WBC, then ↑ at 24h post-WBC in OC	WBC, 1x per day for 10 days. 3min at -110°C.	Straburzynska-Lupa et al. (2021)
OPG	Protects against excessive resorption. Decoy receptor for RANKL	↑ OPG ↑OPG/RANKL ratio	Daily WBC (-60°C for 30s, -110°C for 2min) for 5 days vs. no WBC.	Galliera et al. (2013)
		↔ OPG	WBC, 1x per day for 10 days. 3min at -110°C.	Straburzynska-Lupa et al. (2021)
METRNL	Enhance osteoblast differentiation. Enhances mineralisation (in vitro).	↔ METRNL	Ice swimming <5 °C (time and distance not mandated)	Mu et al. (2023)
Irisin	Promotes formation by enhancing osteoblast differentiation. Inhibits resorption by reducing osteoclast activity.	↑ irisin in low fitness obese men only, correlating with amount of fat tissue.	10 sessions (once per day) of WBC. 3 min at -110°C	Dulian et al. (2015)
		↑ irisin in low fitness group 24h after 10th exposure	WBC, 1x per day for 10 days. WBC= 30s at -60°C followed by 3min at -110°C	Sliwicka et al. (2020)
IGF-1	Stimulates osteoblast differentiation of MSC's. Levels directly correlated with bone mass.	No association IGF-1 with BAT	2h in 19°C room with cooling vest at 17°C	Bredella et al. (2013)
25(OH)D	Important in calcium absorption and bone mineralisation. Low levels linked to ↓BMD and ↑ bone turnover.	After single session: ↓ in low active group After 10 sessions: ↑ in high active group, ↓ low active group	WBC, 1x per day for 10 days. WBC= 30s at -60°C followed by 3min at -110°C	Sliwicka et al. (2020)
RANK	Bone resorption. Interaction essential for osteoclastogenesis and osteoclast activation.	↔ RANK	Daily WBC (-60°C for 30s, -110°C for 2min) for 5 days vs. no WBC.	Galliera et al. (2013)
RANKL		↔RANKL	Daily WBC (-60°C for 30s, -110°C for 2min) for 5 days vs. no WBC.	Galliera et al. (2013)
		↔sRANKL	WBC, 1x per day for 10 days. 3min at -110°C.	Straburzynska-Lupa et al. (2021)
β-CTX	Bone resorption marker.	↓ β-CTX	Ice swimming <5 °C (time and distance not mandated)	Mu et al. (2021)
		↓ 30 min post-WBC, then ↑ at 24h post-WBC in CTx-1	WBC, 1x per day for 10 days. 3min at -110°C.	Straburzynska-Lupa et al. (2021)
		↔CTX	60 minutes of treadmill walking at 70-80% HRmax at 21°C	Wherry et al. (2019)
Sclerostin	Inhibits Wnt pathway ↓ osteoblast activity	↓ sclerostin	Ice swimming <5 °C (time and distance not mandated)	Mu et al. (2023)
		After 1 exposure ↑ sclerostin	WBC, 1x per day for 10 days. 3min at -110°C.	Straburzynska-Lupa et al. (2021)
IGFBP-2	High levels linked to increased markers of resorption.	Negative predictor of BAT and BMD	2h in 19°C room with cooling vest at 17°C	Bredella et al. (2013)
IL-6	Increase resorption by activating osteoclast formation. Decrease formation by reducing mineralisation and differentiation of osteoblasts.	↔ IL-6 after 1st or 10th session	10 sessions (once per day) of WBC. 3 min at -110°C	Dulian et al. (2015)
		↑ IL-6 30 min post single exposure in high fitness group	WBC, 1x per day for 10 days. WBC= 30s at -60°C followed by 3min at -110°C	Sliwicka et al. (2020)
CRP	Increased levels associated with greater risk of fracture.	↓ 24h after 1st and 10th exposure	10 sessions (once per day) of WBC. 3 min at -110°C	Dulian et al. (2015)
		↔ CRP	WBC, 1x per day for 10 days. WBC= 30s at -60°C followed by 3min at -110°C	Sliwicka et al. (2020)
TSH	Supresses remodelling. Can reduce resorption and formation.	Cohort 1 - ↑TSH Cohort 2 & 3 - Cold exposure aimed at inducing nonshivering thermogenesis ↓TSH in acclimatised and non-acclimatised populations	Cohort 1 – cold acclimatised swimmers, 15 min swim at 2.6°C Cohort 2 – cold acclimatised swimmers, 150min water perfused vest (6.5°C) Cohort 3 – Non-acclimatised subjects, β3 agonist followed by 120min cooling pads at 10°C.	Kovanicova et al. (2020)
PTH	Regulator of extracellular calcium and phosphate. Chronic elevation leads to bone loss. Acute elevation can increase bone mass.	Cohort 1 - ↑PTH 78% Cohort 2 - ↔ PTH	Cohort 1 – cold acclimatised swimmers, 15 min swim at 2.6°C Cohort 2 – cold acclimatised swimmers, 150min water perfused vest (6.5°C) Cohort 3 – Non-acclimatised subjects, β3 agonist followed by 120min cooling pads at 10°C.	Kovanicova et al. (2020)
		↔ PTH	60 minutes of treadmill walking at 70-80% HRmax at 21°C	Wherry et al. (2019)
Testosterone	Too much or too little can lead to increased or decreased bone turnover.	Cohort 1 - ↓ serum free T3 and serum and total T4, but not total T3 Cohort 2 - ↓ fT3 in acclimatised only	Cohort 1 – cold acclimatised swimmers, 15 min swim at 2.6°C Cohort 2 – cold acclimatised swimmers, 150min water perfused vest (6.5°C) Cohort 3 – Non-acclimatised subjects, β3 agonist followed by 120min cooling pads at 10°C.	Kovanicova et al. (2020)
		Greater T3 in women with cold activated BAT	2h in 19°C room with cooling vest at 17°C	Bredella et al. (2012)

osteoblast activity and/or bone formation are inconsistent and contrasting, seemingly dependant on the cold stimulus applied.

3.6. Biomarkers promoting or assisting in resorption

Markers associated with bone resorption showed better agreement than those of formation. Mu and colleagues (2021, 2023) in their ice swimming experiments showed decreases in the bone resorption marker β-CTX and sclerostin, a marker said to inhibit pathways associated with osteoblast activity. Contrasting results were seen following a different stimulus, with WBC decreasing β-CTX immediately after cooling and increasing it 24h later, whilst sclerostin increased after a single WBC exposure (Straburzyńska-Lupa et al., 2021). Elsewhere a cold stimulus had very little impact on markers of bone resorption, with no changes seen in RANK, RANKL (Galliera et al., 2013; Straburzyńska-Lupa et al., 2021), IL-6 (Dulian et al., 2015) and CRP (Śliwicka et al., 2020). The only exceptions here were increases in IL-6 30 min after a single WBC exposure in a high fitness group (Śliwicka et al., 2020) and decreases in CRP 24h after both the 1st and 10th WBC exposure (Dulian et al., 2015). These findings suggest a more uniform trend toward an acute reduction in resorption markers, pointing to a short-term dampening of bone breakdown processes immediately following exposure.

3.7. Bone turnover; balance or homeostasis

Three hormones that play a role in the homeostatic processes of bone turnover were also measured in the returned articles. Different cold stimuli produced different results. In cold acclimatised swimmers a cold swim at 2.6 °C increased TSH, whereas a water perfused vest used to stimulate non-shivering thermogenesis decreased TSH (Kovaničová et al., 2020). A similar response was also seen for PTH, with a 78 % increase in PTH concentration following a cold swim, but no change seen with the water perfused vest (Kovaničová et al., 2020). However, both methods of cold stimulation decreased serum free T3 and total T4 following a cold swim, and fT3 decreased using a water perfused vest; in acclimatised cohorts only, with no change seen in non-acclimatised cohorts (Kovaničová et al., 2020). In summary, the hormonal regulation of bone turnover demonstrates significant divergence, as the direction of these homeostatic shifts is largely determined by the type of cold stimulus applied and the acclimatisation status of the participants.

To summarise, markers of formation and homeostatic control were largely contrasting dependent on the cold stimulus, with markers of resorption often being unchanged or decreasing following cold exposure.

4. Discussion

The aim of this scoping review was to explore the impact of cold exposure on markers of bone health in human populations. While the effects of cold exposure on bone physiology are relatively well-established in animal and cellular models, this review represents the first attempt to systematically summarise the available evidence in humans.

The majority of studies included in this review employed cold exposure, primarily in the form of extreme cold via whole body cryotherapy at −110 °C. This approach is a logical avenue of investigation, as previous research has suggested that chronic exposure to cold environments may negatively affect bone health. For example, studies of cold-dwelling human populations have reported reduced cortical thickness and lower BMD, and accelerated age-related bone loss (Robbins et al., 2018). These findings are supported by animal models, whereby rodents raised in cold temperatures developed significantly and permanently shorter limb lengths compared to those raised in warmer conditions (Serrat, 2013).

In many of the studies returned in this scoping review, cold exposure was applied primarily to stimulate brown adipose tissue (BAT) and examine associated metabolic effects. BAT is a highly metabolically active tissue, known for its capacity to generate heat through energy expenditure. Because of its role in regulating glucose and lipid metabolism, BAT has emerged as a target for therapeutic strategies against obesity and related metabolic conditions (Bahler et al., 2017). Interestingly, cold-activated BAT has also been linked to bone health. Animal studies have shown that mice with defective BAT exhibit reduced bone mass (Motyl and Rosen, 2011, 2013), although the underlying mechanisms remain unclear. One hypothesis proposed by Lee and colleagues (2013) is that individuals with greater BAT mass harbour a more osteoblastogenic bone marrow microenvironment, leading to higher BMD.

Supporting this view, a study identified in this review reported that women with anorexia nervosa exhibited both lower BAT volume and reduced BMD. Additionally, positive correlations were observed between cold-induced BAT activity and BMD at the femoral neck, total hip, and total lumbar spine (Bredella et al., 2012). Lee et al. (2013) also demonstrated a similar association between BAT mass and BMD in healthy women, but not in men. Although the reason for sex-specific differences is unclear, it has been suggested that women generally have greater BAT stores than men (Lee et al., 2013). Beyond BAT related mechanisms, Abdo et al. (2020) reported a direct benefit of cold therapy on bone health, whereby postmenopausal women who underwent WBC 3 sessions per week for 4 weeks at 16 °C experienced a 10 % increase in BMD. These findings suggest cold therapies may hold potential in mitigating age-related bone loss.

To investigate the mechanisms behind the potential positive effect of cold exposure on BMD, it is essential to examine biomarkers involved in the bone remodelling process. Bone remodelling is a tightly regulated physiological process that maintains skeletal integrity through a balance between bone resorption, driven by osteoclasts, and bone formation, driven by osteoblasts. Dysregulation of this process can lead to a wide spectrum of skeletal disorders ranging from reduced bone mass to abnormal bone accumulation, with associated clinical manifestations of bone-related diseases (Salhotra et al., 2020). Several studies included in this scoping review assessed important biomarkers of both resorption and formation. These markers provide insight into the underlying biological responses to cold exposure and may help explain how such interventions influence bone homeostasis.

In the present scoping review, seven markers of bone formation were assessed across 7 of the 13 included studies. Osteoblast activity, or activity of the biomarkers either produced by or promoting osteoblast function, provides insight into how cold exposure may influence bone formation. Among these, the myokines insulin like growth factor 1 (IGF-1) and irisin have been implicated in stimulating or enhancing osteoblast differentiation (Kirk et al., 2020; Greeves et al., 2023). IGF-1 showed a neutral response to cold exposure in one study, where participants were exposed to a 19 °C room while wearing a cooling vest at 17 °C for 2 h (Bredella et al., 2013). In contrast, irisin demonstrated positive effects in multiple studies. Ten days of WBC (3 min at −110 °C) led to increased irisin concentrations 24 h after the final (10th) session in individuals with low fitness (Śliwicka et al., 2020). Similarly, Dulian et al. (2015) reported increases in irisin among low fitness obese men, with levels positively correlating with fat mass. The metabolic cytokine meteorin-like protein (METRNL), which has been shown to increase osteoblast differentiation and mineralisation in vitro (Huang et al., 2022) was also examined. However, a single bout of ice swimming in water below 5 °C did not significantly alter METRNL concentrations (Mu et al., 2023) despite earlier evidence of cold induced secretion (Rao et al., 2014). Collectively, these findings suggest that cold exposure may elicit either a neutral or positive effect on biomarkers associated with osteoblast differentiation and function.

Articles within this scoping review also assessed alternative markers of bone formation in response to different cold stimuli. Osteocalcin is synthesised and released by osteoblasts during new bone matrix deposition (Brown et al., 2022). One study returned in this scoping review showed no change in osteocalcin concentrations after a single ice swimming session (<5 °C) by acclimatised ice swimmers (Mu et al., 2021). Yet in the same study, Procollagen Type 1 N-terminal propeptide (P1NP), a direct marker of osteoblast activity as it reflects the synthesis of type 1 collagen, a primary protein in bone matrix (Brown et al., 2022), showed a reduction following a single ice swimming session in water <5 °C (Mu et al., 2021). This finding is interesting as these results agree with previous work of Farr et al., 2012, who showed a negative correlation between SNS activity and P1NP. It could be postulated that the ice swimming protocol used by Mu and colleagues sufficiently activated the SNS, as cold-water immersion has been shown to do so previously (Allan et al., 2017, 2019). Taken together, this would suggest a cold-induced SNS mediated dampening in this marker of bone formation (P1NP). Meanwhile, 25(OH)D, which supports bone formation by improving calcium absorption for mineralisation, decreased in a low active group after 1 and 10 sessions of WBC (−110 °C for 3 min) but improved after 10 sessions in a highly active group (Śliwicka et al., 2020). Overall, the studies included in this scoping review suggest that whilst cold exposure may positively influence markers of osteoblast differentiation, this does not translate into markers of bone formation. It is not clear why these biomarkers associated with bone formation do not align with the results of Abdo et al. (2020) who showed improvements in BMD following regular cold exposure. Individual differences such as body fat, activity

levels and aerobic fitness, as well as timing of measurements may seemingly influence outcomes, and future work should take these factors into consideration.

Bone remodelling is an intricate balance between formation and resorption. Articles in this scoping review also measured markers of bone resorption. Receptor activator of NF-κB (RANK) is expressed on osteoclast precursor cells and is activated by its ligand, RANKL, to promote differentiation in mature osteoclasts. Without RANKL binding to RANK, osteoclast formation is impaired (Boyce and Xing, 2008). Thus, the interaction between RANK and RANKL is essential for bone resorption within the remodelling process. Galliera et al. (2013) found no changes in either RANK or RANKL in response to daily WBC at −110 °C for 2 min over 5 days. This finding is supported by Straburzyńska-Lupa et al. (2021), who also reported no change in serum RANKL after 10 days of WBC -110 °C for 3 min. In this sense, a neutral effect could be seen as positive, in that cold exposure does not augment resorption. One study measured osteoprotogerin (OPG), a protein that helps protect against excessive resorption by acting as a decoy receptor for RANKL, which is important in osteoclast activation (Boyce and Xing, 2008). Galliera et al. (2013) demonstrated that daily WBC at −110 °C for 2 min over 5 days improved both OPG and OPG:RANKL ratio, again suggesting that cold induced protection against bone resorption may occur. Therefore, the benefits of cold exposure on bone remodelling may stem not from enhanced bone formation, but rather from attenuation of, or protection against, resorption.

Another marker of bone resorption, beta isomerised C terminal telopeptide of type 1 collagen (β-CTX), reflects the degradation of type 1 collagen, the main structural protein in bone (Brown et al., 2022). This scoping review shows acute decreases in β-CTX were observed approximately 30 min following cold exposure, including ice swimming in water below 5 °C (Mu et al., 2021) and after WBC at −110 °C for 3 min (Straburzyńska-Lupa et al., 2021), suggesting a potential suppression or interruption of bone resorption by cold. However, β-CTX was elevated 24 h after WBC in the same study by Straburzyńska-Lupa et al. (2021) indicating that cold exposure may have time dependent effects on bone resorption markers. It remains unclear whether these time-dependent effects are because of a rebound effect, a disruption in the natural circadian rhythm or a biphasic physiological response. Further research is required to establish time-dependent mechanisms.

With acute reductions in β-CTX and increases in OPG, observed alongside no changes in RANK/RANKL, data from this review suggests a protective effect of cooling against bone resorption. Contrastingly, previous research suggests that SNS activation triggers the Tumor Necrosis Factor Superfamily Member 11 (TNFSF11) gene pathway that encodes for RANKL (Elefteriou et al., 2005; Khosla et al., 2018), however the SNS activation in these studies was not cold generated. Nevertheless, it is somewhat surprising that the cold-exposure used by Galliera et al. (2013; WBC at −110 °C for 2 min over 5 days) and Straburzyńska-Lupa et al. (2021; 10 days of WBC -110 °C for 3 min) did not stimulate a negative response in resorption markers, whilst the ice swimming <5 °C in Mu et al. (2021) did. Divergent findings might be a result of utilising different methods of cooling and therefore exposing participants to a different dose of cold exposure. The dose of cold exposure can be altered through different temperatures, durations and types of cooling. Indeed, we have previously discussed the thermal conductivity, or heat transfer co-efficient, being greater for ice (2.18 k) and water (0.58 k) than it is air (0.024 k), suggesting both ice and water (i.e., ice swimming) have a greater ability to remove heat from the body than air (i.e., WBC) (Allan et al., 2022), thus a greater cooling stimulus, or dose. Srámek et al. (2000) has also noted a greater sympathetic (plasma norepinephrine) response is seen following colder water immersion temperatures. As such the negative responses in the resorption marker P1NP for Mu and colleagues (2021) might be explained by a greater dose of cold activating a greater SNS response. Mu and colleagues (2021) failed to measure SNS activity either directly or indirectly via plasma norepinephrine, however, if a greater dose was used the theory postulated by Robbins et al. (2018) makes sense, with a cold-activated axis of SNS-RANKL-activated osteoclast resorption. However, the dose in the study by Mu and colleagues (2021, 2023) remains speculative as duration of the ice swim was not mandated and therefore could have varied significantly. Additionally, this may only be applicable from an acute perspective as habituation to cold exposure leads to a gradual reduction in SNS activity when regular cold exposures occur (Yurkevicius et al., 2021). With habituation there is also a reduced SNS activation following chronic cold exposures (Savourey et al., 1996). This would suggest less sympathetically stimulated RANKL production and therefore greater protection against cold-induced bone loss for habituated individuals, offering a suitable explanation for the reduced β-CTX values seen in habituated ice swimmers from Mu et al. (2021).

Elsewhere, decreases in sclerostin (Mu et al., 2023) and C-reactive protein (CRP) (Dulian et al., 2015) suggest a positive effect of cooling on bone health. Sclerostin is known to decrease osteoblast activity by inhibiting the Wnt pathway (Ke et al., 2012), while elevated CRP is associated with increased fracture risk (Ahmadi-Abhari et al., 2013). Thus, a decrease in these markers would again support the notion of cold-induced protection against bone resorption. However, like RANKL and β-CTX, these markers are also subject to contradictory findings. Straburzyńska-Lupa et al. (2021) reported increased sclerostin after a single WBC exposure (−110 °C for 3 min), while Śliwicka et al. (2020) observed no change in CRP following daily WBC for 10 days (−110 °C for 3 min). Perhaps habituation effects can explain divergent results here also. Mu and colleagues (2023) utilised habituated ice swimmers, measuring decreased sclerostin to a single ice-swimming event, whilst Straburzyńska-Lupa et al. (2021) recruited non-habituated participants of different fitness. This inconsistency extends to Interleukin-6 (IL-6), a cytokine said to play a role in preventing excessive bone resorption during steady-state bone remodelling (Yoshitake et al., 2008) inhibiting bone formation by reducing mineralisation and osteoblast differentiation (Harmer et al., 2019). Studies in this review show either no change in IL-6 concentration acutely (after a single session) or chronically (after 10 WBC sessions (Dulian et al., 2015), whereas Śliwicka et al. (2020) reported an increase IL-6 30 min post-WBC in a high fitness group.

Hormone responses to cold exposure also appear to vary considerably, particularly for those linked to bone remodelling. Thyroid stimulating hormone (TSH) is believed to supress both bone formation and resorption (Abe et al., 2003), while Parathyroid hormone (PTH) plays a key role in regulating extracellular calcium (Dvorak and Riccardi, 2004). Triiodothyronine (T3) has also been implicated in bone turnover when imbalances occur (Bassett and Williams, 2016). Several studies have examined these hormones in response to cold exposure, with considerable variability in findings. Kovaničová et al. (2020) investigated responses across three distinct cohorts: cold-acclimatised swimmers completing a 15-min swim at 2.6 °C; cold-acclimatised swimmers wearing a water-perfused vest at 6.5 °C for 150-min; and non-acclimatised individuals receiving a β3-agonist prior to 120-min of cooling with 10 °C pads. In the cold-acclimatised swimmers who exercised during exposure, substantial increases in TSH and PTH were observed, alongside a reduction in free (but not total) T3. In contrast, the other cohorts, who were exposed to passive cold without exercise, showed no change or even decreases in these hormones. It is not clear if these discrepancies are attributable to the presence of exercise in the first group, differences in cooling dosage and stimulus across cohorts, or acclimatisation. With that, and the variation in cooling protocols and participant characteristics, it becomes difficult to determine the dominant factor driving the increases in TSH and PTH observed in the exercising cohort. Accordingly, future research should investigate how the timing and presence of exercise (e.g., pre-cooling, during exercise, or post-cooling) influences hormonal responses. Additionally, careful standardisation or matching of cold exposure dose across study protocols is warranted to improve comparability and interpretation.

An important point of interest is the widespread use of cold-water immersion (CWI) in both health and sport settings, typically following

or independent of exercise, to support recovery or general well-being. Individuals often immerse themselves in water at 10–15 °C for 10–15 min (Machado et al., 2016), and sometimes even colder (Ihsan et al., 2025), with the aim of enhancing post-exercise recovery (Choo et al., 2022; Ihsan et al., 2021), decreasing pain or soreness (Machado et al., 2016), lowering inflammation (Cain et al., 2025), improving immune function (Dugué and Leppänen, 2000), promoting sleep (Cain et al., 2025; Knill-Jones et al., 2025), and enhancing overall wellbeing (Knill-Jones et al., 2025). Despite the breadth of research supporting these applications, this scoping review identified only three studies using CWI in the context of bone health, each involving ice swimming in water temperatures below 5 °C (Kovaničová et al., 2020; Mu et al., 2021, 2023). As such, the potential effects of therapeutic CWI for health and/or sporting recovery on markers of bone health has not yet been established in humans.

5. Conclusions

The limited evidence does not support a clear bone-forming benefit of cold exposure. Whilst certain studies indicate enhanced osteoblast differentiation with cold exposure, this does not appear to translate into increased osteoblast activity downstream. However, evidence does suggest a possible positive effect of cooling on bone health might come in the form of suppression or interruption of several bone resorption processes. Further research is needed to clarify the direct effects of cold exposure on BMD as only one study investigated this, with positive effects. Future studies should examine how individual characteristics such as body composition, physical activity, acclimatisation, and fitness levels influences responses to cold, as variation in these factors appears to contribute to the inconsistencies in current findings. Additionally, research should investigate the combined effects of preceding exercise and post-exercise cold exposure on bone health. This not only due to lack of existing data but also because exercise-induced hormonal responses may play a key role in mediating any potential bone-related benefits of cooling.

CRediT authorship contribution statement

R. Allan: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **H.T. Hurst:** Writing – review & editing, Supervision, Methodology, Investigation. **B. Akin:** Writing – original draft, Formal analysis, Data curation. **N. Liles:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J. Dickson:** Project administration, Methodology, Investigation, Data curation, Conceptualization. **J. Knill-Jones:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **J. Sinclair:** Writing – review & editing, Supervision, Methodology, Formal analysis. **S. Dillon:** Writing – review & editing, Visualization, Validation, Supervision, Conceptualization. **S.J. Hesketh:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **C. Mawhinney:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Investigation, Data curation, Conceptualization.

Disclosures

The authors report no conflicts of interest.

Funding

None.

Declaration of competing interest

Authors report no conflicts of interest.

Data availability

No data was used for the research described in the article.

References

Abdo, S.M., Nashed, A.B., Hasanin, M.E., Yassin, R.E.S., 2020. Effect of interferential current therapy versus cryotherapy on knee pain in osteoporotic postmenopausal women: a single-blind randomized controlled trial. Physiother. Quarter. 28 (1), 30–34.

Abe, E., Marians, R.C., Yu, W., Wu, X.B., Ando, T., Li, Y., Iqbal, J., Eldeiry, L., Rajendren, G., Blair, H.C., Davies, T.F., Zaidi, M., 2003. TSH is a negative regulator of skeletal remodeling. Cell 115 (2), 151–162. https://doi.org/10.1016/s0092-8674(03)00771-2.

Ahmadi-Abhari, S., Luben, R.N., Wareham, N.J., Khaw, K.T., 2013. C_reactive protein and fracture risk: european prospective investigation into cancer Norfolk study. Bone 56 (1), 67–72.

Allan, R., Sharples, A.P., Close, G.L., Drust, B., Shepherd, S.O., Dutton, J., Morton, J.P., Gregson, W., 2017. Postexercise cold water immersion modulates skeletal muscle PGC-1α mRNA expression in immersed and nonimmersed limbs: evidence of systemic regulation. J. Appl. Physiol. 123 (2), 451–459. https://doi.org/10.1152/japplphysiol.00096.2017. Bethesda, Md. : 1985.

Allan, R., Malone, J., Alexander, J., Vorajee, S., Ihsan, M., Gregson, W., Kwiecien, S., Mawhinney, C., 2022. Cold for centuries: a brief history of cryotherapies to improve health, injury and post-exercise recovery. Eur. J. Appl. Physiol. 122 (5), 1153–1162. https://doi.org/10.1007/s00421-022-04915-5.

Allan, R., Sharples, A.P., Cocks, M., Drust, B., Dutton, J., Dugdale, H.F., Mawhinney, C., Clucas, A., Hawkins, W., Morton, J.P., Gregson, W., 2019. Low pre-exercise muscle glycogen availability offsets the effect of post-exercise cold water immersion in augmenting PGC-1α gene expression. Physiol. Rep. 7 (11), e14082. https://doi.org/10.14814/phy2.14082.

Bahler, L., Holleman, F., Booij, J., Hoekstra, J.B., Verberne, H.J., 2017. Hot heads & cool bodies: the conundrums of human brown adipose tissue (BAT) activity research. Eur. J. Intern. Med. 40, 26–29. https://doi.org/10.1016/j.ejim.2016.12.023.

Bassett, J.H., Williams, G.R., 2016. Role of thyroid hormones in skeletal development and bone maintenance. Endocr. Rev. 37 (2), 135–187. https://doi.org/10.1210/er.2015-1106. Epub 2016 Feb 10. PMID: 26862888; PMCID: PMC4823381.

Betti, L., Lycett, S.J., von Cramon-Taubadel, N., Pearson, O.M., 2015. Are human hands and feet affected by climate? A test of Allen's rule. Am. J. Phys. Anthropol. 158 (1), 132–140. https://doi.org/10.1002/ajpa.22774.

Bonnet, N., Pierroz, D.D., Ferrari, S.L., 2008. Adrenergic control of bone remodeling and its implications for the treatment of osteoporosis. J. Musculoskelet. Neuronal Interact. 8 (2), 94–104.

Boyce, B.F., Xing, L., 2008. Functions of RANKL/RANK/OPG in bone modeling and remodeling. Arch. Biochem. Biophys. 473 (2), 139–146. https://doi.org/10.1016/j.abb.2008.03.018.

Bredella, M.A., Fazeli, P.K., Freedman, L.M., Calder, G., Lee, H., Rosen, C.J., Klibanski, A., 2012. Young women with cold-activated brown adipose tissue have higher bone mineral density and lower Pref-1 than women without brown adipose tissue: a study in women with anorexia nervosa, women recovered from anorexia nervosa, and normal-weight women. J. Clin. Endocrinol. Metab. 97 (4), E584–E590. https://doi.org/10.1210/jc.2011-2246.

Bredella, M.A., Fazeli, P.K., Lecka-Czernik, B., Rosen, C.J., Klibanski, A., 2013. IGFBP-2 is a negative predictor of cold-induced brown fat and bone mineral density in young non-obese women. Bone 53 (2), 336–339. https://doi.org/10.1016/j.bone.2012.12.046.

Brown, J.P., Don-Wauchope, A., Douville, P., Albert, C., Vasikaran, S.D., 2022. Current use of bone turnover markers in the management of osteoporosis. Clin. Biochem. 109–110, 1–10. https://doi.org/10.1016/j.clinbiochem.2022.09.002.

Cain, T., Brinsley, J., Bennett, H., Nelson, M., Maher, C., Singh, B., 2025. Effects of cold-water immersion on health and wellbeing: a systematic review and meta-analysis. PLoS One 20 (1), e0317615. https://doi.org/10.1371/journal.pone.0317615.

Choo, H.C., Lee, M., Yeo, V., Poon, W., Ihsan, M., 2022. The effect of cold water immersion on the recovery of physical performance revisited: a systematic review with meta-analysis. J. Sports Sci. 40 (23), 2608–2638. https://doi.org/10.1080/02640414.2023.2178872.

Dugué, B., Leppänen, E., 2000. Adaptation related to cytokines in man: effects of regular swimming in ice-cold water. Clin. Physiol. (Oxford, England) 20 (2), 114–121. https://doi.org/10.1046/j.1365-2281.2000.00235.x.

Dulian, K., Laskowski, R., Grzywacz, T., Kujach, S., Flis, D.J., Smaruj, M., Ziemann, E., 2015. The whole body cryostimulation modifies irisin concentration and reduces inflammation in middle aged, obese men. Cryobiology 71 (3), 398–404. https://doi.org/10.1016/j.cryobiol.2015.10.143.

Dvorak, M.M., Riccardi, D., 2004. Ca2+ as an extracellular signal in bone. Cell Calcium 35 (3), 249–255.

Elefteriou, F., Ahn, J.D., Takeda, S., Starbuck, M., Yang, X., Liu, X., Kondo, H., Richards, W.G., Bannon, T.W., Noda, M., Clement, K., Vaisse, C., Karsenty, G., 2005. Leptin regulation of bone resorption by the sympathetic nervous system and CART. Nature 434 (7032), 514–520. https://doi.org/10.1038/nature03398.

Farr, J.N., Charkoudian, N., Barnes, J.N., Monroe, D.G., McCready, L.K., Atkinson, E.J., Amin, S., Melton 3rd, L.J., Joyner, M.J., Khosla, S., 2012. Relationship of sympathetic activity to bone microstructure, turnover, and plasma osteopontin levels in women. J. Clin. Endocrinol. Metab. 97 (11), 4219–4227. https://doi.org/10.1210/jc.2012-2381.

Galliera, E., Dogliotti, G., Melegati, G., Corsi Romanelli, M.M., Cabitza, P., Banfi, G., 2013. Bone remodelling biomarkers after whole body cryotherapy (WBC) in elite rugby players. Injury 44 (8), 1117–1121. https://doi.org/10.1016/j.injury.2012.08.057.

Greeves, J.P., Beck, B., Nindl, B.C., O'Leary, T.J., 2023. Current risks factors and emerging biomarkers for bone stress injuries in military personnel. J. Sci. Med. Sport 26 (Suppl. 1), S14–S21. https://doi.org/10.1016/j.jsams.2023.04.006.

Harmer, D., Falank, C., Reagan, M.R., 2019. Interleukin-6 interweaves the bone marrow microenvironment, bone loss, and multiple myeloma. Front. Endocrinol. 9, 788. https://doi.org/10.3389/fendo.2018.00788.

Hernlund, E., Svedbom, A., Ivergård, M., Compston, J., Cooper, C., Stenmark, J., McCloskey, E.V., Jönsson, B., Kanis, J.A., 2013. Osteoporosis in the European Union: medical management, epidemiology and economic burden. A report prepared in collaboration with the International Osteoporosis Foundation (IOF) and the European Federation of Pharmaceutical Industry Associations (EFPIA). Arch. Osteoporosis 8 (1), 136. https://doi.org/10.1007/s11657-013-0136-1.

Herrera, E., Sandoval, M.C., Camargo, D.M., Salvini, T.F., 2010. Motor and sensory nerve conduction are affected differently by ice pack, ice massage, and cold water immersion. Phys. Ther. 90 (4), 581–591. https://doi.org/10.2522/ptj.20090131.

Herrera, E., Sandoval, M.C., Camargo, D.M., Salvini, T.F., 2011. Effect of walking and resting after three cryotherapy modalities on the recovery of sensory and motor nerve conduction velocity in healthy subjects. Rev. Brasileira Fisioterapia 15 (3), 233–240. https://doi.org/10.1590/s1413-35552011000300010.

Huang, R., Balu, A.R., Molitoris, K.H., White, J.P., Robling, A.G., Ayturk, U.M., Baht, G. S., 2022. The role of Meteorin-like in skeletal development and bone fracture healing. J. Orthop. Res. : Off. Publ. Ortho. Res. Soc. 40 (11), 2510–2521. https://doi.org/10.1002/jor.25286.

Ihsan, M., Abbiss, C.R., Allan, R., 2021. Adaptations to post-exercise cold water immersion: Friend, foe, or futile? Front. Sports Act. Living 3, 714148. https://doi.org/10.3389/fspor.2021.714148.

Ihsan, M., Bieuzen, F., Thorpe, R., Alexander, J., Allan, R., 2025. Physiological mechanisms and performance recovery following post-exercise cold water immersion. Phys. Act. 3 (1), 25–33. https://doi.org/10.63020/pa.2025.3.1.25.

Kajimura, D., Hinoi, E., Ferron, M., Kode, A., Riley, K.J., Zhou, B., Guo, X.E., Karsenty, G., 2011. Genetic determination of the cellular basis of the sympathetic regulation of bone mass accrual. J. Exp. Med. 208 (4), 841–851. https://doi.org/10.1084/jem.20102608.

Ke, H.Z., Richards, W.G., Li, X., Ominsky, M.S., 2012. Sclerostin and Dickkopf-1 as therapeutic targets in bone diseases. Endocr. Rev. 33 (5), 747–783. https://doi.org/10.1210/er.2011-1060.

Khosla, S., Drake, M.T., Volkman, T.L., Thicke, B.S., Achenbach, S.J., Atkinson, E.J., Joyner, M.J., Rosen, C.J., Monroe, D.G., Farr, J.N., 2018. Sympathetic β1-adrenergic signaling contributes to regulation of human bone metabolism. J. Clin. Investig. 128 (11), 4832–4842. https://doi.org/10.1172/JCI122151.

Kirk, B., Feehan, J., Lombardi, G., Duque, G., 2020. Muscle, bone, and fat crosstalk: the biological role of myokines, osteokines, and adipokines. Curr. Osteoporos. Rep. 18 (4), 388–400. https://doi.org/10.1007/s11914-020-00599-y.

Knill-Jones, J., Shadwell, G., Hurst, H.T., Mawhinney, C., Sinclair, J.K., Allan, R., 2025. Influence of acute and chronic therapeutic cooling on cognitive performance and well-being. Physiol. Behav. 289, 114728. https://doi.org/10.1016/j.physbeh.2024.114728.

Kovaničová, Z., Kurdiová, T., Baláž, M., Štefanička, P., Varga, L., Kulterer, O.C., Betz, M. J., Haug, A.R., Burger, I.A., Kiefer, F.W., Wolfrum, C., Ukropcová, B., Ukropec, J., 2020. Cold exposure distinctively modulates parathyroid and thyroid hormones in cold-acclimatized and non-acclimatized humans. Endocrinology 161 (7). https://doi.org/10.1210/endocr/bqaa051 bqaa051.

Lee, P., Brychta, R.J., Collins, M.T., Linderman, J., Smith, S., Herscovitch, P., Millo, C., Chen, K.Y., Celi, F.S., 2013. Cold-activated brown adipose tissue is an independent predictor of higher bone mineral density in women. Osteoporos. Int. : J. Result Cooperat. Between Europ Foundat. Osteoporosis Nat. Osteoporosis Found. USA 24 (4), 1513–1518. https://doi.org/10.1007/s00198-012-2110-y.

Machado, A.F., Ferreira, P.H., Micheletti, J.K., et al., 2016. Can water temperature and immersion time influence the effect of cold water immersion on muscle soreness? A systematic review and meta-analysis. Sports Med. 46, 503–514. https://doi.org/10.1007/s40279-015-0431-7.

Motyl, K.J., Bishop, K.A., DeMambro, V.E., Bornstein, S.A., Le, P., Kawai, M., Lotinun, S., Horowitz, M.C., Baron, R., Bouxsein, M.L., Rosen, C.J., 2013. Altered thermogenesis and impaired bone remodeling in Misty mice. J. Bone Miner. Res. : Off. J. Am Soc. Bone Mineral Res. 28 (9), 1885–1897. https://doi.org/10.1002/jbmr.1943.

Motyl, K.J., Rosen, C.J., 2011. Temperatures rising: brown fat and bone. Discov. Med. 11 (58), 179–185.

Mu, S., Xia, Y., Wu, Q., Ji, C., Dai, H., Zhang, M., Jiao, J., Shi, F., Liu, S., Wang, G., Shen, T., Tian, Y., Yang, L., Fu, Q., Zhao, Y., 2021. Response of bone metabolism markers to ice swimming in regular practitioners. Front. Physiol. 12, 731523. https://doi.org/10.3389/fphys.2021.731523.

Mu, S., Huang, C., Chen, B., Zhao, P., Xu, H., Zhang, W., Dai, H., 2023. Sclerostin decreases in regular swimmers after ice swimming and is associated with meteorin-like protein serum levels. Front. Physiol. 14, 1210457. https://doi.org/10.3389/fphys.2023.1210457.

Ouzzani, M., Hammady, H., Fedorowicz, Z., Elmagarmid, A., 2016. Rayyan-a web and mobile app for systematic reviews. Syst. Rev. 5 (1), 210. https://doi.org/10.1186/s13643-016-0384-4.

Rao, R.R., Long, J.Z., White, J.P., Svensson, K.J., Lou, J., Lokurkar, I., Jedrychowski, M. P., Ruas, J.L., Wrann, C.D., Lo, J.C., Camera, D.M., Lachey, J., Gygi, S., Seehra, J., Hawley, J.A., Spiegelman, B.M., 2014. Meteorin-like is a hormone that regulates immune-adipose interactions to increase beige fat thermogenesis. Cell 157 (6), 1279–1291. https://doi.org/10.1016/j.cell.2014.03.065.

Reginster, J.Y., Burlet, N., 2006. Osteoporosis: a still increasing prevalence. Bone 38 (2 Suppl. 1), S4–S9. https://doi.org/10.1016/j.bone.2005.11.024.

Robbins, A., Tom, C.A.T.M.B., Cosman, M.N., Moursi, C., Shipp, L., Spencer, T.M., Brash, T., Devlin, M.J., 2018. Low temperature decreases bone mass in mice: implications for humans. Am. J. Phys. Anthropol. 167 (3), 557–568. https://doi.org/10.1002/ajpa.23684.

Salhotra, A., Shah, H.N., Levi, B., Longaker, M.T., 2020. Mechanisms of bone development and repair. Nat. Rev. Mol. Cell Biol. 21 (11), 696–711. https://doi.org/10.1038/s41580-020-00279-w.

Sanchez-Delgado, G., Martinez-Tellez, B., Garcia-Rivero, Y., Acosta, F.M., Alcantara, J.M. A., Amaro-Gahete, F.J., Llamas-Elvira, J.M., Gracia-Marco, L., Ruiz, J.R., 2019. Association between brown adipose tissue and bone mineral density in humans. Int. J. Obes. 43 (8), 1516–1525. https://doi.org/10.1038/s41366-018-0261-4, 2005.

Savourey, G., Barnavol, B., Caravel, J.P., Feuerstein, C., Bittel, J.H., 1996. Hypothermic general cold adaptation induced by local cold acclimation. Eur. J. Appl. Physiol. Occup. Physiol. 73 (3–4), 237–244. https://doi.org/10.1007/BF02425482.

Serrat, M.A., 2013. Allen's rule revisited: temperature influences bone elongation during a critical period of postnatal development. Anat. Rec. 296 (10), 1534–1545. https://doi.org/10.1002/ar.22763. Hoboken, N.J. : 2007.

Śliwicka, E., Cisoń, T., Straburzyńska-Lupa, A., Pilaczyńska-Szcześniak, Ł., 2020. Effects of whole-body cryotherapy on 25-hydroxyvitamin D, irisin, myostatin, and interleukin-6 levels in healthy young men of different fitness levels. Sci. Rep. 10 (1), 6175. https://doi.org/10.1038/s41598-020-63002-x.

Sözen, T., Özışık, L., Başaran, N.Ç., 2017. An overview and management of osteoporosis. Europ J. Rheumatol. 4 (1), 46–56. https://doi.org/10.5152/eurjrheum.2016.048.

Srámek, P., Simecková, M., Janský, L., Savlíková, J., Vybíral, S., 2000. Human physiological responses to immersion into water of different temperatures. Eur. J. Appl. Physiol. 81 (5), 436–442. https://doi.org/10.1007/s004210050065.

Straburzyńska-Lupa, A., Cisoń, T., Gomarasca, M., Babińska, A., Banfi, G., Lombardi, G., Śliwicka, E., 2021. Sclerostin and bone remodeling biomarkers responses to whole-body cryotherapy (- 110 °C) in healthy young men with different physical fitness levels. Sci. Rep. 11 (1), 16156. https://doi.org/10.1038/s41598-021-95492-8.

Tricco, A.C., Lillie, E., Zarin, W., O'Brien, K.K., Colquhoun, H., Levac, D., Moher, D., Peters, M.D.J., Horsley, T., Weeks, L., Hempel, S., Akl, E.A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M.G., Garritty, C., Lewin, S., et al., 2018. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann. Intern. Med. 169 (7), 467–473. https://doi.org/10.7326/M18-0850.

Wherry, S.J., Swanson, C.M., Wolfe, P., Wellington, T., Boxer, R.S., Schwartz, R.S., Kohrt, W.M., 2019. Bone biomarker response to walking under different thermal conditions in older adults. Med. Sci. Sports Exerc. 51 (8), 1599–1605. https://doi.org/10.1249/MSS.0000000000001967.

Xue, Y., Fleet, J.C., 2009. Intestinal vitamin D receptor is required for normal calcium and bone metabolism in mice. Gastroenterology 136 (4). https://doi.org/10.1053/j.gastro.2008.12.051, 1317–e2.

Yoshitake, F., Itoh, S., Narita, H., Ishihara, K., Ebisu, S., 2008. Interleukin-6 directly inhibits osteoclast differentiation by suppressing receptor activator of NF-kappaB signaling pathways. J. Biol. Chem. 283 (17), 11535–11540. https://doi.org/10.1074/jbc.M607999200.

Yurkevicius, B.R., Alba, B.K., Seeley, A.D., Castellani, J.W., 2021. Human cold habituation: physiology, timeline, and modifiers. Temperature (Austin, Tex.) 9 (2), 122–157. https://doi.org/10.1080/23328940.2021.1903145.