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Skin temperature of the knee was effectively reduced when using a new continuous cold-flow cryocompression device: a randomised controlled crossover trial☆

James Belsey*, Ryan Gregory, Eloise Paine, James Faulkner

University of Winchester, Department of Sport, Health & Community, Sparkford Road, Winchester, United Kingdom

Abstract

Objective To determine which temperature settings on a new continuous cold-flow cryocompression device effectively reduce knee skin temperature to 10–15 °C, where pain and swelling are expected to be attenuated.
Design Randomised controlled crossover trial.
Setting University laboratory.
Participants 32 healthy adult participants recruited (1 dropout) with no contraindications to cryocompressive therapy.
Intervention A k-type thermocouple was used to record skin temperature at baseline and every five minutes during a 30-minute cryocompression treatment in a control condition and when using four different device temperature settings (6 °C, 8 °C, 10 °C, and 12 °C) on a continuous cold-flow cryocompression device. Conditions were labelled Control, Con-6, Con-8, Con-10, and Con-12, respectively.
Main outcome measures Skin temperature change (°C) throughout cryocompression; time taken (mins) to achieve skin temperature < 15 °C; and the difference between final skin temperature and device temperature setting (°C).
Results Median (IQR) skin temperature after cryocompression was 32.1 °C (29.3–33.4), 12.8 °C (12.1–14.6), 14.3 °C (13.8–15.7), 16.1 °C (15.2–17.3), and 17.7 °C (16.9–18.9) for the Control condition and Con-6, Con-8, Con-10 and Con-12, respectively. It took 20 min (Con-6) and 25 min (Con-8) for skin temperature to reach < 15 °C. A median (IQR) difference of 6.8 °C (6.1–8.6), 6.3 °C (5.8–7.7), 6.1 °C (5.2–7.3), and 5.7 °C (4.9–6.9) for Con-6, Con-8, Con-10, and Con-12, respectively was observed between device temperature setting and final skin temperature.
Conclusions The device is recommended as it reduced skin temperature to the therapeutic range of 10–15 °C during a 30-minute treatment when using the 6 °C or 8 °C device temperature settings. Future research should determine optimal treatment lengths for cryocompression.

Contribution of the Paper

- The Physiolab S1 cryocompression device allows users to determine precise temperatures of the ice-water that is circulated around the knee during a treatment.
- This paper demonstrates the ability of each temperature setting to reduce skin temperature around the knee to within the target therapeutic range of 10–15 °C.
- There is a significant discrepancy between the temperature setting of the device and the skin temperature achieved during a treatment.
- Clinicians should not assume that all temperature settings on this and similar devices sufficiently reduce skin temperature of the knee to confer a therapeutic benefit.

Keywords: Cryotherapy; Skin temperature; Rehabilitation; Arthroplasty; Arthroscopy

☆ Clinical trial registration number: NCT05136482.

* Corresponding author.
E-mail address: KneeResearch@pm.me (J. Belsey).

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Introduction

The application of cold and pressure to the skin around an affected area is commonly used as part of standard rehabilitation protocols for patients recovering from joint surgeries [1–3]. Traditionally, cryotherapy has comprised the application of ice to an affected area, and has been used for centuries for its analgesic effect and to limit the negative effects of inflammation [1,4]. The addition of compression to cryotherapy is traditionally achieved through the addition of a bandage around an ice pack, and is thought to further enhance improvements in pain and swelling by aiding vasoconstriction, thereby reducing bleeding and aiding venous return [5,6].

Recent advances in technology have resulted in the development of electronic devices that are able to deliver a continuous cold-flow of temperature-controlled water to a cuff wrapped around the leg, while simultaneously exerting either intermittent or static compression to the treatment area. The introduction of continuous cold-flow cryocompression devices within rehabilitation protocols provides patients and clinicians with greater confidence over the precise temperatures applied to the affected area for the duration of a treatment compared to ice packs, which begin to increase in temperature as soon as they are removed from the freezer. The combination of compression and cold application by such a device has been shown to cause a greater decrease in local skin and muscular temperature than when no compression is applied [7]. Clinically, a number of studies have demonstrated superior post-operative outcomes (pain, swelling, range-of-motion, and use-of-analgesia) with continuous cold-flow cryocompression devices compared to more traditional methods like ice packs and bandages, though consistency regarding the temperature and pressure settings of the investigated devices is lacking [1,8–10]. Although cryocompression has been shown to have a greater impact on local temperature than cryotherapy alone [7], there is no current consensus regarding the capability of modern cryocompression devices to provide an effective treatment when using the various temperature and pressure settings available.

Previous studies have suggested that cryocompression therapies need to reduce the skin temperature within the treatment area to within 10–15 °C in order for intra-articular temperatures to decrease sufficiently for pain and swelling reductions to be achieved [11–17]. When skin temperature around the knee is reduced to below 15 °C nerve conduction velocity is impeded and vasoconstriction occurs [3,11]. The impedance of nerve conduction velocity dampens signal transmission to the brain, which increases an individual's pain tolerance threshold and provides an analgesic effect [1]. Vasoconstriction reduces blood flow to the damaged area, which reduces the amount of local oedema, blood loss, and pro-inflammatory metabolic activity [1,18]. Skin temperatures below 10 °C result in an increased risk of adverse events such as cold injury (e.g. frostbite) and should be avoided [19].

Newer continuous cold-flow cryocompression devices allow the user to select from a range of water temperatures to be circulated through the cuff during a treatment. However, little is known as to the degree to which different device temperature settings influence the effectiveness of a treatment, and whether device settings result in a skin temperature within the target therapeutic zone of 10–15 °C. Existing literature either does not state the temperature setting used during the investigation [8,20,21], or only used a subjective rationale for the selected temperature setting [2,9,17,22–26]. Understanding the relationship between device temperature settings and skin temperature would help increase the likelihood that users receive a treatment that is beneficial. This information could then be used to provide individualised treatment protocols.

The research question for this study was: can the Physiolab S1 continuous cold-flow cryocompression device reduce skin temperature of the knee to the target therapeutic zone of 10–15 °C ? To our knowledge, no other study has investigated the degree to which different temperature settings on a device match and affect the skin temperature that is achieved during a treatment.

It was hypothesised that the device would successfully lower skin temperature to within this range during a standard treatment, but that there would be a difference within each condition between the device setting and the final temperature measured at the skin.

Materials and methods

Design

This randomised controlled crossover trial used a random number generator to assign the test order for each participant. Randomisation was carried out by the lead author, and two of the authors (JB and RG) were responsible for participant enrolment. Five conditions – a control plus four different device temperature settings (6 °C, 8 °C, 10 °C, 12 °C) - were completed by each participant. These conditions were labelled Control, Con-6, Con-8, Con-10, and Con-12, respectively. The control condition comprised the cryocompression device being applied to the participant without any cold or pressure delivery. The device used in the present study was a Physiolab S1 cryocompression device (Physiolab Technologies Ltd, Milton Keynes, UK), which consists of an electronic central unit connected via insulated tubing to a knee cuff (Fig. 1).

A random number generator selected the leg of each participant that was used for the duration of the study. A minimum of 24 h was left between tests with the same participant to allow the leg to fully return to a baseline temperature before the next treatment. All tests took part within a laboratory environment and informed consent was obtained in advance. Ethical approval was granted by the University of Winchester, Faculty of Health & Wellbeing ethics committee and the study was pre-registered in the

Fig. 1. The Physiolab S1 continuous cold-flow cryocompression device.

Table 1
Exclusion criteria.

- Body mass index > 40 kg/m^2
- History of nerve damage or sensory deficit in the lower limbs (inc. frostbite)
- Hypersensitivity to cold (inc. hives)
- Active inflammation or pain of the knee
- History of thrombosis, embolism, or other conditions related to impaired peripheral circulation
- Suffering from diagnosed diabetes, multiple sclerosis, rheumatoid arthritis, spinal cord injury, cardiovascular disease, hypertension, Raynaud's phenomenon, cryoglobulinemia, or hemoglobinuria
- Confirmed or suspected tissue infection, an unstable fracture, a skin condition, or tumour in the treatment area
- Cognitive impairment or communication barriers

ClinicalTrials.gov registry (ID: NCT05136482). A power analysis was conducted a-priori, which showed that 30 participants (150 observations) would be required to achieve a power of 0.8 and alpha error of 0.05, for a small-medium effect size of f= 0.2.

Participants

32 healthy adult participants (median age 25 years; median BMI 24.6 kg/m^2; 22 males) were recruited from a university population between November 2021 and May 2022. Participants were screened prior to testing to avoid including anyone who would be normally contraindicated for cryocompression therapy (Table 1), as defined by the device manufacturer's guidelines and previously determined common contraindications for this type of treatment [12,16,17].

Intervention

Participants were positioned in a seated position on a physiotherapy bed with the bed head raised to degrees and with their legs in full extension parallel to the floor, to allow the device to be applied in accordance with the manufacturer's guidelines. A k-type thermocouple was then taped 20 mm distal to the patella to measure skin temperature during testing. The Physiolab S1 cryocompression device was then applied to the leg of the participant, with the knee positioned centrally within the cuff. The participant then received a cryocompression treatment depending on the randomly assigned test condition (Control, Con-6, Con-8, Con-10, Con-12). The device was set to its static pressure setting (25 mmHg) for the duration of each test.

Skin temperature measurement

Upon arrival, participants were first allowed to acclimatise to the laboratory environment. They were seated in the position for testing with the thermocouple attached to their knee and had their skin temperature measured every minute for 5 min or until the temperature values were consistent to within 0.5 °C for 3 consecutive minutes; whichever was longest. Once the acclimatisation period had begun, participants were not allowed to move from their seated position until all testing had been completed.

Single time-point skin temperature measurements were taken immediately following the acclimatisation period and prior to the application of the cryocompression device to the leg; and then every 5 min during a treatment. The device was applied for 30-minutes per test before the cuff was removed. If skin temperature was below 15 °C at the end of a 30-minute test, it was further monitored every 5 min until it rose above 15 °C. This allowed for the total time spent with skin temperature within the target therapeutic zone of 10–15 °C to be measured. If skin temperature did not reach this threshold during the treatment, the cuff was removed from the leg and the test was ended.

Outcome measures

The primary outcomes were changes in skin temperature over time compared to baseline values within each condition; and differences in skin temperature over time between conditions. The time taken to achieve a skin temperature of 10–15 °C - and the time spent within this range - were secondary outcomes. Finally, the mean difference between device temperature settings and measured skin temperature settings at the end of a test was also measured.

Data analysis

A Kolmogorov-Smirnov test was first conducted, which indicated that the data were not normally distributed. Therefore, a Friedman test was conducted to analyse changes in skin temperature changes over time within conditions. A Kruskal-Wallis test was conducted to analyse differences in skin temperature between conditions at each measurement point. Where relevant, Dunn's test for multiple comparisons and a Wilcoxon test was performed post-hoc. A Mann-Whitney test was conducted to determine whether binary demographic characteristics (leg and sex) influenced the outcomes. Finally, a Spearman correlation was used to identify any relationships between skin

Table 2
Participant demographics.

Participants (n)	31
Median (IQR) age (y)	25 (21-36)
Sex (M:F)	22:9
Leg (L:R)	15:16
Median (IQR) height (m)	1.76 (1.72-1.82)
Median (IQR) mass (kg)	76.3 (67.0-82.0)
Median (IQR) BMI (kg/m^2)	25 (22-27)

IQR Interquartile Range (Q1 - Q3)
BMI = Body mass index

temperature and the continuous demographic variables (age, height, mass, and BMI). Correlation coefficients of 0.3–0.5, 0.5–0.7, and > 0.7 were considered low, moderate, and high, respectively [27]. All statistical analysis was performed using IBM SPSS Statistics 27 software and differences were considered significant if $p < 0.05$.

Results

Baseline measures

32 participants were recruited for this study but one withdrew after three tests. Therefore, the results presented are based on the remaining 31 participants. Full demographic information of these participants can be found in Table 2.

The mean (SD) ambient temperature for each test was 20.5 (0.2) °C and there were no significant differences in ambient temperature between test conditions. The mean (SD) baseline skin temperature for each test was 30.4 (0.3) °C and there were no significant differences in baseline skin temperature between test conditions.

Skin temperature during cryocompression

A significant increase in skin temperature was detected over time within the control condition, and a significant decrease in skin temperature was detected over time within all other conditions (Fig. 2; $p < 0.001$). Significant differences were also detected between all conditions over time ($p < 0.001$). Median skin temperature after a 30-minute cryocompression treatment was 32.1 °C (IQR 29.3–33.4), 12.8 °C (IQR 12.1–14.6), 14.3 °C (IQR 13.8–15.7), 16.1 °C (IQR 15.2–17.3), and 17.7 °C (IQR 16.9–18.9) for the Control condition and Con-6, Con-8, Con-10, and Con-12, respectively.

Con-6 and Con-8 achieved median skin temperatures within the target therapeutic range of 10–15 °C after 20 min (14.6 °C; IQR 13.6–16.2) and 25 min (15.0 °C; IQR 14.4–16.6) of cryocompression, respectively. 74% of participants in Con-6, 65% in Con-8%, and 16% in condition Con-10 achieved a skin temperature within the target therapeutic range of 10–15 °C during the 30-minute cryocompression treatment (Fig. 3). None of the participants in the Control condition or Con-12 achieved skin temperatures within this target zone. Of the participants who achieved a skin temperature of 10–15 °C within the 30-minute treatment, 52% in Con-6 (n = 12), 50% in Con-8 (n = 10), and 20% in Con-10 (n = 1) remained within this range 5 min after the removal of the cuff (median 13.4 °C [IQR 12.6–13.9], 14.5 °C [IQR 14.2–14.8], and 14.5 °C, respectively). No participants remained within the 10–15 °C range 10 min after the removal of the cuff.

The median difference between the temperature of the ice-water being circulated by the device, and the temperature at the skin after 30 min of cryocompression was 6.8 °C IQR 6.1–8.6) for Con-6, 6.3 °C (IQR 5.8–7.7) for Con-8, 6.1 °C (IQR 5.2–7.3) for Con-10, and 5.7 °C (IQR 4.9–6.9) for Con-12. It was not relevant to record this difference for

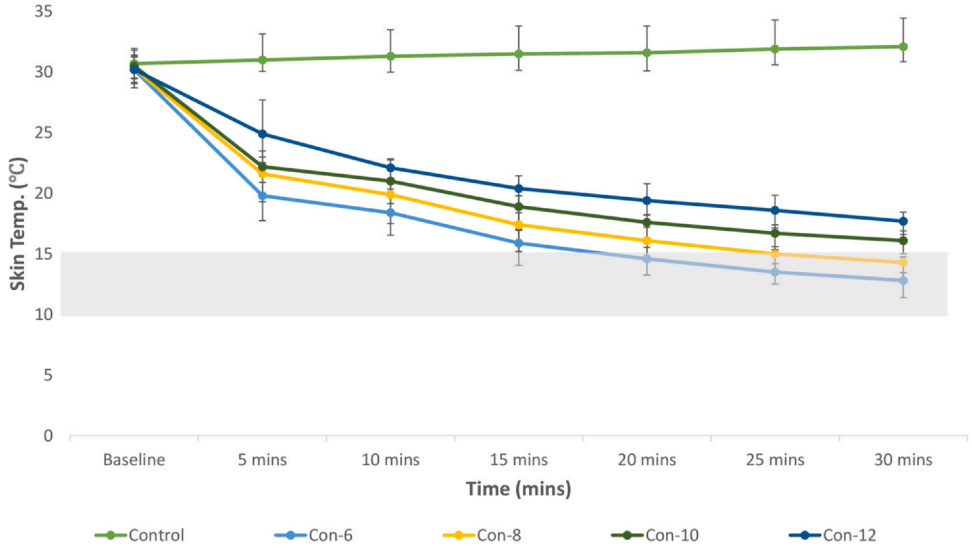

Fig. 2. Median skin temperature during cryocompression treatments for all conditions. Shaded area indicates the target therapeutic zone of 10–15 °C. Error bars indicate interquartile range.

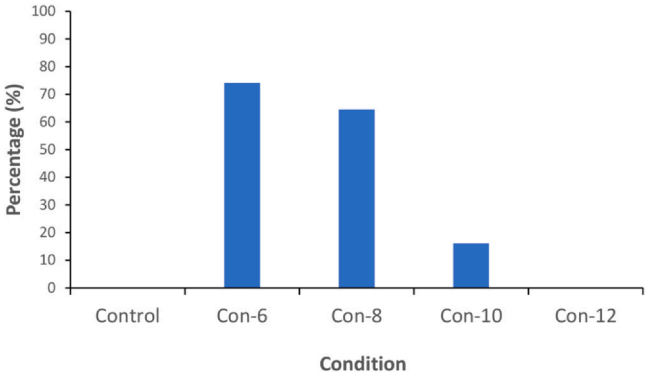

Fig. 3. Percentage of participants within each condition to achieve a skin temperature within the target therapeutic zone of 10–15 ℃.

the Control condition since no water was circulated through the device during tests in this condition.

No significant relationships were detected between skin temperatures and age, height, sex, or leg in all conditions. Significant low-moderate positive correlations were detected between skin temperature and the demographic variables of mass (Table 3) and BMI (Table 4) in Con-6, Con-8, Con-10, and Con-12.

Discussion

The question asked for this study was whether the Physiolab S1 continuous cold-flow cryocompression device could reduce skin temperature of the knee to the target therapeutic zone of 10–15 °C ? The main finding from this study, and in support of our hypotheses, was that the Physiolab S1 cryocompression device was successfully able to reduce knee skin temperature to the therapeutic range of 10–15 °C within a 30-minute treatment. However, this was mostly only achieved when the 6 °C or 8 °C device temperature settings were used. An observed rise in skin temperature within the control condition (median 0.9 [IQR 0.3–1.8]) was likely attributable to a mild insulating effect caused by the cuff that was worn for 30-minutes with no cold water circulating through it. A consistent discrepancy of approximately 6 °C was observed between the temperature of the ice-water within the device – regardless of the setting used – and the final skin temperature after a 30-minute treatment. Finally, low-moderate positive correlations were observed between BMI, mass, and skin temperature during continuous cold-flow cryocompression.

The aim of cold application after knee surgery is to lower the intra-articular temperature of the joint, thereby conferring a clinical benefit to the patient. The normal intra-articular temperature of the adult knee is 30–33 °C [18–20] and a decrease in temperature to below 30 °C is required to cause a reduction in the metabolic activity that causes inflammation after trauma [28-30]. A reduction of skin temperature to below 20 °C has been reported to be the point at which changes in intra-articular begin to occur [14], with skin temperatures of 10–15 °C being the optimal range to confer the therapeutic benefits of cold application while minimising the risks of cold injury [4,10,12,14,21–24]. Median skin temperatures in the present study were reduced to within this range when the Physiolab S1 cryocompression device was set to circulate ice-water at 6 °C or 8 °C throughout the treatment. The 10 °C and 12 °C settings did not sufficiently reduce skin temperature to < 15 °C.

Table 3
Correlations between skin temperature and body mass (Spearman's *rho*).

Condition	Baseline	5 mins	10 mins	15 mins	20 mins	25 mins	30 mins
Control	0.08	0.16	0.18	0.23	0.26	0.26	0.29
Con-6	0.09	0.41†	0.50*	0.50*	0.49*	0.44†	0.35
Con-8	-0.02	0.20	0.37†	0.34	0.44†	0.42†	0.36†
Con-10	0.31	0.18	0.26	0.26	0.27	0.37†	0.29
Con-12	-0.08	0.43†	0.43†	0.42†	0.33	0.27	0.33

† significant correlation ($p < 0.05$).
* significant correlation ($p < 0.01$).

Table 4
Correlations between skin temperature and BMI (Spearman's *rho*).

Condition	Baseline	5 mins	10 mins	15 mins	20 mins	25 mins	30 mins
Control	-0.02	0.06	0.06	0.12	0.15	0.17	0.19
Con-6	0.09	0.57 *	0.67 *	0.58 *	0.53 *	0.46 *	0.34
Con-8	0.07	0.24	0.55 *	0.48 *	0.55 *	0.55 *	0.49 *
Con-10	0.12	0.02	0.20	0.17	0.15	0.26	0.21
Con-12	-0.28	0.38†	0.45†	0.48 *	0.41†	0.36†	0.36†

† significant correlation ($p < 0.05$).
* significant correlation ($p < 0.01$).
BMI = Body Mass Index.

The greatest drop in skin temperature was observed within the first 5 min in each of the experimental conditions, which is in line with previous research [3]. Skin temperature continued to reduce throughout the treatments, but at a slower rate at each time point. The cryocompression device successfully reduced the skin temperature to within the target therapeutic range in two of the test conditions, although it took 20 min (Con-6) and 25 min (Con-8) for this to occur. This means that the majority of the duration of the 30-minute treatment was spent cooling the knee to the target therapeutic range of 10–15 °C. This is likely a limiting factor regarding the time-per-treatment that a patient receives the benefit of the therapy. Following a treatment, skin temperature remained within this range for an additional 5–10 min. Therefore, the average time spent with skin temperature within the target range was 15–20 min for Con-6 and 10–15 min for Con-8. The optimal duration of cryocompression treatments remains contentious, with standard guidelines historically suggesting between 15 and 30 min [31], while various studies have successfully applied cryocompression devices continuously for a number of hours with an apparently low risk of complications [18,32–35]. Additional research is required to determine optimal treatment durations with devices like the Physiolab S1.

Previous research has demonstrated that the use of ice packs tended to reduce skin temperature to < 15 °C during a 30-minute treatment [15,28,29], whereas this was not always the case for cryocompression devices [15,29,36,37]. The indication that different cryocompression devices reduce skin temperature to varying degrees demonstrates that they all function differently and do not all reduce skin temperatures to the target 10–15 °C range. One study that used ice packs reported skin temperatures as low as 8 °C after a 30-minute application [29], which is notable since skin temperatures < 10 °C begin to increase the risk of cold injury to the patient [11,19,38]. In contrast, the lowest recorded skin temperature from any participant in the present study was 10.6 °C. These differences in minimum skin temperatures between ice packs and cryocompression devices is likely due to the shallower thermal gradient between the skin and the device circulating cold water, compared to an ice pack at approximately 0 °C. This provides further justification for treatment duration recommendations to be reviewed, and to not merely mirror historic guidelines for ice application [31].

There was a discrepancy of approximately 6 °C in all conditions between the device temperature setting and skin temperature at the end of a treatment. Similar discrepancies between device temperature and skin temperature have also been observed in previous research. Khoshnevis et al. [37] measured skin temperature after 1 h of cryocompression therapy with an Arctic Ice cryotherapy unit, which circulated water at 2.4 °C, resulting in a mean skin temperature of 16.6 ± 0.3 °C. Priego-Quesada et al. [22] recently published a similar study using a GameReady cryocompression device set to circulate water at 0–3 °C, which resulted in minimum average skin temperatures of around 18 °C. Selfe et al. [15] conducted a study comparing the skin temperatures achieved by three different methods of cryotherapy, which ranged in pre-application temperatures between 4 °C and 8 °C, resulting in skin temperatures between 14 °C and 24 °C after a 20-minute treatment. These findings and those of the present study indicate that temperature equilibrium between device and skin is typically not achieved during a treatment, resulting in a discrepancy between the device temperature setting and the actual skin temperature achieved. The results of the present study suggest that the Physiolab S1 should be set to circulate water at 6 °C or 8 °C to increase the probability that skin temperature is reduced to within 10–15 °C during a 30-minute treatment.

Low-moderate positive correlations were observed in the present study for Con-6, Con-8, Con-10, and Con-12 between skin temperature and the demographic variables of mass and BMI (Tables 3 and 4). This is in line with the findings of a literature review by Bleakley and Hopkins [3], who noted that increased skinfold thickness acts as an insulating layer, making large temperature reductions more difficult to induce during cryocompression therapy compared to leaner individuals with low subcutaneous adiposity. Consequently, patients with high mass or BMI should be advised to use the lowest temperature setting on the Physiolab S1 to maximise the likelihood of receiving a therapeutic benefit. More research is needed to confirm the limits of these recommendations and to define what would be considered a BMI or mass requiring a colder temperature setting.

This was the first study to use the Physiolab S1 and the data demonstrated that it was capable of successfully reducing skin temperature to within 10–15 °C when using the 6 °C and 8 °C device temperature settings. At no point in the present study was the skin temperature of a participant lowered to < 10 °C, suggesting that the Physiolab S1 can be used to provide an effective cold treatment to the knee, without increasing the risk of the occurrence of cold injury. This now needs to be confirmed in clinical trials.

A major strength of this study was the randomised crossover design, which helped to reduce bias and remove the impact of potential confounding demographic variables on the collected data. The study was limited by the single location around the knee at which skin temperature was measured. It is possible that skin temperatures may have differed if they were measured, for example, around the posterior knee due to differences in blood vessel location relative to the surface of the skin. Future research should measure skin temperature at various sites around the knee to provide a more comprehensive overview of the body's response to cryocompression around the whole joint. A further limitation is that cryocompression was applied directly to the skin of participants in the present study rather than over a wound dressing, as would more usually be the case in a post-operative setting. Previous

research has demonstrated that wool and crepe dressings significantly impair the ability for cryotherapy to be delivered effectively [3,39]. However, using a cryocompression device over a thin adhesive dressing has been shown to result in similar skin temperatures compared to the device being applied directly to the skin [39]. Therefore, the results of this study can only be extrapolated to clinical settings where cryocompression is applied over the latter type of dressing or to the exposed skin of swollen, painful areas.

Conclusion

The Physiolab S1 continuous cold-flow cryocompression device ice was capable of reducing skin temperature to within the therapeutic range of 10–15 °C within a 30-minute treatment when using the 6 °C or 8 °C device temperature settings. It should be noted that a discrepancy of approximately 6 °C existed between device temperature setting and skin temperature after 30 min of cryocompression. BMI and mass had a low-moderate positive correlation with skin temperature during cryocompression therapy and this relationship requires further investigation. Future research should investigate the effects of different devices and should determine optimal treatment duration to further improve outcomes for patients.

Ethical approval

The University of Winchester Faculty of Health & Wellbeing ethics committee approved this study. All participants gave written informed consent before data collection began.

Competing interests

JB receives monetary compensation for clinical research consultancy from Physiolab Technologies Ltd. The remaining authors have no competing interests to declare.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.physio.2023.12.001.

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