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Physiological Parameters in Response to Levels of Pressure during Contemporary Cryo-Compressive Applications Implications for Protocol Development

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Abstract

Background The effectiveness of simultaneous dosages of compression and cryotherapy that cryo-compressive devices can offer are of interest in the management of sports injury or post-exercise recovery. Dose-response in terms of physiological parameter is required to inform current practice in the remit of sports medicine to help define optimal protocols for application. The current study aimed to investigate the physiological effects and subjective responses of different cryo-compression dosages offered by two cryo-compressive devices over a rewarming period. Methods Twenty-nine healthy male and female participants (male n=18; female n=11) volunteered (mean ± SD: age 22 ± 3.6 years, height 168.2 ± 8.6 cm, weight 67.4 ± 11.5 kg and thigh circumference 50.7 ± 6.7 cm). Objective measures included skin surface temperature, muscle oxygenation saturation, thermal comfort and sensation. Data were collected pre, immediately post and over a 20-minute rewarming period. Participants were randomly assigned to either Group A (Game Ready); B (Squid) or C Control group. Intervention groups received different cryo-compressive protocols for testing, but all received 15-minutes of cooling. Results Significant reductions in skin surface temperature were displayed across the intervention groups for all time-points ($p \leq 0.05$). Analysis of all data displayed a significant effect of time ($p \leq 0.001$) on muscle oxygenation. Collapse of the data indicated significant differences in muscle oxygenation across the different modalities and pressure ($p \leq 0.05$). Conclusion Muscle oxygenation saturation and skin surface temperature responses differ depending on pressure dose in conjunction with cooling. Higher initial increases of muscle oxygenation saturation immediately post intervention correlate to higher levels of compression. Greater magnitudes of cooling can be achieved through the adjunct of compression. Dose-response relationships between cooling and simultaneous compression should be considered and are dependent on the therapeutic aim of treatment. In order to develop optimum protocols for management of either injury or recovery parameters further investigation is required of contemporary cryo-compressive devices.

Keywords

Cryotherapy; Physiology; Muscle oxygenation; Skin temperature; Compression

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Introduction

Cooling for post-exercise recovery or injury management is common practice within sport, with the belief that recovery characteristics benefit from such protocols [1-3]. Symptoms of delayed onset muscle soreness (DOMS) for example reportedly reduce following cryotherapeutic interventions due to positive physiological responses [2,4]. Cryo-compressive devices aim to provide simultaneous cooling and compression for sports injury and enhance recovery benefits. With recent literature, reporting positive influences on performance recovery parameters [5]. Nevertheless, several questions remain that surround the effects of cooling and simultaneous compression on physiological parameters such as SmO_2, and optimal protocols are unsubstantiated from the variability in methodologies published. Thus providing confusing conclusions for sport medicine practitioners unsure on the differences that may exist between cryo-compressive devices, settings and outcomes for optimal applications, Previous literature reports decreases in SmO_2 following cold-water immersion [6,7] it is suggested that compression aids the magnitude of cooling [8-10]. Conversely, isolated external compression is reported to increase SmO_2 [11,12]. To what extent the physiological response of muscle oxygenation is affected by such applications that combine cooling with compression therefore is still under contention.

Measurements of muscle oxygen saturation (SmO_2) and skin surface temperature (T_{sk}) support the understanding of the potential effects local cryotherapy may have on objective markers [3]. Prominently observed in literature, a local cryotherapy application initiates the reduction of T_{sk}, skin blood flow, and muscle oxygenation [13]. The ratio of oxyhaemoglobin concentration to total haemoglobin concentration in the muscle reported as a percentage, is useful in providing real-time physiologic feedback. Indicators of muscle metabolic activity can be noninvasively monitored by collating muscle oxygenation and haemodynamic, with such devices as MOXY sensors (MOXY, Swinco, and Zurich, Switzerland). Previously studies have demonstrated decreases SmO_2 following cooling applications of cold-water immersion [3,6,7]. Simultaneous dosages of compression (mmHg) and cryotherapy that cryo-compressive devices can offer are of interest in the management of sports injury or post-exercise recovery. Consequently, the effectiveness of these devices for injury or recovery management in sport is warranted. An insight as to whether different physiological effects occur after exposures to different cryo-compression dosages is important to inform current practice in the remit of sports medicine. Over a rewarming period, the current study aimed to investigate the physiological effects and subjective responses of different cryo-compression dosages offered by two cryo-compressive devices. We hypothesised that higher compressive dosages would result in greater magnitude of cooling, demonstrating larger reductions in $T_{sk,}$ and subsequently greater reductions in SmO_2.

Materials and Methods

Participants

The host university ethics committee, in accordance with the Declaration of Helsinki, agreed approval of the study. Participants were provided with information regarding study protocol prior to

providing written and verbal consent to take part. The sample size of participants was based on a recently similar methodology [3] and determined using G*Power (version 3.1.10). *A priori* power calculation conducted using pilot data completed by participants matching the criteria determined a minimum sample size of ≥ 21 players required to evaluate the interactions associated with all independent variables (for statistical power >0.8; $p \leq 0.05$). Twenty-nine healthy male and female participants (male n=18; female n=11) volunteered for the study (mean ± SD: age 22 ± 3.6 years, height 168.2 ± 8.6 cm, weight 67.4 ± 11.5 kg and thigh circumference 50.7 ± 6.7 cm) meeting the recommended sample size. All participants took part in land-based university sports. Participants were excluded if they presented with any of the following; any current pain symptoms, reaction to cold (such as Raynauds), pre-existing lower limb injury; cardiovascular disease, cardiac pacemaker or arrhythmia, under any prescribed medication or were smokers. Participants were randomised to either intervention Group (A) (Game Ready®) or intervention Group (B) (Portable Therapeutix Squid Model One Compression device and Cold Pack "Squid") or the Control Group (C) *via* randomisation.com.

Experimental design

Ambient room temperature recorded at 21.5 ± 1.6°C, reported a relatively consistent environmental condition throughout testing. Participant's anthropometric data was collated during a 15-minute acclimatisation period. Data was captured from participants dominant limb, the participant's dominant limb was determined by asking each participant, "If you would shoot a ball on a target, which leg would you use to shoot the ball?" [14]. Baseline testing consisted of T_{sk} captured over the anterior thigh region determined by a region of interest (ROI) [15,16] and SmO_2 data from the rectus femoris muscle in the dominant lower limb. T_{sk} measures were captured using an infrared thermal imaging camera (ThermoVision A40M: Flir Systems, Danderyd, Sweden) following gold-standard recommendations [17,18]. The thermal imaging camera was positioned perpendicular to the anterior lower limb, set at a height of 132 cm from the ground and adhered to TISEM Guidelines [19]. To create the ROI, thermally inert wooden markers were applied to the anterior thigh to create a framework that was identifiable for analysis [15]. Markers were located superiorly (one-third between ASIS-Base of Patella), inferiorly (two-thirds between ASIS-Base of Patella) and central thigh, measured from thigh circumference located at 50% between ASIS and base of the patella [16]. To determine the ROI the markers were placed at a 10% distance from these points to distinguish the anterior thigh region for T_{sk} measurement.

SmO_2 measures were chosen due to extensive reports as a haemodynamic benefit arising from compression garments and devices in the same remit [20]. SmO_2 data was captured using MOXY sensors (MOXY, Swinco, Zurich, Switzerland) using near-infrared spectroscopy (NIRS). The MOXY instrument was held in place over the anterior thigh (vastus lateralis) by pre-cut hyper fix tape to help standardise the external pressure applied holding the device in place [21]. The MOXY device placed midway between the inguinal crease and proximal patella [22]. A small mark using a washable pen identified exact location of the MOXY on each participant's leg to maintain standardisation of MOXY location and re-location throughout testing. Baseline SmO_2 data was collected consistently for 1 minute prior to any intervention. Data capture was then repeated at immediately post (0 minutes) and continually over and up to 20 minutes post intervention time points. In addition, Thermal Comfort and Thermal Sensation were collated both during cooling application at 5 minute increments, and at immediately post and at 20 minute post exposure time points. Immediately after baseline data were recorded, participants in the Control Group were instructed to rest in a supine position on a plinth, remaining as still as possible for 15 minutes, replicating the equivalent period followed in both intervention groups (A) and (B). Participants in intervention Group (A) received a 15-minute application of the Game Ready®, set at a target temperature of 2˚C simultaneously applied with either intermittent ~ high pressure (5-75 mm Hg) (Exposure Protocol 1) or no added pneumatic compression (Exposure Protocol 2) depending on randomisation allocation (Table 1). Participants in intervention Group (B) received a 15 minute application of Squid simultaneously applied with either intermittent ~ high pressure (0-70 mm Hg) (Exposure Protocol 1) or low pneumatic compression (0-30 mm Hg) (Exposure Protocol 2) depending on randomisation allocation (Table 1). Participants returned 1 week later for exposure to the alternative protocol within their specific group allocation. Participants allocated to the Control Group were required to attend only 1 session of data collection.

Thermal sensation and thermal comfort ratings

Both Thermal Sensation and Comfort assessments were carried out following ISO 10551 [23] (ISO Standardisation, Geneva, Switzerland). Participants were asked ''How are you feeling?'' Participants rated their thermal sensation in terms of temperature of the anterior thigh, according to the scale: 4=very hot, 3=hot, 2=warm, 1= slightly warm, 0=neutral, -1 slightly cool, -2=cool, -3=cold, -4=very cold. For Thermal Comfort ratings participants were asked,

Table 1: Group allocations and exposure protocols.

Group Allocation				
Intervention Group A (n=10)		**Intervention Group B (n=10)**		**Control Group (n=9)**
Exposure Protocol 1	**Exposure Protocol 2**	**Exposure Protocol 1**	**Exposure Protocol 2**	**No Exposure**
Game Ready® Duration 15 minutes	Game Ready® Duration 15 minutes	Squid Duration 15 minutes	Squid Duration 15 minutes	Supine laying on plinth duration 15 minutes
Manual T*sk* target 2˚C	Manual T*sk* target 2˚C	'Protocol 3'	'Protocol 1'	No Cooling
High Intermittent Compression (5-75 mm Hg)	No added Compression	High Intermittent Compression (0-70 mm Hg)	Low Intermittent Compression (30 mm Hg)	No Compression
Peak Pressure=75 mm Hg		Peak Pressure=70 mm Hg	Peak Pressure=30 mm Hg	
Rewarming period of 20 minutes	Rewarming period of 20 minutes	Rewarming period of 20 minutes	Rewarming period of 20 minutes	Rewarming period of 20 minutes

"How do you perceive this?" Participants responded based on the feeling of the cryo-compression application using the following scale: 0=comfortable, 1=slightly uncomfortable, 2=uncomfortable, 3=very uncomfortable and 4=extremely uncomfortable. Questionnaire data were collected at baseline, and throughout the intervention applications (Groups A and B), at 5 minutes intervals, followed by immediately post (0 minutes) and 20 minutes post intervention removal.

Statistical analysis

All tests were performed in SPSS (Statistical Package for Social Sciences) version 26.0 (SPSS Inc, Chicago, IL, USA). Level of significance was set at $p \leq 0.05$. All data is expressed as means ± SD. To test for homogeneity of differences in variance, Mauchley's test of sphericity was performed. Normality was assessed *via* the Shapiro-Wilk test. SmO_2 was analysed using normalised values (% mean ± SD). A univariate repeated measures general linear model was used to quantify main effects for intervention and time. Partial eta-squared ($\eta^2_{partial}$) displayed the effect size and were classified as small, medium or large (0.1-0.29, 0.3-0.49 and >0.5 respectively) [24]. Interaction effects were also quantified and significant main effects for pressure were explored using post hoc pairwise comparisons and where appropriate a Bonferroni corrected post hoc analyses were applied. For Thermal Comfort ratings, a Wilcoxon signed-rank test analysed within-group differences and to analyse differences across timepoints for Thermal Sensation data the Friedman test was conducted.

Results

No significant differences were reported for height, weight or body mass index between groups ($p \geq 0.05$).

Skin Surface temperature (T_{sk})

No significant differences were reported for control group at any time point ($p \geq 0.05$) (Table 2). Significant reductions in T_{sk} were reported for Group A (Exposure Protocol 1=Game Ready cooling with high compression) when comparing immediately post exposure to pre exposure data (p=0.00) and 20 minutes post exposure to pre exposure (p=0.00) (Table 2). Similarly for Group A (Exposure Protocol 2=Game Ready cooling and no added compression) when comparing immediately post exposure to pre exposure data (p=0.00) and 20 minutes post exposure to pre exposure (p=0.01) significant values were reported (Table 2). Reductions in T_{sk} were reported for Group B (Exposure Protocol 1=Squid cooling with high compression) when comparing immediately post exposure to pre exposure data (p=0.01) and 20 minutes post exposure to pre exposure (p=0.02). Reductions in T_{sk} were reported for Group B (Exposure Protocol 2=Squid cooling with low compression) when comparing immediately post exposure to pre exposure data (p=0.00) and 20 minutes post exposure to pre exposure (p=0.01). Significant differences between Group (A) and Group (B) for Exposure Protocols 1 (high-compression), were displayed at immediately post time point only ($p \geq 0.05$).

Muscle oxygenation (SmO_2)

Figure 1 represents the effects of all protocols on SmO_2, with analysis of all data displaying a significant effect of time ($p \leq 0.001$; $F=8.58$; $\eta^2=0.17$). With the data set collapsed to consider each intervention protocol in isolation, Group (A) Exposure Protocol 1 displayed a significant effect of time (p=0.02; F=5.62; $\eta^2=0.43$). A significant increase in SmO_2 is also reported for Group (A) (Exposure Protocol 1) at immediately post exposure when compared to pre exposure data time points (p=0.04). Alternatively, when comparing immediately post exposure to 20 minutes post exposure a significant reduction in SmO_2 is displayed for Group (A) (Exposure Protocol 1) (p=0.005) (Figure 1).

Group (A) Exposure Protocol 2 displayed no significant effect of time ($p \geq 0.05$; $F=3.28$; $\eta^2=0.30$). Although a trend toward a decrease in SmO_2 is evident in Figure 1, no significant changes in SmO_2 were reported for Exposure Protocol 2 in the same group for immediately post exposure when compared to pre exposure data or when comparing immediately post exposure to 20 minutes post exposure time point ($p \geq 0.05$) (Figure 1). A significant reduction in SmO_2 was reported however at 20 minutes post exposure (p=0.03) when comparing to pre exposure data for Exposure Protocol 2 (Figure 1) in the same group.

Group (B) Exposure Protocol 1 and Exposure Protocol 2 displayed no significant effect of time ($p \geq 0.05$; $F=0.176$; $\eta^2=0.19$; $p \geq 0.05$; $F=1.10$; $\eta^2=0.13$) respectively. Although a trend toward an increase followed by a decrease in SmO_2 is evident in Figure 1 for timepoints, immediately post and 20 minutes post exposure respectively, no significant changes were reported in SmO_2 for Group (B) (Exposure Protocol 1) or Group (B) (Exposure Protocol 2) at any time point or within time points ($p \geq 0.05$). No significant effect of time ($p \geq 0.05$; $F=0.01$; $\eta^2=0.001$) were displayed for the control group. Furthermore

Table 2: Skin Surface Temperature (T*sk*) for the Anterior Quadriceps (°C) for all groups and exposure protocols.

Group Allocation		Pre Exposure T*sk* (°C) mean ± SD	0 Minutes Post Exposure T*sk* (°C) mean ± SD	20 Minutes Post Exposure T*sk* (°C) mean ± SD
Group A Game Ready®	**Exposure Protocol 1** (Cooling+High Intermittent Compression 5-75 mm Hg)	28.8 ± 0.6	10.7 ± 1.2*‡	23.6 ± 0.6*#
	Exposure Protocol 2 (Cooling with no added compression)	28.4 ± 0.7	14.2 ± 1.2*	25.3 ± 0.4*#
Group B Squid	**Exposure Protocol 1** (Cooling+High Intermittent Compression 0-70 mm Hg)	27.9 ± 1.2	16.6 ± 2.1*‡	25.4 ± 1.2*#
	Exposure Protocol 2 (Cooling+Low Intermittent Compression 0-30 mm Hg)	28.1 ± 0.9	17.2 ± 1.6*	25.6 ± 0.5*#
Control Group	**Control Group** (No cooling / No compression)	28.3 ± 0.6	28.1 ± 0.8	28.5 ± 0.7

*=Significant differences in T*sk* compared to pre exposure data.
#=Significant differences in T*sk* between immediately post exposure and 20 minutes post exposure data.
‡= Significant difference in T*sk* between groups for cooling + 'high-intermittent compression' applications.

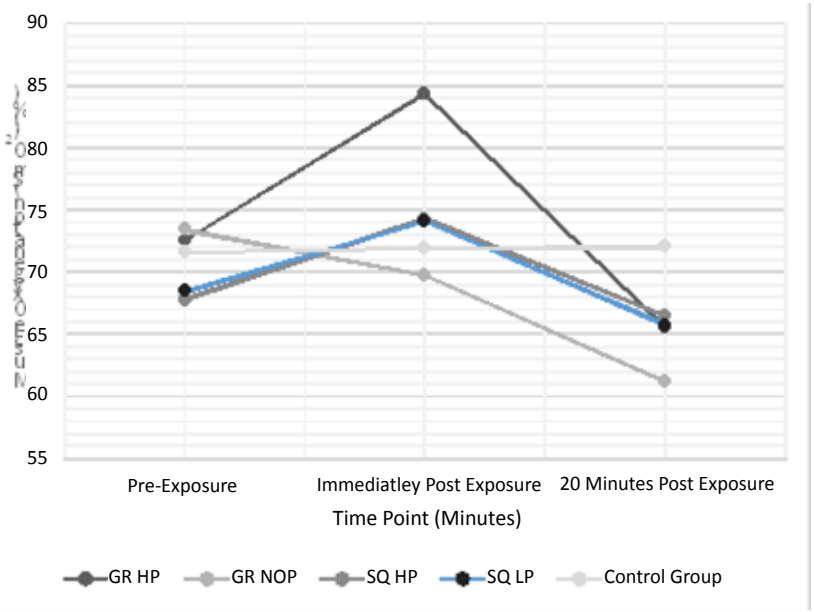

Figure 1: Muscle Oxygenation (SmO_2) (%) for two cooling modalities with variable compression settings over a rewarming period and a control group. (GR: Game Ready®; SQ: Squid; HP: High Pressure; NOP: No Pressure; LP: Low Pressure).

no significant differences were reported for the Control Group for SmO_2 at any time point or between time points ($p \geq 0.05$).

Thermal sensation and comfort scores

Significant reductions were displayed for intervention Groups (A) and (B) for Thermal Sensation scores when comparing throughout device application (at 5 minute increments), immediately post to pre-exposure timepoints ($p \leq 0.05$). Compared to Group (B) and control group, participants in the Group (A) reported to be feel significantly colder compared to pre-exposure scores at both immediately and 20 minutes post timepoints ($p=0.05$) and regardless of compression settings.

Significant reductions in Thermal Comfort scores were displayed when comparing both Group (A) and Group (B) to the control group and regardless of pressure setting ($p \leq 0.05$), however no significant differences were reported when comparing Group (A) and Group (B) ($p \geq 0.05$). Further comparison of Thermal Comfort scores between compression settings within and across intervention groups however displayed significant increases in discomfort when experiencing the higher pressure settings compared to lower/no pressure settings ($p \leq 0.05$).

Discussion

The aim of the investigation was to examine the physiological effects of two different cryo-compressive devices on SmO_2, $T_{sk,}$ Thermal Comfort and Sensation, when applied circumferentially around the thigh. Primarily findings report physiological changes in SmO_2 following simultaneous cooling and compression protocols, with significantly greater reductions in T_{sk} occurring from the addition of compression. SmO_2 demonstrated an increase from baseline, immediately (0 minutes) after applications of combined cooling with compression, followed by a decline, in both intervention groups (A) and (B). SmO_2 demonstrated a decline immediately post exposure (0 minutes) in the group exposed to cooling only with no additional controlled compression. The trend displayed toward a decline in SmO_2 over the 20 minute rewarming period in groups (A) and (B) regardless of compression adjunct supports previous findings, albeit with varying methods of cryotherapy [3,6]. Relationships between pressure (mmHg), T_{sk} (˚C) and SmO_2 (%) are observed. The implications of which may be of interest to sports medicine practitioners when considering the adjunct of pneumatic compression applied alongside cooling for injury or recovery management in sport.

Literature suggests external compression increases SmO_2 [11,12] with cryotherapy reducing SmO_2 [3] when observed independently. All protocols in the current study that applied simultaneous cooling and compression indicated an initial rise in SmO_2 followed by a decline. It may be assumed that once pressure is removed there is no longer an effect on SmO_2 and the effect of cooling dominates SmO_2 response. The initial increase in SmO_2 in response to pressure from the compression adjunct of the devices applied is interesting. It appears that compression counteracts the response of SmO_2 to the simultaneous cooling but only initially after removal this is noticed, as SmO_2 thereafter follows a pattern of decline recognised in literature in response to cold over the rewarming period [3,6,7]. The decline of SmO_2 seen up to 20 minutes post simultaneous cooling and compression is consistent with previous literature of similarity [3] and supports the hypothesis. We assume the similar pattern displayed by SmO_2 demonstrating a continual decline, is in response to cooling rather than compression if, as presumed compression no longer affects SmO_2 once removed.

Higher compression pressures (mm Hg) resulted in greater percentage increases in SmO_2 response immediately post exposures (0 minutes), but not necessary a greater decrease in SmO_2, thereafter. Interestingly exposure protocol 2 (Table 1) (no added compression) demonstrated the lowest SmO_2 value achieved at 20 minutes post exposure. Reasons for this contradict the proposal of a potential relationship between T_{sk} and SmO_2 as this particular exposure did not correlate to the lowest T_{sk} achieved immediate post removal (Table 2). Despite agreement that magnitude of cooling is enhanced by

compression [10], and supported here, the added adjunct of pressure may in fact influence SmO_2 responses over a rewarming period; lessening the overall reduction in SmO_2 compared to cooling alone. Potentially dismaying the presumption that compression fails to affect SmO_2 once removed. Whether this is considered as a positive or negative reaction may be determined by the context in which cryo-compression is intended. Throughout the inflammatory phases of healing oxygen plays an important role [25]. For example, the demand for muscle oxygen varies at different stages of the natural inflammatory process of injured tissues [26], in turn influencing the choice of modality with/without compression adjunct and protocol applied.

Results illustrate that without the adjunct of circumferential compression SmO_2 is lower 20 minutes post exposure compared to those protocols with added compression at the same time point. As T_{sk} response fluctuated across modalities the impact on key physiological reactions known to occur in response to local cooling is assumed to also differ. Considerations should be made as to whether magnitude of cooling or reduction of SmO_2 is more important in the choice of protocol. Clearly different physiological responses occur in response to compression adjunct dosages. Therefore, despite higher pressures influencing an initial higher increase in SmO_2 it appears cooling affect takes over during the rewarming period, and although compression aids magnitude of cooling, colder T_{sk} achieved because of this does not necessarily mean lower SmO_2 results will be reported over a rewarming period.

Interestingly in Group (A) when no additional compression was applied (Exposure Protocol 2) SmO_2 did not increase initially as per protocols with combined compression (Figure 1). Instead, SmO_2 reduced at immediately post exposure and continued to decline, although not significantly, but following previous literature findings [6]. It is however difficult to compare results as previous literature uses cold-water immersion as opposed to circumferential local cryo-compressive devices. At 20 minutes post exposure all protocols demonstrated reductions in SmO_2, which did not return to pre exposure measures, with Group (A) Exposure Protocol 2 being the only application demonstrating significant decreases in SmO_2 at this time point. This was also the lowest value of SmO_2 recorded across the rewarming period for all protocols. Consequently, it is presumed that the addition of compression lessens the ability of SmO_2 to reduce perhaps as quickly from immediately post (0 minutes) to 20 minutes post exposure. The higher-pressure protocols achieved the lower T_{sk} and we presume greater magnitudes of cooling in deeper tissues based on previous literature [10]. The assumption that although T_{sk} is reduced and larger reductions coinciding with higher-compression dosages. the physiological effects of compression appears to override the effects of cooling on SmO_2, Thought to be due to the known response of intramuscular temperatures over rewarming periods post removal of cooling [15].

Results in the current study agree that larger reductions in T_{sk} occur when cooling is combined with compression, in line with previous literature [10]. Larger reductions in T_{sk} correlated to higher compressive pressures across both devices. Significant differences were further observed for T_{sk} reductions between cryocompressive devices and protocols ($p \leq 0.05$) (Figure 1). For example, at immediately post exposure time point for 'high' pressure protocols, Group A (Exposure Protocol 1) achieved a lower T_{sk} of 10.7 ± 1.2˚C, meeting target therapeutic ranges for physiological effects to proceed, compared to Group (B) (Exposure Protocol 1) (16.6 ± 2.1˚C) when the same dose (time) and similar pressure (mmHg) was applied. Previously, research has examined the insulation effects of various external compressions reporting compressive wraps with higher average atmosphere-interface temperature generate enhanced temperature decreases [10]. We consider this may have affected the differences found in the current study, in support of this, visual thermo-graphic differences when comparing high-compression protocols from each intervention group were also displayed. Differences in contact capability between the device and skin interface was anticipated and based on recent literature [27]. We consider that differences displayed in T_{sk} between the cryo-compression devices are also due to greater phase change ability of the device applied in Group (A) due to the mechanism of continuous cycles of circulating cool liquid compared to gel pack applied in Group (B). This would support known differences in cooling efficiency of cryotherapeutic modalities due to phase change capability of materials [8]. For all protocols, across both groups T_{sk} did not return to base line at 20 minutes post exposure. These findings are in line with previous literature reporting similar rewarming periods for local cooling over the thigh regions [16]. More efficient cooling therefore was demonstrated in Group (A) compared to Group (B), and applications of higher pressure produced lower T_{sk}, of which has implications on modality choice and optimal protocol development dependent on therapeutic aim of treatment or recovery.

Although not measured in the current study, intramuscular temperatures are known to continue to decline following removal of cooling [15] and studies report variable responses to compression adjuncts previously [10,28]. It may be proposed that a relationship exists similar to that of intramuscular and T_{sk} responses to cooling between SmO_2 and intramuscular cooling post application. Conversely, SmO_2 was not continuously measured during the intervention exposure, only immediately after removal. Therefore, it is unknown whether SmO_2 decreased or increased from baseline during the intervention applications (15-minute exposures) of either device where simultaneous pressure was applied in the protocol. The assumption based on previous literature and immediately post application SmO_2 values in the current study suggests an increase in SmO_2 values during the application period [11,12]. An immediate increase in SmO_2 for acutely injured soft tissue may be undesirable for tissue healing, however this is presumptuous, as only healthy populations were utilised in this investigation. Alternatively, the decline of SmO_2 following removal of simultaneous cryo-compression may not be as beneficial for tissues recovering from exercise induced fatigue, supporting previous literature [5]. Ultimately, these findings continue the debate around cooling and compression in sports medicine, which evidently supports the need for the development of current contemporary cryotherapeutic protocols for injury management and recovery.

Limitations

It is unknown as to how long after 20 minutes post exposure SmO_2 or T_{sk} would return to baseline, as data was not collected past a 20 minute rewarming period in the current study. Longer periods of rewarming observation may be warranted therefore. No direct comparisons of 'no pressure' between devices were reported as the option of no pressure as a pre-set application is available of the Squid device unless the device is applied only as a wrap. Actual pressure measure (mmHg) for devices were not quantified, therefore it is assumed that levels of compression were as per the manufactures information provided. Future studies may consider the quantification of pressure settings using appropriate objective measures for pressure in relation to skin surface as mm Hg output may not be accurately represented. Relationships between pressure outputs from contemporary cryo-compressive cooling devices and physiological

responses may be drawn from such data, however other factors such as levels of adipose tissue may also impede results and should be considered in future work.

Conclusion

In summary the investigation into the effects of multiple cryo-compressive applications, suggest SmO_2 and T_{sk} responses differ depending on pressure dose in conjunction with cooling. Higher initial increases of SmO_2 at 0 minutes post intervention correlate to higher levels of compression. Findings in the current study also agree with the consensus that greater magnitudes of cooling can be achieved through the adjunct of compression. With higher compression resulting in colder $T_{sk.}$ This however does not necessarily result in the greatest reduction of SmO_2 when observed over a rewarming period up to 20 minutes. Although it is thought that, the cooling response over this period has a greater influence on SmO_2. Depending on therapeutic aim of treatment dose-response relationships between cooling and simultaneous compression should be considered in order to develop optimum protocols for management of either injury or recovery parameters. To establish a comprehensive understanding of dose-response relationships for cryotherapeutic modalities that combine cooling and compression further investigation is required across other modalities.

Key findings/Implications

- Greater reductions in T_{sk} are reported for simultaneous applications of cooling and compression in line with previous literature, where it is suggested that the magnitude of cooling benefits from added compression.
- The extent of physiological response varies depending on dosage of compression adjunct to cooling for T_{sk} and SmO_2.
- Protocols that apply simultaneous cooling and compression should be adapted in terms of compression dosage to meet target aim of application.

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