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1 **Title:** Cryotherapy re-invented: application of phase change material for recovery in elite
2 soccer

3 **Submission style:** Original investigation

4 **Authors:** Tom Clifford^{1,5}, Will Abbott^{2,3}, Susan Y. Kwiecien^{4,5}, Glyn Howatson^{5,6},
5 Malachy P. McHugh^{4,5}.

6 ¹School of Biomedical Sciences, Newcastle University, United Kingdom; ²School of Sport
7 and Service Management, Brighton University, UK; ³Brighton and Hove Albion F.C,
8 American Express Elite Performance Centre, Lancing, UK; ⁴Nicholas Institute of Sports
9 Medicine and Athletic Trauma, Lenox Hill Hospital, New York, NY; ⁵Department of Sport,
10 Exercise and Rehabilitation, Northumbria University, Newcastle, United Kingdom; ⁶Water
11 Research Group, School of Environmental Sciences and Development, Northwest University,
12 Potchefstroom, South Africa.

13

14 **Corresponding author:**

15 Tom Clifford, Newcastle University, Faculty of Medical Sciences, School of Biomedicine
16 Newcastle-upon-Tyne, NE2 4HH, UK Tel: +44 0192 088 311

17

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23

24

25 **Abstract**

26 **Purpose:** This study examined whether donning lower body garments fitted with cooled
27 phase change material (PCM) would enhance recovery after a soccer match.

28 **Methods:** In a randomized, crossover design, eleven elite-soccer players from the reserve
29 squad of a team in the 2nd highest league in England wore PCM cooled to 15°C (PCM_{cold}) or
30 left at ambient temperature (PCM_{amb}) for 3 h after a soccer match. To assess recovery,
31 countermovement jump (CMJ) height, maximal isometric voluntary contraction (MIVC),
32 muscle soreness (MS), and the adapted Brief Assessment of Mood Questionnaire (BAM+)
33 were measured before, 12, 36 and 60 h after each match. Pre and post intervention, a belief
34 questionnaire (BFQ) was completed to determine perceived effectiveness of each garment.

35 **Results:** Results are comparisons between the two conditions at each time point post-match.
36 MIVC at 36 h post was greater with PCM_{cold} vs. PCM_{warm} ($P=0.005$; ES=1.59; 95% CI=3.9 to
37 17.1%). MIVC also tended to be higher at 60 h post ($P=0.051$; ES=0.85; 95% CI= -0.4 to
38 11.1%). MS was 26.5% lower in PCM_{cold} vs. PCM_{warm} at 36 h ($P=0.02$; ES=1.7; 95% CI=
39 -50.4 mm to -16.1 mm) and 24.3% lower at 60 h ($P=0.039$; ES=1.1; 95% CI= -26.9 mm to
40 -0.874 mm). There were no between condition differences in post-match CMJ height or
41 BAM+ ($P>0.05$). The BFQ revealed that players felt the PCM_{cold} was more effective than the
42 PCM_{amb} after the intervention ($P=0.004$).

43 **Conclusions:** PCM cooling garments provide a practical means of delivering prolonged post-
44 exercise cooling and thereby accelerating recovery in elite soccer players.

45

46 **Key words:** Recovery, cryotherapy, soccer, muscle damage, exercise.

47

48

49 **Introduction**

50 It is well established that a soccer match can induce muscle damage that persists for several
51 days¹⁻³. Typically, this muscle damage manifests as increased feelings of muscle soreness
52 and a reduced force generating capacity, both of which can increase the risk of injury⁴, and
53 negatively affect the ability to perform the explosive movements integral to soccer
54 performance, such as sprinting, jumping, accelerating and changing direction^{2 5 6}.

55 The aetiology of muscle damage after a soccer match is multifactorial and complex, but,
56 broadly speaking, it is likely to be initiated by direct mechanical stress to the contractile and
57 non-contractile muscle apparatus, and then followed by a cascade of immunological mediated
58 processes that orchestrate repair and recovery⁵⁻⁷. Indeed, there is now a growing body of
59 evidence that this inflammatory response is crucial to muscle regeneration after muscle-
60 damaging exercise⁸. With that said, because of the secondary damage that inflammation can
61 provoke in the initial aftermath of the damaging insult, it is also postulated that an
62 intervention that might temporarily reduce inflammation might help to expedite the recovery
63 process⁹, where adaptation to an exercise stimulus is of secondary importance during periods
64 of competition or fixture congestion.

65 One of the most popular recovery interventions used in soccer is cold water immersion (CWI)
66¹. Following a soccer match or training, players often use CWI applied to the lower body in
67 the belief that recovery will be facilitated¹⁰. Such effects are purported to reduce tissue
68 temperature and increase hydrostatic pressure, leading to a reduction in inflammation and
69 oxidative stress¹⁰⁻¹³. Nonetheless, it remains equivocal as to whether cooling the muscles
70 does actually reduce inflammation¹⁴. Additionally, the effectiveness of CWI as a recovery
71 aid has been questioned, with large meta-analyses suggesting small to moderate benefits^{12 15}.
72 There are, however, some studies reporting that CWI can assist recovery in the days

73 following intermittent exercise or competitive soccer matches that was summarised in a
74 narrative review ¹.

75 In addition to the limited benefits of CWI in exercise recovery ¹², its use also comes with
76 logistical challenges such as facilities to cater for its use immediately following a soccer
77 match. Also, some players might be put off by the thermal discomfort associated with CWI
78 ¹⁶. With these limitations in mind, alternative approaches for muscle cooling are necessary.
79 One such approach is the use of temperature controlled phase change material (PCM). To
80 date, PCM has principally been used in clothing to reduce thermal stress in occupational
81 settings ¹⁷. An attractive feature of PCM is that while absorbing heat from the body; for
82 example, when the PCM is set at 15° C, it maintains this constant temperature until the
83 material has changed from a solid to a liquid, which takes approximately 3 hours. The
84 potential benefits of local PCM application for exercise recovery have recently been
85 explored, and indicate that wearing PCM (15°C) can aid recovery following muscle-
86 damaging exercise in untrained individuals ¹⁸.

87 The clear advantage of PCM over CWI and other cytotherapeutic methods, at least from a
88 practical perspective, is that they are extremely portable, easy to apply to entire squads—and
89 can be worn for an extended period of time with minimal thermal discomfort or obstruction,
90 thereby allowing athletes to freely move around during application. Such advantages could be
91 particularly useful in elite team sports like soccer, where access to CWI might not be
92 available when traveling for away matches or at tournaments. In this study, we hypothesised
93 that PCM would attenuate muscle soreness and restore muscle function in the 3 days
94 following a soccer match. Accordingly, the aim was to examine if PCM garments (with a 15°
95 C freeze-thaw temperature), worn for 3 h after a soccer match, could accelerate functional
96 and perceived recovery in elite soccer players after a competitive league match.

97 **Methods**

98 *Participants*

99 This study received ethical approval from Faculty of Health and Life Sciences, Northumbria
100 University. Eleven elite male, outfield soccer players (Age, 19 ± 1 yrs; height, 1.80 ± 0.57 m;
101 mass, 75.9 ± 7.2 kg; bodyfat, 7.9 ± 1.3 %) were recruited from the under-23 squad of a
102 professional soccer team playing in the Sky Bet Championship in England. Players were
103 given a detailed outline of the study procedures before providing written informed consent
104 and completing a health history questionnaire. The use of any other cytotherapeutic
105 interventions (i.e., CWI) or form of compression was prohibited throughout testing.

106 *Experimental design*

107 This study employed a crossover design. After two league matches between the period of Jan
108 – March 2017, players wore, in a randomized fashion, PCM (Glacier Tek, USDA
109 BioPreferred PureTemp, Plymouth, MN, USA) that were either cooled in a freezer to 15° C
110 (intervention; PCM_{cold}) or left at ambient ($\sim 22^{\circ}$ C) temperature (control; PCM_{amb}). PCM
111 blocks were worn on the quadriceps muscles inside compression shorts for 3 h in total from
112 approximately 45 mins post-match. They were worn while travelling back from the matches
113 on the team bus, which had an air temperature between 18 - 21° C. During their application, the
114 players sat upright on the bus, only moving to use the bathroom. For blinding purposes, prior
115 to the intervention players were informed that both the PCM_{cold} and PCM_{amb} were equally
116 effective for recovery and that we were only interested in which they preferred in terms of
117 comfort. The order of randomization for the garments was performed using an online
118 generator (www.randomizer.org) by an individual not involved in data collection. A range of
119 dependent variables were collected before the matches (PRE: ~ 84 h after their last match and
120 ~ 84 h prior to their next match) and 12, 36 and 60 h after the match to monitor recovery.

121 These variables were all recorded prior to training (between 09:00 – 10:30) and in the
122 following order: an adapted Brief Assessment of Mood (BAM+), muscle soreness (MS),
123 counter movement jump (CMJ) height, and maximal isometric voluntary contraction
124 (MIVC). Participants were familiarized with the above procedures prior to the main data
125 collection. Players wore GPS units (Catapult, Leeds, UK) to track their external load during
126 each match.

127 *Maximal isometric voluntary contraction*

128 As in previous studies^{19 20}, MIVC of the right knee extensors was measured with a portable
129 strain gauge (MIE Medical Research Ltd., Leeds, UK) at an approximately 70° angle of knee
130 flexion. Players were seated upright on a physio bench and had a plinth (attached to the strain
131 gauge), placed just above the malleoli of the right ankle. Players were asked to push against
132 the plinth maximally and hold the contraction for 3 s Three maximal efforts were performed,
133 each separated by 60 s of passive, seated recovery, with the mean value (N) used for analysis.
134 The inter-day coefficient of variation (CV) for this protocol was calculated as <8%.

135 *Countermovement jump*

136 CMJ height was measured in cm with an Optojump system (Bolzano, Italy). Participants
137 started the movement upright with hands fixed to their hips and after a verbal cue, descended
138 into a squat prior to performing a maximal effort vertical jump. Participants performed 3
139 maximal efforts, separated by approximately 60 s of standing recovery; the mean of the 3
140 jumps was used for analysis. The CV for this protocol was <5%.

141 *Muscle soreness*

142 Muscle soreness (MS) was rated by marking a vertical line on a 200 mm visual analogue
143 (VAS). At one end read “no soreness” and the other “unbearably painful”; the marked line
144 was measured with a ruler and recorded.

145 *Questionnaires*

146 As in a previous study²¹, before and after the intervention participants rated how effective
147 they felt the interventions were *going to be* for recovery (PRE) and how effective they felt
148 *they were* for recovery (60 h). They completed a likert scale from 1 ‘not effective at all’ to 5
149 ‘extremely effective’ for each condition. The aim of this was to gauge the player’s perception
150 of how effective they felt the interventions were before and after using them. On each day
151 (PRE – 60 h), players also completed a recently developed questionnaire for qualitatively
152 assessing athlete’s mood, recovery status and overall performance readiness²⁰. The
153 questionnaire, known as the BAM+, contains 6 items from The Brief Assessment of Mood
154 (BAM) and 4 questions relating to confidence, motivation, muscle soreness and sleep
155 quality²⁰. For each of the 10 questions, players drew a vertical line on a 100 mm visual
156 analogue scale (VAS), which has “not at all” and “extremely” at opposing ends. The lines
157 were measured with a ruler and recorded and an overall score calculated with the following
158 equation: positively associated questions (x4) – the negatively associated questions (x6 from
159 the BAM). Further details of the BAM+ and its development are available in²².

160 *Data analysis*

161 All data are expressed as mean \pm SD and statistical significance was set at $P < 0.05$ prior to
162 analyses. MIVC, CMJ, MS and BAM+ values were analysed using a repeated measures
163 ANOVA with 2 treatment levels (PCM_{cold} vs. PCM_{amb}) and 4 repeated measures time points
164 (PRE, 12 h, 36 h, 60 h). If the ANOVA indicated a significant interaction effect
165 (treatment*time) Bonferroni *post hoc* analysis was performed to locate where the differences

166 lie. The *post hoc* comparisons refer to a difference in conditions at a specific time point post-
167 match (e.g., MIVC at 36 h post with PCM_{warm} vs. PCM_{cold}). In the event of a significant
168 violation of sphericity, Greenhouse-Geisser adjustments were used. External load data was
169 analysed with paired student t-tests. The BFQ was analysed using the Wilcoxon signed-rank
170 test. All data were analysed using IBM SPSS Statistics 23 for Windows (Surrey, UK). To
171 estimate the magnitude of the treatment effects, Cohen's d effect sizes (ES) were calculated
172 with the magnitude of effects considered either small (0.20–0.49), medium (0.50–0.79) and
173 large (>0.80).

174

175 **Results**

176 *External load*

177 As shown in Table 1, there were no differences in any of the external load variables,
178 including time on the field, between the two conditions ($P < 0.01$). The requirement for being
179 included in the intervention was that 60 minutes of the match had to be completed; no players
180 had to be excluded on this criterion. In terms of treatment order, 8 players used PCM_{cold} first
181 and 3 players PCM_{warm}.

182 *Muscle function*

183 As shown in Figure 1, MIVC was reduced after both treatments (time effect; $P = 0.0001$) but
184 recovery was faster with PCM_{cold} (treatment*time effect; $P = 0.001$) at 36 h ($P = 0.005$; large
185 ES = 1.59; 95% CI = 3.9 to 17.1%). MIVC also tended to be higher at 60 h after PCM_{cold}
186 treatment ($P = 0.051$; large ES = 0.85; 95% CI = -0.4 to 11.1%). Although to a smaller
187 extent, CMJ performance also decreased after both treatments (time effect; $P = 0.032$), with
188 losses peaking at 36 h (Figure 2). PCM_{cold} tended to increase CMJ performance after the

189 match vs. PCM_{warm} but this did not reach statistical significance (treatment effect; $P = 0.064$;
190 treatment*time effect; $P = 0.095$).

191 *Muscle soreness*

192 A time effect for increased MS was observed ($P = 0.0001$; Figure 3); however, MS was lower
193 after PCM_{cold} (treatment effect; $P = 0.02$; treatment*time effect; $P = 0.010$; Figure 3). At 36 h
194 post, MS was, on average, 26.5% lower after PCM_{cold} vs. PCM_{amb} ($P = 0.02$; large ES = 1.70;
195 95% CI = -50.4 mm to -16.1 mm) and, at 60 h, 24.3% lower in the PCM_{cold} ($P = 0.039$; large
196 ES = 1.10; 95% CI = -26.9 mm to -0.874 mm).

197 Readiness to play, as measured by the BAM+ questionnaire, was reduced after wearing both
198 garments post-match (time effect; $P = 0.0001$); however, no treatment ($P = 0.438$) or
199 treatment*time effects were observed ($P = 0.164$; Figure 4).

200 Before the intervention, there was no difference in the player's perception of how effective
201 they felt each treatment would be ($P = 0.480$), suggesting that the PCM_{amb} served as a good
202 control, and limited the possibility of a placebo effect at the outset. In contrast, at post-
203 intervention, it was felt that PCM_{cold} was more effective than PCM_{amb} (Table 2; $P = 0.004$).

204 **Discussion**

205 The main finding of this study was that donning PCM garments for 3 h after a competitive
206 soccer match enhanced functional recovery; more specifically, both isometric strength loss
207 and MS were significantly attenuated 2-3 days after the match. In line with these findings, the
208 players felt the cooled garments were more effective than the ambient garments after the
209 intervention (Table 2). This study provides the first evidence that the application of these
210 novel cooling garments aid functional recovery in elite soccer players.

211 The enhanced recovery of MIVC and reduction in MS with PCM_{cold} is consistent with recent
212 findings¹⁸, which showed that applying PCM_{cold} for 6 h following 120 isolated eccentric
213 knee extensions attenuated MIVC loss and MS for up to 4 days' post-exercise. The present
214 study, however, expands upon these findings, indicating that; 1) the beneficial effects of these
215 garments are not just limited to recreationally active individuals but also extend to elite-level
216 soccer players, and; 2) a ~3 h application is sufficient for accelerating functional recovery—
217 at least in this population and under these very applied conditions. Of course, it is unclear if a
218 6 h application would have further augmented the effects in the present study; however, the
219 optimal application time for these garments does require further investigation.

220 Interestingly, the beneficial effects of PCM_{cold} on MIVC and MS only became evident at 36
221 and 60 h post-match. As to why the PCM_{cold} was not beneficial at 12 h post-match is unclear
222 and difficult to explain. However, given the loss in MIVC and MS peaked at this time point,
223 one plausible explanation is that the magnitude of damage was simply too large for the
224 PCM_{cold} to have any discernible effects. Alternatively, the discrepancy could be related to
225 how soon this measure was collected after the end of the match. Indeed, it is possible that the
226 changes in MIVC and MS at this time point were more a reflection of lingering physiological
227 and mental fatigue rather than muscle-damage *per se*, which is generally more evident ≥ 24 h
228 post-exercise^{7 23}. Additionally, in terms of MIVC, at this time point a greater proportion of
229 the strength loss was probably more attributable to mechanisms which are not postulated to
230 be amenable to cryotherapy (e.g., a loss of Ca²⁺ homeostasis and failure of the excitation-
231 contraction coupling system;²⁴). Instead, muscle cooling is thought to affect the
232 immunological responses associated with secondary damage; most notably local
233 inflammation and oxidative stress, which develop more gradually following the initial
234 muscle-damaging stimulus, generally peaking 24 – 96 h post-exercise^{25 26}. Thus, given the
235 time course of events, it would be reasonable to assume that the benefits of PCM_{cold} would

236 become more apparent at later stages in the recovery process when functional recovery (e.g.,
237 MIVC loss and MS) are more likely to be hindered by secondary processes. Following this
238 logic, a possible mechanism by which the PCM_{cold} application could have accelerated
239 recovery, was by reducing the number of inflammatory cells, especially phagocytes, that
240 adhere to the vascular endothelium and infiltrate the damaged tissues for remodelling.
241 Although such effects remain equivocal with acute CWI (10 min)¹⁴, a more prolonged
242 cooling intervention (6 h) was shown to reduce phagocyte adherence and desmin loss 24 h
243 after muscle damage in mice¹³, lending some support to this theory. Such effects are, in turn,
244 likely to blunt the neutrophil mediated release of reactive oxygen species, which, in a non-
245 discriminate manner, can degrade both damaged and healthy cells, inhibiting recovery^{11 13 27}.
246 There is indeed evidence in humans that have shown a link between exercise-induced
247 inflammation and isometric strength loss²⁵, and some in animals showing that attenuating
248 inflammation enhances the recovery of muscle function after muscle lengthening
249 contraction²⁷, which would support this proposition. Nonetheless, it is important to note that
250 not all studies have found a link between inflammation and muscle function after muscle-
251 damaging exercise²⁸. Thus, while such effects are plausible, without measuring inflammation
252 this is somewhat speculative; this postulation needs to be tested experimentally to confirm
253 this idea.

254 Another interesting finding from this study is that despite the benefits of PCM_{cold} on MIVC
255 recovery, CMJ performance was not significantly altered. This could be largely due to the
256 fact that the magnitude of CMJ loss after the match was only small; thus, there was not a
257 large enough impairment to detect a significant treatment effect. With that said, CMJ height
258 did tend to be greater at 36 and 60 h post-match in the present study, with 9 of the 11 players
259 scoring higher relative to their baseline values after PCM_{cold} at 36 h, revealing a large effect

260 size (1.2). Therefore, these findings might be interpreted as practically meaningful by a
261 practitioner or coach working in elite soccer.

262 In contrast to the functional measures, the BAM+ was not different between the two
263 treatments. This could be interpreted to suggest that the PCM_{cold} was more effective for
264 aiding physiological/biomechanical recovery rather than the psychological/wellbeing aspects
265 of recovery. Indeed, these two could represent distinct aspects of recovery, given the recent
266 suggestion they do not tend to correlate well using a number of measures²⁹. Notwithstanding,
267 the BAM+ is a new tool and is yet to be validated as a recovery marker so perhaps this
268 measure is not sensitive enough for detecting significant changes between treatments.

269 It is important to acknowledge the limitations of this work. Firstly, we were unable to
270 measure local tissue temperature between the two conditions to confirm that the PCM_{cold} was
271 having the desired effect. However, because in previous work the same PCM_{cold} reduced skin
272 temperature to 22° C¹⁸, —similar to that reported after CWI³⁰, we are confident that the skin
273 temperature was similarly decreased in the present study. Another limitation, which is
274 inherent in all cryotherapy based research, is our inability to rule out that these results were
275 largely a result of a placebo effect due to the players pre-conceived belief about how cold
276 exposure might benefit their recovery. However, it is important to note that at the outset of
277 the study, the players did not believe that the PCM_{cold} would be more beneficial than the
278 PCM_{warm} (Table 1). Finally, again due to the practical constraints of working with elite
279 athletes, the potential underlying mechanisms could not be determined. These are important
280 questions that need to be examined in future work.

281 **Practical applications**

282 The phase change garments used in this study are also easily portable, can be applied to large
283 groups of athletes, and allow the athletes to move freely during use; consequently, they offer

284 a highly practical means of applying cryotherapy to enhance recovery following competitive
285 team-sport matches. While it remains to be seen if the phase change material garments used
286 in this study are more efficacious than other forms of cryotherapy, from a practical
287 perspective, at the very least these garments offer an attractive alternative method of
288 enhancing recovery when access to CWI is not available, perhaps in away competition or
289 tournament scenarios.

290 **Conclusions**

291 In conclusion, the present findings showed, for the first time, that applying cooled PCM to
292 the quadriceps for 3 h after a soccer match lowers MS and improves the recovery of MIVC.
293 Studies examining the effects of these garments in other sporting populations (e.g., rugby)
294 along with the potential mechanisms involved, are warranted.

295

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298 to accelerate recovery following exercise and injury and reduce pain was conceptualized and
299 implemented by the author Dr Malachy McHugh.

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415 Table 1. A comparison of external load during match-play for the two conditions (PCM_{cold}
 416 vs. PCM_{amb}). Total distance is the total distance covered during the match; explosive distance
 417 refers to the distance travelled accelerating at $\geq 2 \text{ m}\cdot\text{sec}^{-1}$ and decelerating at $\leq 2 \text{ m}\cdot\text{sec}^{-1}$; sprint
 418 distance is the distance travelled at $\geq 60\%$ of maximum speed ($\text{km}\cdot\text{h}^{-1}$); and duration is the
 419 total number of minutes spent on the field of play.

	PCM _{cold}	PCM _{amb}
Total distance (m)	9414 ± 2142	9742 ± 1365
Explosive distance (m)	628 ± 149	637 ± 78
Sprint distance (m)	330 ± 129	339 ± 85
Duration (min)	81 ± 18	83 ± 11

420 There were no differences between conditions for any variable ($P > 0.05$).
 421 Values are mean ± SD; $n = 11$.
 422

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424 Table 2. Perceived effectiveness of the PCM garments for recovery before
 425 and after the intervention.
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	PCM _{cold}	PCM _{amb}
Pre	3.55 ± 0.69	3.36 ± 0.50
Post (M+3)	4.18 ± 0.60*	2.55 ± 1.04

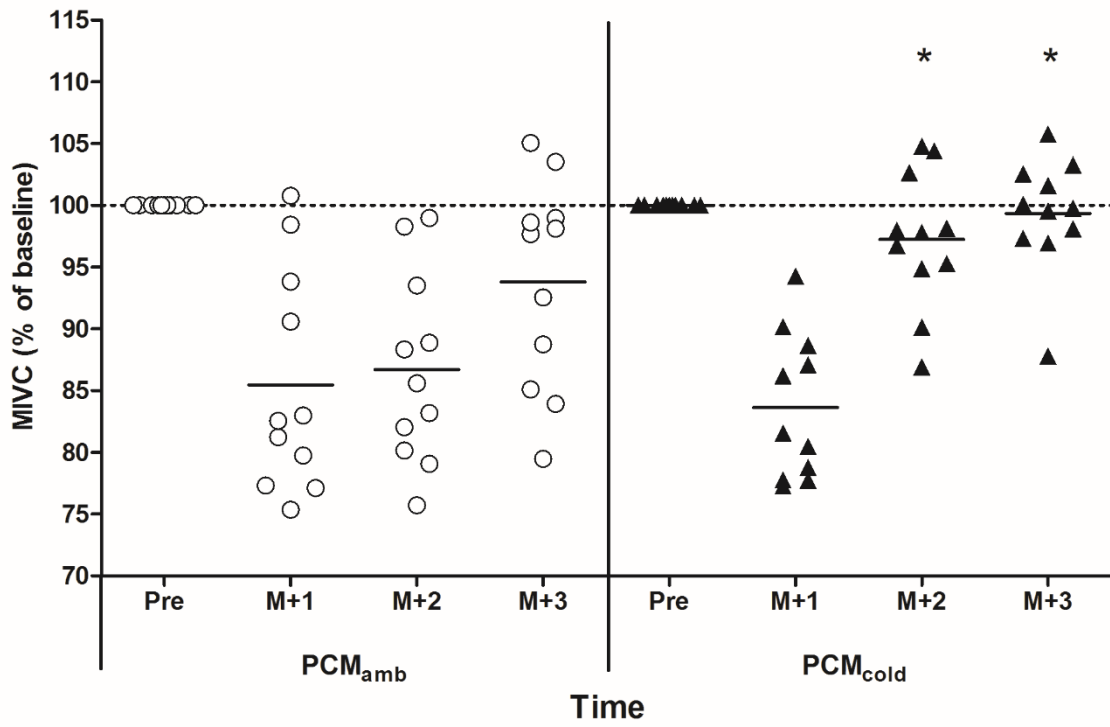
427 * PCM_{cold} perceived to be more effective than PCM_{amb} post intervention
 428 ($P = 0.004$).

429 Table 2. Perceived effectiveness of the PCM garments for recovery before
430 and after the intervention.
431

	PCM_{cold}	PCM_{amb}
Pre	3.55 ± 0.69	3.36 ± 0.50
Post (M+3)	4.18 ± 0.60*	2.55 ± 1.04

432 * PCM_{cold} perceived to be more effective than PCM_{amb} post intervention
433 ($P = 0.004$).
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439 Figure 1. Percentage changes in MIVC before and up to 3 days after a match (M+3). *MIVC
 440 recovered quicker after PCM_{cold} vs. PCM_{amb} ($P < 0.05$). Values are mean \pm SD ($n = 11$).

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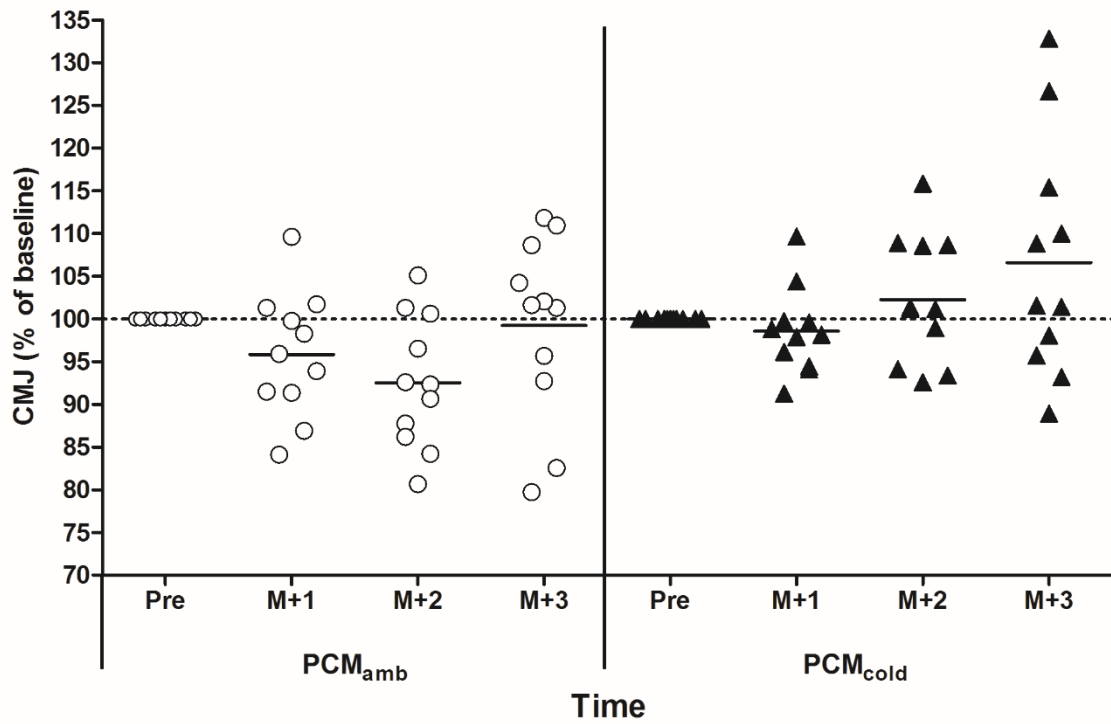
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459 Figure 2. Percentage changes in CMJ height before up to 3 days after each match (M+3).

460 Values are mean \pm SD ($n = 11$).

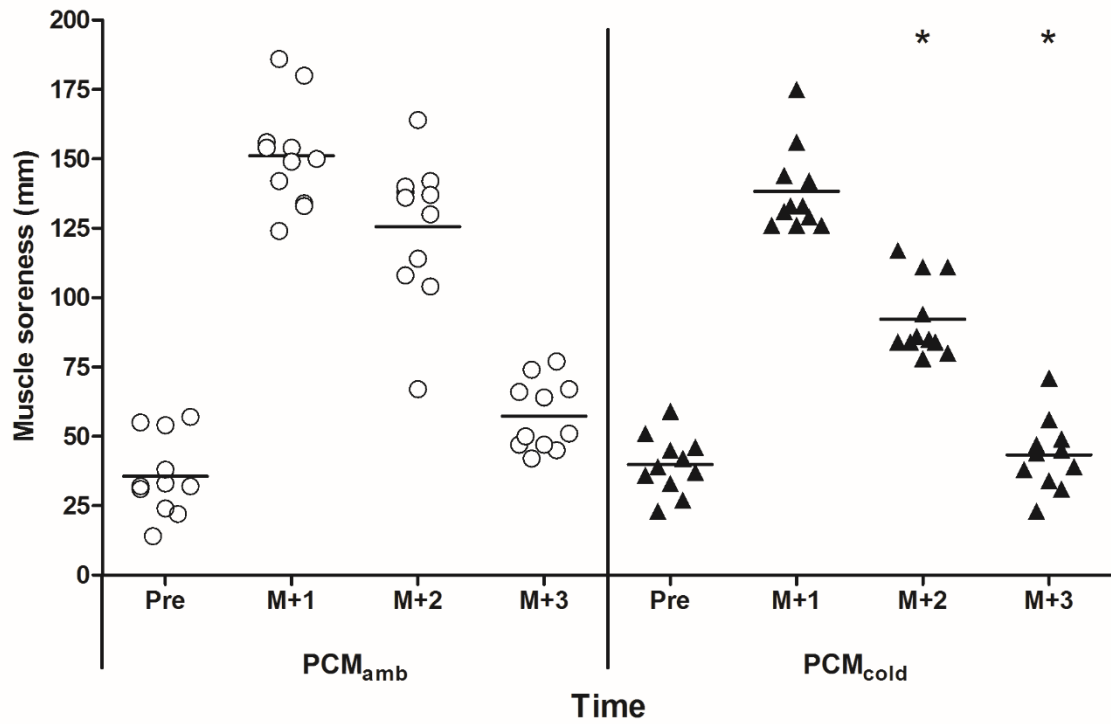
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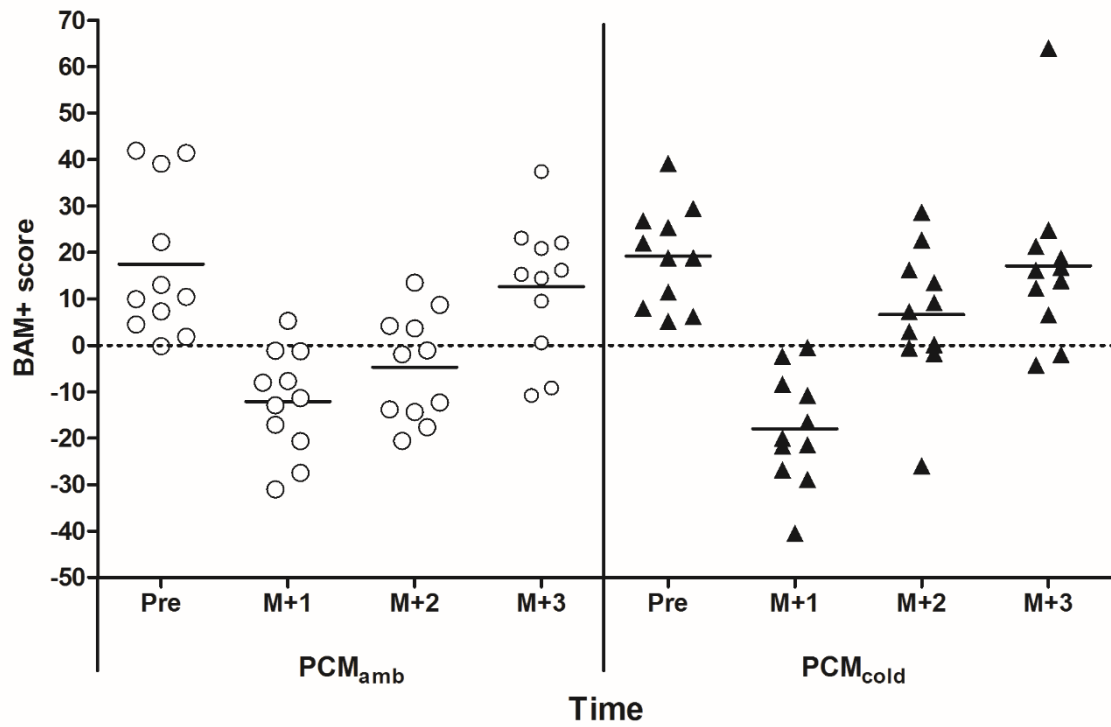
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Figure 3. Muscle soreness before up to 3 days after a match (M+3). *Muscle soreness lower after PCM_{cold} vs. PCM_{amb}; $P < 0.05$. Values are mean \pm SD ($n = 11$).



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486

487 Figure 4. Changes in BAM+ score for each condition before up to 3 days after a match

488 (M+3). Values are mean \pm SD ($n = 11$).