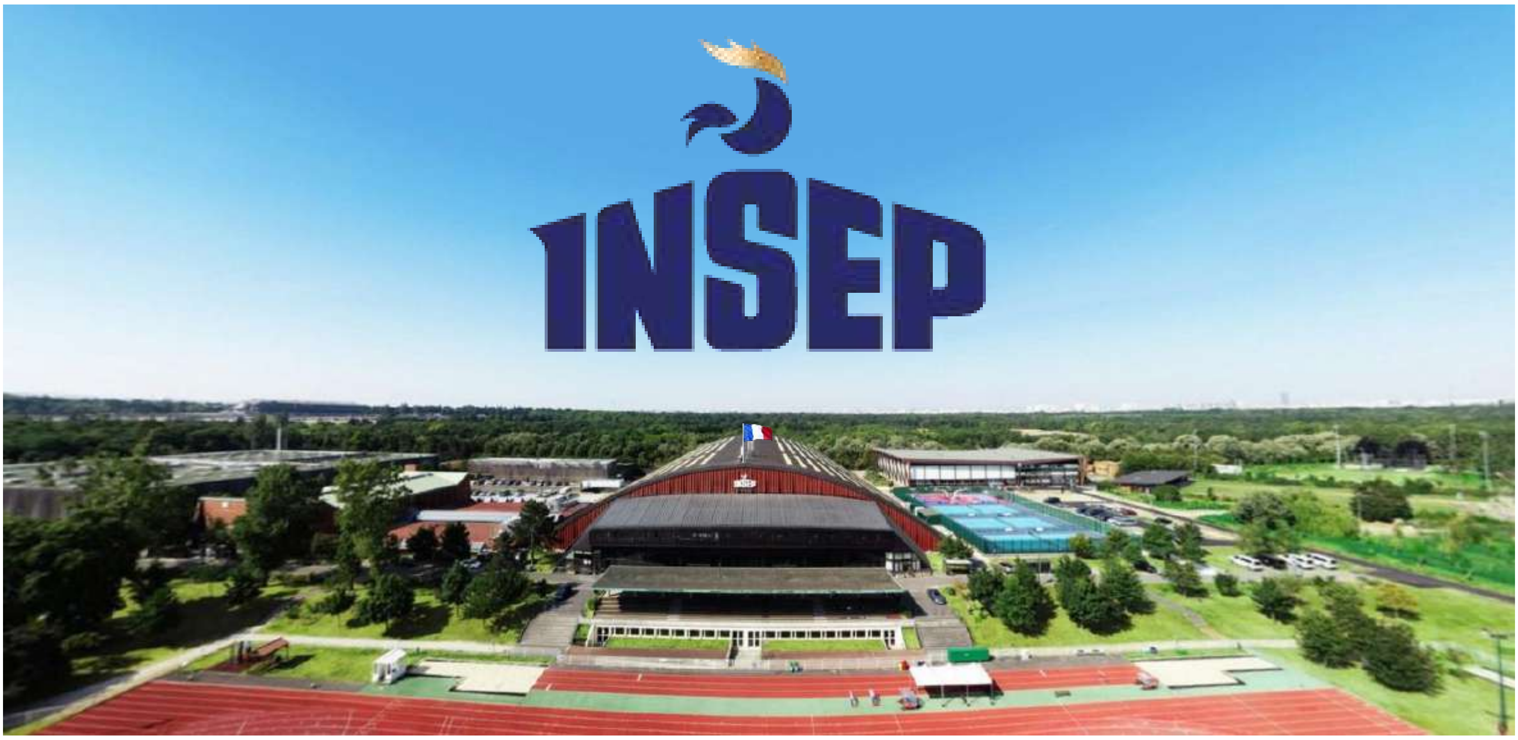
CRYOVEST®

Articles & Publications Scientifiques



Figurant parmi les plus grands centres internationaux d'entrainement Olympique et Paralympique, l'Institut National du Sport et de l'Expertise de la Performance incarne le savoir-faire à la française, qui mixe expertise technique et scientifique dans le respect de l'athlète.

L'INSEP Paris offre aux espoirs du sport mondial, comme aux grands champions, des services uniques à la pointe de la préparation et de la formation.

C'est en partenariat avec le département Recherche que la société CRYOINNOV, start-up implantée à Melesse en Bretagne et reconnue par sa technologie de froid unique, a été choisie pour concevoir et developper un vêtement réfrigérant de haute performance permettant la « Thermorégulation » des athlètes lors de préparations et de compétitions en ambiance chaude.

C'est de cette étroite collaboration qu'est né le gilet réfrigérant CRYOVEST. Ce vêtement spécifique est « dit » de thermorégulation. Testé et validé d'un point de vue scientifique et médical, CRYOVEST est considéré clairement comme le meilleur produit au Monde disponible sur le Marché sur ce segment.

INSEP

En Chiffre

2	LABORATOIRES de RECHERCHE A LA POINTE DE L'INNOVATION
24	DISCIPLINES OLYMPIQUES ET PARALYMPIQUES
150	ENTRAÎNEURS NATIONAUX
800	SPORTIFS DE HAUT-NIVEAU

INSTITUT NATIONAL DU SPORT, DE L'EXPERTISE ET DE LA PERFORMANCE

Améliorer sa récupération en sport

[illegible]

INSEP

Chapitre 14 bis. Étude de cas

Comparaison entre deux gilets refroidissants : effets sur le rendement énergétique lors d'un exercice de pédalage en condition chaude et humide, et lors de la période de récupération

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Texte intégral / https://books.openedition.org/insep/1320

Introduction

1Il est clairement établi qu'en ambiance chaude et humide, les performances physiques sont réduites (Bell et Provins 1962 ; Shvartz, Saar *et al.* 1973). La thématique du refroidissement corporel dans le milieu sportif a bénéficié d'une grande attention de la part du milieu scientifique (Booth, Marino *et al.* 1997), en particulier au cours des trois récentes olympiades (Atlanta, 1996 ; Athènes, 2004 et Pékin, 2008). De nombreuses méthodes permettent de réduire artificiellement la température corporelle avant un exercice. Les méthodes les plus étudiées dans la littérature sont l'exposition à de l'air froid ou l'immersion en eau froide (Marino 2002 ; Quod, Martin *et al.* 2006 ; Vaile, Halson *et al.* 2008). L'utilisation d'un gilet refroidissant (GR) est l'une des techniques les plus simples et les plus utilisées par les athlètes. De nombreux modèles de GR sont disponibles sur le marché, utilisant des techniques de refroidissement et des propriétés thermiques différentes. Pour ces raisons, ces divers GR ont tous des impacts différents sur la performance sportive réalisée en ambiance chaude (Quod, Martin *et al.* 2006).

2Lors des derniers Jeux olympiques de Pékin (2008), l'un des GR les plus populaires était l'Arctic-heat® (Burleigh Heads, Arctic-heat®, Australie). Arngrimsson *et al.* (2004) ont déjà validé ce GR et ont rapporté une réduction significative (13 s) du temps nécessaire pour parcourir 5 km en course à pied (Arngrimsson, Petitt *et al.* 2004). Pour la plupart des modèles de GR disponibles, les sportifs mettent directement sur la peau un GR venant juste de sortir du congélateur, ce qui a pour conséquence une vasoconstriction cutanée importante, réduisant ainsi la conductivité thermique de l'enveloppe corporelle, ce qui induit une isolation thermique de l'organisme. Or, lors de la réalisation d'un exercice physique en ambiance chaude, l'organisme doit évacuer la chaleur métabolique produite par vasodilatation cutanée (Arngrimsson, Petitt *et al.* 2004). Dans ce cadre, nous pensons qu'un concept de GR ne refroidissant pas la peau de manière trop drastique permettrait d'augmenter la dispersion de la chaleur corporelle durant l'exercice physique. Par ailleurs, le temps durant lequel cet environnement froid peut être maintenu au contact direct de la peau est un élément important pour juger de l'efficacité d'un GR utilisé en ambiance chaude. Étonnamment, à notre connaissance, les fabricants de GR actuels ne prennent pas en compte ces deux mécanismes (temps et dispersion de la chaleur). C'est dans ce cadre qu'un nouveau GR, appelé Cryovest® (IMNSSA-IRBA-Paul Boyé Technologie-SM Europe, France), a été réalisé pour la délégation française ayant participé aux Jeux olympiques de Pékin 2008.

3Bien qu'il existe différents modèles de GR partageant le même objectif thermique, aucune étude n'a quantifié, au sein d'une même population, les effets du modèle de GR sur la tolérance au stress thermique durant un exercice physique réalisé en ambiance chaude. Dans le cadre de cette présente étude, nous avons comparé l'efficacité de l'Arctic-heat® et celle de la Cryovest®, en particulier sur le rendement énergétique lors d'un exercice de pédalage et sur la qualité de la récupération subséquente.

1. Matériels et méthodes

1.1 Population

4Huit sujets sportifs masculins ont donné leur consentement écrit pour participer à cette étude. Ont été exclus tous les participants qui avaient des antécédents de maladies liées à la chaleur, de problèmes de santé chroniques, de limitation orthopédique, de maladies cardiovasculaires, métaboliques ou respiratoires. Toutes les expérimentations ont été réalisées en accord avec la déclaration d'Helsinki (1980). Les valeurs moyennes (± écart type) de l'âge, de la taille, de la masse corporelle et de la masse grasse des sujets étaient respectivement de 31,2 ± 2,5 ans, 183,4 ± 7,6 cm, 74,6 ± 6,7 kg et 9,8 ± 2,5 %.

1.2 Résumé du protocole

5Dans un premier temps, chaque sujet a réalisé une épreuve d'effort maximal incrémentée de 25 W toutes les deux minutes sur ergocycle *(Excalibur®,* Lode, Groningen, Pays-Bas) dans une chambre climatique (CC, 30 °C, 80 % d'humidité), de façon à définir leur consommation maximale d'oxygène ($\dot{V}O_2max$) et leur puissance maximale aérobie (PMA). Dans un second temps, les sujets ont effectué trois tests à puissance constante sur ergocycle (60 % PMA) selon trois conditions expérimentales différentes appliquées dans un ordre aléatoire (les sujets portaient soit un tee-shirt en coton standard, soit le GR Arctic-heat®, soit le GR Cryovest®).

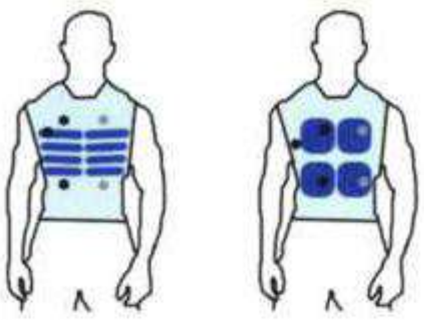
6Sur l'ensemble du protocole, tous les sujets ont été évalués à la même heure de la journée, afin de réduire les effets du rythme circadien sur la fréquence cardiaque (FC) et la température corporelle, et une période de repos d'au moins deux jours a été respectée entre chaque test.

1.3 Description des gilets refroidissants

7Le modèle Arctic-heat® est composé de quatre bandes horizontales sur les faces antérieure et postérieure, couvrant une surface totale de 0,1039 m^2 (Fig. 14.5). Le gel cristallisé contenu dans ces bandes absorbe l'eau lorsqu'il est immergé. Ce gel ainsi réhydraté doit ensuite être placé dans un congélateur avant son utilisation. Une fois activé, le GR Arcticheat® pèse 1 900 g.

8Le modèle Cryovest®est composé de huit poches (quatre sur l'avant et quatre dans le dos) couvrant une surface de 0,1800 m^2 (Fig. 14.5). Dans chaque poche viennent s'insérer des packs refroidissants mesurant 15 x 15 cm et pesant 178 g (Firstice®, USA). Pour être activé, chaque pack Firstice® doit être placé pendant deux heures dans un congélateur. Le poids du GR Cryovest®, une fois activé, est de 1 920 g.

Figure 14.5. Représentation schématique des deux gilets refroidissants (GR) : Arctic-heat® à gauche et Cryovest ® à droite. En bleu clair sont représentées les formes générales des GR, en bleu foncé, sont représentées les zones refroidissantes des GR. Pour les deux GR pris séparément, les faces antérieures et postérieures étant identiques, seules les faces antérieures sont représentées. Les points représentent les positionnements des sondes de température placées sur le tronc des sujets ; les points noirs pour la face antérieure du tronc, et les points gris pour la face postérieure.



1.4 Évaluation des caractéristiques thermiques des GR

9Afin d'apprécier les caractéristiques techniques des GR, nous les avons disposés sur des cintres (non portés par des sujets) et placés dans la CC (30 °C, 80 % d'humidité). Au moyen d'une caméra infrarouge (ThermaCAM™ SC640, Flir Systems, Dandery, Suède), la température des surfaces (interne et externe) de chacun des GR testés a été mesurée de manière itérative, permettant ainsi d'établir leur cinétique de réchauffement (Fig. 14.6). De la même façon, la variation de température cutanée en réponse au port des GR a été quantifiée chez trois sujets qui ont porté pendant 60 min chaque GR à même la peau, dans une pièce tenue à la thermoneutralité (27 °C). À la dixième et à la soixantième minute, les sujets ont enlevé leur GR pendant quelques secondes de façon à ce que des photographies de leur peau soient réalisées par thermographie infrarouge (Fig. 14.7).

Figure 14.6. Thermographie infrarouge des faces internes et externes des deux gilets refroidissants (GR) suspendus à un cintre durant 80 min dans une chambre climatique (température de l'air : 30 °C, humidité relative de l'air : 80 %). Plus les zones sont sombres, plus elles sont froides.

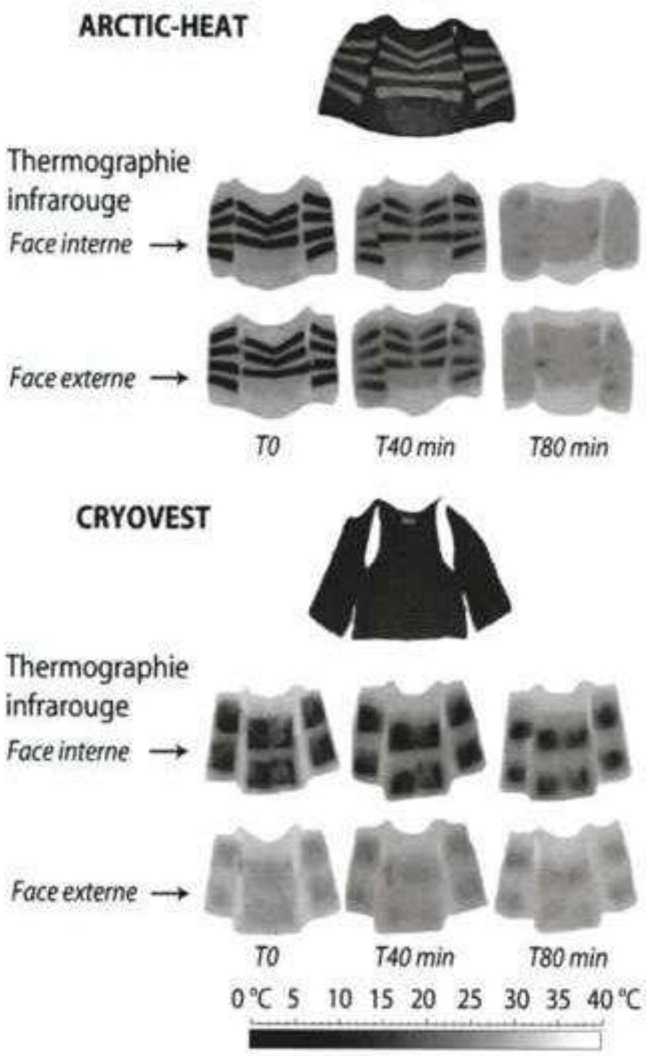


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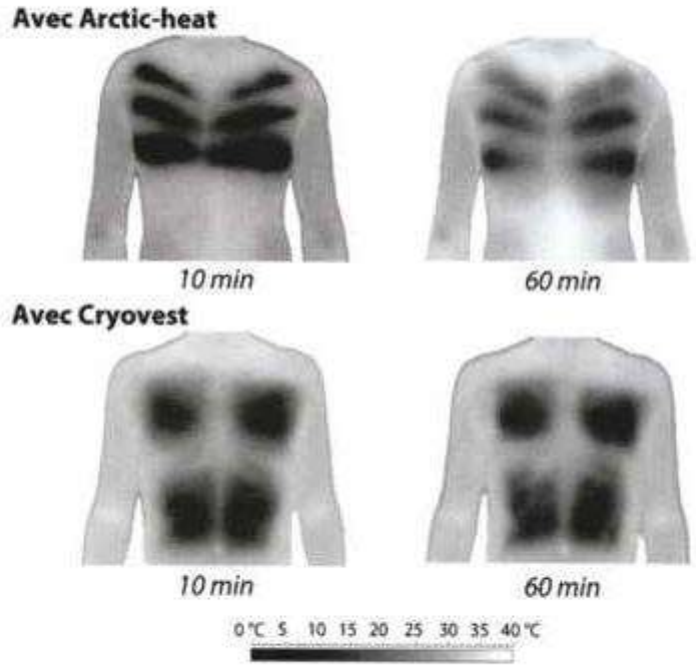
Figure 14.7. Thermographie cutanée infrarouge du tronc d'un sujet après le port, pendant respectivement 10 et 60 min, de l'un puis de l'autre modèle de GR. Les deux GR sont portés à même la peau dans une pièce maintenue à thermoneutralité (27 °C), les sujets restant au repos. Plus les zones sont sombres, plus elles sont froides.



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2. Description précise du protocole

10Chaque sujet est arrivé à 11 heures du matin au laboratoire, à jeun depuis 3 heures. Il leur a été demandé de ne pas consommer d'alcool, de caféine ou de médicaments dans les 48 heures précédant l'expérimentation.

11Dans un premier temps, une mesure de la masse corporelle a été réalisée avec une balance électronique (Tanita, Japon), les sujets étant en sous-vêtements. À l'issue de cette mesure, les différents capteurs thermiques et physiologiques ont été placés sur le sujet. Le protocole subséquent était subdivisé en cinq périodes (Fig. 14.8) :

Figure 14.8. Représentation schématique du protocole.

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1. *Repos ext. :* 30 min de repos, assis dans une pièce maintenue à neutralité thermique (27 °C).
2. *Repos CC :* 30 min de repos, assis dans la CC maintenue à une ambiance de 30 °C et à 80 % d'humidité relative de l'air.
3. *Éch. :* 30 min d'échauffement sur ergocycle dans la CC (30 °C et 80 % d'humidité relative) à une puissance correspondant à 25 % de la PMA du sujet.
4. *Exe.* : 15 min d'effort sur ergocycle dans la CC (30 °C et 80 % d'humidité relative) à une puissance correspondant à 60 % de la PMA du sujet.
5. *Récup.* : 20 min de récupération dans la CC (30 °C et 80 % d'humidité relative), phase décomposée en 5 min de récupération active à une puissance correspondant à 10 % de la PMA, suivies de 15 min de repos assis.

12Durant la période *Repos ext.*, les sujets portaient un simple tee-shirt en coton. Du début de la seconde période de repos à la fin de la récupération, les sujets étaient dans la CC et dans une des trois conditions expérimentales suivantes :

a. T-shirt » : les sujets portaient un tee-shirt en coton,
b. Arctic-heat » : les sujets portaient le GR Arctic-heat®,
c. Cryovest » : les sujets portaient le GR Cryovest®.

13Durant toute la durée du test, les sujets n'étaient pas autorisés à s'hydrater. À la fin de la période de récupération, une nouvelle mesure de la masse corporelle des sujets, en sous-vêtements, était réalisée.

2.1 Mesures thermophysiologiques

14La température rectale (T_{re}) était mesurée à l'aide d'une sonde thermique (Ysi 440 USA) introduite dans le rectum à 10 cm de la marge anale. Quatre sondes de température cutanée étaient placées sur la peau (Pt100), respectivement au niveau de la cage thoracique, de l'abdomen, de la zone scapulaire et de la région lombaire (Fig. 14.5). La température cutanée moyenne ($\bar{T}_{sk}$) était calculée à l'aide de ces quatre sondes. Quatre disques de flux thermique (FQ A020C, Ahlborn, Allemagne) étaient placés sur la peau des sujets contre chacune des sondes thermiques.

2.2 Mesures des paramètres énergétiques

15Tout au long des 90 min passées dans la CC, une analyse cycle à cycle des gaz expirés était effectuée à l'aide d'un métabographe portable (K_4b^2, Cosmed, Rome, Italie). Les paramètres mesurés étaient la consommation d'oxygène ($\dot{V}CO_2$ $ml.kg^{-1}.min^{-1}$), la production de dioxyde de carbone ($\dot{V}CO_2$, $ml.kg^{-1}.min^{-1}$) et le quotient respiratoire (QR, $\dot{V}CO_2/\dot{V}O_2$). La fréquence cardiaque était obtenue à l'aide d'une ceinture de type Polar® (Polar Electro Oy, Helsinky, Finland), placée sur le thorax des sujets, et exprimée en pourcentage de la réserve de la fréquence cardiaque (% AFC) [Karvonen et Vuorimaa 1988]. L'intensité relative de l'exercice était calculée à partir du pourcentage de la consommation maximale d'oxygène ($\%\dot{V}O_2max$).

2.3 Mesures des paramètres biologiques

16Deux prélèvements de 100 µl de sang total, réalisés aux lobes de l'oreille, ont permis de mesurer les paramètres biologiques au repos et à la fin de l'exercice. Les prélèvements ont été immédiatement analysés au moyen d'un automate de type l-Stat® analyzer (Abbott Point of Care Inc., Illinois, USA). Les cinq paramètres biologiques analysés étaient la natrémie ($[Na^+]$), la concentration sanguine en lactate ($[La^-]_b$), l'acidité du sang (pH), la concentration sanguine en bicarbonate($[HCO_3^-]$) et le taux d'hématocrite (Htc). Le pourcentage de variation du volume plasmatique (ΔVP) a été calculé en application de la formule proposée par Dill et Costill (1974) :

$$\Delta VP\ (\%) = \frac{100}{100 \times Htc_{\text{avant l'exercice}} \times \dfrac{100 \times \left(Htc_{\text{avant l'exercice}} - Htc_{\text{après l'exercice}}\right)}{Htc_{\text{après l'exercice}}}}$$

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2.4 Analyse statistique

17L'ensemble des valeurs est présenté sous forme de moyennes (± ET). La comparaison des données mesurées et calculées au terme des tests passés sous les trois conditions expérimentales a été réalisée par ANOVA pour mesures répétées à deux voies (Période x Condition). Le test *post-hoc* de Newman Keuls a permis de mettre en évidence les différences significatives au cours de la même période entre les trois conditions expérimentales. Les différentes variables dépendantes considérées étaient la FC, la $\dot{V}O_2$, la T_{re}, la $\bar{T}_{sk}$, les flux thermiques, ainsi que tous les paramètres biologiques. Le niveau de significativité a été défini pour $p < 0,05$.

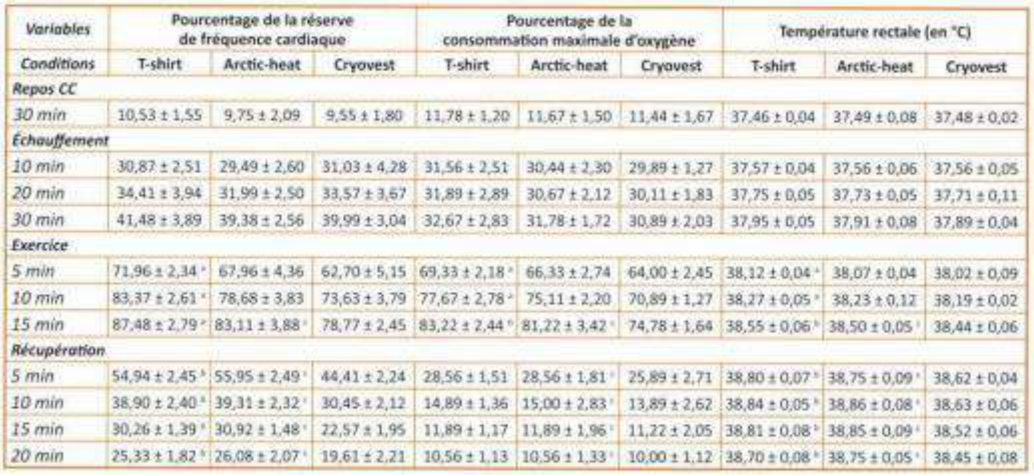
3. Résultats

18Lors du test incrémental maximal, les valeurs moyennes de FCmax, de $\dot{V}O_2$max et de PMA étaient respectivement de 186 ± 8 bpm, 52,3 ± 5,1 ml.kg^{-1}.min^{-1} et 255 ± 25 W.

19Au cours des périodes de repos, à l'extérieur puis à l'intérieur de la CC, aucune différence significative n'a été observée entre les trois conditions expérimentales quant aux valeurs de FC, $\dot{V}O_2$ et T_{re} (valeurs non présentées).

20Les valeurs de FC, de $\dot{V}O_2$ et de T_{re}, obtenues au cours de l'échauffement, de l'exercice et de la récupération réalisés dans la CC, sont présentées dans le tableau 14.3. Quelles que soient les conditions expérimentales, les valeurs de FC, $\dot{V}O_2$ et T_{re} augmentent au cours des 30 min d'échauffement et des 30 min d'exercice. Au cours des 10 premières minutes d'exercice, les valeurs de FC, $\dot{V}O_2$ et T_{re} observées dans la condition « T-shirt » étaient significativement plus élevées que dans les deux autres conditions. Lors des 5 dernières minutes d'exercice et durant la période de récupération, les valeurs de FC, $\dot{V}O_2$ et T_{re} enregistrées avec la Cryovest® étaient significativement plus faibles, comparées à celles enregistrées avec l'Arctic-heat®, elles-mêmes significativement plus faibles que celles observées dans la condition « T-shirt ».

Tableau 14.3. Valeurs moyennes (± ET) de la fréquence cardiaque, de la consommation d'oxygène et de la température rectale lors de chaque période du protocole et pour les trois conditions expérimentales.



Variables	Pourcentage de la réserve de fréquence cardiaque			Pourcentage de la consommation maximale d'oxygène			Température rectale (en °C)		
Conditions	T-shirt	Arctic-heat	Cryovest	T-shirt	Arctic-heat	Cryovest	T-shirt	Arctic-heat	Cryovest
Repos CC									
30 min	10,53 ± 1,55	9,75 ± 2,09	9,55 ± 1,80	11,78 ± 1,20	11,67 ± 1,50	11,44 ± 1,67	37,46 ± 0,04	37,49 ± 0,08	37,48 ± 0,02
Échauffement									
10 min	30,87 ± 2,51	29,49 ± 2,60	31,03 ± 4,28	31,56 ± 2,51	30,44 ± 2,30	29,89 ± 1,27	37,57 ± 0,04	37,56 ± 0,06	37,56 ± 0,05
20 min	34,41 ± 3,94	31,99 ± 2,50	33,57 ± 3,67	31,89 ± 2,89	30,67 ± 2,12	30,11 ± 1,83	37,75 ± 0,05	37,73 ± 0,05	37,71 ± 0,11
30 min	41,48 ± 3,89	39,38 ± 2,56	39,99 ± 3,04	32,67 ± 2,83	31,78 ± 1,72	30,89 ± 2,03	37,95 ± 0,05	37,91 ± 0,08	37,89 ± 0,04
Exercice									
5 min	71,96 ± 2,34 ^{a}	67,96 ± 4,36	62,70 ± 5,15	69,33 ± 2,18 ^{a}	66,33 ± 2,74	64,00 ± 2,45	38,12 ± 0,04 ^{a}	38,07 ± 0,04	38,02 ± 0,09
10 min	83,37 ± 2,61 ^{a}	78,68 ± 3,83	73,63 ± 3,79	77,67 ± 2,78 ^{a}	75,11 ± 2,20	70,89 ± 1,27	38,27 ± 0,05 ^{a}	38,23 ± 0,12	38,19 ± 0,02
15 min	87,48 ± 2,79 ^{a}	83,11 ± 3,88 ^{c}	78,77 ± 2,45	83,22 ± 2,44 ^{b}	81,22 ± 3,42 ^{c}	74,78 ± 1,64	38,55 ± 0,06 ^{b}	38,50 ± 0,05 ^{c}	38,44 ± 0,06
Récupération									
5 min	54,94 ± 2,45 ^{b}	55,95 ± 2,49 ^{c}	44,41 ± 2,24	28,56 ± 1,51	28,56 ± 1,81 ^{c}	25,89 ± 2,71	38,80 ± 0,07 ^{b}	38,75 ± 0,09 ^{c}	38,62 ± 0,04
10 min	38,90 ± 2,40 ^{b}	39,31 ± 2,32 ^{c}	30,45 ± 2,12	14,89 ± 1,36	15,00 ± 2,83 ^{c}	13,89 ± 2,62	38,84 ± 0,05 ^{b}	38,86 ± 0,08 ^{c}	38,63 ± 0,06
15 min	30,26 ± 1,39 ^{b}	30,92 ± 1,48 ^{c}	22,57 ± 1,95	11,89 ± 1,17	11,89 ± 1,96 ^{c}	11,22 ± 2,05	38,81 ± 0,08 ^{b}	38,85 ± 0,09 ^{c}	38,52 ± 0,06
20 min	25,33 ± 1,82 ^{b}	26,08 ± 2,07 ^{c}	19,61 ± 2,21	10,56 ± 1,13	10,56 ± 1,33 ^{c}	10,00 ± 1,12	38,70 ± 0,08 ^{b}	38,75 ± 0,05 ^{c}	38,45 ± 0,08

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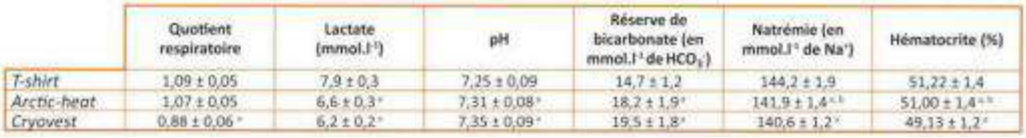
^{a} : différence significative à $p < 0,05$ entre la condition « T-shirt » et les conditions « Arctic-heat » et « Cryovest » ;
^{b} : différence significative à $p < 0,05$ entre les conditions « T-shirt » et « Cryovest » ;
^{c} : différence significative à $p < 0,05$ entre les conditions « Arctic-heat » et « Cryovest ».

21L'analyse des paramètres biologiques de repos ne révèle aucune différence significative entre les trois conditions : les valeurs moyennes de $[La]_b$, pH, $[HCO_3^-]$, $[Na^+]$ et Htc sont respectivement de 0,96 ± 0,18 mmol.ml^{-1}, 7,42 ± 0,03, 27,4 ± 1,2 mmol.l^{-1}, 140,7 ± 1,3 mmol.l^{-1} et 46,3 ± 1,8 %. L'ensemble des paramètres biologiques enregistrés à la fin de l'exercice et pour les trois conditions expérimentales est présenté dans le tableau 14.4. Quelles que soient les conditions expérimentales, les valeurs de $[La]_b$, Na^+ et Htc augmentent pendant la période d'exercice alors que les valeurs de pH et $[HCO_3^-]$ diminuent.

22Au cours de l'exercice, les valeurs de $[La]_b$, Na^+ et Htc observées dans la condition « T-shirt » sont significativement plus élevées que celles obtenues dans les deux autres conditions. À l'inverse, les valeurs de pH et $[HCO_3^-]$ sont plus basses dans la condition « T-shirt ». Au cours de cette même période, les valeurs de Na^+ et Htc observées dans la condition « Arctic-heat » sont significativement plus élevées que dans la condition « Cryovest » (Tableau 14.4).

Tableau 14.4. Valeurs moyennes (± ET) des paramètres biologiques et du quotient respiratoire mesurées à la fin des 15 min d'exercice.



	Quotient respiratoire	Lactate (mmol.l^{-1})	pH	Réserve de bicarbonate (en mmol.l^{-1} de HCO_3^-)	Natrémie (en mmol.l^{-1} de Na^+)	Hématocrite (%)
T-shirt	1,09 ± 0,05	7,9 ± 0,3	7,25 ± 0,09	14,7 ± 1,2	144,2 ± 1,9	51,22 ± 1,4
Arctic-heat	1,07 ± 0,05	6,6 ± 0,3^{a}	7,31 ± 0,08^{a}	18,2 ± 1,9^{a}	141,9 ± 1,4^{a,b}	51,00 ± 1,4^{a,b}
Cryovest	0,88 ± 0,06^{a}	6,2 ± 0,2^{a}	7,35 ± 0,09^{a}	19,5 ± 1,8^{a}	140,6 ± 1,2^{a}	49,13 ± 1,2^{a}

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[a] : différence significative à $p < 0,05$ avec la condition « T-shirt » *;*
[b] *:* différence significative à $p < 0,05$ entre les conditions « Arctic-heat » et « Cryovest ».

23Les variations de la masse corporelle (ΔMC) et du volume plasmatique (ΔVP), calculées entre la période de repos et la fin de la période de récupération, sont présentées dans le tableau 14.5. Les valeurs de ΔMC et de ΔVP observées dans la condition « T-shirt » sont significativement plus élevées lorsqu'on les compare aux deux autres conditions expérimentales. De la même façon, les variations obtenues dans la condition « Arctic-heat » sont elles-mêmes plus élevées que celles observées dans la condition « Cryovest ».

Tableau 14.5. Valeurs moyennes (± ET) des variations de la masse corporelle (ΔMC) et du volume plasmatique (ΔVP) entre le début et la fin du test à puissance constante.

Conditions	**ΔMC (g)**	**ΔVP (%)**
T-shirt	1 062 ± 98	-2,52 ± 0,25
Arctic-heat	961 ± 96$^{a, b}$	-1,76 ± 0,12$^{a, b}$
Cryovest	832 ± 53^{a}	-1,16 ± 0,14^{a}

[a] : différence significative à $p < 0,05$ avec la condition « T-shirt » ;
[b] : différence significative à $p < 0,05$ entre les conditions « Arctic-heat » et « Cryovest ».

4. Discussion

24Cette étude démontre que les caractéristiques techniques des GR influencent les cinétiques d'échanges thermiques avec la peau. Ces différences influencent de façon significative la tolérance à l'exercice réalisé en ambiance chaude, et jouent également un rôle déterminant lors de la phase de récupération subséquente.

25Concrètement, avec la Cryovest®, le gradient de température entre la peau et la face interne de la veste reste élevé durant les 85 min du test. À l'opposé, ce gradient disparaît à la dixième minute d'exercice lorsque le sujet utilise le GR Arctic-heat®. Par conséquent, les valeurs de FC et de $\dot{V}O_2$ sont significativement plus faibles durant l'exercice physique réalisé avec le GR Cryovest® et décroissent plus rapidement durant la période de récupération. De même, le niveau de déshydratation est moins important avec la Cryovest® comparé aux conditions « Arctic-heat » ou « T-shirt ».

4.1 Influence des caractéristiques techniques des deux GR sur les échanges thermiques

26Dans cette étude, la principale différence technique entre les deux GR est l'isolation thermique des packs refroidissants. Pour la Cryovest®, ces packs refroidissants étaient thermiquement isolés, aussi bien dans la face interne que dans la face externe des gilets. À l'inverse, pour l'Arctic-heat®, les éléments refroidissants étaient insérés dans un tissu très fin qui n'était isolé ni dans la face interne, ni dans la face externe du gilet. Par ailleurs, la face externe de la Cryovest® était recouverte d'un tissu classiquement utilisé chez les pompiers, permettant de réduire les échanges thermiques entre le milieu ambiant et les packs refroidissants.

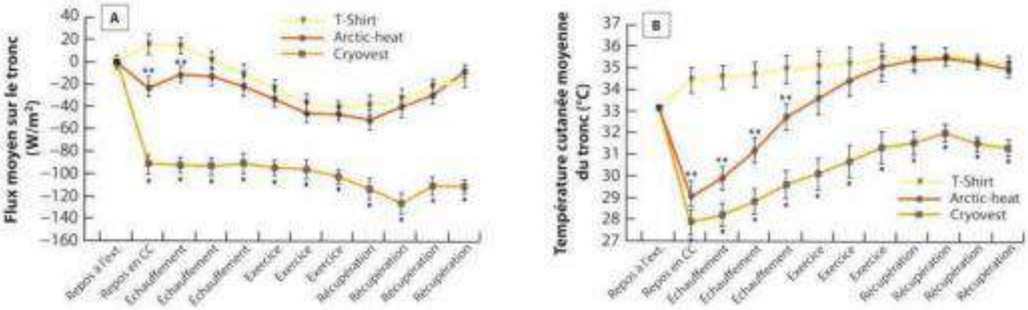
Enfin, la surface refroidissante de la Cryovest en contact avec la peau était supérieure (de 75 %) à celle de l'Arctic-heat® (Fig. 14.5).

27Lorsque les GR, totalement rechargés, étaient placés sur un cintre dans la CC (Fig. 14.6), les faces internes et externes des deux modèles présentaient des niveaux de température et des cinétiques de réchauffement différents. L'Arcticheat® était particulièrement froid (entre 3 et 8 °C) lors des dix premières minutes mais se réchauffait très rapidement pour atteindre une température de surface de 27 °C après 60 min d'exposition. Dans les mêmes conditions ambiantes, la température de surface de la Cryovest® était restée stable, aux alentours de 20 °C pour la face interne et de 27 °C pour la face externe du gilet (Fig. 14.6). Il nous semble donc possible de conclure que l'Arctic-heat® absorbe une quantité importante de la chaleur environnementale par sa face externe, ce qui n'est pas le but recherché par ce type de GR.

28Afin d'étudier les conséquences de ces caractéristiques techniques sur les échanges thermiques corporels, les deux vestes ont été portées par trois sujets au repos dans une pièce maintenue à thermoneutralité (27 °C). La température de surface de la peau était plus basse avec l'Arctic-heat® pendant les dix premières minutes et sur une surface faible (Fig. 14.7). En effet, la température cutanée des sujets refroidis par l'Arctic-heat® était comprise entre 5 et 9 °C. Avec la Cryovest®, la température des zones cutanées refroidies ne descendait pas en dessous de 20 °C. Entre la dixième et la soixantième minute, la surface de peau en contact avec les éléments refroidissants de l'Arctic-heat® se réchauffait rapidement et finissait par atteindre la valeur de 27 °C à la soixantième minute. Par contre, l'utilisation de la Cryovest® favorisait une stabilité de la température cutanée aux alentours de 20 °C tout au long de l'exposition.

29Lors de cette étude, lorsque les sujets étaient au repos en ambiance chaude (*Repos CC*), le stress thermique était uniquement environnemental. Les contraintes thermiques étaient minimes et l'organisme était capable de compenser ce stress thermique facilement. Cependant, au cours de cette période de repos, et en fonction des conditions expérimentales, la chaleur et l'humidité de l'environnement ont largement modifié les flux thermiques entre l'enveloppe corporelle et l'environnement (Fig. 14.9).

Figure 14.9. Flux moyen de chaleur (A) et température moyenne (B) mesurés au niveau du tronc dans les trois conditions expérimentales.



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* : différence significative entre les conditions « Cryovest » et, respectivement, « T-shirt » et « Arctic-heat » ($p < 0,05$) ;
** : différence significative entre les conditions « Arctic-heat » et « T-shirt » ($p < 0,05$).

30Lors de cette période (*Repos CC*), la température des zones cutanées directement en contact avec les éléments refroidissants de l'Arctic-heat® était significativement plus basse, comparée à la condition « Cryovest ». Pourtant, les mesures de la température cutanée moyenne pour la même période étaient plus élevées avec l'Arctic-heat® qu'avec la Cryovest® (Fig. 14.8). Cela s'explique par le fait que les surfaces de peau refroidies par l'Arctic-heat® étaient nettement inférieures à celles de la Cryovest®, et que trois des quatre capteurs de température cutanée étaient placés en dehors des zones refroidies par l'Arctic-heat® (Fig. 14.5). Le même constat était observable pour les flux thermiques (Fig. 14.9), plus élevés avec la Cryovest®, bien que la température cutanée fût plus élevée. Dans la condition « Arctic-heat », les zones cutanées étaient suffisamment basses pour créer une vasoconstriction importante, réduisant de manière drastique les échanges thermiques entre l'organisme et son environnement.

31Lors de cette phase de *Repos CC*, dans la condition « T-shirt », l'organisme emmagasinait la chaleur provenant de l'environnement, comme en témoigne l'augmentation du flux thermique (comparée à la période *Repos ext*). À l'inverse, le GR Arctic-heat® absorbait une grande partie de la chaleur environnementale (Fig. 14.9).

32En somme, bien que nous n'observions aucune modification des valeurs de la température rectale lors de cette période statique (*Repos CC*), il convient de considérer que la chaleur était régulée par des mécanismes d'ajustement physiologique, au premier rang desquels une redistribution vasculaire périphérique par vasodilatation. Ces ajustements étant très fins, il ne nous a pas été possible d'observer de modifications de la température rectale ou de la fréquence cardiaque (Tableau 14.3), et cela pour aucune des trois conditions expérimentales. Pourtant, les échanges thermiques au cours de cette phase de *Repos CC* étaient importants. Afin de maintenir constantes les valeurs de la température corporelle profonde, l'organisme devait s'adapter, de manière plus ou moins importante, en fonction du vêtement porté. Plus cet ajustement physiologique était élevé et moins l'organisme pouvait accepter la nouvelle contrainte thermique que l'exercice physique allait imposer.

■ Influence des caractéristiques thermiques sur l'exercice physique

33Dans notre étude, nous observons des niveaux de tolérance à l'exercice différents pour chacune des trois conditions expérimentales appliquées. Les études précédentes portaient sur les effets de différentes techniques de *pré-cooling* et sur leur incidence sur la réduction de la fréquence cardiaque du niveau de déshydratation (Booth, Marino *et al.* 1997 ; Sleivert, Cotter *et al.* 2001 ; Arngrimsson, Petitt *et al.* 2004 ; Webster, Holland *et al.* 2005 ; Duffield et Marino 2007). Bien que les résultats varient de manière importante en fonction des conditions expérimentales utilisées, les résultats de notre étude sont en adéquation avec ceux rapportés par les études scientifiques préalables. En effet, nous observons que la tolérance à l'exercice est d'autant moins bonne que le stress thermique imposé aux sujets est plus important. Or, c'est la qualité technique et thermique de chaque GR qui va déterminer l'importance du stress thermique imposé.

■ Influence des caractéristiques techniques des GR sur le stress thermique

34D'un point de vue physiologique, il est classiquement admis que lors d'un exercice physique réalisé à température élevée, le flux sanguin sous-cutané augmente afin d'améliorer la régulation de la température, ce qui s'accompagne d'une augmentation de la FC. Par ailleurs, la production de sueur augmente afin d'améliorer ce processus de thermorégulation, conduisant à une augmentation de la perte en fluides et donc à une déshydratation (Bell et Provins 1962 ; Febbraio 2001).

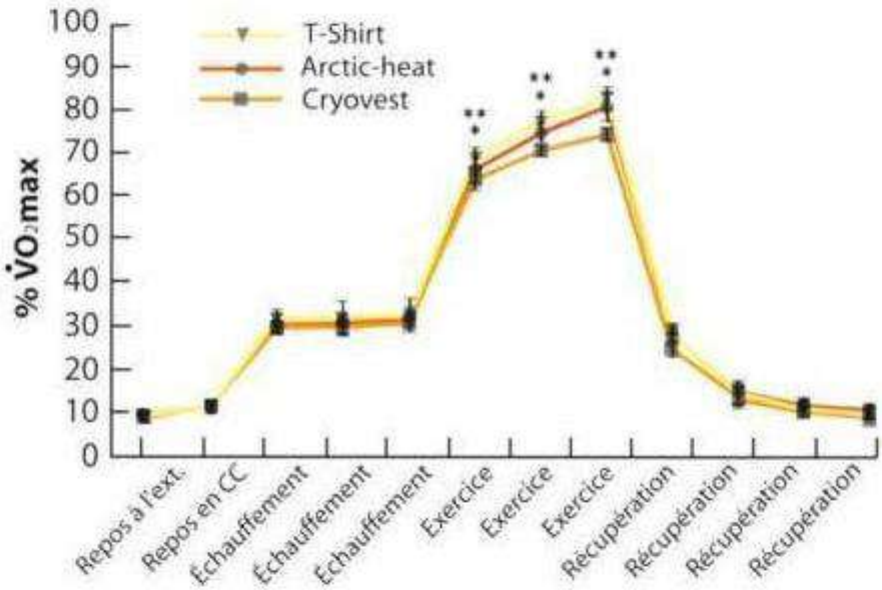
35Pour les trois conditions expérimentales de notre étude, nous observons une augmentation significative de ces deux marqueurs (FC et Tre) durant la phase d'échauffement et d'exercice, l'importance de cette augmentation restant malgré tout spécifique de chacune des conditions expérimentales testées (Tableaux 14.4 et 14.5).

36Dans cette étude, nous avons utilisé la condition « T-shirt » comme condition de référence car, dans cette situation, les capacités d'évaporation de la sueur sont réduites au minimum, induisant ainsi une contrainte thermique élevée et une sollicitation cardiaque importante (Tableau 14.3). De plus, dans cette condition expérimentale, les marqueurs de la déshydratation sont significativement plus élevés comparés aux deux autres conditions expérimentales (Tableau 14.4). Par exemple, après seulement 30 min d'échauffement et 20 min d'un exercice modéré, la ΔMC était significativement plus élevée dans la condition « T-shirt » (Tableau 14.5). Par ailleurs, en comparant les deux GR, nous observons une différence significative pour tous les indicateurs du stress thermique (FC, T_{re} et les marqueurs du statut hydrique). Ainsi, à la fin de l'exercice, tous ces marqueurs sont significativement plus détériorés dans la condition « Arctic-heat » que dans la condition « Cryovest » (Tableau 14.3). D'un point de vue physiologique, cette différence de tolérance du stress thermique va influencer de manière significative les capacités physiques de l'exercice physique à venir.

■ Influence des caractéristiques techniques des GR sur la dépense énergétique lors d'un exercice physique

37Lors d'un exercice sur bicyclette, le rendement énergétique (RE) est traditionnellement considéré comme l'un des facteurs déterminants de la performance, spécialement lors d'exercices de durée prolongée (di Prampero 1986 ; Hausswirth et Lehénaff 2001). Le RE est estimé à partir de l'équivalent énergétique de l'oxygène consommé : il représente le rapport entre le travail utile fourni et la quantité d'oxygène consommé (Daanen, van Es *et al.* 2006). Le RE peut ainsi être utilisé pour comparer les performances lors d'exercices réalisés en ambiance chaude. Dans la littérature scientifique, le rendement énergétique sur bicyclette se situe aux alentours de 18 % pour un exercice d'intensité similaire à celui de notre étude et réalisé sans aucune contrainte thermique (Gaesser et Brooks 1975), et tombe entre 14 et 16 % en ambiance chaude. Les résultats de notre étude sont donc en adéquation avec ces observations, puisque nous rapportons des valeurs de RE de 13,8 ± 0,9 % (condition « T-shirt »), 14,1 ± 1,1 % (condition « Arctic-heat ») et 15,9 ± 1,1 % (condition « Cryovest »). Dannen *et al.* (2006) rapportent que le pré-cooling réduit de manière significative la détérioration du RE (Fig. 14.10) lors d'un exercice réalisé en ambiance chaude. Les GR utilisés dans notre étude permettent une amélioration du RE, respectivement de 2,2 ±0,3 % (pour l'Arctic-heat$^{®}$) et 15,8 ± 1,4 % (pour la Cryovest$^{®}$). Par ailleurs, les valeurs de RE mesurées dans la condition « Cryovest » sont significativement supérieures à celles observées dans les conditions « T-shirt » et « Arcticheat ». La réduction du RE, classiquement observée lors de la réalisation d'un exercice physique en ambiance chaude, s'explique par une augmentation de la sollicitation de la filière énergétique aérobie et anaérobie (Sawka, Young *et al.* 1985 ; Young, Sawka *et al.* 1985). Pour la plupart des auteurs, l'élévation de la sollicitation de la filière aérobie s'explique par une augmentation des coûts de la transpiration, de la circulation vasculaire, de la ventilation pulmonaire et du métabolisme tissulaire induits par la chaleur (Fink, Costill *et al.* 1975). Selon des travaux plus récents des augmentations de la réponse sympatho-adrénergique et de la température intramusculaire pourraient être responsables de l'élévation du métabolisme anaérobie (Febbraio, Snow *et al.* 1994 ; Febbraio 2001).

Figure 14.10. Consommation d'oxygène ($\dot{V}O_2$) exprimée en pourcentage de la $\dot{V}O_2$max selon les trois conditions expérimentales.



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* : différence significative entre les conditions
« Cryovest » et « Arctic-heat » ($p < 0,05$) ;
** : $p < 0,01$.

38Dans notre étude, au cours des 15 min de pédalage à charge constante (60 % PMA), nous observons une dérive régulière de la $\dot{V}O_2$ respectivement de 20,1 ± 1,8 % (condition « T-shirt »), de 22,4 ± 2,4 % (condition « Arctic-heat ») et de 16,8 ± 1,2 % (condition « Cryovest ») [Tableau 14.3]. Dans les dix premières minutes de l'exercice, le port d'un GR s'accompagne d'une moindre élévation de la $\dot{V}O_2$. Néanmoins, à l'issue des 15 min de pédalage, nous n'observons plus de différences de la $\dot{V}O_2$ entre les conditions « T-shirt » et « Arctic-heat ». Seul l'exercice réalisé avec la Cryovest® présente des valeurs significativement plus faibles. D'un point de vue strictement énergétique, au-delà des dix premières minutes d'exercice, le port de l'Arctic-heat® ne présente plus d'intérêt comparé à la situation « T-shirt ». En utilisant les valeurs du quotient respiratoire comme témoin de la sollicitation de la filière anaérobie, on note que la sollicitation de cette filière glycolytique est plus élevée dans la condition « Arctic-heat » que dans la condition « Cryovest » (Tableau 14.4). Une récente revue de question (Quod *et al.* 2006) rapporte que l'utilisation d'un GR s'accompagne en général d'une très faible amélioration des performances (entre 1 et 3 % selon les études). Notre étude suggère qu'une amélioration plus importante de la performance est possible, en particulier lorsque la durée d'utilisation du GR est élevée, et démontre que les spécificités techniques et les propriétés thermiques des GR ont un impact direct et majeur sur les effets bénéfiques du *pré-cooling.*

Effet sur la qualité de la récupération.

39À l'issue de l'exercice physique, les valeurs de $\overline{T}_{sk}$ sont significativement plus basses dans la condition « Cryovest » (31,54 ± 0,18 °C) comparée aux deux autres conditions (« T-shirt » : 35,71 ± 0,28 °C ; « Arctic-heat » : 35,07 ± 0,21 °C) [Fig. 14.9b]. Ce résultat s'explique principalement par un avantage technique qui permet à la Cryovest® d'apporter du froid au contact de la peau pendant une durée plus longue. À l'inverse, et à partir de la dixième minute d'exercice, l'Arctic-heat® perd sa propriété refroidissante et se comporte, sur le plan thermique, comme le T-shirt.

40À la fin de l'exercice, les valeurs de T_{re} sont significativement plus basses dans la condition « Cryovest ». C'est ce qui explique principalement que les sujets portant la Cryovest® présentent des diminutions de T_{re} et de FC plus rapides lors de la période de récupération. Ainsi, à l'issue des 20 min de récupération, qui ont succédé à 15 min d'un exercice modéré (60 % PMA) réalisé en ambiance chaude et humide, les valeurs de Tre et de FC sont significativement plus basses dans la condition « Cryovest » (T_{re} : 38,45 ± 0,11 °C ; FC : 83,6 ± 7,3 bpm) que dans les conditions « T-shirt » (T_{re} : 38,71 ± 0,07 °C ; FC : 90,8 ± 4,7 bpm) et « Arctic-heat » (T_{re} : 38,45 ± 0,12 °C ; FC : 91,8 ± 4,9 bpm).

41Dans notre étude, nous observons des valeurs significativement différentes de la température rectale, du statut hydrique, de la contrainte cardiaque et de la dépense énergétique, selon le modèle de GR utilisé. De notre point de vue, les sportifs devraient choisir avec précaution le modèle de GR qu'ils souhaitent utiliser, en fonction des contraintes spécifiques de leur sport (durée, répétition des efforts, etc.), des conditions environnementales attendues et des caractéristiques techniques des différents modèles de GR disponibles sur le marché.

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Bibliographie

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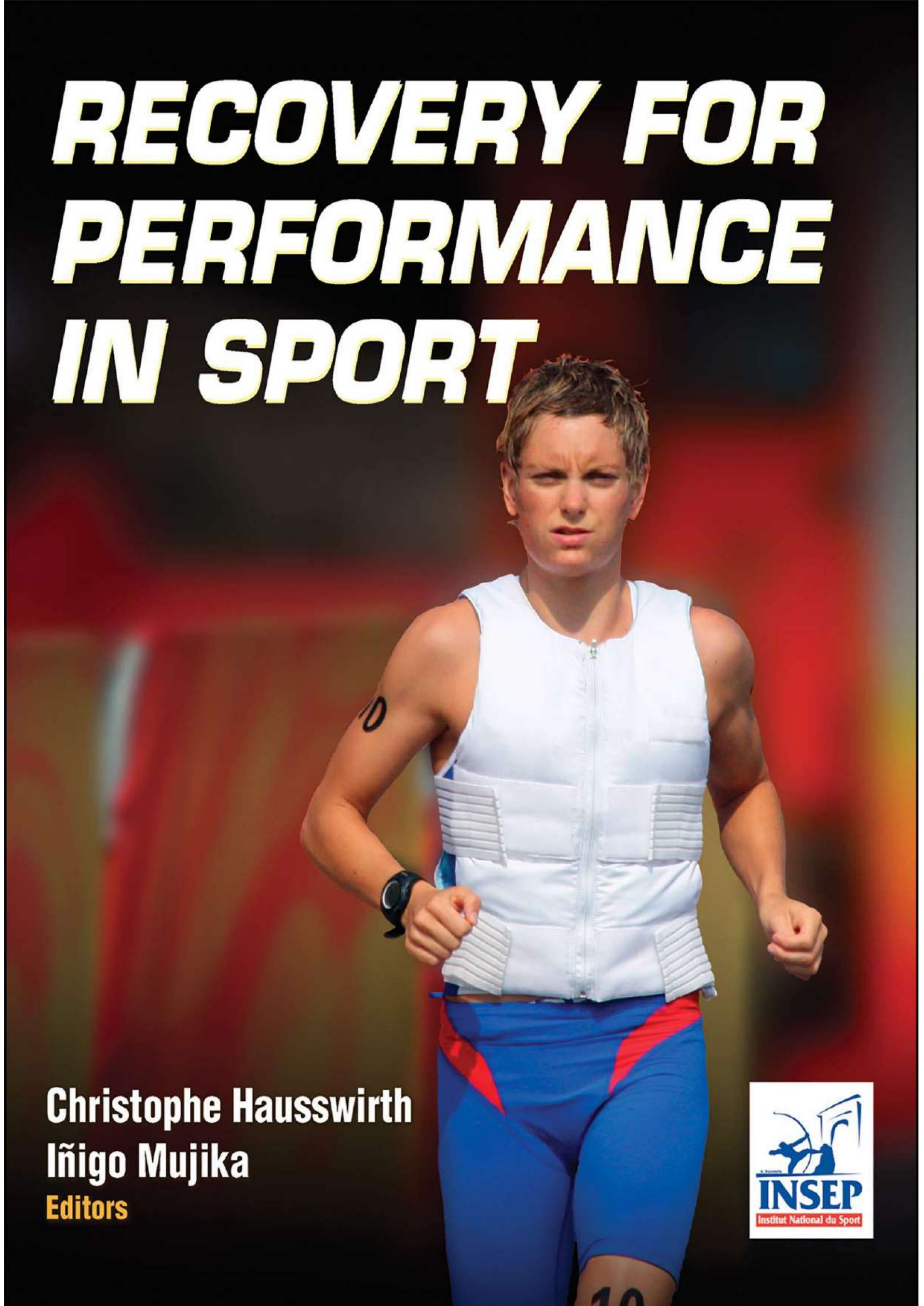
RECOVERY FOR PERFORMANCE IN SPORT



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Schmit, C., Le Meur, Y., Duffield, R., Robach, P., Oussedik, N., Coutts, A. J., & Hausswirth, C. (2015). Heat-acclimatization and pre-cooling: a further boost for endurance performance?. *Scandinavian journal of medicine & science in sports*.

Résumé en français

Afin de déterminer si l'usage bénéfique du pre-cooling (PC) reste ergogénique pour la performance en endurance en chaleur après une phase d'acclimatatisation (HA), 13 triathlètes ont réalisé deux contre-la-montre (CLM) de 20km à 35°C, 50% d'humidité, avant et à la suite d'un camp d'entraînement en chaleur de 8 jours, chaque fois avec et sans PC. Les stratégies d'allure, réponses physiologiques et perceptives ont été évaluées au cours de chaque CLM. L'usage du PC et de HA ont induits des augmentations *modérées* (+10 ± 18W ; ES 4,4 ± 4,6%) et *très larges* (+28 ± 19W ; ES 11,7 ± 4,1%) de la puissance de pédalage, respectivement. L'effet global de PC est resté *peu clair* après HA (+4 ± 14W ; ES 1,4 ± 3,0%). Cependant, les analyses de pacing ont révélé que PC restait transitoirement bénéfique post-HA *i.e.,* au cours de la première partie du CLM. PC et HA ont tous deux été caractérisés par une augmentation de la puissance de pédalage sans perturbations cardio-thermorégulatoires ou perceptives supplémentaires, tandis que PC post-HA induisait une amélioration du confort thermique. L'usage du PC améliore la performance en CLM de 20km chez des sujets non-acclimatés, mais une période HA de 8 jours atténue la magnitude de cet effet. Les incidences physiologiques respectives du PC et de HA peuvent expliquer cette inhibition de la réponse au PC. Cependant, les bénéfices perceptifs du PC pourraient rester présents post-HA et expliquer les légers ajustements de la stratégie d'allure observés.

Cette étude a permis d'apporter un éclairage sur l'intérêt et les mécanismes ergogéniques de la combinaison entre *cooling* et acclimatation pour la performance en endurance en chaleur. Associés avec le travail de thèse précédent, la question de la limite (*i.e.,* un plafonnement) de l'utilité de ce type de stratégie se pose alors.

Scand J Med Sci Sports 2015: ●●: ●●–●●
doi: 10.1111/sms.12629

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SCANDINAVIAN JOURNAL OF
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Heat-acclimatization and pre-cooling: a further boost for endurance performance?

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Accepted for publication 30 October 2015

To determine if pre-cooling (PC) following heat-acclimatization (HA) can further improve self-paced endurance performance in the heat, 13 male triathletes performed two 20-km cycling time-trials (TT) at 35 °C, 50% relative humidity, before and after an 8-day training camp, each time with (PC) or without (control) ice vest PC. Pacing strategies, physiological and perceptual responses were assessed during each TT. PC and HA induced *moderate* (+10 ± 18 W; effect size [ES] 4.4 ± 4.6%) and *very large* (+28 ± 19 W; ES 11.7 ± 4.1%) increases in power output (PO), respectively. The overall PC effect became *unclear* after HA (+4 ± 14 W; ES 1.4 ± 3.0%). However, pacing analysis revealed that PC remained transiently beneficial post-HA, i.e., during the first half of the TT. Both HA and PC pre-HA were characterized by an enhanced PO without increased cardio-thermoregulatory or perceptual disturbances, while post-HA PC only improved thermal comfort. PC improved 20-km TT performance in unacclimatized athletes, but an 8-day HA period attenuated the magnitude of this effect. The respective converging physiological responses to HA and PC may explain the blunting of PC effectiveness. However, perceptual benefits from PC can still account for the small alterations to pacing noted post-HA.

Self-paced endurance exercise is reported to be compromised in the heat, with important implications for competitive endurance events (e.g., World Triathlon Series, Athletics Championships). As evidence, the −0.3% to −0.9% performance decrement per 1 °C increase in ambient temperature above 10 °C is well noted (Racinais et al., 2015) and these negative effects on performance are increased with greater exercise duration (~2% for ~6.5 min, Altareki et al., 2009; ~7% for 30 min, Tatterson et al., 2000; ~16% for ~70 min, Racinais et al., 2015). To improve both performance and athlete health, various strategies have been developed to cope with exercise in the heat (Coris et al., 2004). In particular, heat-acclimatization (HA) and pre-cooling (PC) procedures have both been shown to increase work capacity in the heat (e.g., Garrett et al., 2011; Ross et al., 2013). However, it is currently unknown if when combined, these strategies provide additional physiological benefits or ergogenic effects on endurance performance.

Medium-term heat-acclimation, i.e., 7–14 training days in the heat, improves endurance performance at high ambient temperatures for both fixed- (e.g., Nielsen et al., 1993) and self-paced (e.g., Lorenzo et al., 2010; Racinais et al., 2015) cycling. Systemic protective adaptations against heat stress have been suggested to underpin these benefits. For example, decreases in sweat electrolyte (e.g., sodium), and increases in plasma volume (PV) and sweat rate have been reported to provide cardiovascular and thermoregulatory benefits (Nielsen et al., 1993). In addition to these physiological adaptations, lower perception of effort and reduced feelings of heat stress have also been reported (Daanen et al., 2011), although these have received less attention as to their ergogenic benefits. Given the role of passive exposure (i.e., free living) in addition to training in the heat during HA to maximize these adaptations (Shido et al., 1999), there has been increased interest in the efficacy of using heat training camps to prepare athlete for competition (e.g., Racinais et al., 2013, 2015).

Cooling the body prior to exercise in the heat has been shown to protect athletes from the negative effects of the heat through delaying the rise in endogenous temperature and limiting the decrement in endurance performance (Bongers et al., 2015). Reduced skin temperature (Tskin) following PC has been proposed an important factor determining aerobic performance during submaximal exercise in the heat, via improved core-to-skin temperature gradients and thermal comfort (TC) (Cuddy et al., 2014). A greater core-to-skin gradient is rationalized to be ergogenic by improving heat transfer from the core to the periphery, and heart rate by reducing skin perfusion (Cuddy et al., 2014). Given their low level of invasiveness on athletes preparation or competition routines, and avoidance of cooling active musculature, cooling vests have become a popular form of PC. Worn either at rest or during warm-up, ice vests enable improved steady- and self-paced endurance cycling tests in the heat (Johnson et al., 2008; Bogerd et al., 2010). In part, this improvement may occur as a result of augmented perception of TC (Schlader et al., 2011), though high variability between athletes in perceived thermal comfort may subsequently influence the magnitude of performance changes.

It is presently unknown if there is additional benefit of combining PC following HA to performance in hot conditions for endurance athletes. Indeed, it is possible that the HA-related thermoregulatory adjustments (e.g., lower increase in core temperature [Tcore] for sweat onset) could be further improved during exercise by the addition of a favorable core-to-skin gradient achieved with PC. The improved metabolic efficiency achieved with HA (Febbraio et al., 1994) might also add to the lowered energy expenditure reported with PC. In contrast, the PV expansion following HA may not allow PC to provide the same magnitude of benefit to cardiovascular function (i.e., preserved blood volume) to exercise in the heat that has been reported in unacclimatized athletes (Quod et al., 2008), and this may reduce the expected performance effects. Similarly, it is presently unknown whether perceptual improvements from HA interact with the PC-related increased TC of unacclimatized athletes.

To date, few studies have combined these strategies. Recently, after a 10-day heat-acclimation period, Castle et al. (2011) reported no further ergogenic effect of thigh PC in moderately trained subjects during an intermittent-sprint exercise protocol in the heat. However, this type of performance may be impaired by muscle PC due to loss in metabolic and neuromuscular efficiency (e.g., Sleivert et al., 2001), and thus not adequately reflect the HA–PC interaction for endurance performance. Brade et al. (2013) reported the same absence of cumulative effect in moderately trained participants using ice-slushie and cooling jackets after a five-session heat-acclimation exposure. However, in this study, no effect of PC on performance was reported pre-acclimation, making interpretation of the PC–HA interaction difficult. Accordingly, the present study investigated the effects of PC prior to, and following a period of HA on self-paced endurance performance in the heat. At the end of the training camp, we hypothesized ice vest PC would absorb excess body heat and increase TC prior to exercise, and HA would further reduce heat storage during exercise, resulting in greater performance improvement than each method separately.

Methods

Participants

Thirteen well-trained national-level males triathletes (age 31 ± 4 years, height 179.5 ± 4 cm, body mass 71.7 ± 5.6 kg, maximal oxygen consumption [VO_{2max}] 64.9 ± 6.9 mL/kg/min, maximal power output [MPO] 406 ± 34 W) volunteered to participate in this study. All subjects had competed at the national level for at least 3 years and trained ≥7 sessions/week. Prior to inclusion in the study, participants were examined by a cardiologist to obtain a medical clearance. The experimental design of the study was approved by the Ethics Committee of *Hôtel Dieu*, Paris (acceptance no. 2013-A00824-41) and the protocol was performed in accordance with the Declaration of Helsinki. After comprehensive verbal and written explanations of the study, all subjects gave their written informed consent for participation.

Experimental design

An outline of the full protocol is presented in Fig. 1. All participants performed repeated testing with and without PC in a randomized fashion, before and after a period of HA. Specifically, at the commencement of the study, all athletes resided in Paris (France) and had no heat exposure in the previous 6 months. Each participant attended five pre- and three post-HA sessions (all at the same time of day), either at INSEP (Paris, France) or at the Centre of Sports Resources, Expertise and Performance (CREPS) of Pointe-à-Pitre (Guadeloupe). Performance testing was conducted on two consecutive days before traveling (7 h) to Pointe-à-Pitre (departure at 10:00, west direction) or to Paris (departure at 17:00, east direction). Furthermore, on the day prior to departure for Guadeloupe and on the day of return to Paris, PV was determined and a heat tolerance test (HTT) was completed. At both testing locations, the research equipment and procedures were standardized and overseen by the same research team. To note, as pre-HA sessions were performed in a climate chamber, at least 7 days were allowed between the familiarization and the experimental sessions to avoid initiating heat adaptations prior to the training camp.

During the first pre-HA session, a graded exercise test was performed in normothermic conditions (21 °C, 40% RH) using an electronically braked cycle ergometer (Excalibur Sport, Lode®, Groningen, The Netherlands). Subjects wore a facemask covering their mouth and nose to collect all expired breath (Hans Rudolph, Kansas City, Missouri, USA). The exercise protocol started with a 5-min warm-up at a workload of 100 W, and then increased by 20 W/min until voluntary

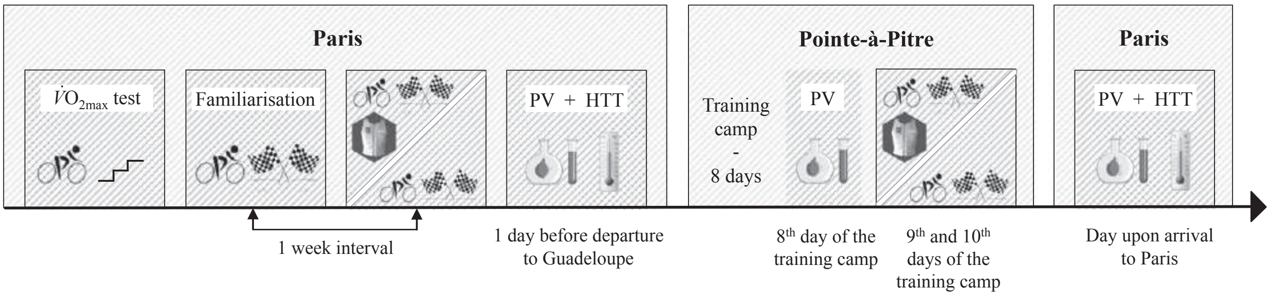

Fig. 1. Schematic representation of the full experimental protocol. VO_{2max}, maximal oxygen consumption; PV, estimated plasma volume; HTT, heat tolerance test.

exhaustion to estimate VO_{2max} (Quark, Cosmed®, Rome, Italy) and MPO.

To limit learning-induced changes in pacing strategy, all participants were familiarized with the exercise protocol (time-trial) in the heat during the second session. The protocol commenced with a 10-min passive seated period, followed by a 15-min warm-up involving 10 min at a workload of 100 W and 5 min at 50% of the individual's MPO in a climate chamber (Thermo Training Room, Paris, France) at 35 °C, 50% relative humidity (RH). After the warm-up, a 20-km time-trial (TT) was performed. Each participant performed both the warm-up and the TT on their own bike mounted on a braked Cyclus2 ergometer (RBM GmbH, Leipzig, Germany). To control for fluid intake between sessions, the participants were instructed that they could drink *ad libitum* during the passive phase, warm-up, and TT, with the volume of water ingested measured, and then replicated for the ensuing experimental sessions.

For the two experimental pre-HA sessions, participants completed the protocol in the above laboratory conditions, either with (PC) or without (NC) a PC intervention, in a randomized and counterbalanced order (seven participants completed PC session in the first session). During the NC condition, the participants performed the same protocol as the familiarization session. During the PC session, an ice vest (CryoVest®, CryoInnov, Saint Grégoire, France) was used that included four anterior and posterior pockets equipped with sealed packs of FirstIce® (150 × 150 mm, 120 g; EzyWrap, EzyWrap, CryoInnov, Saint Grégoire, France; body surface cooling = 0.18 m^2; total weight with the compresses ~1.9 kg). Ten minutes before the participant entered the room, the ice packs were removed from a −18 °C freezer and placed inside the pockets to allow cold transfer to the vest. The vest was worn during both the passive phase and the warm-up, though removed before the TT.

The two post-HA sessions were performed in a heat chamber at CREPS (Guadeloupe) at the end of the training camp and in the same order as the pre-HA sessions. To reproduce pre-HA conditions, participants were asked to rest in a temperate room at the same temperature as the pre-HA environment (~21 °C) for 20 min before entering the heat chamber. Ambient conditions (temperature and RH) from the heat chambers of the two laboratories were controlled (Kestrel 4500; Nielsen-Kellerman Co, Boothwyn, Pennsylvania, USA) every 5 min throughout experimental sessions.

To ensure that any variations in performance during the TTs were due to experimental procedures and not to the previous training load, subjects were required to avoid heavy training or fatiguing activities during the 20 h prior to each laboratory session. During the TT, convective airflow from a fan set to a standard speed (750 mm, 1450 ± 5 rpm, ~8.5 ms) facing the participant was used to mimic field conditions. The main measurements performed during the TT were the time required to complete the 20 km and the power output (PO) and speed (km/h) recorded by the Cyclus2 software at a sampling rate of 2 Hz. No feedback was provided to the subjects during TTs except for the distance remaining, and they were not informed of their performance until the end of the study. To show the participant's mean pacing strategy, PO values obtained for each TT were reported per km of the TT.

Experimental measurements for the time-trial protocol

Six and a half hours (Lee et al., 2010) before arriving at the laboratory, the participants were instructed to swallow an ingestible radio telemetry capsule (VitalSense; Mini Mitter, Bend, Oregon) to measure Tcore via an external sensor (HQI Inc, Coretemp®, Sarasota, Florida, USA). The participants were also instructed to consume 1 L of water in the 2 h prior to visiting the laboratory. Upon arrival at the laboratory, the subjects provided a urine sample as an indicator of hydration status based on urine specific gravity (USG) measured using a clinical refractometer (PAL-10S, Atago Co. Ltd, Tokyo, Japan). Following provision of a urine sample, participants then filled out a questionnaire assessing fatigue, motivation, and delayed onset muscle soreness (DOMS; Vaile et al., 2008).

Tskin was measured in temperate conditions (~21 °C) before the passive phase, immediately after the warm-up, and the TT (~20 s) using a Thermo Vision SC 640 Thermal imaging camera (Flir Systems, Danderyd, Sweden) with the corresponding software (Thermacam Researcher Pro 2.10, Flir Systems, Danderyd, Sweden). Thermograms of the body (torso, abdominal, right and left forearms, arms, thighs, and legs, and respective posterior regions all towel dried) were obtained with the camera placed 4 m from the participant.

Immediately after each Tskin measurement, towel dried nude body mass (BM) was measured using a digital platform scale (± 100 g, ED3300; Sauter Multi-Range, Ebingen, West Germany) to estimate sweat loss (pre – post BM + fluid ingested).

During the TT, RPE was assessed every 4 km from the start to the end of the TT (Borg, 1998). At the same time, Tcore values were recorded, and TC was assessed using a 10-point scale, with −5 as "very uncomfortable" and +5 as "very comfortable". Heart rate (HR) was continuously sampled every 5 s (Polar, Kempele, Finland) during the TT.

Heat-acclimatization measurements

Plasma volume

Plasma volume was determined before (on the day before departure to Guadeloupe), during (on the day before experimental sessions), and after (upon arrival in Paris) the training camp. Before and after the camp, PV was derived from the measurement of total hemoglobin mass, performed with a carbon monoxide (CO) rebreathing technique, as previously described (Robach et al., 2014). Briefly, after 20 min of rest, the subject breathed 100% O_2 for 4 min, before rebreathing chemically pure CO (CO N47; Air Liquide, Paris, France) for 10 min. After rest and immediately at the end of the rebreathing period, 1.5 mL of blood was obtained for percent carboxyhemoglobin, hemoglobin concentration (hemoximeter ABL800; Radiometer, Copenhagen, Denmark), and hematocrit to derive PV (Robach et al., 2014). During the camp, hematocrit percentage (micromethod, 4 min at 13 500 rpm) and hemoglobin concentration (Dill & Costill, 1974) were analyzed in quadruplicate and used to estimate percent changes in PV. All tests were performed by the same operator.

Heat Tolerance Test

The HTT was performed to examine thermoregulatory responses to given thermal and exercise stresses. Participants were instructed to standardize their hydration prior to each TT, and were not allowed to consume fluid during the HTT. The test consisted of a 10-min rest period and 30 min of cycling exercise at 50% of MPO (same ergometer and adjustments as the MPO test) in a climate chamber set at 35 °C, 50% RH. Every 5 min during the cycling test, Tcore and perceived TC sensations were recorded.

Sweat concentration analysis

Before participants entered the heat chamber, dermal patches (5 × 9 cm, Tegaderm, HP, 3M®, Neuss, Germany) were applied inferiorly to the participants' *scapula* to collect sweat samples. At the end of the HTT, the absorbent tissue contained in the patch was carefully separated from the adhesive tape using sterile tweezers, before being inserted into the tube of a single-use syringe (Terumo syringe SS+10ES1 10 mL, Terumo Europe, Belgium) for sweat extraction. The sweat sample obtained was then stored frozen at −18 °C in aliquots (Eppendorf type, 2000 μL per sample) until analysis.

Sweat samples from the HTTs were analyzed for sodium concentration using Inductively Coupled Plasma Atomic Spectrometry (ICP-AES) on a ICAP® 6300 DV simultaneous spectrometer (Thermo Scientific, Les Ulis, France). Samples were diluted 1:10 in ultrapure water (MilliQ®, Millipore, Guyancourt, France). Calibration curves were made with NaCl 0.09% in place of sweat and spiked with 0.1 g/L multielements standard solution (CCS-4, Inorganic™ Ventures, distributed by Analab, Hœnheim, France). Final standard concentrations were: 0; 62.5; 125; 250 mg/L. Utak® urine normal and high ranges (Utak Laboratories Valencia, CA, USA) and Seronorm urine Level 2 (Sero) both distributed by Ingen-Biosciences (Chilli-Mazarin, France) were used as internal QC control.

Heat-acclimatization procedure

During the 8-day training camp in Guadeloupe, from breakfast to dinner, participants were instructed to remain outdoors and asked to return to their accommodation only to shower after training sessions. Meals, recovery periods, and social activities were completed outdoors. Running, cycling, and swimming sessions were all performed outdoors (30 ± 5 °C, 74 ± 15% RH), while strength and conditioning training was performed in a weight room (26 ± 3 °C, 43 ± 16% RH). The participants reproduced their habitual weekly training program so that training distribution, activities, and content were kept constant from Paris to the training camp (see next section and Table 1 for details).

Training monitoring

The participant's internal and external training loads were monitored throughout the study. Before the training camp, subjects continuously recorded their usual training program over a 3-week period. For each training session, they were equipped with a Global Positioning System (GPS) monitor (Garmin Forerunner 305 GPS®, Garmin International, Inc., Kansas, Missouri, USA) to measure training distance and speed. Based on these measures, a typical training week was calculated so that participants could reproduce it during the training camp (i.e., matched for weekly training distribution, activities, and content). To ensure that the training completed in Guadeloupe was similar to those applied in France, the external training loads were also monitored. Additionally, all training sessions were monitored using the session-RPE method (Foster et al., 2001) using Borg's category-ratio 15 scale (Borg, 1998).

Data analysis

As previously recommended by Hopkins et al. (2009a, b) for studies in sports medicine and exercise sciences, magnitude-based inference analyses were performed on each aforementioned dependent variable. Accordingly, we calculated the between-trial standardized differences or effect sizes (ES, 90% CI) using the pooled standard deviation (Cohen, 1988). Threshold values for ES statistics were 0.2, 0.6, 1.2, 2.0, and 4.0 of the within-athlete variation, as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the changes observed between trials (Hopkins et al., 2009a , b). The smallest worthwhile change (SWC) was defined as (a) 0.2 × 1.3 for TT's performance (Paton & Hopkins, 2006), (b) 0.2 × 1.3 × 2.5 for PO values (Bonetti & Hopkins, 2009), and (c) a small standardized effect based on Cohen's effect size principle (0.2× between-athletes standard deviation [Hopkins et al., 2009a, b]) for other parameters. Accordingly, the SWC was determined to be 0.3% in performance time, and 0.7% in PO. Quantitative chances of higher or lower differences were qualitatively evaluated as follows: <1%, *almost certainly not*; 1–5%, *very unlikely*; 5–25%, *unlikely*; 25–75%, *possible*; 75–95%, *likely*; 95–99%, *very likely*; >99%, *almost certain*. If the chance of higher or lower differences was >5% when considering the proportion of positive vs negative effects of the intervention on the variable of interest (e.g., 50/25/25), the true difference was deemed *unclear*. Otherwise, we interpreted that change as the observed chance. All values are presented as means ± standard deviation (SD).

As the effects of PC progressively dissipate as exercise in the heat continues, we investigated whether the pattern of PC-related effects on performance at Post (Guadeloupe) differed from these at Pre (Paris). To examine this, a Pearson correlation was performed between PC-induced differences in PO before and after HA on a 5-km-block basis. In addition, as individual responses may be observed relative to PC-induced TC, and that this may affect performance, associations between individual perceptual responses to PC and PO were also explored.

Table 1. Mean environmental and individual characteristics, and data from training monitoring for Paris and Guadeloupe

	Variables	Pre-HA		Post-HA	
		NC	PC	NC	PC
Testing data	Env Temperature [°C]	35.2 ± 0.8	35.1 ± 0.7	35 ± 0.5	35.1 ± 0.5
	RH [%]	51.9 ± 4.5	49.9 ± 2.9	51.2 ± 3.5	50.3 ± 2.5
	DOMS [Likert]	2.2 ± 0.8	2.2 ± 0.9	2.6 ± 0.9	2.5 ± 0.9
	Fatigue [Likert]	3.7 ± 1	3.6 ± 0.9	0.7 ± 1.3	3.6 ± 1.4
	Motivation [Likert]	4.2 ± 0.4	4.2 ± 0.7	4 ± 1	4.2 ± 0.7
	USG	1.008 ± 0.006	1.009 ± 0.009	1.011 ± 0.007	1.011 ± 0.007
	Heart rate (bpm)	167 ± 10	165 ± 9	164 ± 8	165 ± 8
	Thermal comfort (AU)	−1.7 ± 1.3	−0.9 ± 1.4[†]	−1.7 ± 0.9	−1.2 ± 1.1[‡]
		Paris		Guadeloupe	
Training data	Training volume (min)	843 ± 216		842 ± 216	
	Training load	11245 ± 2305		11901 ± 2355*	
	Distance (km) Cycling	263 ± 84		261 ± 74	
	Running	35 ± 21		31 ± 17	
	Swimming	8 ± 3		9 ± 5	
	Frequency Cycling	5 ± 2		5 ± 1	
	Running	3 ± 1		3 ± 1	
	Swimming	3 ± 1		3 ± 1	

Results are presented as the group mean ± SD.

NC, non-cooling; PC, pre-cooling; env, environmental; RH, relative humidity; DOMS, delayed onset muscle soreness; USG, urine specific gravity upon arriving at the laboratory.

**Likely* increase compared to Paris (ES ± 90% CI, 0.33 ± 0.32).

[†] *Almost certain* increase compared to NC Pre-HA (ES ± 90% CI, 0.52 ± 0.26).

[‡] *Likely* increase compared to NC post-HA (ES ± 90% CI, 0.32 ± 0.28).

Results

Participant, environmental, and training characteristics

Characteristics of each parameter are shown in Table 1. Differences in DOMS, fatigue, motivation, USG levels, and thermal environment between the four conditions, as well as differences in the weekly training characteristics (volume, distance, or frequency) between Paris and Guadeloupe were *unclear*. In contrast, as compared to Paris, the training camp induced a *likely* (76/23/1, ES ± 90% CI, 0.33 ± 0.32) increase in internal training load.

Heat-acclimatization

During each day of the training camp, the athletes spent ~14 h in outdoor natural heat exposure and 121 ± 31 min per day training in the heat. Changes in PV were *almost certain* (100/0/0) both during (from 3603 ± 508 to 4190 ± 602 mL, 16.6 ± 8.5%, ES ± 90% CI, 0.98 ± 0.23) and after the camp (4068 ± 492 mL, 11.8 ± 6.9%, ES ± 90% CI, 0.71 ± 0.20). From pre- to post-training camp, smaller increases in Tcore during the HTT were *almost certain* (−0.2 ± 0.3 °C, 0/2/97, ES ± 90% CI, −0.85 ± 0.54) (Fig. 2a), although changes in TC were *unclear* (0.6 ± 1.3, 35/14/51, ES ± 90% CI, −0.23 ± 2.15) (Fig. 2b). Increases in sweat loss from the HTT were *almost certain* (0.26 ± 0.25 L, 99/1/0, ES ± 90% CI, 0.95 ± 0.49) (Fig. 2c), while the decrease in sweat sodium concentration was *likely* (221 ± 200 mg/L, 1/12/87, ES ± 90% CI, −0.50 ± 0.47) (Fig. 2d).

Time-trial performances

Power output

The temporal changes in PO for each TT are shown in Fig. 3. An overall range of individual effects of *likely* and *trivial* to *very large* beneficial effects of PC on PO was observed Pre-HA (249 ± 38 and 259 ± 35 W for the NC and PC conditions, respectively, 94/1/5, 4.4 ± 4.6%). Specifically, during each 5-km split of the TT, PC benefits were *likely* (0–5 km: 14 ± 29 W, 93/1/6, 6.5 ± 7.4%), *very likely* (5–10 km: 13 ± 23 W, 95/1/4, 6.1 ± 6.0%; 10–15 km: 11 ± 19 W, 95/1/4, 4.7 ± 4.6%), and *unclear* (15–20 km: 2 ± 22 W, 57/6/38, 0.6 ± 4.6%).

When comparing the pre- to post-HA NC trials, the training camp induced an *almost certain very large* to *extremely large* improvement in PO (28 ± 19 W, 100/0/0, 11.7 ± 4.1%).

At the end of the training camp, PC induced an overall *unclear* effect on PO (from 277 ± 37 to 281 ± 35 W, 76/7/17, 1.4 ± 3.0%). During each 5-km split of the TT, however, PC-related benefits were first *possible* (0–5 km: 5 ± 25 W, 70/5/25, 1.7 ± 5.0%) and *likely* (5–10 km: 5 ± 19 W, 80/4/16, 2.2 ± 4.9%), before becoming *unclear* (10–15 km, 3 ± 21 W, 65/6/29, 1.1 ± 4.2%; 15–20 km: 2 ± 16 W, 64/8/27, 0.8 ± 2.9%). As compared to pre-HA, wearing the ice vest post-HA induced a

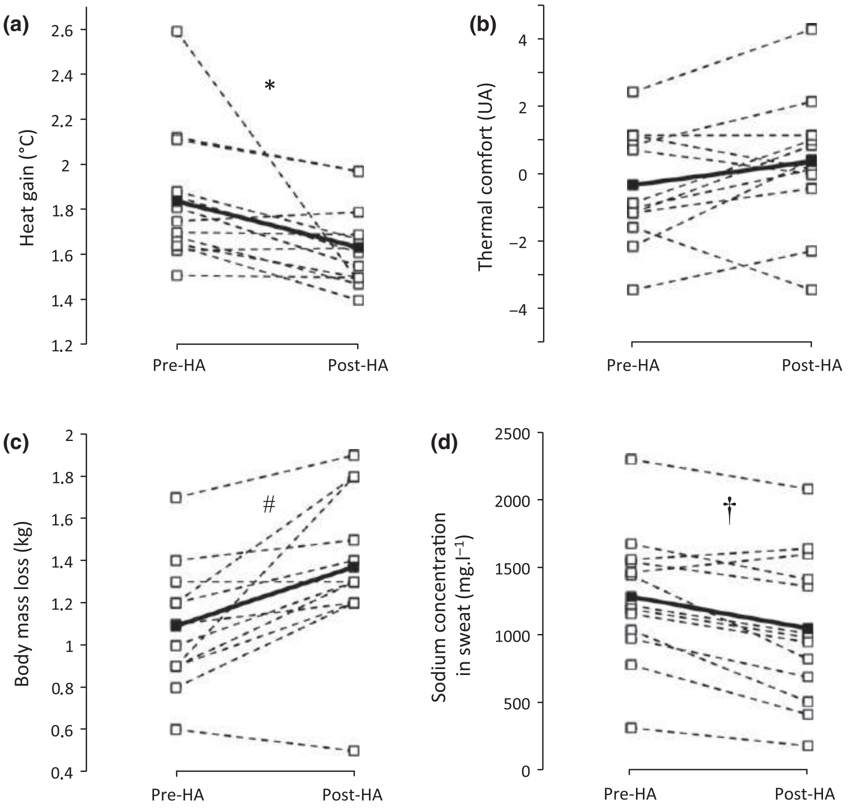

Fig. 2. Individual changes to heat-acclimatization-related HTT measurements pre- and post-training camp in (a) Tcore; (b) Thermal comfort; (c) Body mass loss; (d) Sodium concentration in sweat. *Almost certain decrease compared to pre (ES ± 90% CI, −0.85 ± 0.54); #Almost certain decrease compared to pre (ES ± 90% CI, 0.95 ± 0.49); †Likely decrease compared to pre (ES ± 90% CI, −0.50 ± 0.47).

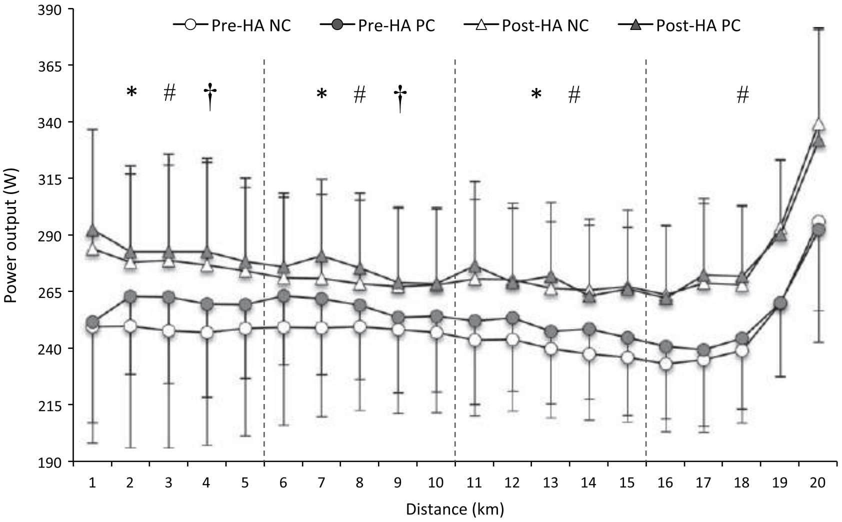

Fig. 3. Power output per kilometer for the four time-trials in the experimental protocol. Results are presented as the group mean ± SD. HA, heat-acclimatization; NC, non-cooling; PC, pre-cooling. *Changes at least *likely* between Pre-NC and Pre-PC; #Changes at least *almost certain* between Pre-NC and Post-NC; †Changes at least *possible* between Post-NC and Post-PC

likely (93/3/5) and *trivial* to *very large* (8.4 ± 9.3%) beneficial effect on PO.

Finally, correlational analyses revealed that PC-induced differences in PO before and after HA were positively correlated (r = 0.43 ± 20). Furthermore, individual differences in PC-related changes in TC between Post and Pre were related to individual changes in PC effects on PO between Post and Pre.

In particular, this was evident at 4 km ($r = 0.54 \pm 0.38$) and 8 km ($r = 0.48 \pm 0.39$), then reducing in association for the rest of the TT (12 km, $r = 0.26 \pm 39$; 16 km, $r = 0.23 \pm 35$; 20 km, $r = 0.09 \pm 32$).

TT duration

Changes in individual performance for each TT are shown in Fig. 4. Before HA, PC induced a *likely* benefit on TT duration (min:s; from 32:29 ± 01:39 to 32:04 ± 01:14 for NC and PC, respectively; 4/8/87, −1.3 ± 1.6%). The training camp had an *almost certain* positive effect on TT duration (−67 ± 58 s from the NC test at Pre to the NC test at Post; 100/0/0, −3.1 ± 1.7%). At the end of the training camp, the overall PC effect on TT duration was *unclear* (−6 ± 42 s, 14/30/56, −0.4 ± 1.1%). As compared to pre-HA, wearing the ice vest post-HA induced a *likely* (94/2/4) beneficial effect on TT duration (−1.7 ± 1.5%).

Physiological and perceptual measurements during the TT

TT core and skin temperatures

Time-trials resulted in *almost certain* increases in Tcore (from 37.6 ± 0.5 °C pre-TT to 39.5 ± 0.6 °C post-TT, 100/0/0, ES ± 90% CI, 4.61 ± 0.52). However, the changes in Tcore within and between pre- and post-HA TTs were *unclear*.

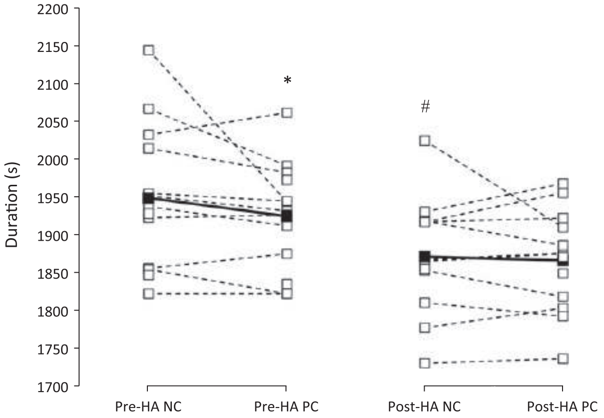

Fig. 4. Individual time-trial duration for the four conditions of the experimental protocol. HA, heat-acclimatization; NC, non-cooling; PC, pre-cooling. **Likely* decrease compared to Pre-HA NC (ES ± 90% CI, −1.3 ± 1.6%); #*Almost certain* decrease compared to Pre-HA NC (ES ± 90% CI, −3.1 ± 1.7%). Without the participant reporting drastic decreases in the two PC conditions (at the top of the graphs), results were as follow: *possible* between Pre-HA NC and Pre-HA PC (4/23/72; ES ± 90% CI, −0.6 ± 0.8%); *very likely* between Pre-HA NC and Post-HA NC (2/3/95; ES ± 90% CI, −2.5 ± 2.1%), and *unclear* between Post-HA NC and Post-HA PC (31/51/17; ES ± 90% CI, 0.1 ± 0.7%).

PC-induced decreases in whole body Tskin pre-TT were *almost certain* both pre- and post-HA (−1.5 ± 0.9 °C, 100/0/0, ES ± 90% CI, 3.23 ± 0.56 and −1.2 ± 0.7 °C, 100/0/0, ES ± 90% CI, 2.43 ± 0.55, respectively) (Fig. 5). Before the training camp, during the NC condition, the increase in Tskin was *likely* during the TT (0.9 ± 1.5 °C W, 90/9/1, ES ± 90% CI, 0.59 ± 0.51). In contrast, during the NC condition post-HA, changes in Tskin were *unclear* during the TT (0.2 ± 1.1 °C, 41/24/35, ES ± 90% CI, 0.06 ± 1.15).

Accordingly, the increase in the gradient of temperature during the TTs, post-HA was *likely* higher as compared to pre-HA (1.0 ± 0.3 °C, 82/15/4, ES ± 90% CI, 0.53 ± 0.65). Moreover, regardless of the HA status, changes in the core-to-skin gradient were *almost certain* during the TT in the NC condition (1.2 ± 0.3 °C, 100/0/0, ES ± 90% CI, 3.44 ± 0.47) though *unclear* using the ice vest (0.0 ± 0.3 °C, 31/28/41, ES ± 90% CI, −0.07 ± 0.99).

TT sweat loss and heart rate

Sweat losses during the TT were *likely* increased due to HA (0.28 ± 0.32 L, 93/6/1, ES ± 90% CI, −0.75 ± 0.60), and *likely* reduced by PC pre-HA (−0.05 ± 0.23 L, 3/22/75, ES ± 90% CI, −0.40 ± 0.52), but not post-HA (*unclear*, −0.03 ± 0.23 L, 8/52/39, CI ± 90%, −0.14 ± 0.41). Changes in HR due to HA (−2 ± 10 bpm, 17/35/48, ES ± 90% CI, −0.18 ± 0.69), PC pre-HA (−1 ± 5 bpm, 8/83/8,

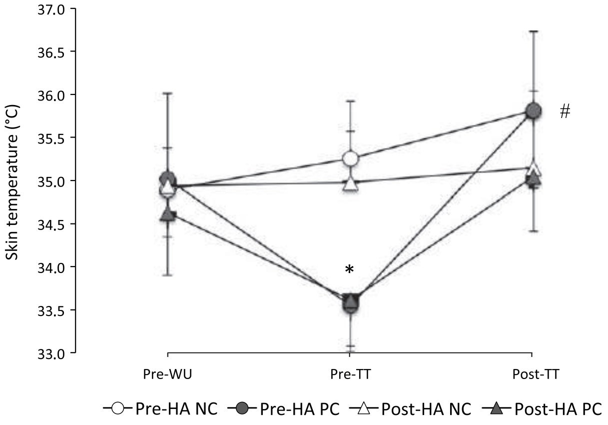

Fig. 5. Changes in skin temperature at different times during the experiment for each condition Pre- and Post-training camp. Results are presented as the group mean ± SD. HA, heat-acclimatization; NC, non-cooling; PC, pre-cooling; Pre-WU, before the passive phase; Pre-TT, immediately before the time-trial; Post-TT, immediately after the time-trial. **Almost certain* decrease compared to NC conditions (ES ± 90% CI, 3.23 ± 0.56 and ES ± 90% CI, 2.43 ± 0.55 for Pre-HA and Post-HA, respectively); #*Likely* increase compared to Pre-WU (ES ± 90% CI, 0.59 ± 0.51).

ES ± 90% CI, 0.00 ± 0.24), or PC post-HA (1 ± 7 bpm, 25/64/10, ES ± 90% CI, 0.06 ± 0.36) were *unclear* (Table 1).

Thermal comfort and RPE

Pre- and post-HA, TC was *almost certainly* (0.7 ± 0.8 UA, 98/2/, ES ± 90% CI, 0.52 ± 0.26) and *likely* (0.4 ± 0.8 UA, 77/22/0, ES ± 90% CI, 0.32 ± 0.28) improved due to PC, respectively. HA-related changes in TC were *unclear* (0.0 ± 1.2 UA, 20/58/22, ES ± 90% CI, −0.01 ± 0.43). Changes in RPE values due to HA (0.4 ± 0.8 UA, 49/44/8, ES ± 90% CI, 0.19 ± 0.46), PC pre-HA (−0.2 ± 1.1 UA, 6/36/58, ES ± 90% CI, −0.26 ± 0.48), or PC post-HA (0.2 ± 1.0 UA, 20/64/16, ES ± 90% CI, 0.01 ± 0.38) were *unclear*.

Discussion

The primary aim of this study was to test the hypothesis that HA and PC cumulate to improve self-paced endurance performance in the heat. In contrast to our hypothesis, the results showed that the combination of HA and PC using an ice vest did not further improve 20-km TT performance in the heat as compared to HA alone. Nonetheless, analysis of pre- and post-HA pacing strategies based on presence of PC revealed a small effect of PC on PO during the initial stages of the TT post-HA. Given that both PC and HA improved TT performance without exacerbated physiological responses, it is likely that the HA-induced cardiovascular and thermoregulatory adaptations reduced the ergogenic effects of PC. Despite the blunted effects on the overall performance, PC following HA improved perceptions of thermal tolerance, which appeared to be related to pacing.

Acute pre-cooling for endurance performance in the heat

In agreement with some (Johnson et al., 2008; Bogerd et al., 2010), but not all (Quod et al., 2008; Stannard et al., 2011) studies, the present results showed that ice vest PC improved 20-km TT performance in the heat. While the 4.4% increase in PO observed in the current study is similar to the 5.2% improvement during a 20-km TT reported by Johnson et al. (2008), Quod et al. (2008) only reported a 1.5% improvement in similar environmental and self-paced exercise conditions to the present study. However, in their study, Quod et al. (2008) removed the cooling vest before the 20-min warm-up, which may have reduced the efficacy of PC on the TT performance. Also, despite comparable durations of PC during the warm-up, our results differ from those of Stannard et al. (2011), who reported no effect of wearing a cooling vest before 40-min running exercise in warm conditions. The greater thermal stress imposed in our study (35 °C vs ~25 °C in Stannard et al. (2011)), as well as the ice vests' cooling efficiency may explain this difference (Ross et al., 2013). Notably, the Cryo-Vest® (body surface cooling = 0.18 m^2; weight <2 kg) enhanced TT performance despite fan-related airflow – which restricts PC benefits in laboratory settings (Morrison et al., 2014). This type of cooling might thus be relevant for outdoor competitions in the heat of ~30 min, as the effects of PC on PO progressively decreased with exercise duration.

As expected, PC reduced Tskin at the beginning of the TT, which likely enabled participants to adopt a higher PO (+10 ± 18 W) while maintaining similar cardiovascular and thermoregulatory responses to the NC condition. This absence of increases in HR, Tcore, and sweat loss despite the greater PO may be due to cooling-related reduced cutaneous vasodilatation and higher heat loss via tissue conduction (transfer from the core to the skin) and subsequent fan-based convection (transfer from the skin to the environment), respectively (Saunders et al., 2005). Tskin reached similar temperatures at the end of the TTs in both NC and PC conditions, suggesting the PC-induced benefits on PO paralleled the ephemeral PC effect on the core-to-skin gradient. Either due to, or alongside the reduced relative physiological loads, PC up-regulated the pacing pattern while maintaining the same perceptual exertion as in NC. This may result from the central integration of cutaneous afferences, as TC *per se* is able to influence PO without modifying RPE (Schlader et al., 2011, Flouris & Schlader 2015).

Heat-acclimatization and endurance performance in the heat

As determined from the HTT, the participant's exhibited symptoms of HA such as reduced heat gain (−0.2 ± 0.3 °C) and improved sweating rate (0.26 ± 0.25 L). PV also increased (16.6 ± 8.5% on day 7, 11.8 ± 6.9% on day 11) and sweat sodium concentrations were reduced during the TT (−17 ± 19%). Comparatively, these changes are similar to those observed in well-trained cyclists after a 2-week training camp (Karlsen et al., 2015), but greater than those previously reported using training camp models in professional football players (see Buchheit et al., 2011; Racinais et al., 2013). Such discrepancies may be as a result of the effective training volume of the present triathlete population and/or the large daily passive phases spent outdoors (Garrett et al., 2011).

The HA exhibited a *very large* effect on PO in the NC condition (ES ± 90% CI, 11.7 ± 4.1%). Such extent of performance improvement has not previously been reported on self-paced cycling exercise after heat-acclimation of similar duration (e.g., Lorenzo et al., 2010). Hence, it may be the combination of daily passive heat exposure with the heat training that amplified the performance improvement (Shido et al., 1999; Racinais et al., 2015). Moreover, the magnitude of physiological (i.e., cardiovascular and thermoregulatory) changes and perceptual adaptations may explain this improvement. Specifically, it is possible PV expansion and Tskin reduction enabled increased PO while limiting homeostasis disturbance (e.g., Tcore and cardiac strain, muscle metabolism). As evidence, PV expansion is suggested to offset increased HR responses by facilitating improved blood flow distribution during exercise (Nielsen et al., 1993). In parallel, as supported by our results, increased sweat losses provided greater evaporative cooling and core-to-skin gradient, especially in the presence of airflow (Saunders et al., 2005). Additionally, as a result of, or alongside these improved thermoregulatory adaptations, the athletes TC during the 20-km TT was similar to pre-HA despite the higher metabolic rate, and this may also allowed for increased PO (Schlader et al., 2011; Schulze et al., 2015).

Effect of pre-cooling after heat-acclimatization

In contrast to the initial hypothesis, PC did not provide further benefits on the overall performance once athletes were heat-acclimatized (4 ± 14 W). These findings extend previous studies (Castle et al., 2011; Brade et al., 2013) that examined the combined effects of PC with HA during repeated intermittent sprints performed in the heat. Accordingly, it is possible that the HA from the training camp led to a "ceiling effect" (i.e., saturation) of physiological adaptations (Castle et al., 2011), or blunted the PC-related physiological effects (i.e., converging effects), thus reducing the likelihood of further notable PC benefits on performance. Crucially, although our results do not enable to distinguish between these two hypotheses, both strategies demonstrated similar influence on the physiological responses to the TT. Specifically, while post-HA PC decreased Tskin to a similar extent as pre-HA, the sudomotor adjustments resulting from the heat exposure also promoted a lowering of Tskin during the TT. It is therefore possible that earlier and larger sweat losses resulting from HA (Shido et al., 1999) may have subsequently reduced the effectiveness of PC by inducing a larger core-to-skin temperature gradient than pre-HA. Similarly, PC improved cardiovascular efficiency during the unacclimatized TTs, which was also reflected in the post-HA responses in regard to PV expansion. However, the extent of PV increase (16.6 ± 8.5%) may have minimized the cardiovascular effect of PC observed Pre-HA by facilitating both cutaneous and muscle blood flow distribution (Nielsen et al., 1993). Together with the absence of any changes in psychometric variables pre-TTs, these results suggest that HA did not allow PC-related initial effects on PO to be as evident post-HA as pre-HA due to consubstantial physiological (i.e., cardiovascular and thermoregulatory) adaptations.

Although this study shows the advantage of PC is minimized by HA, the analysis of pacing suggests that PC still may have some role in the *acute* protection of exercise performance in the heat, regardless of acclimatization status. Indeed, at post-HA, PC temporarily induced *small* to *moderate* benefits in the TT, though only during the initial 10 km. This observation is consistent with the fact that PC- and post-HA PC-pacing profiles demonstrated comparable relationships (r = 0.43) for the trend of diminished benefit throughout the TTs (from 14 ± 29 to 2 ± 22 W at Pre, and from 5 ± 25 to 2 ± 16 W at Post). Such similarity in the temporal profiles, albeit with a smaller magnitude at Post-HA, suggests that the effectiveness of PC be related to individual athletes HA level – and it could further be speculated that the lesser the extent of HA the more effective PC would be.

Despite the smaller magnitude, the ephemeral beneficial effect of post-HA PC is likely related to perceptual improvements. For individual participants, an additional increase in TC from the vest at Post- compared to Pre-HA was associated with an additional increase in PO, notably during the first half of the TT (r = 0.54 and r = 0.48, at 4 and 8 km, respectively), i.e., when PC-induced benefits were the most remarkable. This suggests that when pre-cooled, athletes who perceived a greater increase in TC following HA were those continuing to gain performance benefit from wearing the vest. This relationship reduces with increased TT duration. Nonetheless, these observations highlight the purported role of improvements in TC following PC to improve endurance performance beyond cardiovascular or thermoregulatory implications (Schulze et al., 2015).

Perspectives

This study strengthens previous findings that PC (Johnson et al., 2008) and HA (Lorenzo et al., 2010) independently improve self-paced endurance performance in the heat (Castle et al., 2011). However, given each of these heat-combating strategies are likely to induce convergent physiological effects, the combination of HA and ice vest PC provided no additional overall ergogenic effect to 20-km TT performance in the heat. In spite of this, when considering pacing adjustments, PC-induced ergogenic effects were still persistent post-HA during the first half of the TT, and thus remain of interest for HA athletes. Accordingly, we would still recommend that these combined strategies be encouraged when competing in the heat to ensure improved TC and assist performance benefits. Indeed, individual perceptual benefits from PC may potentially up-regulate pacing strategies – particularly if effective HA has already provided the athlete an improved physiological tolerance of the heat. In this perspective, the respective role of physiological (Bogerd et al., 2010; Bongers et al., 2015) vs perceptive (Schlader et al., 2011; Schulze et al., 2015) pathways inherent to PC strategies and leading to endurance performance improvement in the heat remains to be fully elucidated.

Key words: Heat-dissipating strategies, tropical climate, time-trial, pacing, cycling.

Acknowledgements

This study was made possible by technical support from the French Federation of Triathlon. The authors are grateful to Anaël Aubry, Bruno Coutant, and the Centre of Sports Resources, Expertise and Performance (CREPS) of Pointe-à-Pitre (Guadeloupe) for their help and cooperation. We receive funding for research on which this article is based from the French Ministry of Sport and the French National Institute of Sport, Expertise and Performance (Paris). The authors report no conflict of interest.

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Scand J Med Sci Sports 2015: 25 (Suppl. 1): 219–228
doi: 10.1111/sms.12392

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Low-frequency electrical stimulation combined with a cooling vest improves recovery of elite kayakers following a simulated 1000-m race in a hot environment

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Accepted for publication 17 November 2014

This study compared the effects of a low-frequency electrical stimulation (LFES; Veinoplus® Sport, Ad Rem Technology, Paris, France), a low-frequency electrical stimulation combined with a cooling vest ($LFES_{CR}$) and an active recovery combined with a cooling vest (ACT_{CR}) as recovery strategies on performance (racing time and pacing strategies), physiologic and perceptual responses between two sprint kayak simulated races, in a hot environment (~32 wet-bulb-globe temperature). Eight elite male kayakers performed two successive 1000-m kayak time trials (TT1 and TT2), separated by a short-term recovery period, including a 30-min of the respective recovery intervention protocol, in a randomized cross-over design. Racing time, power output, and stroke rate were recorded for each time trial. Blood lactate concentration, pH, core, skin and body temperatures were measured before and after both TT1 and TT2 and at mid- and post-recovery intervention. Perceptual ratings of thermal sensation were also collected. $LFES_{CR}$ was associated with a *very likely* effect in performance restoration compared with ACT_{CR} (99/0/1%) and LFES conditions (98/0/2%). $LFES_{CR}$ induced a significant decrease in body temperature and thermal sensation at post-recovery intervention, which is not observed in ACT_{CR} condition. In conclusion, the combination of LFES and wearing a cooling vest ($LFES_{CR}$) improves performance restoration between two 1000-m kayak time trials achieved by elite athletes, in the heat.

Canoe sprint has been an Olympic sport since 1936 and comprises of two distinct disciplines – kayak and canoe. The international sprint canoeing competition typically comprises one to three days of races. Heats and semifinals are often 3 h or 4 h apart with the final the following day. Depending on the strategy of the teams, many athletes compete in several events with multiple races per day in individual (C1, K1), crew (C2, K2 or C4, K4), or both, interspaced by short recovery periods (less than 2 h). Furthermore, in the last few years, the main international events in canoe sprint (Milan World Cup Series in 2014, Moscow World Championships in 2014, Zagreb European Championships in 2012, Beijing Olympic Games in 2008) regularly took place under hot and/or humid conditions, which seriously limit human performance (Kay et al., 1999; Wendt et al., 2007; Periard et al., 2014). Accordingly, it is challenging for coaches and scientists to establish competition strategies that allow athletes to regulate effort in order to achieve optimal performance. Therefore, in an attempt to overcome these intensive training and competition demands, recovery from exercise is a priority in elite canoeing as it contributes to metabolic, cognitive, and physical regeneration (Vaile et al., 2008; Crampton et al., 2011).

One of the most frequently applied recovery interventions in canoeing is active recovery, where athletes exercise at low to moderate intensities (workloads corresponding to 30–40% $\dot{V}O_{2peak}$) in an attempt to increase systemic and muscular blood flows improving oxygenation and nutrients delivery, while at the same time assisting in the removal of metabolic by-products. However, in the heat, active recovery can elicit sustained cardiovascular and thermoregulatory strains, as the muscles continue to work and therefore to produce metabolic heat (De Pauw et al., 2014). Recently, low-frequency electrical stimulation (LFES) has been investigated as an alternative to active recovery (Bieuzen et al., 2012). The physiologic rationale for using LFES during recovery from exercise is to increase blood flow in the muscles. This is achieved when LFES is applied at intensities sufficient to initiate a low-intensity, involuntary, repetitive mechanical contraction–relaxation cycle. Results from recent studies suggest that increased systemic blood flow following LFES is beneficial to performance restoration after a short-term recovery, in a temperate environment (Bieuzen et al., 2012, 2014; Finberg et al., 2013). By being a non-active strategy, using LFES after exercise in a hot environment could limit heat development and may even enhance conductive and evaporative cooling by maximizing peripheral blood flow, and consequently, improve recovery in athletes.

Several external and internal cooling methods are also employed in elite sport to reduce thermal stress and improve recovery in-between exercise bouts in the heat. Although cold-water immersion is one of the most effective cooling strategies (Bleakley et al., 2014), it is rarely used in the field because of practical considerations. Recently, the use of cooling vests has increased and several countries have adopted this strategy as a method of reducing thermoregulatory strain in elite canoeing. Wearing a cooling vest during exercise has been shown to enhance the rate of perceived thermal comfort and physical performance in hot conditions (Hasegawa et al., 2005); however, the effectiveness of using cooling vests as a post-exercise recovery strategy has not been studied extensively (Hausswirth et al., 2012). Moreover, the effects of cooling vests on short-duration exercise performance remain inconclusive.

As is evident from earlier, acute recovery has been studied in depth, yet many questions remain unanswered. The most prevalent is the effectiveness of using mixed-method recovery intervention that can both prevent excessive heat storage and facilitate heat loss from the body as well as increasing blood flow, oxygen supply, and metabolites washout, and ultimately improve subsequent exercise performance in the heat. The combination of LFES, which prevents thermal strain and enhances blood flow, and wearing a cooling vest, which reduces thermal strain, could be an effective recovery strategy and warrants investigation.

Therefore, the aim of this study was to investigate the performance (racing time and pacing strategies), physiologic, and perceptual responses to repeated 1000-m sprint kayak races using (a) LFES, (b) active recovery combined with a cooling vest, and (c) LFES combined with a cooling vest between races in the heat. It was hypothesized that the combination of blood flow stimulation with the cooling vest between races would reduce thermal strain and improve subsequent 1000-m kayak sprint performance, in comparison with the other interventions.

Methods

Participants

Eight elite Caucasian male kayakers unacclimatized to heat participated in this study (mean ± standard deviation: age 22 ± 3 years; stature 183.3 ± 6 cm; body mass: 86.6 ± 7.3 kg; body surface area: 2.08 ± 0.1 m^2). All participants were K1, 1000-m paddlers, recruited from the French national Under 23 team, and had previously competed in the World and European Junior Championships. Data collection occurred during an international pre-competitive period in which all participants were accustomed to training up to six times per week and one to two sessions per day. Participants were informed of the possible risks and benefits of their participation in writing and an informed consent was obtained prior to data collection. The experimental protocol was conducted according to the Declaration of Helsinki statement and approved by a local ethics committee, CCP Ile-de-France XI (Ref. A006S7-S0).

Overview

Participants were familiarized with all equipment and procedures under experimental conditions before reporting to the laboratory for three separate experimental trials that were separated by a minimum of 24 h. In the 12 h prior to each testing session, participants were asked to refrain from strenuous physical exercise, caffeine and alcohol, to stay well hydrated, and to maintain a consistent dietary intake, in-line with their usual daily practice. Finally, they were asked to prepare for each testing session as they would for an important race. Each experimental trial lasted 3 h and included two 1000-m kayak time trials, TT1 and TT2, separated by a 70-min recovery period, including a 30-min recovery intervention protocol. The time recovery protocol corresponded to the mean time interval of French elite paddlers, in cases in which they are competing in different national and international races depending on the distance and the discipline. All trials were completed in a hot environment, (38.1 ± 1.1 °C, 26.4 ± 3% relative humidity, ~32 wet-bulb-globe temperature), in a temperature-controlled chamber without simulated wind condition.

Upon completion of the TT1, participants underwent a post-exercise recovery intervention administered using a randomized, repeated-measures crossover design. The randomization procedure (i.e., draw from a hat) was administered by an assistant not involved in the experiment. Recovery modalities consisted of (a) LFES; (b) active recovery combined with a cooling vest; and (c) LFES combined with a cooling vest. Performance (racing time and pacing strategies), physiologic, and perceptual responses were obtained at pre- and post-exercise and at mid- and post-recovery intervention period. During the trials, participants were allowed to ingest water and sport drink (Gatorade®, Pepsico, Colombes, France, for 100 mL: 5.9 g carbohydrates with 3.9 g sucrose, 0.13 g salt, 50 mg sodium, 47 mg chloride, 12 mg potassium, 5 mg magnesium) *ad libitum* in order to cover water and nutrients requirements.

Exercise protocol

Upon arrival to the laboratory on each testing day, participants were allowed to adjust their seat position and footrest dimensions on the kayak ergometer to simulate as close as possible their usual boat set-up. Testing sessions were performed on a kayak ergometer (Dansprint, I Bergmann A/S, Hvidovre, Denmark) set to a drag factor of 40 as per the National Australian testing protocols (Jones & Peeling, 2014). The paddle tension of the ergometer was calibrated prior to testing by standardizing the load factor of the bungee cords when they were extended to 210 cm to a tension value of 1.5 kg ± 20 g using a Kern HDB 10K10N scale (Kern & Sohn GmbH, Balingen, Germany). The paddle shaft length was fixed at 166 cm. First, participants performed a 10.7-min standardized warm-up, based on the recommendation of the French national kayak head coach and during the experiments participants wore only kayaking short. After a 10-min rest period, participants then performed a 1000-m kayak time trial. Participants were encouraged to finish exercise as fast as possible. No information with regard to time, resistance, heart rate, or cadence was provided at any time throughout the race. Only the distance to be covered was available. Again, participants had to cover a certain amount of work as fast as possible and were free to increase or decrease their power output as desired from the outset. The second warm-up consisted of a 4.5-min paddling. After a rest period of 10-min, participants completed exactly the same kayak time trial as for the TT1.

All power outputs and stroke rates recorded from the Dansprint ergometer were captured into an Excel spread sheet via the manufacturer provided software (Microsoft Excel 2011, Microsoft Corp., Redmond, Washington, USA).

Recovery interventions

The recovery intervention period comprised a 70-min recovery period, including a 30-min recovery intervention protocol. Two 20-min transition periods were necessary to ensure all measurements before and after the recovery intervention protocol. The participants underwent the three recovery interventions, in a random manner: (a) LFES; (b) active recovery combined with a cooling vest (ACT_{CR}); and (c) LFES combined with a cooling vest ($LFES_{CR}$).

Participants in the LFES condition used an electric blood flow stimulator of the muscles (Veinoplus® Sport, Ad Rem Technology, Paris, France) for 30-min, in a seated position, with bent legs and arms. The duration and intensity settings of LFES were chosen based on pilot testing in order to obtain the same physiologic effects, based on blood lactate clearance, as the 15-min active and 15-min passive recovery combination. The stimulation was applied via four self-adhesive Veinopack 8 × 13 cm surface electrodes (Ad Rem Technology), which were replaced after each trial. One electrode was placed on the medio-central part of the calf on the left leg and the second electrode was placed symmetrically on the medio-central part of the calf on the right leg. The two others were placed in the same manner on the medio-central of the biceps brachii. The stimulation pattern delivered by Veinoplus Sport consisted of a series of rectangular pulses of low energy (< 25 µC), low voltage (50 Vpeak), with a carrier frequency of 250 Hz and impulse durations modulated from 25 to 250 µs. The specific stimulation modulation pattern of the Veinoplus Sport resulted in calf and biceps brachii muscles contractions of 60 to 90 contractions per minute during the 30-min stimulation session. The frequency of contractions automatically changed every 1-min. The device output is voltage controlled within the range of 0.5–50.0 Vp in 100 steps of 0.5 V each. During interventions, the voltage of stimulation was adjusted manually in a range of 9–18 Vp, depending on participant tolerance. The application of such stimulation voltages resulted in nearly symmetric contractions of the muscles in each leg and arm of participants. Indeed, there is a wide inter-individual difference on the voltage required to reach muscle contraction, as well as the voltage level to reach stimulation-induced pain. To limit differences among participants, a minimal threshold was fixed by the investigators corresponding to a visible contraction of the calf and biceps brachii muscles with comfortable sensation. The output impulses from Veinoplus Sport produced ~150 msec long-fused twitches of muscle contractions without pain reported by participants.

The ACT_{CR} recovery consisted of a 15-min period of paddling between 60 and 80 W on the kayak ergometer with time and power output visible and a 15-min period of a passive recovery, comfortably seated on a chair. For 30-min, participants wore a cooling vest (Cryovest®, SM Europe, La Mézière, France) composed of nine Cryopacks stored at –4 °C until use and applied on torso, back and neck. The dry weight of the vest with the inserted cooling elements was 2.2 kg.

The $LFES_{CR}$ condition involved exactly the same procedure as LFES with the addition of the cooling vest worn in the ACT_{CR}.

Measurements

Blood parameters

In order to measure blood concentration of lactate $[La^-]_b$, capillary earlobe samples (20 µL) were collected and analyzed with a Biosen Lactate analyser (Biosen C-line analyser, EKF Industrie, Elektronik GmbH, Barbelen, Germany) at rest, 3 min after both TT1 and TT2 and at mid- (15 min) and post-recovery (30 min) intervention. Additional blood samples (50 µL) were also collected from the earlobe at the same four time points and analyzed to determine serum sodium concentration $[Na^+]$, blood bicarbonate concentration $[HCO_3^-]$, blood pH, and hematocrit (Hct). Samples were collected in heparinized capillary tubes and immediately placed in the receptacle of a GC8 + cartridge for clinical chemistry analysis on an I-Stat analyzer (Abbott Point of Care Inc., Princeton, New Jersey, USA).

Thermoregulatory measures

Core temperature (T_{core}) was assessed during exercise and recovery periods via thermosensitive capsule (HQ, Inc., Thermo Pills, Palmetto, Florida, USA) ingested 4 h prior to starting the trial. Skin temperature was analyzed at four different sites (on the upper chest, lower forearm, upper thigh, and medial side of the calf) using a thermal imaging camera (ThermaCam SC 640, Flir Systems AB, Danderyd, Sweden) in accordance with the standard protocol of infrared imaging in medicine. In order to guarantee an optimal measure of skin temperature at the upper chest, the cooling vest was removed from participants for each picture taken during the protocol. Mean skin temperature (T_{skin}) was calculated according to the equation established by Ramanathan (1964) (Equation 1). Mean body temperature (T_{body}), measured prior to the initial warm-up (rest), after both TT1 and TT2, and at mid- (15 min) and post-recovery (30 min) intervention, was estimated according to the methods described by Schmidt and Bruck (1981) (Equation 2).

$$T_{skin} = 0.3 \times (T_{chest} + T_{arm}) + 0.2 \times (T_{thigh} + T_{leg}) \tag{1}$$

$$T_{body} = 0.87T_{core} + 0.13T_{skin} \tag{2}$$

Hydration status and sweat secretion

Urine specific gravity (USG) was assessed upon arrival to the laboratory and after both TT1 and TT2 via the provision of a mid-stream urine sample analyzed using a refractometer (PAL-10S, Atago Co., Ltd, Tokyo, Japan). Body mass loss (BML) was calculated from measures of clothed body mass prior to the initial warm-up (rest) and at the completion of TT2 using a digital platform scale (Seca 877, Seca, Hamburg, Germany) as a representative of sweat mass loss. The total amount of water and sport drink ingested was accounted for in BML calculation by adding the estimated mass of fluid consumed to the difference in rest to post-TT2 change in body mass.

Perceptual measures

Rating of perceived exertion (RPE) was recorded after each exercise on a Borg scale of 6 (*no exertion*) to 20 (*maximal exertion*) (Borg, 1998). Thermal comfort (–3 "*cold*" to +3 "*hot*") (Epstein & Moran, 2006) and sensation (–2 "*very uncomfortable*" to +2 "*very comfortable*") (Zhang & Zhao, 2008) were recorded at pre- and post-TT1 and TT2. Participants were also asked to evaluate the recovery intervention ("How do you rate the efficacy of this

Table 1. Scales used to interpret the magnitude of between-condition differences in the change for time trial performance using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-athlete variation (CV) as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the change between trials

	TT (%)
CV (%)	1.0
Trivial	< 0.3
Small	0.3–0.9
Moderate	0.9–1.5
Large	1.5–2.3
Very large	2.3–3.6
Extremely large	> 3.6

CV, coefficient variation; TT, time trial.

recovery intervention?" and "How did you like this recovery intervention?") by means of a 10-point Likert scale, ranging from 1 (not at all) to 10 (very, very much) (Bieuzen et al., 2014).

Statistic analysis

Physiologic and perceptual data were compared between groups and time using nonparametric tests. Nonparametric tests were necessary (a) because of the small sample size inherent in the training level of our population (elite paddlers); and (b) because of the non normality of the data distribution revealed by the Shapiro-Wilk test. A Kruskal–Wallis matched-pairs test was completed to assess significant differences between groups and a Friedman rank test was undertaken to evaluate the statistic differences in time for each recovery modality. When a significant *F*-value in Friedmans' analysis was found, a post-hoc test with a Bonferroni correction was used to determine the between-means differences. These statistic tests were conducted using the Statistical Package for the Social Sciences (SPSS v. 20.0, IBM Corporation, Inc., Armonk, New York, USA) and the data are presented as median, the value of the lower quartile (Q_{25}) and the value of the upper quartile (Q_{75}). For these analyses, significance was accepted at $P < 0.05$.

The performance data were analyzed using the magnitude-based inference approach recommended for studies in sports medicine and exercise sciences (Hopkins et al., 2009). We used this qualitative approach (a) because of the small sample size inherent in the training level of our population (elite paddlers) and (b) because traditional statistic approaches often do not indicate the magnitude of an effect, which is typically more relevant than any statistically significant effect to infer clinical recommendations. Although no variable exhibited non-uniformity of error, the performance data from the two bouts (TT1 and TT2) were log-transformed before analysis to reduce the tendency ($P < 0.10$) of some parameters to demonstrate a skewed distribution (Hopkins et al., 2009). The magnitude of the within-condition changes, or between-condition differences in the changes, was interpreted using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-participant coefficient variation (CV; see Tables 1 and 2) as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the change between the trials (Hopkins et al., 2009). Quantitative chances of higher or lower differences were evaluated qualitatively as follows: < 1%, almost certainly not; 1–5%, very unlikely; 5–25%, unlikely; 25–75%, possible; 75–95%, likely; 95–99%, very likely; > 99%, almost certain. The practical interpretation of an effect is deemed *unclear* when the magnitude of change is substantial that is the 90% confidence interval (CI) (precision of estimation) could result in positive and negative outcomes (Batterham & Hopkins, 2006). The data are reported as

Table 2. Scales used to interpret the magnitude of between-condition differences in the change for average power output and stroke rate during time trials using values of 0.3, 0.9, 1.6, 2.5, and 4.0 of the within-athlete variation (CV) as thresholds for *small*, *moderate*, *large*, *very large*, and *extremely large* differences in the change between trials

	0–100 m	100–200 m	200–300 m	300–400 m	400–500 m	500–600 m	600–700 m	700–800 m	800–900 m	900–1000 m
Average power output										
CV (%)	7%	8%	5%	3%	3%	4%	4%	5%	5%	6%
Trivial	< 2%	< 2%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 2%	< 2%
Small	2–7%	2–7%	1–4%	1–3%	1–3%	1–4%	1–4%	1–4%	2–5%	2–5%
Moderate	7–12%	7–12%	4–8%	3–6%	3–5%	4–7%	4–6%	4–7%	5–8%	5–9%
Large	12–17%	12–19%	8–12%	6–8%	5–7%	7–10%	6–10%	7–11%	8–13%	9–14%
Very large	17–29%	19–31%	12–19%	8–14%	7–12%	10–17%	10–16%	11–18%	13–21%	14–23%
Extremely large	> 29%	> 31%	> 19%	> 14%	> 12%	> 17%	> 16%	> 18%	> 21%	> 23%
Average stroke rate										
CV (%)	4%	3%	3%	3%	2%	2%	3%	3%	3%	4%
Trivial	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%	< 1%
Small	1–4%	1–3%	1–2%	1–2%	1–2%	1–2%	1–3%	1–3%	1–3%	1–3%
Moderate	4–7%	3–5%	2–4%	2–4%	2–3%	2–4%	3–5%	3–5%	3–5%	3–6%
Large	7–10%	5–8%	4–7%	4–6%	3–5%	4–6%	5–7%	5–7%	5–8%	6–9%
Very large	10–17%	8–13%	7–11%	6–10%	5–8%	6–10%	7–11%	7–12%	8–14%	9–14%
Extremely large	> 17%	> 13%	> 11%	> 10%	> 8%	> 10%	> 11%	> 12%	> 14%	> 14%

CV, coefficient variation.

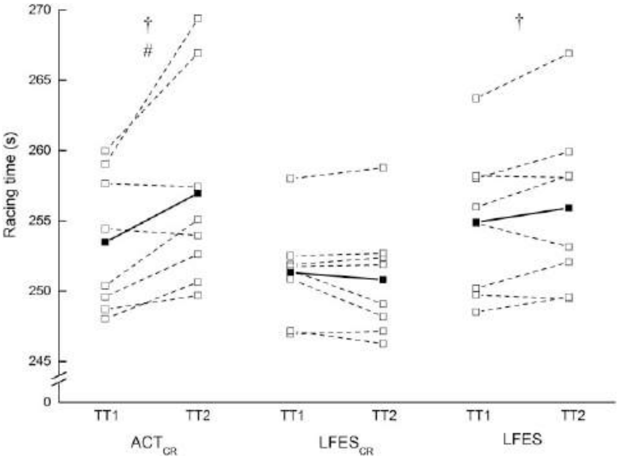

Fig. 1. Individual changes (dashed lines) and group mean changes (straigth lines) between TT1 and TT2. Between-condition difference in the change versus LFESCR: † *very likely*. Between-condition difference in the change versus LFES: # *very likely*.

qualitative and percentage chances, the mean change effect size (ES) and the confidence interval.

Results

Performance and pacing strategy

Figure 1 details the between-condition difference in racing time variation of the TT1 and the TT2. There was *no clear* difference in racing time between all conditions during TT1. Changes in TT1 vs TT2 were –0.52 ± 0.60 s for LFES$_{CR}$, 3.49 ± 2.44 s for ACT$_{CR}$ and 1.02 ± 0.79 s for LFES. The TT2 racing time was *very likely* faster after the LFES$_{CR}$ condition compared with ACT$_{CR}$ [99/0/1%, ES = 1.6 (0.71; 2.44)] and LFES [98/0/2%, ES = 0.6 (0.1; 1.1)]. The TT2 racing time was *very likely* faster after the LFES condition compared with ACT$_{CR}$ [97/0/3%, ES = 1.0 (0.1; 1.8)].

During TT1, there was *no clear* difference in pacing strategies among all conditions (i.e., power output and stroke rate). The between-condition difference in average power output and stroke rate during TT2 is presented Fig. 2. The power output during TT2 after the LFES$_{CR}$ condition was *very likely* higher than after ACT$_{CR}$, for the 100–300 m and 500–800 m sections [100–200 m: 99/0/1%, ES = 7.1 (2.9; 11.5); 200–300 m: 99/0/1%, ES = 5.8 (2.3; 9.5); 500–600 m: 97/0/3%, ES = 5.8 (0.97; 10.8); 600–700 m: 97/0/3%, ES = 3.0 (0.5; 5.6); 700–800 m: 99/0/1%, ES = 4.8 (2.1; 7.7)].

The stroke rate during TT2 after the LFES$_{CR}$ condition was *very likely* higher than after ACT$_{CR}$ and LFES, for the 100–200 m section [ACT$_{CR}$: 99/0/1%, ES = 3.2 (1.4; 4.9); LFES: 98/0/2, ES = 3.1 (0.7; 5.5)]. The stroke rate during TT2 after the LFES condition was *very likely* higher than after LFES$_{CR}$ and ACT$_{CR}$ for the 600–800 m section [LFES$_{CR}$: 600–700 m: 98/0/2%, ES = 3.4 (0.8; 6.1); 700–800 m: 98/0/2%, ES = 2.7 (0.8; 4.7) and ACT$_{CR}$: 600–700 m: 97/0/3%, ES = 2.2 (0.3; 4.1); 700–800 m: 98/0/2%, ES = 3.2 (0.9; 5.6)].

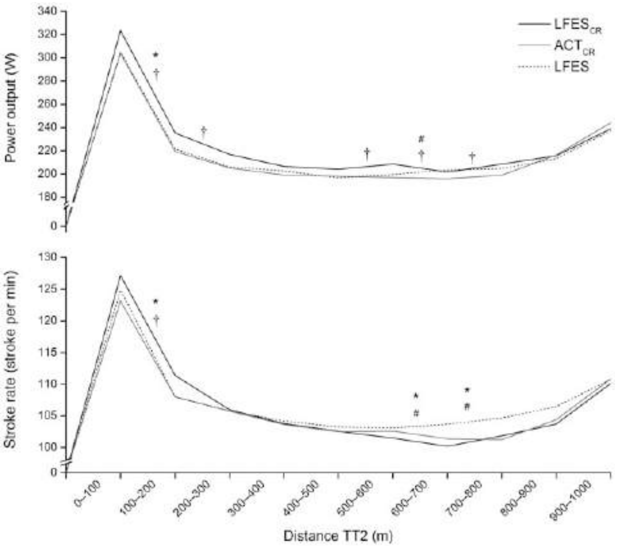

Fig. 2. Average power output and stroke rate during the second self-paced time trial (TT2). Between-condition difference in the change for LFESCR versus ACTCR, † *very likely*. Between-condition difference for LFESCR versus LFES, * *very likely*. Between-condition difference for ACTCR versus LFES, # *very likely*.

Thermoregulatory measures

The T_{core}, T_{skin}, and T_{body} values are presented in Fig. 3. There was no between-condition difference in T_{core}, T_{skin}, and T_{body} at rest and prior to the recovery intervention (post-TT1). The Friedman test revealed a significant difference in T_{body}, T_{core}, and T_{skin} between time measurements for the three conditions ($P < 0.05$). Post-hoc analysis revealed that T_{core} and T_{body} increased from the start to the end of the TT1 (average temperatures: T_{core}: 37.8 ± 0.4 °C, T_{body}: 37.4 ± 0.3 °C) and TT2 compared with baseline (rest) (average temperatures: T_{core}: 37.2 ± 0.5 °C, T_{body}: 36.9 ± 0.5 °C) for the all conditions. In the ACT$_{CR}$ condition, the increased in T_{core} and T_{body} persists at mid-recovery and post-recovery, respectively, while these temperatures in the LFES$_{CR}$ and LFES conditions return to the initial state from mid-recovery. Analyses of T_{body} from post-TT1 measurement showed significant ($P < 0.05$) difference between time measurements with significant lower values at mid-recovery and post-recovery for the LFES$_{CR}$ only. Post-hoc analysis also revealed that T_{skin} at mid-recovery was significantly lower than post-TT1 for the LFES$_{CR}$ condition and ACT$_{CR}$ conditions whereas T_{skin} at post-recovery was significantly lower than rest for the ACT$_{CR}$ condition only.

Perceptual measures

RPE, thermal sensation and comfort, efficacy, and well-being recovery perceptions in the three conditions are depicted in Table 3. All participants' RPE ranged

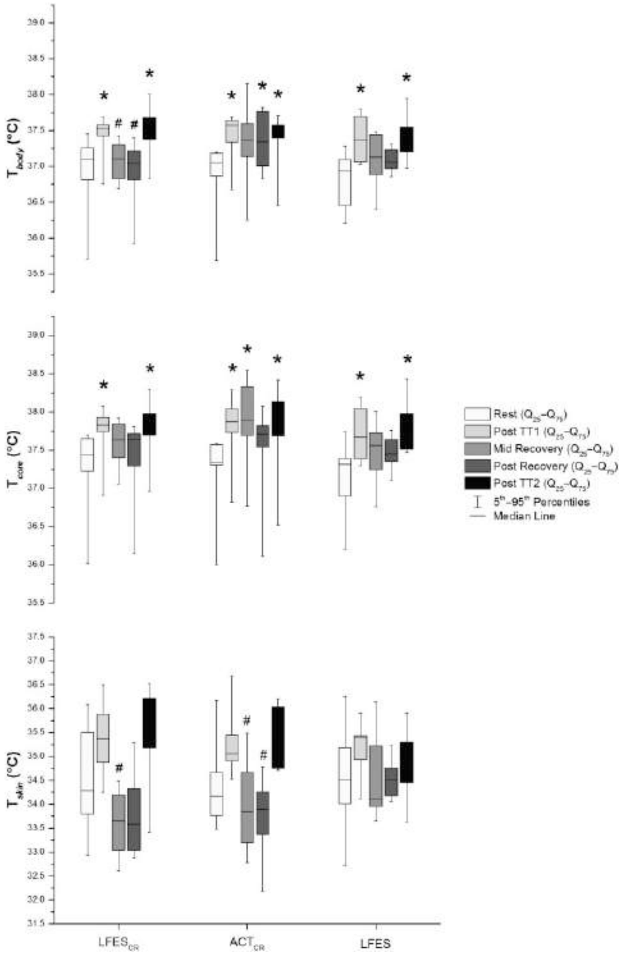

Fig. 3. Body (T_{body}), core (T_{core}), and skin (T_{skin}) temperatures during the testing session. *Significant difference from Pre ($P < 0.05$). #Significant difference from Post TT1 ($P < 0.05$).

between *very difficult* and *very very difficult* at TT1 and TT2 cessation during the whole experience (range, 17–20). The Kruskal–Wallis test revealed no significant between-condition difference in RPE ($P > 0.05$) at anytime point. The Friedman test revealed a significant difference in thermal sensation and comfort between time measurements for the three conditions ($P < 0.05$). Post-hoc analysis revealed that thermal sensation at post-recovery was significantly lower than post-TT1 for the LFES_{CR} condition only. Post-hoc analysis revealed that comfort sensation at post-recovery was significantly higher than post-TT1 for all conditions.

The Kruskal–Wallis test revealed a significant less good perception of well-being from post-recovery in the ACT_{CR} compared to LFES_{CR} conditions. There was no significant between-condition difference in the perception of efficacy from post-recovery ($P > 0.05$).

Hydration status and sweat secretion

USG, body mass, and BML in the three conditions are depicted in Table 3. The Friedman test revealed no significant time effect in USG ($P > 0.05$). The Friedman test revealed a significant difference in body mass between time measurements for the LFES_{CR} condition only ($P < 0.05$). Post-hoc analysis revealed that body mass at post-TT2 was significantly lower than rest for the LFES_{CR} condition. The Kruskal–Wallis test revealed no significant between-condition difference in BML ($P > 0.05$).

Blood parameters

Examination of blood parameters is presented Table 3. The Friedman test revealed no significant time effect in $[\text{Na}^+]$ ($P > 0.05$). A significant time effect was recorded for all conditions for pH, $[\text{La}^-]_b$ and hematocrit without significant between-condition difference. Post-hoc analysis revealed that hematocrit at post-TT1 was slightly higher than rest for the LFES_{CR} condition only.

Discussion

The present study examined the effectiveness of three recovery interventions, applied during a short-term recovery period (70 min) between two kayak time trials performed in the heat, on race performance, physiologic, and perceptual responses. The main findings that can be drawn from this investigation are: (a) LFES combined with the wearing of a cooling vest (LFES_{CR}) resulted in a faster 1000-m time trial (TT2) compared with an active cooling intervention (ACT_{CR}); (b) no significant differences in $[\text{La}^-]_b$ and pH values were observed between the three interventions, at the end of the recovery intervention period; (c) only LFES_{CR} intervention induced a significant decrease in body temperature and thermal sensation at post-recovery intervention; and (d) perception of well-being recovery was increased after the LFES_{CR} intervention compared with the ACT_{CR} condition. It is expected that these findings will help inform athletic preparations and the scientific results will be translated to an elite real-world competitive setting.

In accordance with the proposed hypotheses, our data demonstrated that the LFES_{CR} condition was the most efficient recovery strategy compared with the LFES condition, and in particular, the ACT_{CR} condition (Fig. 1). Compared with the active recovery strategy, LFES_{CR} reduced the second 1000-m time trial by more than 3.5 s. In the last Canoe Sprint World Championships (Duisburg, 2013), Olympic Games (London, 2012) and European championships (Brandenburg, 2014), such a difference on the racing time during the Final A for K1, 1000-m boats, represented a difference between the first and fifth places in the ranking of the race. Therefore, these results outline the importance of the smallest change in real-life time trial performance. In addition to the time needed to complete the second time trial, the pacing strategy employed by the athletes is of major importance, as it is fundamental to kayak performance. It

Table 3. Blood parameters, perceptual measures, hydration status and sweat secretion measures at rest, post TT1 and TT2, and mid- and post-recovery intervention for the three groups

	Median and the value of the lower and the upper quartile (Q_{25}–Q_{75})				
	Rest	Post TT1	Mid-recovery	Post-recovery	Post TT2
Thermal sensation					
LFES$_{CR}^{\dagger}$	2.0 (1.0–3.0)	3.0 (2.8–3.0)	–	1.0 (0.8–1.0)‡	3.0 (2.8–3.0)
ACT$_{CR}$ †	1.0 (1.0–2.0)	3.0 (3.0–3.0)	–	1.5 (1.0–2.3)	3.0 (3.0–3.0)
LFES†	2.0 (1.0–2.0)	3.0 (2.8–3.0)	–	1.5 (1.0–2.3)	3.0 (3.0–3.0)
Comfort sensation					
LFES$_{CR}^{\dagger}$	1.0 (0.5–1.3)	−1.0 (−2.0–−0.8)	–	1.0 (1.0–1.0)‡	−1.0 (−1.3–0.0)
ACT$_{CR}^{\dagger}$	1.0 (0.0–1.0)	−1.0 (−2.0–−1.0)	–	0.5 (0.0–1.0)‡	−1.0 (−2.0–0.0)
LFES†	1.0 (1.0–1.0)	−1.0 (−2.0–−1.0)	–	1.0 (0.8–1.3)‡	−1.0 (−1.3–0.3)
Recovery efficacy					
LFES$_{CR}$	–	–	–	8.3 (7.3–8.5)	–
ACT$_{CR}$	–	–	–	6.9 (6.4–7.4)	–
LFES	–	–	–	7.8 (6.5–7.9)	–
Recovery well-being					
LFES$_{CR}$	–	–	–	8.7 (8.3–9.0)	–
ACT$_{CR}$	–	–	–	6.4 (6.2–6.9)§	–
LFES	–	–	–	7.5 (6.8–9.0)	–
RPE					
LFES$_{CR}$	–	19.0 (19.0–19.3)	–	–	19.0 (19.0–19.3)
ACT$_{CR}$	–	19.0 (18.8–19.0)	–	–	19.0 (18.8–19.0)
LFES	–	19.0 (19.0–19.0)	–	–	19.0 (18.0–19.0)
Urine specify gravity					
LFES$_{CR}$	1.024 (1.014–1.026)	–	–	–	1.025 (1.019–1.027)
ACT$_{CR}$	1.024 (1.018–1.026)	–	–	–	1.025 (1.021–1.029)
LFES	1.018 (1.017–1.025)	–	–	–	1.020 (1.018–1.022)
Body mass (kg)					
LFES$_{CR}^{\dagger}$	87.6 (82.1–91.9)	87.4 (82.1–91.7)	–	87.3 (82.0–92.1)	87.2 (81.9–91.6)*
ACT$_{CR}$	87.2 (81.9–91.3)	87.1 (81.7–91.0)	–	87.2 (81.4–91.2)	87.2 (81.3–91.1)
LFES	87.3 (81.7–91.4)	86.1 (81.5–90.4)	–	87.3 (81.0–90.3)	87.0 (81.1–90.2)
Body mass loss (kg)					
LFES$_{CR}$	–	–	–	–	1.88 (1.41–2.01)
ACT$_{CR}$	–	–	–	–	2.25 (1.86–2.56)
LFES	–	–	–	–	2.08 (1.95–2.29)
[Na^{+}]					
LFES$_{CR}$	142 (140–143)	143 (142–144)	143 (142–143)	142 (142–142)	143 (142–143)
ACT$_{CR}$	140 (140–142)	141 (139–143)	142 (141–144)	142 (141–144)	141 (140–143)
LFES	142 (140–142)	142 (139–142)	142 (140–143)	142 (141–142)	143 (140–143)
pH					
LFES$_{CR}^{\dagger}$	7.41 (7.38–7.43)	7.22 (7.18–7.29)*	7.39 (7.37–7.39)	7.40 (7.38–7.42)‡	7.31 (7.24–7.38)
ACT$_{CR}^{\dagger}$	7.41 (7.40–7.42)	7.20 (7.14–7.26)*	7.40 (7.38–7.43)	7.44 (7.43–7.45)‡	7.32 (7.26–7.38)
LFES†	7.40 (7.39–7.42)	7.24 (7.12–7.28)*	7.38 (7.37–7.42)	7.42 (7.40–7.43)‡	7.26 (7.21–7.31)
[La^{-}]$_{b}$					
LFES$_{CR}^{\dagger}$	1.18 (1.00–1.52)	12.50 (9.81–13.42)*	3.85 (3.25–4.73)	2.58 (2.02–2.70)‡	11.81 (10.50–13.13)*
ACT$_{CR}^{\dagger}$	1.19 (1.08–1.25)	11.89 (10.25–12.90)*	2.78 (1.79–3.92)	1.93 (1.12–2.44)‡	9.90 (8.91–11.80)*
LFES†	1.36 (1.06–1.55)	10.43 (9.47–12.91)*	3.71 (3.21–4.64)	2.41 (2.26–3.24)‡	10.96 (9.20–11.53)*
Hct					
LFES$_{CR}^{\dagger}$	47 (45–49)	50 (49–53)*	48 (44–49)	46 (44–47)	48 (47–50)
ACT$_{CR}$	48 (46–49)	50 (48–51)	47 (47–48)	47 (46–49)	52 (50–54)
LFES†	48 (48–49)	49 (47–51)	47 (43–49)	46 (44–47)	49 (48–52)

*Represents a significant ($P < 0.05$) difference from rest.

†Represents a significant ($P < 0.05$) time effect.

‡Represents a significant ($P < 0.05$) difference from Post TT1. All significant results were not pointed except from Rest and Post TT1 to avoid overloading the table.

§Represents a significant ($P < 0.05$) difference between LFES$_{CR}$ and ACT$_{CR}$.

ACT$_{CR}$, active recovery combined with a cooling vest; Hct, hematocrit; LFES, low-frequency electrical stimulation combined without cooling vest; LFES$_{CR}$, low-frequency electrical stimulation combined with cooling vest; RPE, rating of perceived exertion; TT, time trial.

appears that pacing strategies are dependent on the recovery method used between the two time trials. In accordance to Borges et al. (2013), 1000-m kayak races all displayed a reverse J-shaped pacing profile, with a fast start, a slower middle part and an increase in the final sprint. The minimal differences in performance and regulation of pace variability between conditions during TT1, allow us to confirm the elite status of the paddlers involved in the present study. Pacing strategies differ during TT2 as LFES$_{CR}$ resulted in a higher power output compared with other conditions and a higher stroke rate during the first sprint, maintained during the middle part until the final stage of the second race (Fig. 2). Conversely, after LFES and ACT_{CR}, paddlers displayed an immediate decline of power output after the onset of the second exercise. This fast start strategy observed in the $LFES_{CR}$ condition has been suggested as beneficial to kayakers because of several reasons. Firstly, athletes and coaches consider positions at the front of the group early in the race to be tactically advantageous to have better control on the opponents and avoid 'wash' of the other boats (Borges et al., 2013). Secondly, the fast start strategy may also provide physiologic advantages such as improving the energy production through the aerobic pathway (Abbiss & Laursen, 2008).

In the present study, the metabolic fuel restoration and/or by-products washout do not seem to be the primary factors affecting the performance and the pacing strategies. Indeed, this study involved one repetition of 1000-m time trial, considered as short duration mainly aerobic exercise (79% aerobic, 21% anaerobic; see review of Gastin, 2001), combined with the *ad libitum* ingestion of sport drink (5.9 g carbohydrates with 3.9 g sucrose). This methodologic design enabled us to study the impact of different recovery interventions on kayaking performance in the heat without associated confounders such as dehydration (as evidenced by no significant difference in USG between conditions; Table 3) and/or glycogen depletion. The mean $[La^-]_b$ of all kayakers in this study increased first to a peak value of 11.0 ± 0.4 mmol/L after TT1, before continually decreasing until the end of the recovery intervention period, irrespective of the recovery strategy used. This mean peak value is in close agreement with the results reported by Michael et al. (2008) during laboratory and on water testing. Thus, the non-significant differences in $[La^-]_b$ and pH kinetics between the three conditions might reflect that LFES and active recovery, irrespective of the cooling vest, induced adequate blood flow to the recovering muscles allowing clearance of the accumulated blood lactate and other metabolic by-products, which can adversely affect muscle function.

Given these results, we suggest it is likely that other mechanisms apart from enhanced metabolic by-products removal from the muscle could explain the improved performance restoration after $LFES_{CR}$ recovery. An interesting finding in the current study was the differences in T_{body}, T_{core} and T_{skin} following $LFES_{CR}$, LFES and ACT_{CR} (Fig. 3). The participants in the passive interventions (i.e., LFES and $LFES_{CR}$) reduced T_{core} in a shorter period (i.e., 15 min recovery period) than participants in the ACT_{CR} condition following TT1. Active recovery implemented in a hot environment is likely to increase heat storage during low-intensity exercise as well as increasing both cardiovascular and thermoregulatory strain (Bishop et al., 2007; De Pauw et al., 2014). It has previously been demonstrated that reducing T_{core} is extremely important during recovery. Yeargin et al. (2006) suggested that lowering rectal temperature by 0.5 °C between two bouts of exercise in the heat (~27 °C) can improve 2 miles running. As an increase in T_{core} is the main determinant for initiating a thermoeffector response (sweating) (Werner, 1998) the upward trend in BML reported in the ACT_{CR} compared with LFES and $LFES_{CR}$ (Table 3) leads us to hypothesize that greater levels of heat accumulation, stimulating cutaneous vasodilatation and peripheral blood flow necessary for conductive and evaporative cooling, were experienced during ACT_{CR} (Bishop et al., 2007).

Moreover, $LFES_{CR}$ and ACT_{CR} lowered T_{skin} at mid-recovery intervention (i.e., 15 min, Fig. 3). Numerous studies (Hasegawa et al., 2005; Webster et al., 2005) have previously reported that cooling vests are an effective method of reducing T_{skin}. Although Duffield et al. (2003) observed a significant decrease of skin temperature and indicators of perceived thermal discomfort in hockey players after wearing a cooling vest for 5 min before and during the recovery periods, comparatively few studies have examined the use of cooling vests during repeated exercise bouts. Our data support these findings and suggest that cooling vests are an effective method of reducing T_{skin} and facilitating heat dissipation during exercise in the heat. The current findings also demonstrate that the reduction in T_{core} during recovery was primarily the result of the cessation of the activity and the cooling vest was only effective in reducing surface temperature.

Finally, only the $LFES_{CR}$ condition demonstrated a significant reduction of mean T_{body} at the end of the recovery intervention. Taken together, these results suggest that the non-active and cooling combination recovery (i.e., $LFES_{CR}$) was an efficient mean to impact positively the heat loss. It can be assumed that blood flow exchanges between the core and the periphery were facilitated during LFES (Glaser, 1994), thereby optimizing the cooling effect of the vest and lowering T_{body}. Therefore, the cumulative effect of non-active recovery and the cooling intervention could enhance performance and thermoregulation via greater temperature gradients between the skin and the core, indicated by a larger gradient before the start of the second time trial. In the current study, subjects did not attain high core temperatures during TT2 (~38.5 °C), indicating that aerobic exercise performance may degrade in hot environments without marked hyperthermia (De Pauw et al., 2014). The present study was mainly designed to simulate the environmental conditions athletes encounter during official competitions. However, when translating the results of the current study to the field of kayak, subtle differences between laboratory and kayaking must be considered. Indeed, kayaking causes increased air movement around the athlete, which results in faster heat dissipation by evaporation and convection. This convective cooling, which may result in an attenuated increase of the T_{core} and T_{skin} temperature in the field, was not been taken into account in this controlled laboratory study.

The reduced thermal stress experienced after the combination of the cooling vest and the LFES intervention may partly explain how high-intensity performance have been restored during the second time trial. The reduced thermal stress may have altered motor-unit recruitment, explaining the sustained high-power output during the first part of the TT2. Indeed, neuromuscular functioning and exercise capacity are inversely associated with an elevated T_{core} temperature, as the recruitment of motor units during voluntary activation of skeletal muscle is reduced under heat stress (Cheung, 2007). Concomitantly, increasing thermal strain reduces cerebral blood flow velocity and oxygenation, also contributing to declines in motor outflow and exercise performance or to alter the perception of effort (Minett et al., 2014). Some authors have also postulated that cooling alters the activity of the central nervous system, which is linked to pacing strategies (Minett et al., 2011). Further work is necessary to determine the implications of LFES_{CR} on neurophysiologic restoration.

Finally, the perceptual effects of LFES and cooling interventions have been suggested to explain performance and especially pacing strategy improvements. In the present study, we observed higher scores on recovery well-being perception scale after the LFES_{CR} intervention when compared with active recovery condition (Table 3). It was also reported a better thermal sensation (Table 3) and a very likely faster completion time during the second 1000-m time trial after LFES_{CR} condition. It has been proposed that the internal physiologic state, and also thermal sensation, play an anticipatory role in exercise regulation (Tucker, 2009). In addition, humans appear to be able to anticipate the intensity of heat stress they will be exposed to, in order to ensure the maintenance of homeostasis and prevent critically high temperature (Marino, 2004). As a result, the complex interactions of feedforward and feedback mechanisms appear to act in complementary ways to regulate pace in order to resist fatigue. Accordingly, we hypothesize that the combined reduction in T_{core} and T_{skin} induced by the LFES_{CR} strategy before the TT2 could have been beneficial on thermal sensation and recovery perception, resulting in facilitating the regulation of pace and the maintenance of subsequent exercise performance. These observations are supported by the beneficial effect of LFES recovery regarding feeling of recovery and reported by some studies in temperate environments (Cortis et al., 2010). To a lesser extent, the addition of a cooling vest to the LFES in a hot environment appears to be beneficial to perceptions of recovery (Luomala et al., 2012). However, literature on perceptual effects of recovery modalities is rather scarce, and further investigations are required to address this paucity of research.

In summary, these findings highlighted the performance, physiologic, and perceptual benefits of the combination of LFES and wearing a cooling vest between repeated high-intensity exercise bouts in a hot environment, when athletes are adequately hydrated and have normal glycogen stores. Importantly, LFES_{CR} rapidly decreased exercise-induced elevation of body temperature and improved thermal and recovery perceptions. Presumably, this hastened the recovery of power output, resulting in an efficient pacing strategy compared with ACT_{CR} and LFES recoveries.

Perspectives

The combination of LFES and the wearing of a cooling vest enhance athletic recovery and improve subsequent high-intensity self-paced sprint exercise in hot conditions. This is likely a result of reductions in core and skin temperatures during recovery. Furthermore, this may be related to some neurophysiological effect on muscle drive/activation and/or psychologic effect rather than any peripheral effect on metabolites by-products clearance throughout the recovery period. However, further research is needed to clearly evaluate these mechanisms. In addition, future research should attempt to investigate the effects of this recovery intervention in other sports, environmental conditions and in acclimatized athletes.

Key words: Post-race recovery strategy, high-intensity exercise, exercise-induced heat stress, cooling strategy, low-intensity exercise.

Acknowledgements

This study was supported by a grant of French Ministry of Sport. It was made possible by technical support from the French Federation of Canoe Kayak. Authors are especially grateful to the athletes for their effort and coaches (François During and Nicolas Maillotte) for their help and cooperation.

Conflicts of interest: The authors of this study declare that they have no conflict of interest.

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Precooling Can Prevent the Reduction of Self-Paced Exercise Intensity in the Heat

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[1]School of Human Movement Studies, Charles Sturt University, Bathurst, New South Wales, AUSTRALIA; [2]Chelsea School University of Brighton, Eastbourne, ENGLAND; and [3]The Department of Sport and Exercise Science, University of Bedfordshire, Bedfordshire, ENGLAND

ABSTRACT

DUFFIELD, R., R. GREEN, P. CASTLE, and N. MAXWELL. Precooling Can Prevent the Reduction of Self-Paced Exercise Intensity in the Heat. *Med. Sci. Sports Exerc.*, Vol. 42, No. 3, pp. 577–584, 2010. **Purpose**: This study investigated the effects of precooling on performance and pacing during self-paced endurance cycling in the heat and, further, the effects of cooling on contractile function as a mechanism for performance changes. **Methods**: After familiarization, eight male cyclists performed two randomized 40-min time trials on a cycle ergometer in 33°C. Before the time trials, participants underwent either a 20-min lower-body cold-water immersion procedure or no cooling intervention. Before and after the intervention and the time trial, voluntary force (maximal voluntary contraction (MVC)), superimposed force (SIF), evoked twitch force (peak twitch force (Pf)), muscle temperature, and blood metabolites were measured. Further, measures of core and skin temperature and HR were recorded before, during, and after cooling and time trial. **Results**: Results indicated that cycling performance was improved with precooling (198 ± 25 vs 178 ± 26 W for precooling and control, respectively; $P = 0.05$). Although core, muscle, skin, and mean body temperatures were lower in the cooling condition until the 20th minute ($P < 0.05$), performance did not differ until the last 10 min of the time trial, by which time no differences in physiological measures were present. Further, while MVC and SIF were reduced postexercise in both conditions, MVC, SIF, and Pf were not different between conditions preexercise or postexercise. **Conclusion**: In conclusion, a precooling intervention improved self-paced endurance exercise; however, the improvement in performance became evident after measured physiological differences induced by precooling had dissipated. Further, the lack of difference between conditions in MVC, SIF, or Pf indicates that improvements in performance did not result from an improvement in contractile function, suggesting that improvements may result from other mechanisms such as muscle recruitment. **Key Words:** CRYOTHERAPY, PACING, PERFORMANCE, THERMOREGULATION

The increased physiological load and reduced performances noted during prolonged exercise in the heat are well documented (9,11). Further, the ergogenic benefits of precooling before exercising in hot conditions are also well established (17,28). Despite these findings, not all precooling studies have demonstrated an improvement in exercise performance, particularly during prolonged intermittent-sprint exercise (7,8), and as yet, the mechanisms relating to the ergogenic qualities of precooling remain equivocal (17,25). In addition, with the relatively more recent use of self-paced exercise protocols (14,26), the proposed mechanisms relating to performance improvements from precooling have been hypothesized to include alterations in muscle recruitment and the pacing strategies adopted rather than a direct response to the reduction in cardiovascular or thermoregulatory load *per se* (14,26).

Precooling procedures can be loosely classified as those designed to reduce skin temperature (ice vests, cold towels, sprays) or to reduce skin and muscle/core temperature (cold-water immersion, cold rooms, cold showers) (17). It is proposed that a longer and larger cooling stimulus will result in larger physiological perturbations and greater performance improvements (26), although the two are not necessarily directly linked (6,12,14). Traditionally, the ergogenic benefits of precooling were highlighted as a reduction in cardiovascular load, improved oxygen supply, and reduced accumulation of anaerobic metabolic products (16,24). However, the use of constant-intensity exercise protocols somewhat skewed these conclusions and also lack the ecological validity for the application to athletic environments. Research incorporating self-paced intermittent and continuous protocols has reported improved performances, without significant differences in HR, $\dot{V}O_2$, anaerobic metabolic markers, or end-exercise body temperatures (2,10,26). Accordingly, the mechanisms relating to improved exercise performance after precooling have been postulated to include the prevention of the heat-induced

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Submitted for publication April 2009.
Accepted for publication July 2009.

0195-9131/10/4203-0577/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0b013e3181b675da

down-regulation of muscle recruitment (8,14,17), the prevention of the reduction in peak evoked torque and fiber recovery time (17,31), or the prevention of contractile force inhibition due to thermal sensory feedback (1,25). However, despite these proposed mechanisms, to date no research has provided evidence to show how precooling may be ergogenic for exercise in the heat.

Recent research has proposed that exercise in the heat results in the self-selection of lower exercise intensities (pacing), possibly resulting from a reduction in muscle recruitment or contractile function (18,21). Accordingly, the suppression of preexercise core temperatures via precooling may promote the ensuing selection of higher exercise intensities (2,14). Despite this proposition relating to pacing strategies, there is little evidence to substantiate whether and when pacing strategies are altered and, further, whether these alterations result from postcooling changes in contractile function. Accordingly, the aim of this study was to investigate the effects of precooling on pacing strategies during self-paced endurance exercise and, further, to determine the effect of precooling on voluntary and evoked contractile function and the ensuing effect on exercise performance.

METHODS

Subjects

Eight male, moderate- to well-trained cyclists (age = 24.8 ± 3.3 yr, height = 178.3 ± 8.0 cm, body mass = 76.1 ± 2.7 kg, sum of seven skinfolds = 54.4 ± 10.9 mm, and lactate threshold (LT) = 221 ± 42 W) volunteered to participate in this study. Participants were club and regional standard cyclists who trained multiple times a week, competing in regional competitions, and were familiar with the physical demands of set distance or duration time trials. All participants gave verbal and written consent to engage in all testing procedures, and human ethics clearance was granted by the institutional ethics committee.

Overview

Subjects performed three testing sessions, including an initial session to measure anthropometric characteristics and LT and to ensure familiarity with all equipment, procedures, measures, and the exercise protocol. The two following sessions involved the completion of either a precooling intervention or a control condition (no cooling) before a 40-min cycling time trial in hot conditions (33 ± 0.8°C and 50% ± 3% relative humidity) in an environmental chamber (WatFlow control system; TISS, Hampshire, UK) without any additional convective airflow (fan). The two time trial conditions were performed in a randomized, crossover design and involved identical procedures apart from the implementation or lack of a precooling intervention. Most subjects had prior familiarity with the time trial, having completed similar testing sessions previously. However, those subjects who had not recently undergone a 40-min time trial test performed a familiarization session of the trial before any testing. All testing sessions were performed at the same time of day, separated by at least 4 d of recovery. Participants were required to abstain from strenuous physical activity and the ingestion of alcohol for 24 h before testing and all caffeine and food substances 3 h before testing. In addition, participants recorded all food consumed and activity performed in the 48 h before the first testing session and were required to replicate these for the ensuing session.

Familiarization Session and Graded Exercise Test

On arrival, anthropometric data were collected, including age, height (Detecto® Physicians Scales; Cranlea & Co., Birmingham, UK), body mass (SECA 778; Seca GmbH & Co., Hamburg, Germany), and sum of seven skinfold thickness (biceps, triceps, subscapular, abdominal, suprailiac, quadricep, and calf; Harpenden Skinfold Callipers; British Indicators, West Sussex, UK). After collection of anthropometric data, a graded exercise test was performed to determine LT using an SRM cycle ergometer (SRM, Welldorf, Germany) and an associated software (SRM Training Software, version 6.40.07). The SRM ergometer hertz offset was corrected at zero load before each testing session according to the manufacturer's recommendations. The exercise protocol consisted of 3-min stages commencing at 95 W and increasing by 25 W each stage. In the last 30 s of each stage, a capillary blood sample was obtained from a finger tip to measure lactate ($[\mathrm{La}^-]$, YSI 2300 Stat Plus; Analox, Sheffield, UK). The test was complete once blood $[\mathrm{La}^-]$ concentration showed a sudden, sustained increase of at least 1.0 $\mathrm{mmol{\cdot}L^{-1}}$, with LT calculated as the power output associated with a 1.0-$\mathrm{mmol{\cdot}L^{-1}}$ increase above resting values (13). Testing procedures to determine LT were conducted under normothermic laboratory conditions (22.0 ± 1.0°C). As most subjects had prior and recent familiarity with the time trial procedures, after a sufficient recovery from the graded exercise test (GXT), only those who had not recently performed the 40-min trial completed a familiarization of the time trial.

Exercise Protocol

During both testing sessions, participants performed a 5-min warm-up and a 40-min self-paced cycling time trial on a customized cycle ergometer (620 Ergomedic; Monark, Varberg, Sweden) fitted with power measuring cranks (Pro Track, 8; SRM) connected to an SRM recording device (SRM Power Control V) that continuously recorded power and cadence at a frequency of 1 Hz. The warm-up was performed in the climate chamber and consisted of unweighted cycling at a standardized cadence of 60 RPM. During the trial, participants were blind to performance measures (power or cadence); however, they were aware of elapsed time because of the recording of measures every 5 min. Exercise intensity during the respective trials was regulated by the adjustment of cadence to alter power output. Performance was determined from both overall mean and minute-by-minute power outputs completed over the 40-min trial. Further, total distance was estimated on the basis of the second-by-second power output, cadence, and flywheel circumference. Standard cycling apparel was worn by all subjects, with the clothing worn standardized between respective conditions.

Measures

Hydration status. To standardize hydration status, participants ingested 500 mL of water 60 min before arrival at the laboratory. On arrival for each testing session, participants voided their bladder to provide a urine sample for measurement of urine specific gravity (URICON-N_E 2722; Atago Co., Ltd., Tokyo, Japan) and osmolality (Osmocheck™; Vitech Scientific Ltd., West Sussex, UK) as measures of preexercise hydration status. Further, towel-dried nude mass was measured before and after the 40-min time trial on a set of calibrated weigh scales as a measure of nonurine fluid loss. No fluid was consumed by participants during either condition.

Core, skin, muscle, and body temperature. After measurement of nude mass, participants inserted a rectal thermometer (Henley single use temperature probe, 4491H; Henleys Medical Supplies Ltd., Herts, UK) 10 cm past the anal sphincter to measure core temperature. Skin thermistors (EUS-U-VS5; Wessex Power Technology, Poole, UK) were attached under cycling apparel to the midpoint of the right pectoralis major and exposed skin of the midpoint of the right triceps brachii lateral head, right rectus femoris, and right gastrocnemius lateral head and connected to a 1000 series, 8-bit squirrel meter logger (Grant Instruments Ltd., Cambridge, UK) to record skin temperature. Core and skin temperature measures were recorded before cooling, every 5 min during the preexercise intervention, after the warm-up, and every 5 min during the time trial. Mean skin temperature (MST) was calculated on the basis of the equation of Ramanathan (27), $\text{MST} = 0.3T_{\text{ch}} + 0.3T_a + 0.2T_t + 0.2T_l$, where T_{ch} is the chest temperature, T_a is the arm temperature, T_t is the thigh temperature, and T_l is the calf temperature. In addition, mean body temperature (T_b) was calculated on the basis of the equation $T_b = (0.87 \times \text{core temperature}) + (0.13\ \text{MST})$ (5). A 2-g sample of an anesthetic cream (EMLA™ Cream 5%; AstraZeneca Ltd., Bedfordshire, UK) was applied to the right vastus lateralis muscle 30 min before measurement of resting muscle temperature. With participants seated with the lower leg supported at 90°, a needle (18 G 1.5 inches; BD Microlance 3, Drogheda, Ireland) and a sterile, flexible muscle temperature probe (medical precision thermometer; Ellab, Copenhagen, Denmark) were inserted 4 cm into the belly of the vastus lateralis until a constant temperature was recorded. After removal of the needle, pressure and small adhesive bandage were applied to the entry site to prevent bleeding. Muscle temperature was recorded before and after both preexercise intervention and time trial.

HR and perceived exertion and thermal stress. HR was measured with a chest monitor and telemetric receiver (Accurex Plus; Polar Electro Oy, Kempele, Finland). RPE and rating from the thermal sensation scale (TSS) were obtained on the basis of a 10-point CR-10 Borg scale (4) and an eight-point (32) Likert scale, respectively. HR, RPE, and TSS measures were recorded before cooling, every 5 min during the preexercise intervention, after the warm-up, and every 5 min during the time trial.

Capillary blood measures. A sample of capillary blood was obtained from a fingertip with a sterilized lancet to measure [La^-] and glucose (Glu) concentrations (YSI 2300 Stat Plus; Analox). Blood samples for the measurement of [La^-] and Glu were obtained at rest before cooling, postcooling, after warm-up, and postexercise.

Voluntary and evoked twitch contractile properties. Voluntary and evoked twitch properties of the right knee extensors were assessed using repeated isometric contractions against a stable tension load cell (Model 616, RS Components; Tedea Huntleigh, Cardiff, UK) linked to a host computer and data acquisition and analysis system (Spike2 v3.21; Cambridge Electronic, Cambridge Design, Cambridge, UK). During testing, participants were seated upright with the knee flexed at 90° (0° being full extension) and secured to the dynamometer via waist and shoulder straps. Muscle activation was achieved by stimulation of the quadriceps using two 110 × 80-mm reusable electrodes positioned on the anterior surface of the right thigh, 2 cm above the superior border of the patella and 1 cm below the inguinal fold. The current was delivered by a Digitimer DS7AH stimulator (Digitimer, Welwyn Garden City, England) using a single square-wave pulse with a width of 200 μs (400 V with a current of 150–800 mA). Initially, the current was applied in incremental steps until peak twitch force (Pf) was attained. After this, stimulus intensity was increased by a further 10% to ensure that supramaximal stimulation was achieved. Four pulses each separated by 10 s were delivered at a current of 500–600 mA in a resting state. For analysis, twitch force was averaged over all four evoked contractions with the mean used to determine Pf, defined as the highest isometric force value achieved during the evoked contraction. After evoked twitch assessment, maximal voluntary contraction (MVC) performance testing consisted of 10 × 5 s of maximal isometric trials, where participants were instructed to exert maximal effort throughout each contraction, with a recovery of 5 s between efforts. MVC was defined as the highest isometric force value achieved during the voluntary contraction. Further, on the first three contractions, a superimposed twitch was delivered after the initial plateau of MVC (after 2 s) to measure superimposed force (SIF). SIF was determined as the mean of the highest isometric force values achieved during all superimposed contractions. Voluntary and

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evoked measures were obtained before the cooling intervention, after cooling and postexercise.

Cooling Intervention

After recording of all resting measures, participants performed either the precooling or the control interventions. The precooling procedure involved immersing the lower body to the level of the greater trochanter in 14 ± 0.3°C water for 20 min. This procedure was achieved by participants standing in an environmental tank filled with cool water located outside the chamber in ambient laboratory conditions of 22 ± 1.0°C. In addition, after postcooling MVC measures, cooling of the quadriceps and hamstrings were maintained during the warm-up via the application of thin, gel-based cold packs (3M; Boots, Nottingham, UK), weighing no more than 800 g in total per leg, and were held in place with tubular bandaging (Boots). The packs were removed from a −16°C freezer and placed between layers of the bandaging around the thigh, with three packs on the quadriceps and three packs on the hamstrings for each leg. The ice packs and the bandages were removed before recording of post–warm-up measures. During the control condition, participants stood in the environmental chamber for 20 min and received no cooling during the warm-up. The duration between the completion of the intervention and the warm-up was 8–10 min, whereas the duration between the cessation of the warm-up and the start of the time trial was less than 5 min.

Statistical Analyses

Data are reported as mean ± SD. Respective paired-samples *t*-tests were used to compare between conditions for mean power output, percentage of LT, distance covered, and body mass. For all other performance and physiological measures, a two-way (condition × time) repeated-measures ANOVA was used to determine the main effects between the two conditions (cooling vs control). *Post hoc* paired *t*-test analyses with Bonferroni corrections were performed to determine the location of significant differences. Significance was set at $P \leq 0.05$.

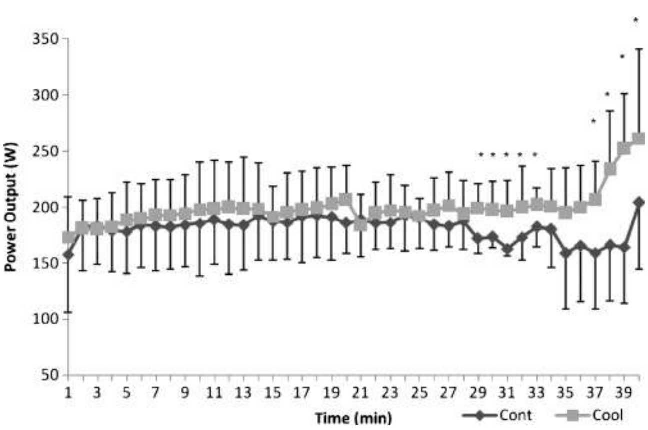

FIGURE 1—Mean ± SD of minute-by-minute power output (W) for precooling (Cool) and control (Cont) conditions during the 40-min time trial. *Significantly different between conditions ($P < 0.05$).

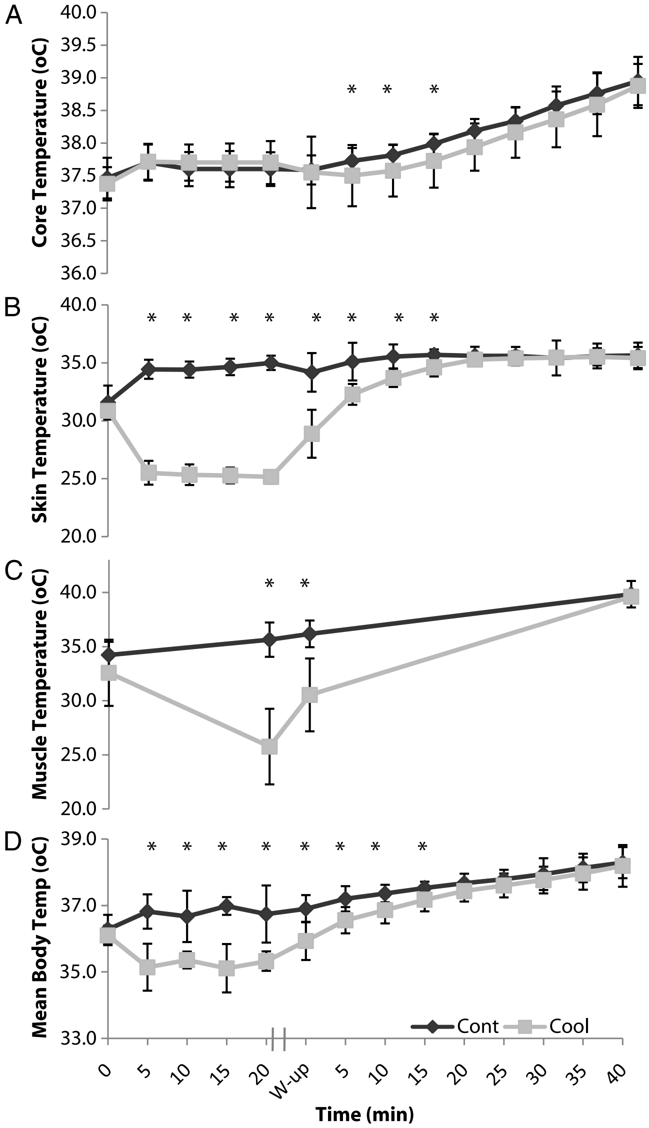

FIGURE 2—Mean ± SD of (*A*) core temperature (°C), (*B*) mean skin temperature (°C), (*C*) muscle temperature (°C), and (*D*) mean body temperature (°C) for precooling (Cool) and control (Cont) conditions for the 20-min cooling intervention, the 5-min warm-up, and the 40-min time trial. W-up, at the end of the warm-up. *Significantly different between conditions ($P < 0.05$).

RESULTS

Performance. Precooling resulted in a significantly greater mean power during the 40-min time trial (198 ± 25 vs 178 ± 26 W for precooling and control, respectively; $P = 0.05$). There was no significant main effect present ($P = 0.25$) for minute-by-minute power output; however, differences in minute power output between conditions were present during the last 10 min of the time trial, specifically the 29th–33rd and the 37th–40th min, when a significantly increased power output was produced in the

TABLE 1. Mean ± SD of HR, RPE, rating of TSS, blood [La$^-$], and blood Glu for precooling (Cool) and control (Cont) conditions during the cooling intervention and 40-min time trial.

		Preintervention	**Postintervention**	**After Warm-Up**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
HR (bpm)	Cool	73 ± 7	74 ± 16	107 ± 17	132 ± 16	148 ± 10	157 ± 7	162 ± 8	165 ± 8	171 ± 8	173 ± 9	183 ± 9
	Cont	76 ± 8	79 ± 15	116 ± 11	137 ± 19	155 ± 7	159 ± 8	163 ± 9	166 ± 6	167 ± 9	169 ± 9	178 ± 14
RPE (AU)	Cool			9.0 ± 1.2	12.0 ± 0.6	13.3 ± 1.2	14.4 ± 1.2	15.4 ± 1.6	16.1 ± 1.9	17.1 ± 2.0	18.1 ± 1.6	19.1 ± 1.4
	Cont			9.1 ± 2.0	12.8 ± 1.4	14.1 ± 1.4	15.3 ± 1.7	16.0 ± 1.3	17.0 ± 1.3	17.9 ± 1.1	18.4 ± 1.3	19.3 ± 1.0
TSS (AU)	Cool	4.1 ± 0.2	2.7 ± 1.0*	4.1 ± 0.7*	4.8 ± 0.7*	5.3 ± 0.9*	5.7 ± 1.0*	6.2 ± 0.8	6.7 ± 0.7	7.0 ± 1.0	7.4 ± 0.9	7.4 ± 0.7
	Cont	4.3 ± 0.7	5.2 ± 0.4	5.4 ± 0.6	6.0 ± 0.5	6.3 ± 0.5	6.6 ± 0.6	6.8 ± 0.7	7.1 ± 0.6	7.3 ± 0.7	7.5 ± 0.7	7.8 ± 0.4
Glu (mmol·L^{-1})	Cool	4.9 ± 1.0	4.7 ± 0.9	4.0 ± 1.6								4.8 ± 1.0
	Cont	4.9 ± 0.2	5.1 ± 0.7	4.1 ± 0.7								4.2 ± 0.5
[La$^-$] (mmol·L^{-1})	Cool	1.4 ± 0.5	1.3 ± 0.2*	1.5 ± 0.6*								5.7 ± 2.4
	Cont	1.5 ± 0.9	2.2 ± 0.8	2.4 ± 0.9								5.3 ± 2.2

AU, arbitray units.

* Significantly different from control condition for respective measure ($P < 0.05$).

cooling condition ($P < 0.02$; Fig. 1). Further, the overall mean power output represented the maintenance of a higher percentage of LT during the cooling condition (88% ± 9% vs 78% ± 9% for precooling and control, respectively; $P = 0.05$). Finally, a significantly greater distance was estimated for the precooling condition (19.3 ± 1.3 vs 18.0 ± 1.4 km for precooling and control, respectively; $P = 0.05$).

Physiological and perceptual. Preexercise hydration status was not significantly different between conditions for either urine specific gravity (1.025 ± 0.022 vs 1.015 ± 0.008; $P = 0.30$) or urine osmolality (611 ± 217 vs 595 ± 290 mOsm·L^{-1}; $P = 0.40$) for cooling and control conditions, respectively. The change in body mass after the time trial, representing nonurine fluid loss, was significantly smaller (by 300 mL) in the precooling condition (0.8 ± 0.2 vs 1.1 ± 0.2 kg for precooling and control, respectively; $P = 0.05$).

Core, skin, muscle, and mean body temperature data are presented in Figure 2. Significant main effects were present for a reduction in core ($P = 0.04$), mean skin ($P = 0.01$), mean body ($P = 0.01$), and muscle ($P = 0.01$) temperatures, respectively. The lower-body precooling intervention did not reduce core temperature at the start of exercise ($P = 0.25$); however, it did suppress core temperature until the 20th minute of the time trial (0.2 ± 0.1°C; $P < 0.05$). Despite a blunted initial rise in core temperature after precooling, there were no differences between conditions after the 20th minute of exercise ($P > 0.05$). Both skin and mean body temperatures were significantly reduced in the precooling condition during the intervention and the warm-up and until the 20th minute of the time trial (1.0–3.0°C; $P < 0.05$). Muscle temperature was also significantly reduced after the cooling intervention and before exercise in the cooling condition (10 ± 2.0°C; $P < 0.01$).

Results for HR, RPE, TSS, and capillary blood measures are presented in Table 1. No significant main effects were present for HR ($P = 0.61$) or RPE ($P = 0.81$) measures. HR was not significantly different between conditions during the intervention, warm-up, or time trial ($P > 0.05$). Similarly, RPE was also not different between conditions during the exercise protocol ($P > 0.05$). However, a main effect was present for TSS ($P < 0.01$), with significantly lower values in the precooling condition during the intervention and until the 20th minute of the time trial ($P < 0.05$). Capillary blood measures of [La$^-$] and Glu were not significantly different preintervention ($P > 0.05$); however, postintervention and preexercise [La$^-$] values were significantly lower ($P = 0.04$) in the cooling condition. Finally, there were no differences ($P > 0.05$) between conditions in preexercise or postexercise Glu or postexercise [La$^-$] values.

Voluntary and evoked muscle properties. No significant main effects were present for MVC ($P = 0.65$),

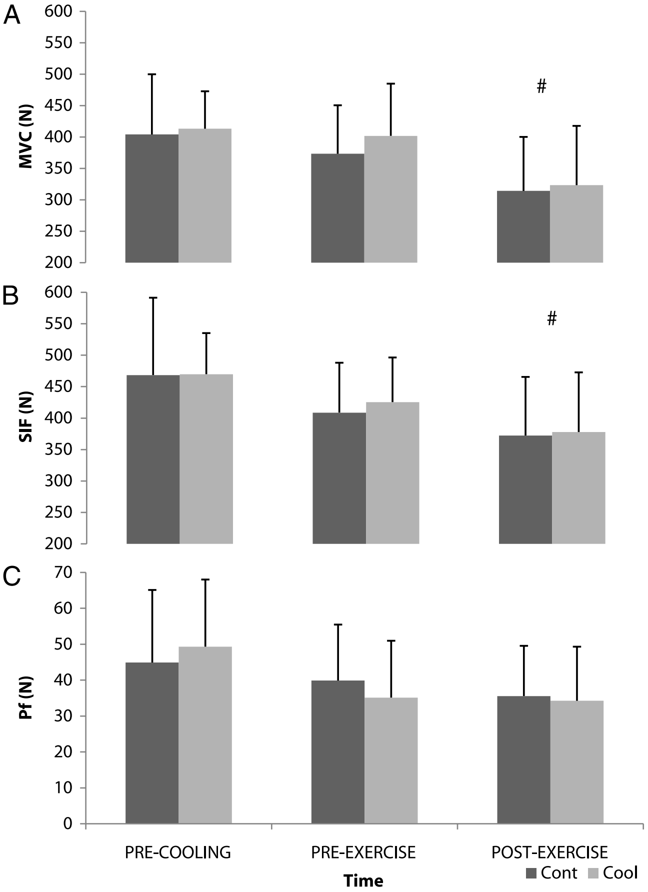

FIGURE 3—Mean ± SD of (*A*) MVC (N), (*B*) SIF (N), and (*C*) Pf (N) for precooling (Cool) and Control (Cont) conditions precooling and postcooling intervention and after time trial. $^\#$Significantly different from preexercise for both conditions ($P < 0.05$).

SIF (P = 0.60), or Pf (P = 0.42). MVC and SIF were significantly reduced postexercise in both conditions (P = 0.03–0.05; Fig. 3); however, there were no significant differences between the respective conditions preexercise or postexercise ($P > 0.05$; Fig. 3). In contrast, Pf was not significantly reduced postexercise in either condition ($P > 0.05$; Fig. 3); however, again there were no significant differences between the respective conditions preexercise or postexercise ($P > 0.05$; Fig. 3). Interestingly, neither preexercise intervention significantly affected ($P > 0.05$) postintervention voluntary or evoked force production; however, nonsignificant tendencies (P = 0.20–0.80) were noted in reduced Pf after exposure to cooling and in smaller MVC and SIF after exposure to hot environments.

DISCUSSION

The implementation of a 20-min lower-body precooling intervention improved 40-min cycling time trial performance compared with the control condition. The precooling intervention reduced muscle, skin, and mean body temperature at the start of the time trial and blunted the rise in core temperature during the first 15 min of exercise. Further, a reduction of nonurine fluid loss was evident in the precooling condition, indicating the potential maintenance of a larger blood volume. Despite a reduced thermal load in the precooling condition, the intervention had no effect on voluntary or evoked force production at the start of exercise. Further, although core and muscle temperature were initially reduced after precooling, MVC was maintained, and the early selection of exercise intensity was similar between conditions. However, performance was improved in the cooling condition during the later stages of the time trial, and of the physiological measures recorded, only nonurine fluid loss differed between conditions.

The present study supports previous findings on the ergogenic benefits of precooling for endurance exercise (3,12,26). Previous studies have reported similar results in self-paced exercise, with a 900-m improvement in performance for a 30-min cycling time trial (14), a 12-W increase in mean power during the 20-min variable-intensity portion of a 40-min cycling trial (26), and a 13-s improvement for a 5-km (19 min) running trial (2). Further, as with the present study, these studies reported the blunting of core and skin temperatures, a reduction in sweat loss, and the reduction in perceived thermal stress. Moreover, as with the present data, most physiological differences between conditions had disappeared by the end of the respective protocols. Collectively, these data, in addition to studies using constant-intensity exercise (16,17,24), highlight the performance improvements after precooling for endurance exercise in the heat. Despite these ergogenic benefits of precooling, few studies have described the pacing or selection of exercise intensity throughout the exercise bout to locate where or how precooling improves exercise performance.

The performance improvements in the precooling condition were not evident until the final 10 min of the time trial, by which time all measured physiological changes (apart from fluid loss) induced by precooling had dissipated. However, it must be noted that rather than cycling performance in the precooling condition being improved *per se*, it seems that the reduction in performance observed in the control condition was prevented in the cooling condition (17). Previously, Tucker et al. (34) have reported that compared with cool conditions, reductions in power output during the 20-km self-paced cycling trials in the heat occurred during the final 20% of the trial, without an abnormally increased core temperature. Accordingly, it seems evident that precooling interventions of sufficient volume or duration may delay the self-regulated reduction in exercise intensity apparent in the control condition. As such, in agreement with previous studies (2,14,26), precooling can have ergogenic benefits for prolonged endurance exercise in the heat, although to date the mechanisms remain equivocal.

The reason for the earlier reduction of exercise intensity in hot conditions remains the topic of some debate (20). Recent research has highlighted the role of the selective and protective reduction in neuromuscular recruitment based on the endogenous thermal strain (20,21,33). Further, this reduction in voluntary recruitment that results in a diminished exercise intensity may develop from either a sensory feedback (11,22) or an anticipatory avoidance of developing cellular harm (19,33). Moreover, other physiological perturbations may also collaborate to invoke a reduced recruitment or be directly responsible for the reduction in exercise intensity (20). Factors potentially responsible for the heat-induced reduction in exercise intensity include a build up of branched chain amino acids in the cerebral blood (23), a reduction in neural transmission or neurochemicals such as dopamine (21), a reduced supply of metabolically active substrates to the cerebrum (21), or any number of peripheral responses (blood volume and core temperature) inducing altered afferent feedback (11,22). As the mechanisms for heat-induced reduction in performance may be intensity and duration specific, the present data indicated an inability of participants to maintain a power output corresponding to 80%–90% LT at a time when the physiological responses were similar to those present at the same stage in the cooling condition.

Given the debate regarding mechanisms regulating exercise performance in the heat, the present study sought to determine the influence of precooling on contractile function and ensuing exercise performance. The precooling intervention reduced muscle temperature at the commencement of the time trial, with minimal alterations to voluntary or evoked force or starting exercise intensity. Together, these data suggest that the ergogenic benefits from precooling were not due to an improvement or maintenance in contractile element function. Given that an improved performance was present in the precooling condition, without changes in muscle contractile force properties, it is assumed that the maintenance of power output after precooling resulted from the sustained recruitment of exercising musculature (15). Although EMG measures were not recorded, the self-paced nature of exercise would have made the interpretation and comparison of these data between conditions difficult. Further, the reduction in EMG alongside power output during exercise in the heat has been previously reported (33). Nonetheless, there was no difference in postexercise MVC, SIF, or Pf, although the cooling condition maintained a greater mean power output by ≈20 W. As such, this may highlight evidence for a selective reduction in voluntary force in the heat that is ameliorated by precooling. In addition, the reduction in SIF in both conditions indicates the presence of some fatigue of peripheral origin and may further highlight that precooling may not act as a protective agent against mechanisms of peripheral fatigue.

Despite performance improvements after precooling, specifically during the final 10 min of the time trial, the only difference between conditions in measured physiological variables after 40 min was a reduced fluid loss in the cooling condition. The possible maintenance of an increased central blood volume (300 mL) due to a reduction in nonurine fluid loss after cooling is a common finding in precooling studies (2,14). Although 300 mL is comparable to results from these studies (200–500 mL [2,14]), it is arguable whether this volume would be sufficient in euhydrated cyclists to elicit reductions in performance. However, these results may suggest that the reduced physiological responses present in the precooling time trial acted to reduce the afferent feedback that would invoke a centrally mediated reduction in muscle recruitment (20). Alternatively, precooling may have allowed these familiarized participants to select a higher-exercise intensity based on a prediction of the ensuing requirement based on the blunted physiologically demands after precooling (18,33). Of interest is that although subjects rated the thermal comfort as lower preexercise, this in itself did not mediate an increased power output at the commencement of the time trial. Previous research highlights either feedback (11,22) or feed-forward (18,29) models regulating exercise in the heat; however, there is the possibility of a mixed-model response, whereby based on both the response to afferent feedback, combined with the knowledge of the required workload to be completed, muscle recruitment is regulated to both tolerate the thermoregulatory load yet optimize power output for the external demands of prolonged performance (21).

The altered physiological and perceptual responses induced by cooling may have resulted in the maintenance of exercise intensity not observed in the control condition. The combination of a slower rise in core and muscle temperature and a larger blood volume (reduced sweat rate) along with a lowered perception of thermal stress may delay the reduction in voluntary force recruitment (21,31,33). To highlight this, although postexercise MVC and SIF do not differ between conditions in absolute values, the reduction in voluntary force based on the amount of work performed is greater in the noncooling condition. The notion of a reduction in voluntary force is supported by previous evidence indicating that passive elevation of core temperature can reduce voluntary activation (19,30). Further, voluntary activation is returned to normal when the endogenous thermal stress is ameliorated (19,30). In relation to the present study, blunting the rise in the thermoregulatory load via precooling may act to delay the reduction in voluntary force and maintain power output. In addition, the reduced physiological (blood volume and core/muscle temperature) and perceptual load (RPE and TSS) resulting from precooling may also assist the self-selection of higher exercise intensities. As such, it is possible that alterations to both feedback and feed-forward mechanisms result from precooling to ensure the maintenance of exercise intensity in the heat.

In conclusion, a 20-min lower-body precooling intervention improved the 40-min cycling time trial performance in the heat. Further, the precooling intervention reduced the thermoregulatory and perceptual strain of the hot conditions, in particular, until the 20th minute of the time trial. However, performance benefits were only evident during the final 10 min of the trial, whereby the reduction in exercise intensity noted in the control condition was not present during the precooling condition, although the measured cooling-induced physiological benefits had dissipated. As a result, given the comparable reduction in postexercise voluntary force for a greater distance covered, is it possible that the advantages of precooling result from the prevention of the down-regulation of exercise intensity present in the heat. However, whether the prevention of the heat-induced reduction in exercise intensity results from either feed-forward or feedback based regulation or a combination of the two remains speculative.

This study was partly funded by a Charles Sturt University Special Studies Program grant. The research team would also like to state that the results of the present study do not constitute endorsement by the American College of Sports Medicine.

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Eur J Appl Physiol (2007) 100:727–735
DOI 10.1007/s00421-007-0468-x

ORIGINAL ARTICLE

Effects of pre-cooling procedures on intermittent-sprint exercise performance in warm conditions

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Accepted: 4 April 2007 / Published online: 3 May 2007

Abstract The aim of this study was to determine whether pre-cooling procedures improve both maximal sprint and sub-maximal work during intermittent-sprint exercise. Nine male rugby players performed a familiarisation session and three testing sessions of a 2 × 30-min intermittent sprint protocol, which consisted of a 15-m sprint every min separated by free-paced hard-running, jogging and walking in 32°C and 30% humidity. The three sessions included a control condition, Ice-vest condition and Ice-bath/Ice-vest condition, with respective cooling interventions imposed for 15-min pre-exercise and 10-min at half-time. Performance measures of sprint time and % decline and distance covered during sub-maximal exercise were recorded, while physiological measures of core temperature (T_{core}), mean skin temperature (T_{skin}), heart rate, heat storage, nude mass, rate of perceived exertion, rate of thermal comfort and capillary blood measures of lactate [La$^-$], pH, Sodium (Na$^+$) and Potassium (K$^+$) were recorded. Results for exercise performance indicated no significant differences between conditions for the time or % decline in 15-m sprint efforts or the distance covered during sub-maximal work bouts; however, large effect size data indicated a greater distance covered during hard running following Ice-bath cooling. Further, lowered T_{core}, T_{skin}, heart rate, sweat loss and thermal comfort following Ice-bath cooling than Ice-vest or Control conditions were present, with no differences present in capillary blood measures of [La$^-$], pH, K$^+$ or Na$^+$. As such, the ergogenic benefits of effective pre-cooling procedures in warm conditions for team-sports may be predominantly evident during sub-maximal bouts of exercise.

Keywords Central fatigue · Heat-strain · Ice-bath · Repeat-sprint · Thermoregulation

Introduction

Training and competition for many team-sports often requires sustained exercise performance in high ambient temperatures. Under these conditions elevated core (T_{core}) and mean skin (T_{skin}) temperatures are noted, resulting in increased cardio-vascular and metabolic loads (Kozlowski et al. 1985; Morris et al. 2000), in addition to hastening neuromuscular fatigue (Kay et al. 2001) and reducing endurance (Gonzalez-Alonso et al. 1999) and intermittent-sprint (Drust et al. 2005) performance compared with normo-thermic conditions. To counter the physiological strain associated with higher environmental temperatures, pre-cooling procedures which reduce pre-exercise T_{skin} and T_{core} have been used in laboratory and field settings (Marino 2002).

Increased thermal stress has shown to excessively elevate T_{core} and subsequently reduce intermittent-sprint performance (Maxwell et al. 1999; Drust et al. 2005; Morris et al. 2005). As such, methods such as cold baths, cold ambient air and ice vests have been utilised to varying effect to delay the rise in T_{core} during prolonged duration repeated sprint efforts (Marino 2002). These procedures have improved endurance performance in exercise protocols consisting of constant-load exercise to fatigue (Lee and Haymes 1995; Hasegawa et al. 2005), total maximal work performed in a set time (Booth et al. 1997) and time to complete variable-paced efforts of set distance (Arngrímsson et al. 2004). However,

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minimal performance benefits have been reported by the small number of studies investigating pre-cooling and intermittent-sprint exercise (simulating team-sport activity) (Drust et al. 2000; Duffield et al. 2003; Cheung and Robinson 2004). Previous research has not shown an improvement in peak or mean power, speed or distance covered in singular (Marsh and Sleivert 1999) or repeated (Drust et al. 2000; Duffield et al. 2003; Cheung and Robinson 2004) maximal sprint efforts of 5- to 30-s in duration following pre-cooling. However, recently Castle et al. (2006) have shown some ergogenic benefits for intermittent-sprint performance following lower body pre-cooling with a 4% increase in peak power. While pre-cooling procedures are generally effective in reducing T_{core}, T_{skin} and the perceived thermal strain of intermittent-sprint exercise protocols (Mitchell et al. 2001; Sleivert et al. 2001), evidence for improved intermittent-sprint performance in warm–hot conditions following pre-cooling is limited.

Team-sport exercise patterns involve intermittent-sprint activity incorporating maximal sprints separated by activity ranging from passive stationary recovery to high-intensity work (Spencer et al. 2005). Traditionally, exercise protocols simulating team-sport exercise involve repeated maximal (2–60) non-specific cycle ergometer sprint efforts (5–30 s) interspersed with sub-maximal recovery bouts (passive–50% $\dot{V}\mathrm{O}_{2\,\mathrm{max}}$) over prolonged durations (30–80 min) (Duffield et al. 2003; Cheung and Robinson 2004). Exercise performance is assessed via measures of peak and mean power, while the sub-maximal exercise separating maximal efforts is normally standardised and ignored as a performance measure. Morris et al. (2005) have previously reported significantly reduced sub-maximal distances covered in 33°C compared to 17°C ambient conditions. Hence, given the improved endurance performance in completing maximal aerobic events, reported for pre-cooling procedures (Arngrímsson et al. 2004), it is surprising more research attention has not incorporated the measurement of sub-maximal exercise in the assessment of performance.

Therefore, given the often ambiguous and non-specific nature of the reported effects of pre-cooling on intermittent-sprint exercise performance, the purpose of the present study was to investigate the effect of two common pre-cooling procedures (ice-bath and ice-vest) on maximal sprint and sub-maximal work during intermittent-sprint exercise in warm conditions.

Methods

Participants

Participants were nine male, moderate to well trained, club-level rugby players with a mean ± SD age 21.4 ± 1.3 year, height 184.1 ± 5.1 cm and body mass 85.16 ± 5.56 kg. All participants gave verbal and written consent prior to engaging in testing procedures and Human Ethics clearance was granted by the Institutional Ethics Committee.

Overview

Participants performed an initial familiarisation session, followed by three testing sessions at the same time of day, separated by 5–7 days and were required to abstain from the ingestion of alcohol, caffeine and food substances 4 h prior to testing. All testing was conducted on a 20-m synthetic running track in an enclosed biomechanics laboratory. Testing was performed in warm/hot environmental conditions (32 ± 1°C and 30 ± 3% relative humidity), with heating provided by a customised gas heating system, supplemented by four electronic 2,000 W room heaters (Kambrook, Australia) placed at 5-m intervals alongside (within 1-m) the running track. Following familiarisation with all measures and procedures, participants performed three identical sessions in a randomised, counter-balanced order, with only the type of cooling intervention varying between sessions. The three sessions consisted of a control session (no cooling intervention), an ice-vest session (cooling intervention with an ice-vest) and an ice-bath session (ice bath and ice-vest). All participants were required to document their physical activity and dietary and fluid consumption in the 24 h prior to the first testing session and replicate these patterns for the following sessions and particularly to standardise fluid consumption.

Exercise protocol

Participants performed an intermittent-sprint protocol consisting of 2 × 30-min identical halves, separated by a 10-min recovery period and performed on an enclosed 20-m synthetic running track. Initially a warm-up consisting of 4 min of running along the 20-m running track with increments in running speed each minute and 5-min of passive stretching was performed. The intermittent-sprint protocol consisted of a maximal 15-m sprint every minute, separated by sub-maximal exercise of varying intensities. The maximal 15-m sprint was performed on the running track, with a 5-m space for deceleration before impact with a large high jump mat to simulate body contact and collisions that occur in many team sports. Further, during the first and last minute of each half, an extra sprint was performed, reducing the recovery to 30 s. Between each maximal sprint effort were bouts of self-paced, sub-maximal activity, consisting of hard running, jogging and walking, respectively. These sub-maximal bouts were performed up and back along the 15-m sprint track in a shuttle-run fashion. A sub-maximal exercise bout was started as soon as the participant had finished the maximal sprint and was ceased 10 s prior to the commencement of the next sprint to allow time for preparation for the ensuing sprint. Only one sub-maximal exercise mode was employed each minute and these were rotated through in the previously mentioned order to ensure correct replication of procedures. Participants were instructed prior to and given verbal support during each session to attempt to cover as much distance as possible during the hard running bouts, and jog or at a self-selected comfortable pace during the respective jogging and walking bouts.

Pre-cooling intervention

A cooling intervention was performed for 15-min prior to exercise, during the warm-up and during the 10-min half-time recovery period. Participants in the control condition sat in the 32°C temperature and within 5-m of a radiant heat source during both the initial 15-min and then 10-min half-time recovery periods with no cooling intervention. During the ice-vest session, participants wore an ice-vest (Artic Heat, Australia) while sitting in the 32°C temperature within 5-m of a radiant heat source for the 15-min pre-cooling and 10-min half-time cooling and also wore the vest during the warm-up and stretching period. The ice-vest was stored in crushed ice prior to and following use. During the ice-bath session, participants were immersed up to the suprasternal notch in a cold water bath (Custom design, CSU, Australia) at 14 ± 1°C for the initial 15-min before donning the ice-vest and performing the warm-up and stretching in the vest, and then donning the vest during the 10-min half-time recovery period while seated as per other conditions. Finally, in all conditions, participants were required to consume a measured 350 ml of water during the half-time break.

Measures

Performance

Exercise performance was assessed by measures of 15-m sprint time and distance covered during sub-maximal exercise bouts. Sprint time was measured by an infra-red timing system (Speed Light, Swift, Australia) while % decrement was calculated according to Dawson et al. (1993). Markings in 1-m increments alongside the 15-m running track allowed for an accurate measure of the distance covered on each individual sub-maximal exercise bout performed in the respective hard running, jogging and walking bouts.

Physiological measures

Before and after each testing session, nude mass was measured on a set of calibrated scales (HW 150 K, A & D, Australia) to estimate changes in body mass due to sweat loss. Heart rate was measured (Vantage NV, Polar, Finland) pre-intervention, post-intervention, pre-exercise and every 5-min throughout the exercise protocol. T_{core} was measured by a telemetric pill (VitalSense, Mini Mitter, USA) that was ingested 4–5 h prior to exercise to ensure it had passed into the Gastro-Intestinal tract. Skin temperature was measured at the sternum, chest, mid-forearm, mid-quadriceps and medial calf via telemetric patches (VitalSense, Mini Mitter, USA). T_{core} and T_{skin} were recorded pre-intervention, post-intervention, pre-exercise and every 10-min throughout the protocol from a hand-held monitor that telemetrically received core pill and skin patch measurements (VitalSense, Mini Mitter, USA). T_{skin} was calculated based on the equation of Ramanathan (1964), while heat storage was calculated based on the equation of Havenith et al. (1995). Ratings of perceived exertion (RPE) and Thermal comfort were obtained pre-intervention, post-intervention, pre-exercise, either side of the half-time break and post-exercise. A 100 μl of capillary blood was sampled from a hyperaemic ear lobe pre-intervention, post-intervention and pre- and post-halves for analysis of capillary blood lactate [La^-], pH, Potassium (K^+) and Sodium (Na^+) (ABL825 Radiometer, Copenhagen, Denmark). Finally, a 60 μl sample of capillary blood was collected pre- and post-exercise and centrifuged to separate blood plasma and analysed for hematocrit (Hct).

Statistical analysis

A repeated measures (condition × time) ANOVA was used to determine significant differences between the respective conditions (Control, Ice-vest, Ice-bath). Tukey's post-hoc HSD tests were used to determine the source of significance, which was set a priori at $P = 0.05$. Effect sizes (ES) (Cohen's *d*) were calculated to analyse potential trends in the data comparing respective cooling conditions to the control condition. An ES of <0.2 is classified as a 'trivial', 0.2–0.4 as a 'small', 0.4–0.7 as a 'moderate' and >0.8 as a 'large' effect.

Results

The results for mean ± SD 15-m sprint time, total sprint time and % decline in sprint time for the first and second half, respectively, for all conditions are presented in Table 1. No significant differences ($P>0.05$) and small ES were present between conditions for mean and total sprint time and % decline. The mean ± SD and total distance covered during hard running, jogging and walking exercise bouts for the first and second half and overall, respectively, for all conditions is presented in Table 2. The overall total distance covered during all sub-maximal exercise bouts were not significantly different ($P = 0.09$) for the ice-bath, ice-vest and control conditions (4865 ± 546, 4551 ± 418 and 4493 ± 403 m, respectively). No significant differences ($P > 0.05$) were noted between conditions for the mean or total distance covered in hard running ($P = 0.09$), jogging ($P = 0.50$) or walking ($P = 0.61$) either in the first or second half or overall. However, large ES data indicated a greater mean and total distance covered in the ice-bath session for hard running in both halves (ES = 0.84 and 0.86) and overall (ES = 0.88). Mean ± SD individual hard running efforts are presented in Fig. 1

Results for mean ± SD T_{core}, T_{skin} and chest temperature (T_{chest}) for all conditions are presented in Fig. 2. A significantly lower T_{core} ($P < 0.05$) was evident following the intervention, prior to the warm-up, in the ice-bath compared to the ice-vest and control condition and remained lower until the fortieth minute. Further, large ES data (ES = 1.0–1.8) indicated a lower T_{core} in the ice-bath condition following the intervention for the entire exercise protocol. No significant differences ($P > 0.05$) and moderate ES data (ES = 0.3–0.5) were evident between the ice-vest and control conditions. A significantly lower T_{skin} ($P < 0.05$) was evident following the intervention in the ice-bath compared to the ice-vest and control conditions throughout the warm-up and until the twentieth minute, with large ES data (ES = 1.0–12.0) indicating lower T_{skin} in the Ice-bath condition following the intervention for the entire exercise protocol. No significant differences ($P > 0.05$), but large ES data (ES = 0.8–1.1) were evident between T_{skin} in the ice-vest and control conditions until the twentieth minute. A significant difference ($P < 0.05$) and large ES (0.8–3.1) were evident in lower T_{chest} values in the ice-bath and ice-vest conditions compared to the control condition following cooling until the tenth minute and again after the half-time cooling procedure. No differences ($P > 0.05$) were present between the respective cooling conditions. Results for change in heat storage over the testing protocol are presented in Fig. 3. In the ice-bath condition an initial loss of body heat was noted following cooling, with a reduction in heat storage until the tenth minute ($P < 0.05$).

Mean ± SD heart rate data are presented in Fig. 4 and show a significantly lower heart rate in the ice-bath condition following the cooling intervention until the tenth minute of the exercise protocol (including the warm-up). Large ES data also indicate reduced heart rates until 15-min of the exercise protocol (ES = 0.8–1.8) and again after half-time (ES = 0.90) in the ice-bath condition. A significant difference ($P < 0.05$) in the amount of sweat loss (as measured by pre-post difference in nude body mass) was evident, with a lower change in mass in the ice-bath than control condition (1.73 ± 0.17, 1.92 ± 0.24 and 2.13 ± 0.19 kg for ice-bath, ice-vest and control conditions, respectively). The large ES data indicated both ice-bath and ice-vest conditions had a reduced sweat loss compared to the control condition.

The mean ± SD capillary blood [La$^-$], pH, Na$^+$, K$^+$ and Hct data is presented in Fig. 5. No significant differences ($P < 0.05$) were evident between conditions for [La$^-$], pH, Na$^+$ or K$^+$ throughout the exercise protocol. Large ES data (ES = 0.70) indicated lower pH values at the end of the first-half in the ice-bath condition; however, all other ES data indicated trivial to small differences. Significant differences ($P < 0.05$) were noted between the ice-bath and ice-vest respectively and control condition for the change in Hct. Attenuated changes in Hct were evident for the ice-bath (1.2 ± 0.4%) and ice-vest (1.6 ± 0.5%) compared to the control condition (2.3 ± 0.5 %).

RPE and Thermal comfort ratings throughout the protocol are presented in Table 3. No significant differences ($P > 0.05$) and small ES data (<0.4) were present between all conditions for RPE values. Significantly ($P < 0.05$) reduced Thermal comfort ratings were present in the ice-bath condition before the start of each half and in the ice-vest before the first-half compared to the control condition. Large ES (d = 1.0–3.5) were present for attenuated ratings in the ice-bath and ice-vest conditions at the start of each half.

Table 1 Mean ± SD 15-m sprint time, total sprint time for all sprints and % decline in sprint time for the first and second halves for the Control, Ice-vest and Ice-bath conditions

	Control	Ice-vest	Ice-bath
First half sprint mean (s)	2.75 ± 0.13	2.74 ± 0.18	2.72 ± 0.14
Second half sprint mean (s)	2.83 ± 0.17	2.82 ± 0.22	2.77 ± 0.16
First half sprint total (s)	90.59 ± 4.40	90.31 ± 5.96	89.81 ± 4.74
Second half sprint total (s)	93.30 ± 5.45	93.11 ± 7.22	91.26 ± 5.32
First half decline (%)	6.2 ± 1.8	7.1 ± 2.5	5.5 ± 2.5
Second half decline (%)	6.3 ± 1.9	6.2 ± 2.1	6.5 ± 2.6

No significant difference between conditions ($P > 0.05$)

Table 2 Mean and total ± SD distance covered for hard running, jogging and walking in the first and second halves respectively for the Control, Ice-vest and Ice-bath conditions

	Control	Ice-vest	Ice-bath
Mean first half hard run (m)	122.7 ± 12.5	127.0 ± 12.6	136.8 ± 14.2[a]
Mean second half hard run (m)	113.3 ± 12.0	115.9 ± 16.4	128.4 ± 15.5[a]
Mean first half jog (m)	93.8 ± 8.3	92.4 ± 10.5	95.0 ± 11.9
Mean second half jog (m)	87.2 ± 8.1	86.4 ± 10.3	91.4 ± 12.3
Mean first half walk (m)	52.2 ± 7.2	53.0 ± 7.3	55.9 ± 7.5
Mean second half walk (m)	50.4 ± 8.7	50.8 ± 5.1	53.9 ± 8.4
Total first half hard run (m)	1104.0 ± 112.3	1143.4 ± 113.5	1231.9 ± 128.6[a]
Total second half hard run (m)	1019.5 ± 107.7	1042.6 ± 147.8	1155.6 ± 139.2[a]
Total first half jog (m)	750.0 ± 66.3	740.0 ± 84.1	759.9 ± 95.0
Total second half jog (m)	697.5 ± 64.4	691.9 ± 82.7	731.3 ± 98.4
Total first half walk (m)	469.6 ± 65.2	476.9 ± 65.4	502.9 ± 67.7
Total second half walk (m)	453.3 ± 77.9	456.8 ± 46.2	484.8 ± 75.2

No significant difference between conditions ($P > 0.05$)

[a] Large effect size (>0.8) compared to control condition

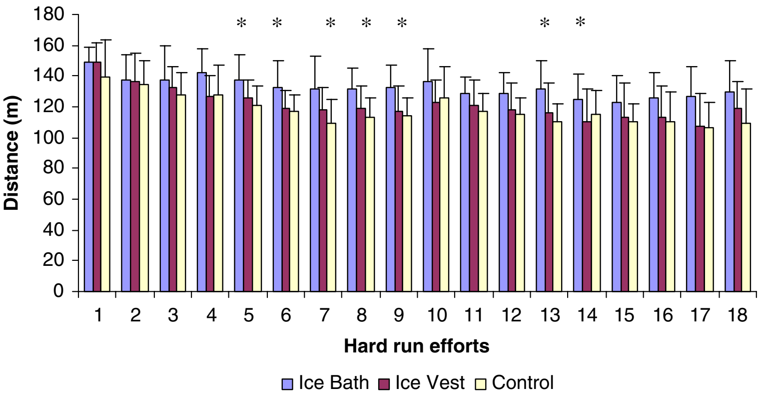

Fig. 1 Mean ± SD distance covered during individual free-paced hard running efforts through out the exercise protocol for Ice-bath, Ice-vest and Control Conditions. * Significant difference between Ice-bath and Control conditions ($P < 0.05$)

Discussion

The aim of the current study was to determine the effect of two different pre-cooling procedures on maximal sprint and sub-maximal work during intermittent-sprint exercise in warm conditions. Results for exercise performance indicated no significant differences between conditions for the time or % decline in 15-m sprint efforts or the distance covered during sub-maximal work bouts; however, large ES data indicate a greater distance covered during hard running following ice-bath cooling procedures. Physiological measures indicated lowered T_{core}, T_{skin}, heart rate, sweat loss and thermal comfort following ice-bath cooling compared with ice-vest or control conditions, with no differences present in capillary blood measures for [La$^-$], pH, K$^+$ or Na$^+$.

Similar to most previous studies investigating the effects of pre-cooling on intermittent-sprint performance in the heat, limited ergogenic effects were apparent (Drust et al. 2000; Duffield et al. 2003; Cheung and Robinson 2004). Castle et al. (2006) recently reported a 4% increase in peak power following leg cooling, but no difference in mean or total work done for any cooling procedure (bath, vest or pack) compared to a control condition. Previous prolonged intermittent-sprint protocols that have shown limited declines in sprint performance in the heat, have reported limited beneficial effects of pre-cooling (Duffield et al. 2003; Cheung and Robinson 2004). In contrast, Castle et al. (2006) demonstrated a significant decline in sprint performance in the control condition and as such reported an ergogenic influence of a cooling intervention to maintain peak power without any significant change in work done.

Exercise protocols that allow sufficient recovery (>60 s) and repletion of PCr between sprints (Bogdanis et al. 1998), with low resistance to sprint efforts may result in limited declines in performance and hence limited pre-cooling ergogenic benefits (Duffield et al. 2003). It is possible that greater resistance and durations tease out declines in sprint performance and allow for a potential ergogenic pre-cooling influence. In the present study, a moderate decline in sprint performance was evident, however, little amelioration of the decline was evident following ice-bath cooling procedures. As such, it is possible that the effects of pre-cooling on intermittent-sprint performance are minor and only manifest when the thermal and exercise stress is sufficient to induce heat strain.

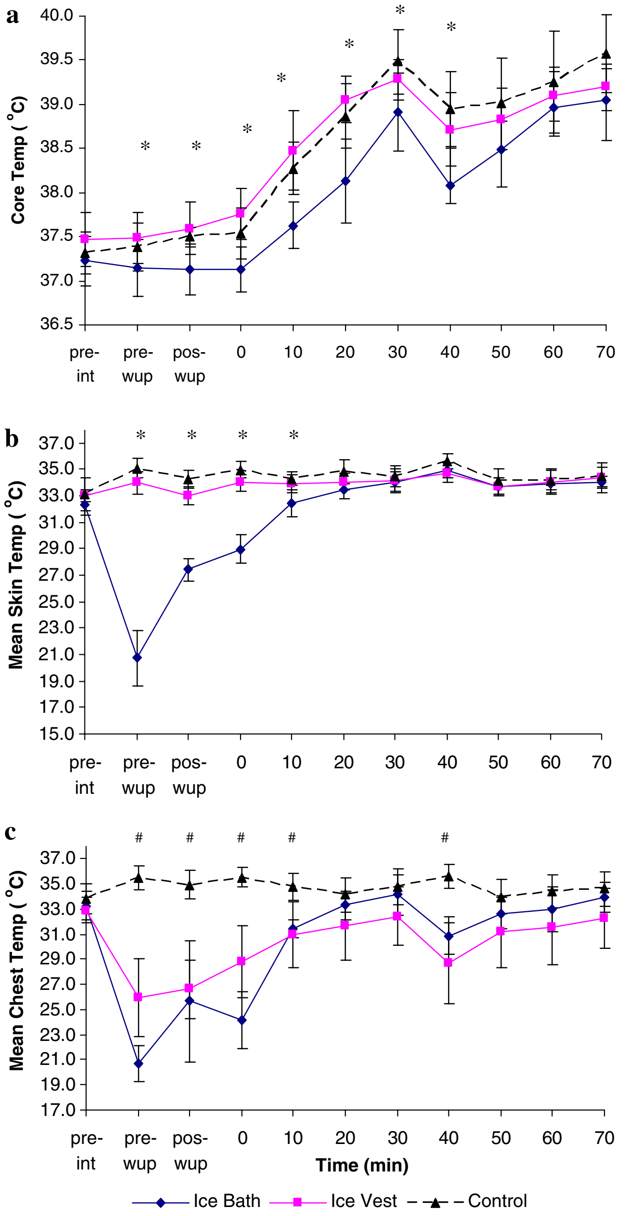

Fig. 2 **a** Mean ± SD Core temperature **b** Mean ± SD skin temperature and **c** mean ± SD chest temperature for Ice-bath, Ice-vest and Control conditions over the duration of the exercise protocol. * Significant difference of Ice-bath to Ice-vest and Control conditions respectively ($P < 0.05$). # Significant difference of both Ice-bath and Ice-vest to Control condition ($P < 0.05$)

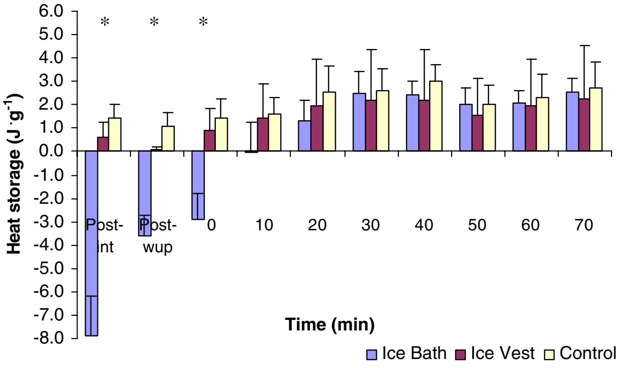

Fig. 3 Mean ± SD heat storage for Ice-bath, Ice-vest and Control conditions over the duration of the exercise protocol. * Significant difference between Ice-bath and Ice-vest and Control conditions respectively ($P < 0.05$)

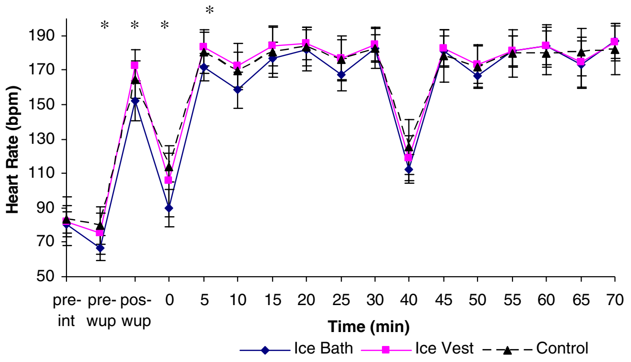

Fig. 4 Mean ± SD heart rate for Ice-bath, Ice-vest and Control conditions over the duration of the exercise protocol. * Significant difference between Ice-bath and Control conditions ($P < 0.05$)

Although limited effects of pre-cooling on sprint performance were evident, a unique aspect of the current study, which has not been previously reported in pre-cooling studies on intermittent-sprint exercise, was the measurement of free-paced distance covered between sprints. The results indicated an increased distance covered during hard-running following ice-bath pre-cooling procedures (Fig. 1). Precooling has been reported to significantly increase the distance covered in 30-min of continuous running by ~300-m (Booth et al. 1997) and decrease time to complete 5-km treadmill efforts by 13-s (Arngrímsson et al. 2004). In the current study, ice-bath cooling increased the total distance covered in the 18 respective 45-s hard-running bouts (~14-min in total) by ~200-m, which approach the distances reported by Booth et al. (1997).

The strategy of combining whole-body pre-cooling prior to warm-up to reduce T_{core} and T_{skin}, and then maintenance of cooling procedures during the warm-up (ice-vest) was effective in improving the distance covered during hard-running, compared to the less effective cooling procedures such as torso cooling alone (ice-vest). Moreover, while minimal differences were evident between conditions for distance covered in jogging and walking, respectively, the total distance covered for all sub-maximal bouts shows that the combined ice-bath and vest cooling procedure increased the distance covered by ~300–400-m compared to control or ice-bath only. Thus, while pre-cooling procedures may have limited influence on intermittent-sprint performance, pre-cooling is potentially effective in improving the sub-maximal work of team-sport athletes in

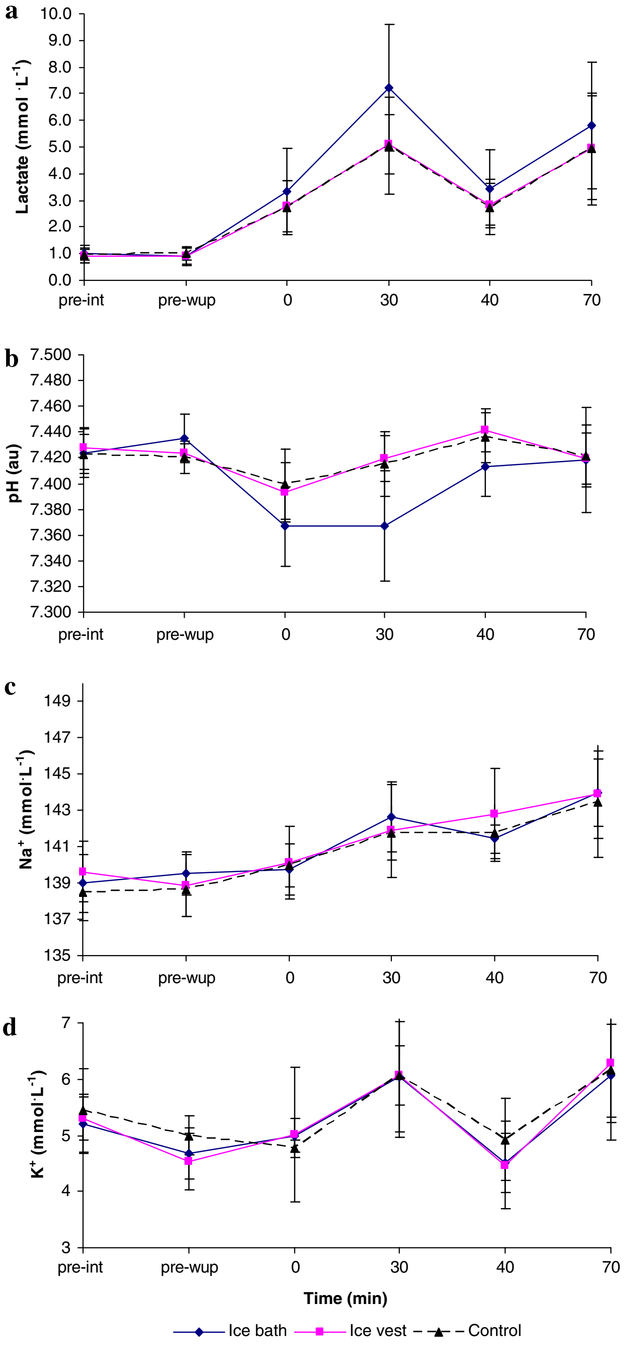

Fig. 5 **a** Mean ± SD capillary blood lactate **b** mean ± SD capillary blood pH, **c** mean ± SD capillary blood Sodium (Na^+) and **d** mean ± SD capillary blood Potassium (K^+) for the Ice-bath, Ice-vest and Control conditions

hot conditions, similar to data previously reported for endurance exercise (Booth et al. 1997; Arngrímsson et al. 2004; Hasegawa et al. 2005).

The proposition that exercise performance is reduced once T_{core} reaches either a critical level or an increment of 2°C is well documented (Gonzalez-Alonso et al. 1999). As a result, physiological mechanisms likely to assist performance improvements following pre-cooling relate to the reduction of T_{core}, T_{skin} and efficiency in heat storage and removal. In the current study, the 15-min ice-bath procedure was effective at blunting the rise in T_{core} throughout the exercise protocol. The effectiveness of cooling strategies varies with the extent and duration of cooling applied (Olshewski and Bruck 1988; Lee and Haymes 1995) and as such it is not unexpected that whole-body immersion maintained a lower T_{core} and T_{skin} compared to the torso-only cooling (only T_{chest} reduced), however, this has not been as evident in all cases (Castle et al. 2006). Increases in heat storage and T_{core} commenced from initial exposure to the warm environment in ice-vest and control conditions, yet were absent in the ice-bath condition. Several studies have indicated that there is a duration of 30–40-min before the thermal and cardio-vascular effects of pre-cooling wane (Hessemer et al. 1984; Wilson et al. 2002). Hence, the importance of maintaining the physiological advantages provided by whole-body pre-cooling until as close as possible to the start of exercise are evident, and therefore including a pre-cooling procedure during the warm-up is likely to be of benefit to performance (Arngrímsson et al. 2004; Webborn et al. 2005).

The reduced T_{skin} and reduction in stored heat in the ice-bath condition blunted the extent of the exercise-induced rise in T_{core}. In turn, a lower T_{core} is likely to be a key contributor to a delayed onset of neurally-mediated peripheral vasodilation and sweating mechanisms, respectively (Kruk et al. 1990). The delay in redistribution of cardiac output to supply cutaneous requirements for the transfer of metabolically generated heat allows the maintenance of a greater central blood volume (Gonzalez-Alonso and Calbet 2003). Further, the maintenance of a lower T_{skin} after pre-cooling results in a more efficient heat transfer gradient and reduces the requirement for evaporative sweat loss (Lee and Haymes 1995). Accordingly, the early presence of a reduced heart rate following ice-bath pre-cooling combined with an ameliorated decline in the respective post-exercise nude mass and Hct indirectly support the maintenance of a greater blood volume and more efficient thermo-regulatory control following pre-cooling; which may be of possible benefit to exercise performance.

The maintenance of a greater central blood volume will potentially reduce cardio-vascular load and provide an increased skeletal muscle blood supply (Gonzalez-Alonso and Calbet 2003) and theoretically assist muscle performance. However, given that differences in nude mass equate to a greater blood volume retention of ~ 400 ml in the ice-bath condition and differences in heart rate were only present up to the tenth min, it is apparent that these factors alone may not sufficiently explain differences in self-selected work patterns. Centrally-mediated mecha-

Table 3 Mean ± SD Rate of perceived exertion (RPE) and rating of Thermal comfort (Therm) pre-intervention (Pre-int), pre-warm up (pre-wup), post warm-up (post-wup), pre-exercise (0 min), end of first-half (30-min), end of half-time (40-min) and end of exercise (70-min) for the Control, Ice-vest and Ice-bath conditions

	Pre-int	Pre-wup	Post-wup	0-min	30-min	40-min	70-min
RPE							
Control	6.0 ± 0.0	6.0 ± 0.0	10.0 ± 2.2	7.0 ± 1.2	18.0 ± 1.4	9.1 ± 3.4	18.4 ± 1.6
Ice-vest	6.0 ± 0.0	6.0 ± 0.0	10.8 ± 1.6	7.2 ± 1.0	16.9 ± 2.7	9.5 ± 3.0	18.1 ± 1.7
Ice-bath	6.0 ± 0.0	6.0 ± 0.0	9.6 ± 2.7	7.0 ± 1.1	16.3 ± 1.8	8.9 ± 2.5	17.8 ± 2.1
Therm							
Control	4.4 ± 0.5	4.7 ± 0.7	5.7 ± 0.5	5.4 ± 0.7	7.2 ± 0.7	5.5 ± 0.9	7.1 ± 0.6
Ice-vest	4.5 ± 0.5	3.8 ± 0.7*	5.6 ± 0.5	5.0 ± 1.0	7.1 ± 0.6	4.5 ± 1.0*	6.9 ± 0.8
Ice-bath	4.4 ± 0.6	1.3 ± 0.5*	4.3 ± 0.8*	3.9 ± 0.7*	6.1 ± 1.6	3.8 ± 0.9*	7.1 ± 0.7

No significant differences ($P > 0.05$) for RPE

* Significantly different ($P < 0.05$) to Control condition for Thermal comfort

nisms resulting in a ‘feed-forward’ control of pacing in endurance exercise have been suggested to result in the selection of lower exercise intensities in warmer conditions or with higher T_{core} (Kay et al. 2001). Recent intermittent-sprint data (Drust et al. 2005; Castle et al. 2006) has further indicated the role of central processes in adjusting motor-unit recruitment based on both the rate of rise and absolute T_{core} per se. Previous research (Morris et al. 2000; Drust et al. 2005; Castle et al. 2006), as with the current study, have reported minimal differences in blood metabolite accumulation for intermittent-sprint exercise in hot and moderate conditions with cooling, further implicating the role of a central fatigue mechanism for the reduction in intermittent-sprint performance. In the current study, exercise was not terminated due to hyperthermia and therefore the adjustment to reduce exercise intensity was self-selected. This is indicated in the present data (Figs. 1, 2) where an increased distance covered during hard running and delayed heat storage following ice-bath cooling, suggests that subjects could perform more work for the same heat strain, especially when the rise in T_{core} was blunted. As such, it is feasible to speculate that the role of a centrally-mediated increase in work may be a result of a greater central drive to skeletal musculature in the pre-cooling condition (Kay et al. 2001; Tucker et al. 2004).

In conclusion, pre-cooling methods did not significantly improve intermittent-sprint performance; however, a combined pre-cooling strategy of an ice-bath followed by ice-vest during warm-up did indicate an effect of increasing distance covered during sub-maximal hard-running bouts. Further, the combined ice-bath and vest procedure resulted in significantly lower T_{core}, T_{skin}, heart rate, sweat loss and thermal comfort than the vest or control conditions respectively. As such, the ergogenic benefits of effective pre-cooling procedures in warm conditions for team-sports may be predominantly evident during sub-maximal bouts of exercise. Further, for maximal benefit, pre-cooling interventions should be continued until as close as possible to exercise (game) commencement.

Acknowledgments The authors gratefully acknowledge the funding of this project from a CSU Small Grant supplied by Charles Sturt University.

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Precooling and Percooling (cooling during exercise) both improve performance in the heat: A Meta-Analytical Review

RUNNING TITLE: Precooling *versus* Percooling

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Total Word Count: 3,347
Word Count Abstract: 250
Total Number of Figures: 4
Total Number of Tables: 2
Total Number of supplementary Tables: 1

Keywords: Cooling, cooling vest, ice slurry, thermoregulation, exercise physiology

Conflicts: None.

Disclosure statement funding: T.M.H.E is financially supported by the Netherlands Organization for Scientific Research (Rubicon Grant 825.12.016), D.H.J.T received an E. Dekker stipend of the Dutch Heart Foundation (2009T064).

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ABSTRACT

Background: Exercise increases core body temperature (Tc), which is necessary to optimise physiological processes. However, excessive increase in Tc may impair performance and places subjects at risk for the development of heat-related illnesses. Cooling is an effective strategy to attenuate the increase in Tc. This meta-analysis compares the effects of cooling *before* (precooling) and *during* exercise (percooling) on performance and physiological outcomes.

Methods: A computerized literature search, citation tracking and hand search was performed up to May 2013. Twenty-eight studies met the inclusion criteria, which were trials that examined the effects of cooling strategies on exercise performance in men, whilst exercise was performed in the heat (>30°C). Twenty studies used precooling, while eight studies used percooling.

Results: Overall effect of pre- and percooling interventions on exercise performance was +6.7±0.9% (effect size (ES)=0.43). We found a comparable effect (p=0.82) of precooling (+5.7±1.0% (ES=0.44)) and percooling (+9.9±1.9% (ES=0.40)) to improve exercise performance. A lower finishing Tc was found in precooling (38.9°C) compared to control condition (39.1°C, p=0.03), whilst Tc was comparable between conditions in percooling studies. No correlation between Tc and performance was found. We found significant differences between cooling strategies, with combination of multiple techniques being most effective for precooling (P<0.01) and ice vest for percooling (P=0.02).

Conclusion: Cooling can significantly improve exercise performance in the heat. We found a comparable effect size for precooling and percooling on exercise performance, while the type of cooling technique importantly impacts the effects. Precooling lowered the finishing core temperature, whilst there was no correlation between Tc and performance.

INTRODUCTION

Paragraph 1. Excessively elevated core body temperature (Tc), arising from a disbalance between heat production and heat loss during prolonged exercise, has a negative impact on physiological functions and exercise performance (1, 2). Moreover, an elevated Tc can even lead to the development of severe heat illnesses, such as heat stroke (2). The relevance of attenuating the increase in Tc during exercise is highlighted by the organization of future major sport events in hot and/or humid climatic conditions (e.g. Olympic Games of Rio de Janeiro 2016 and the FIFA World Cup in Brazil 2014 and Qatar 2022). Moreover, the level of performance decrement progressively increases with a rise in environmental heat stress (3). Strategies that can prevent excessive heat storage during exercise in the heat, and consequently a reduction in exercise performance, are therefore of high interest.

Paragraph 2. Cooling can be applied prior to (*pre*cooling) or during (*per*cooling) exercise to attenuate the increase in Tc and improve exercise performance. Existing reviews and meta-analyses showed that precooling can effectively enhance exercise performance (4-7). A substantially lower number of studies focused on cooling strategies applied *during* exercise: percooling. Performance benefits of precooling normally decrease after 20-25 minutes of exercise (8). Therefore, the use of cooling techniques *during* an exercise bout, especially when involving endurance exercise, may elongate the duration of the beneficial effects of the cooling intervention on exercise performance. In addition to the larger ‘window of opportunity’ to cool the athlete, the level of thermal strain is higher during exercise compared to resting conditions (9). This suggests that cooling during exercise has a large potential in clinical practice to prevent significant thermal strain and maintain exercise performance. These cooling strategies are referred to as percooling, derived from the Latin word *per* meaning ‘during’. To date, relatively little is known about the impact of percooling on exercise performance, or examined the hypothesis that percooling is more effective than precooling (10).

Paragraph 3. The purpose of this meta-analytical review is to compare the effects of precooling and percooling on exercise performance and on relevant thermophysiological outcomes (i.e. core body temperature, skin temperature, heart rate, rate of perceived exertion) in healthy volunteers under hot climatic conditions. Furthermore, the effects of pre- and percooling on performance may vary between cooling techniques (cooling vests, cold water immersion, cold water ingestion, cooling packs, and mixed method cooling) (4-6, 11-13). Better insight into these techniques is necessary to identify the ‘best practice’ cooling technique to improve exercise performance under hot thermal conditions. Therefore, the second aim of this study is to review current literature on this topic and determine differences between cooling techniques.

METHODS

Search strategy

Paragraph 4. We searched Pubmed and Web of Science. Ten mesh terms and keywords (‘exercise’, ’cooling’, ‘performance’, ‘during exercise’, ‘precooling’, ‘effects’, ‘ice slurry ingestion’, ‘cooling vest’, ‘cold water immersion’, and ‘cold water ingestion’) were combined by Boolean logic (AND) and the results were limited to human subjects and articles written in English. Each database was searched from their earliest available article up to May 7, 2013. We also searched in the reference list of all incoming articles.

Study selection

Paragraph 5. Selection of publications for inclusion in this meta-analysis was based on the following criteria. First, only studies applying a cooling intervention before (‘precooling’) or during exercise (‘percooling’) and in a crossover design were selected. Moreover, only studies performed in hot ambient conditions with ambient temperatures ≥30°C were included. Secondly, only study populations comprising male adults, or studies comprising both sexes where data of male subjects was reported separately were included to avoid any potential impact of the menstrual cycle on study results. Furthermore, only studies reporting at least one outcome parameter associated with cycling or running exercise performance (e.g. finish time, completed distance, time to exhaustion, power output, etc.) were included in this meta-analysis. Studies that merely evaluated the effects of cooling on physiological outcomes (heart rate, blood lactate levels) were excluded. The first author was responsible for the study selection. After the selection process, all studies were discussed with two co-authors. In case of disagreement about the inclusion of a study, a voting process was used to determine if a study was included or not. Figure 1 provides a flow chart of our literature search.

Study classification

Paragraph 6. After inclusion, studies were classified into groups based on the following criteria. For our first aim, studies were classified based on the type of cooling (precooling *versus* percooling). For our second aim, studies were classified according to their cooling strategy: 1) cooling vest (ice vests and evaporative cooling vests), 2) cold water immersion, 3) cold water ingestion and/or ice slurry ingestion, 4) cooling packs, and 5) mixed method cooling (combined application of two or more cooling techniques). Furthermore, studies that compared multiple cooling intervention trials with the same control condition, were included more than once.

Effect size assessment

Paragraph 7. For all studies that were included, standardized mean differences (effect size in Hedge's g) and 95% confidence intervals were calculated for continuous outcomes using the Cochrane Collaboration's software Review Manager 5.1.0 (Cochrane IMS, Melbourne, Australia). Statistical analyses were also performed using this software, with the significance level set at $p<0.05$. The calculations in this program were based on the difference in outcome between the intervention and the control condition. To calculate the standard error, we needed the exact p-value (for calculation of the t-value). When the p-value was not provided, we contacted the corresponding author. However, if this information could not be provided or the author did not respond, we used $p=0.049$ and $p=0.051$ for $P<0.05$ and $P>0.05$ respectively. This progressive approach avoids an overestimation of the effect of cooling. However, as it may also cause a selection bias, we performed a sub-analysis including only studies that provided the exact p-values.

Negative effects of cooling were indicated with a minus sign. Data for all single studies and weighted average values were presented as mean±SD. The interpretation of the effect size (ES) was based on the following scale: 0-0.19 = negligible effect, 0.20-0.49 = small effect, 0.50-0.79 = moderate effect and ≥0.80 = large effect (14). The presence of publication bias was established by evaluating Begg's funnel plot asymmetry (15) and the Egger's linear regression test (16), in which $p<0.05$ was considered significant (17).

Physiological parameters

Paragraph 8. We included core temperature (Tc), skin temperature (Tskin) and heart rate (HR) in this meta analysis. Data was extracted from text, tables or figures (using GetData Graph Digitizer software v2.26). The effect of the cooling intervention was calculated by subtracting data of the cooling condition from the control condition (ΔTc, ΔTskin and ΔHR). Correlations between the change in physiological responses and the relative change in performance were calculated using SPSS 20.0 (SPSS, Chicago, USA) and the level of significance was set at $p<0.05$. Student’s paired t-tests were used to examine differences in finishing Tc, Tskin and HR between the cooling and the control condition.

RESULTS

Included studies

Paragraph 9. A total of 28 manuscripts that met our inclusion criteria (11, 12, 18-43) were identified. Some of these studies compared multiple cooling interventions and were therefore included more than once, which resulted in a total of 36 studies with a total number of 323 subjects. Characteristics of the included studies are summarized in the online supplementary Table 1. The average sample size was 9, while the largest study was based on 20 subjects. The weighted average improvement of the cooling strategies on exercise performance in all studies was 6.7±0.9% and the weighted average ES was 0.43±0.06. A funnel plot of all studies demonstrates the presence of publication bias due to asymmetry (Figure 2). The publication bias was confirmed by a statistical significant Egger’s test ($p<0.01$) and a significant Begg’s funnel plot ($p=0.01$). The sub-analysis, in which the studies with exact p-values were included only, did not alter the outcomes of the original analysis. Therefore, only data from the initial analysis are provided.

Precooling *versus* percooling

Paragraph 10. Twenty-seven studies applied a precooling intervention and nine studies applied percooling (Figure 3). The weighted average exercise performance improvement of precooling was 5.7±0.9% (ES=0.44) and for percooling interventions 9.9±1.9% (ES=0.40). We found no significant difference in effect size for both types of cooling on exercise performance in the heat (p=0.82).

Effects on physiological parameters

Paragraph 11. Table 1 shows an overview of the (change in) physiological parameters during the control and cooling condition. We found a significantly lower finishing Tc in the precooling (38.9°C) condition compared to control (39.1°C, p=0.03), whilst Tc was comparable for the percooling studies. Tskin and HR did not differ between the cooling and control condition for both precooling and percooling (all p-values>0.05). Furthermore, no correlations were found between measures of performance and ΔTc, ΔTskin and ΔHR for precooling, percooling and the pooled set of cooling studies (all p-values>0.05).

Table 1. Individual study data regarding the physiological responses, in which Δ were calculated as cooling minus control condition.

Precooling		**Tc max control**	**Tc max cooling**	**Δ Tc max**	**Tskin max control**	**Tskin max cooling**	**Δ Tskin max**	**HR max control**	**HR max cooling**	**Δ HR max**	**Performance (%)**
Cooling packs	Castle et al. 2006c	39.1	38.4	-0.7	36.9	36.4	-0.5	179	181	2	4.3
	Minett et al. 2011a	39.1	39.1	0	34.0	34.2	0.2	173	175	2	4.3
	Weighted average	39.1	38.8	-0.4	35.5	35.3	-0.1	176	178	2	4.3
Cooling vests	Arngrimsson et al. 2004	39.8	39.6	-0.2	34.2	34.5	0.3	195	195	0	1.3
	Castle et al. 2006a	39.1	38.9	-0.2	36.9	36.6	-0.3	179	184	5	1.5
	Duffield et al 2003	38.8	38.7	-0.1	34.0	33.6	-0.4	N.A	N.A	N.A	2.4
	Duffield et al. 2007a	39.6	39.2	-0.4	34.4	34.4	0	182	187	5	1.3
	Quod et al. 2008a	39.6	39.7	0.1	34.6	34.5	-0.1	193	193	0	1.5
	Ückert et al. 2007	38.8	38.4	-0.4	35.6	35.1	-0.5	192	190	-2	7.3
	Weighted average	39.3	39.1	-0.2	35.0	34.8	-0.2	188	190	2	3.4
Cold water ingestion	Burdon et al. 2013	38.7	38.7	0.0	33.4	33.3	-0.1	165	168	3	10.5
	Byrne et al. 2011	38.6	38.1	-0.5	35.4	35.1	-0.3	190	189	-1	2.9
	Ihsan et al. 2010	38.8	39.1	0.3	35.6	35.8	0.2	N.A	N.A	N.A	6.9
	Siegel et al. 2012a	39.5	39.8	0.3	35.7	35.5	-0.2	188	189	1	12.8
	Stanley et al. 2010	39.1	39.0	-0.1	N.A	N.A	N.A	191	191	0	1.9
	Stevens et al. 2013	39.0	38.2	-0.8	N.A	N.A	N.A	N.A	N.A	N.A	2.8
	Weighted average	39.0	38.8	-0.1	35.0	34.9	-0.1	184	184	1	6.3
Mixed method cooling	Cotter et al. 2000	38.9	38.5	-0.4	35.9	35.1	-0.8	178	177	-1	15.2
	Duffield et al. 2007b	39.6	39.0	-0.6	34.4	34.0	-0.4	182	187	5	8.3
	Duffield et al. 2009	39.3	38.8	-0.5	N.A	N.A	N.A	162	146	-16	7.7
	Duffield et al. 2013	39.0	38.9	-0.1	34.6	34.8	0.2	182	186	4	3.0
	Minett et al. 2011b	39.1	39.0	-0.1	34.0	34.1	0.1	173	170	-3	5.2
	Minett et al. 2011c	39.1	38.7	-0.4	34.0	33.1	-0.9	173	169	-4	9.5
	Minett et al. 2012	39.1	38.7	-0.4	33.9	33.1	-0.8	178	170	-8	4.7
	Quod et al. 2008b	39.6	39.5	-0.1	34.6	33.8	-0.8	193	192	-1	4.0
	Weighted average	39.1	38.9	-0.3	34.5	34.0	-0.5	178	175	-3	7.3
Cold water immersion	Castle et al. 2006b	39.1	38.8	-0.3	36.9	34.5	-2.4	179	175	-4	-0.5
	Duffield et al. 2010	39.0	38.9	-0.1	35.7	35.5	-0.2	178	183	5	7.2
	Kay et al. 1999	38.8	38.5	-0.3	34.7	33.6	-1.1	178	177	-1	6.0
	Siegel et al. 2012b	39.5	39.5	0	35.7	35.3	-0.4	188	190	2	21.6
	Skein et al. 2012	38.9	38.7	-0.2	31.5	33.1	1.6	180	182	2	2.4
	Weighted average	39.1	38.9	-0.2	34.9	34.4	-0.5	181	181	1	6.5
Total precooling	**Weighted average**	**39.1**	**38.9**	**-0.2**	**34.9**	**34.5**	**-0.3**	**181**	**181**	**0**	**5.7**
	Students T-test	**0.03**			**0.34**			**0.94**			

Percooling		**Tc max control**	**Tc max cooling**	**∆ Tc max**	**Tskin max control**	**Tskin max cooling**	**∆ Tskin max**	**HR max control**	**HR max cooling**	**∆ HR max**	**Performance (%)**
Cooling packs	Hsu et al. 2005	38.4	38.1	-0.3	N.A	N.A	N.A	159	161	2	6.6
	Minetti et al. 2011	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	N.A	5.4
	Scheadler et al. 2013	39.2	39.4	0.2	N.A	N.A	N.A	178	178	0	-11.6
	Tyler et al. 2010a	39.3	39.1	-0.1	35.0	35.6	0.6	186	188	2	5.1
	Tyler et al. 2010b	38.3	38.4	0.1	35.8	26.1	-9.7	187	187	0	1.9
	Tyler et al. 2011a	39.2	39.7	0.5	35.6	27.6	-8	181	178	-3	7.0
	Tyler et al. 2011b	38.9	38.9	0	34.4	35.3	0.9	185	186	1	13.0
	Average	38.9	38.9	0.1	35.2	31.2	-4.1	179	180	0	3.9
Cooling vest	Luomala et al. 2012	38.9	39.1	0.2	34.5	34.7	0.2	174	178	4	20.4
	Average	38.9	39.1	0.2	34.5	34.7	0.2	174	178	4	20.4
Cold water ingestion	Mündel et al. 2006	38.7	38.4	-0.3	N.A	N.A	N.A	170	165	-5	12.7
	Average	38.7	38.4	-0.3	N.A	N.A	N.A	170	165	-5	12.7
Total percooling	**Average**	**38.9**	**38.9**	**0.0**	**35.1**	**31.9**	**-3.2**	**178**	**178**	**0**	**7.0**
	Students T-test	**0.91**			**0.16**			**0.98**			
Total all studies	**Average**	**39.1**	**38.9**	**-0.2**	**34.9**	**34.1**	**-0.8**	**180**	**180**	**0**	**5.6**
	Students T-test	**0.08**			**0.08**			**0.97**			

Tc = core body temperature; **Tskin** = skin temperature; **HR** = heart rate; **N.A** = not available; **max** = at the end of the exercise protocol

Different cooling techniques

Paragraph 12. *Precooling.* We found that the effect of the different cooling strategies on exercise performance significantly differed across precooling techniques (p<0.001). Mixed method cooling (+7.3%, ES=0.72, Figure 3) demonstrated a significantly larger effect size (p<0.01) compared to cold water immersion (+6.5%, ES=0.49), cold water/ice slurry ingestion (+6.3%, ES= 0.40), cooling packs (+4.3%, ES= 0.40), and cooling vests (+3.4%, ES= 0.19) (Table 2).

Paragraph 13. *Percooling.* For percooling studies, three different cooling techniques were identified; ice vest, cold water ingestion and cooling packs (Table 2). We found a significant difference in effect size between the 3 percooling techniques in our meta-analysis (p=0.01). Wearing an ice vest during exercise (+21.5%, ES= 4.64) was significantly more effective in improving exercise performance compared to cold water ingestion (+11%, ES= 1.75) and cooling packs (+8.4%, ES= 0.39) (p=0.02, Table 2).

Table 2. Overview of subtotal effect sizes ± 95% CI of different cooling techniques for the precooling and percooling interventions.

	Number of studies	**Precooling**	**Number of studies**	**Percooling**
Cooling vest	6	0.19 (0.10-0.28)	1	4.64 (0.96-8.32)
Cold water immersion	5	0.49 (0.09-0.90)	-	Not available
Cold water ingestion	6	0.40 (0.17-0.62)	1	1.75 (0.38-3.12)
Cooling packs	2	0.40 (0.10-0.71)	7	0.34 (0.09-0.58)
Mixed method cooling	8	0.72 (0.49-0.96)	-	Not available
Average effect size	27	0.44 (0.31-0.56)	9	0.40 (0.15-0.66)

DISCUSSION

Paragraph 14.

The purpose of this meta-analysis was to 1) compare the effects of precooling *versus* percooling on exercise performance and thermophysiological reponses in the heat, and 2) to identify the most effective cooling technique for improvement in exercise performance. Reviewing and analyzing data of the existing studies indicates that cooling significantly improves exercise performance, whilst the effect of cooling was similarly present between precooling and percooling. Secondly, thermophysiological (such as core and skin temperature and heart rate) outcomes did not change in response to both precooling and percooling, whilst no correlation was present between the change in thermophysiological measures and exercise performance. Thirdly, we found significant differences between *pre*cooling techniques to improve exercise performance, with the use of a mixed method of cooling being the most effective. Such an effect between different techniques was also observed for percooling, with an ice vest being the most effective strategy. Taken together, cooling prior to or during exercise in the heat improves exercise performance with evidence supporting a superior effect of mixed methods for precooling and ice vests for percooling on performance levels in athletes, whilst these performance effects are unlikely related to a lower skin or core body temperature.

Paragraph 15. Our analysis summarizes and demonstrates a significant effect of cooling interventions on exercise performance in healthy athletes under demanding thermal conditions (1, 7, 44). We extend the current knowledge by the observation that the impact of precooling and percooling on exercise performance is comparable. It is important to take note of the significant publication bias, which is demonstrated in the Funnel plot (Figure 2), suggesting that negative studies may not have been published. Although this could implicate an overestimation of the overall effect of cooling, there is still abundant evidence that cooling effectively improves exercise performance when exercise is performed in the heat. The application of pre- and percooling are therefore both recommended to improve exercise performance while exercising in hot ambient conditions.

Paragraph 16. Although our statistical analysis does not support a difference in effect size between pre- and percooling (ES = 0.44 *versus* 0.40), the variation in performance enhancement between precooling (+5.7%) and percooling (+9.9%) is large. It is believed that both cooling strategies achieve their effects through comparable underlying mechanisms. It is known that exercise leads to a significant level of thermal strain due to a large increase in heat production in the exercising muscles. Maintaining an adequate heat balance requires a significant amount of energy for heat dissipating mechanisms, such as (skin) vasodilation and sweating responses (9, 45). Percooling contributes to a higher heat storage capacity, a more efficient heat loss and may attenuate the increase in core body temperature. The attenuated increase in Tc, may prevent a decrease in exercise performance. The purpose of precooling is to lower Tc before starting the exercise, leading to an increase in heat storage capacity during exercise. It is hypothesized that the larger heat buffer, induced by precooling, enables the body to perform more work prior reaching a critical limit for Tc (13). This suggests that pre- and percooling both enhance exercise performance. Accordingly, we hypothesize that a combination of precooling and percooling may be more effective in improving exercise performance than a single cooling strategy only. To date, only one pilot study (n=9) examined this hypothesis and showed that combined pre- and percooling is superior in improving exercise performance compared to pre- or percooling alone (46). Future studies may be aimed to further explore the combined effect of pre- and percooling on exercise performance.

Paragraph 17. One important question that this meta-analysis tried to answer is whether the impact of cooling strategies can be explained through its effects on thermophysiological factors. Precooling resulted in a significantly lower finishing Tc in the cooling compared to control condition, whilst this finding was absent in percooling studies. Presumably, percooling attenuated the increase in Tc and thus increase the heat storage capacity. For this reason, athletes were able to produce more heat before terminating exercise or lowering exercise intensity, which results in performance enhancements (10, 33). Likewise, we did not find correlations between the change in physiological parameters and the improvement of performance (Figure 4). These findings suggest that a lower Tc at the end of exercise does not necessarily improve exercise performance in the heat. More likely, the cooling interventions resulted in a reduction of the rise in physiological parameters, which enabled athletes to exercise at a higher absolute amount of work resulting in an improved performance but a comparable finishing Tc, Tskin and HR (5).

Paragraph 18. None of the included studies reported any thermoregulatory problems or heat related illnesses amongst their subjects. This may imply that our body applies internal protection mechanisms to avoid reaching a critical high temperature. There are 2 common hypotheses that may explain this thermal behaviour. Firstly, as Tc becomes elevated, exercise will be terminated once critically high internal temperatures are attained, which is a safeguard that limits the potential development of dangerous heat illness (5, 6). Secondly, the rate of heat gain is detected by our body, which could anticipatorily adjust the work rate to ensure that the exercise task can be completed within the homeostatic limits of the body (5, 47). As this meta-analysis included merely information about peak Tc, we could not test which hypothesis was adopted by athletes while performing exercise in the heat. Future studies that compare the threshold- with the anticipatory-theory are recommended, so that appropriate cooling techniques can be selected accordingly.

Paragraph 19. This meta-analysis demonstrated a significant impact of the type of cooling strategy when performing precooling to enhance exercise performance. Our analysis revealed that a combination of techniques (i.e. ‘mixed method precooling’) had a significantly larger effect than individual cooling techniques (cold water/ice slurry ingestion, cooling vests, cooling packs, or cold water immersion alone). This observation is reinforced by a study which examined three precooling strategies; 1) cooling pack, 2) cooling pack + cold water immersion, and 3) cooling pack + cold water immersion + ice vest (27). Whilst no effect was found for the cooling pack, both mixed method cooling trials effectively improved exercise performance (27). The higher cooling capacity in the mixed method cooling compared to individual cooling strategies likely contributes to this finding. Especially mixed techniques with an ‘aggressive' approach and affecting a large body surface seem to contribute to a larger effect on exercise performance. The law of enthalpy of fusion states that ice possesses significantly greater capacity to absorb heat than liquid water (6, 48, 49). Accordingly, more aggressive cooling techniques, typically depending on ice or substances with a temperature below zero, demonstrate a larger effect on changing core body temperature and/or exercise performance. In addition, previous data supports the idea that whole body cooling is more effective than cooling of a part of the body only (27). Indeed, despite the use of a relatively mild stimulus (i.e. 14-24°C), full-body water immersion significantly improved exercise performance (18, 21, 25, 31). The large cooling surface may importantly contribute to the prolonged suppression of increased physiological and thermal loads (22, 50), and thus improve exercise performance. Taken together, a combination of precooling techniques, preferably ‘aggressive’ cooling and interventions that cover a substantial part of the athlete´s body, represent the current ‘best practice’ model for precooling to improve exercise performance.

Paragraph 20. Also for the percooling strategies, our meta-analysis revealed a significant impact of the type of cooling. Our analyses indicate that wearing an ice-vest during exercise has a significantly larger effect than other percooling techniques (cold water ingestion and cooling packs). Interestingly, the ice vests represent an aggressive cooling strategy that impacts upon a relatively large body surface. This provides further support that also during percooling, strategies with an aggressive nature that aim at a relatively large body surface area are the most effective cooling strategies. An important limitation is that we only included a single study on the impact of an ice vest, which coincidently reported a remarkably large effect size. Nonetheless, the similarities between the type of most effective cooling strategies for pre- and percooling is striking. We strongly support future studies to confirm this finding using well-controlled, within-subjects designs, but also to improve our understanding why and how these aggressive types of cooling are more successful.

Practical recommendations

Paragraph 21.

Our meta-analysis combined the results of 323 subjects in 28 peer-reviewed publications and demonstrated the practical value of cooling strategies to improve exercise performance in the heat. More importantly, we showed that pre- and percooling are equally effective in improving exercise performance in the heat. Therefore, a combination of pre- and percooling may be superior compared to a single strategy alone. Moreover, we revealed that a combination of cooling techniques (for precooling) or ice vests (for percooling) results in the largest effect size on exercise performance, possibly due to the aggressive approach and impact on a relatively large body surface. Based on our novel observations, we recommend future studies to investigate the practical performance and effect size of combining pre- and percooling strategies on exercise performance, preferably using aggressive types of strategies. Such joint efforts can further improve exercise performance in the heat, while it also may contribute to a reduction in heat-related illnesses in athletes.

Acknowledgements

T.M.H.E is financially supported by the Netherlands Organization for Scientific Research (Rubicon Grant 825.12.016) and D.H.J.T received an E-Dekker stipend from the Dutch Heart Foundation (2009T064). The authors thank all the authors that provided them with information regarding their investigation that was not available in their original articles.

Conflict of interest

None of the authors reported a conflict of interest.

Contributorship statement

Bongers, Eijsvogels and Hopman designed the study. Bongers, Thijssen and Eijsvogels performed the literature search and selected the included studies. Veltmeijer and Bongers performed the statistical analysis, and all authors contributed to data interpretation. Bongers and Eijsvogels drafted the manuscript, while Veltmeijer, Thijssen and Hopman critically revised the article. All authors gave their final approval of the version published.

Summary box

- Pre- and percooling are equally effective in improving exercise performance in the heat.

- No correlations were found between measures of performance and ΔTc, ΔTskin and ΔHR for precooling, percooling and the pooled set of cooling studies.
- A combination of cooling techniques (for precooling) or ice vests (for percooling) are preferred to maintain exercise performance in the heat.
- The combination of pre-and percooling techniques could be the most effective strategy to improve exercise performance in the heat.

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FIGURE LEGENDS

Figure 1: Overview of selection process of the included studies for this meta-analysis. N indicates the number of studies.

Figure 2: The Funnel plot analysis indicated a possible presence of publication bias due to the asymmetrical shape. The vertical dotted line represents the weighted average effect size of all included studies. The x-axis showed the effect size is shown and the y-axis the standard error of the effect size.

Figure 3: Forest plot summarizing the effects of different cooling techniques on exercise performance for the precooling (A) and the percooling studies (B). The magnitude of the effect size indicates: 0-0.19 = negligible effect, 0.20-0.49 = small effect, 0.50-0.79 = moderate effect and ≥0.80 = large effect (14). The black rectangles represented the weighted effect size and the grey lines are the 95% confidence intervals. The size of the rectangles indicated the weight of the study, which is calculated separately for the precooling and percooling studies.* Studies that used multiple cooling intervention trials were included more than once.

Figure 4. Correlations between change in exercise performance (%) and change in core temperature (ΔTc), skin temperature (ΔTskin) and heart rate (ΔHR) for both precooling (●) and percooling (○). Pearson’s correlation coefficient, significance assumed at p<0.05. Delta (Δ) = cooling – control.