VNIVERSITAT DE VALÈNCIA

Faculty of Medicine and Odontology

Department of Physiology

PhD Program in Physiology

THERMOBIKE: Applicability of infrared thermography in the assessment of the efficiency, performance, and posture of the cyclist.

THERMOBIKE: Aplicabilidad de la termografía infrarroja en la evaluación de la eficiencia, rendimiento y postura del ciclista.

Doctoral Thesis presented by

Mr. Jose Ignacio Priego Quesada

Directed by:
Ms. Rosa María Cibrián Ortiz de Anda
Ms. Mª Rosario Salvador Palmer
Mr. Pedro Pérez Soriano

Valencia, December 2017

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Dña. Rosa Mª Cibrián Ortiz de Anda, Doctora en Física y Profesora Titular del Departamento de Fisiología de la Universidad de Valencia.

Dña. Mª Rosario Salvador Palmer, Doctora en Física y Profesora Titular del Departamento de Fisiología de la Universidad de Valencia.

D. Pedro Pérez Soriano, Doctor en Educación Física y Profesor Titular del Departamento de Educación Física y Deportiva de la Universidad de Valencia.

CERTIFICAN:

Que la presente memoria, "**THERMOBIKE: Aplicabilidad de la termografía infrarroja en la evaluación de la eficiencia, rendimiento y postura del ciclista**" corresponde al trabajo realizado bajo su dirección por D. Jose Ignacio Priego Quesada y constituye su Tesis para optar al grado de Doctor.

Y para que conste y en cumplimiento de la legislación vigente, firman el presente certificado en Valencia, a ocho de noviembre de dos mil diecisiete.

Fdo.: Rosa Mª Cibrián | Fdo.: Mª Rosario Salvador | Fdo.: Pedro Pérez

Para Rosa, mi mujer y mi mejor amiga,

y para mi hija Marina.

Ambas me hacen disfrutar de cada día de mi vida,

y me dan los mayores regalos que se pueden pedir,

el amor y la risa.

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Results obtained from this PhD thesis

Grants and Funding

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Publications

All the contents referred to in this dissertation have been published in international articles and chapters of books.

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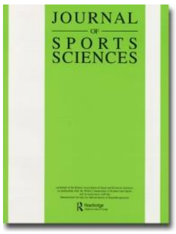
6 

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1 Editor Jose Ignacio Priego Quesada (2017). Application of Infrared Thermography in Sports. Springer International. Cham (Switzerland). http://www.springer.com/us/book/9783319474090. ISBN 978-3-319-47409-0.

BOOK CHAPTERS

Chapter 1

1 Jose Ignacio Priego Quesada; Rosa María Cibrián Ortiz de Anda; Pedro Pérez-Soriano; Rosario Salvador Palmer (2017). Chapter 1. Introduction: Historical Perspective of Infrared Thermography and Its Application in Sport Science. Application of Infrared Thermography in Sports Science (Editor Jose Ignacio Priego Quesada). pp. 1 - 24. Cham (Switzerland): Springer International,

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Chapter 2

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Chapter 3

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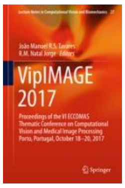

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ABREVIATIONS

ΔSkin temperature: difference between the vastus lateralis skin temperature at each moment (using thermography video) and the temperature measured before the incremental cycling test.

ΔT: Difference between temperature immediately after the cycling test and before.

ΔT10: Difference between temperature 10 min after the cycling test and before.

ΔTafter: Difference between temperature 10 min after and immediately after the cycling test.

ΔHigh: Variation of the high frequency band of the muscle activation (90% - 10% of the total time of test).

ΔLow: Variation of the low frequency band of the muscle activation (90% - 10% of the total time of test).

ΔOverall: Variation of the overall muscle activation (90% - 10% of the total time of test).

%HR_{max}: Percentage of the maximum heart rate.

%VO_{2max}: Percentage of the maximum oxygen consumption.

95%CI: 95% confidence interval.

ATP: Adenosine triphosphate.

BF: Biceps Femoris.

BMI: Body Mass Index.

EMG: Surface electromyography.

GM: Gastrocnemius Medialis.

H_{prod}: Heat production.

HR: Heart rate.

ICC: Intra-class correlation coefficient.

IRT: Infrared thermography.

K: Tucker´s coefficient of congruence.

PO: Power output.

PO_{max}: Peak power output.

PO kg^{-1}: Relative power output.

RF: Rectus Femoris.

ROI: Region of Interest.

Rpm: Revolutions per minute.

SD: Standard deviation.

UV: Ultraviolet.

VL: Vastus Lateralis.

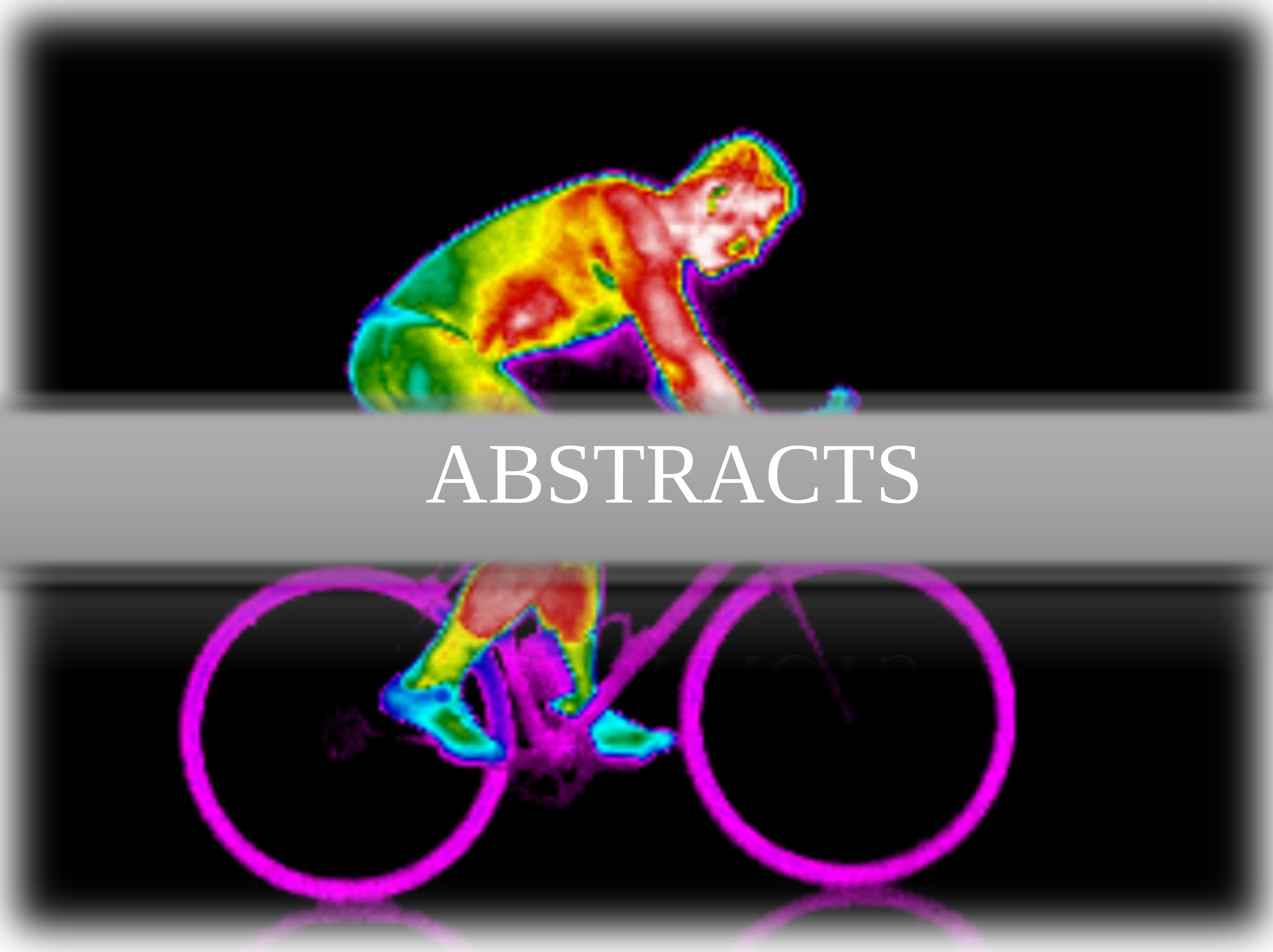
VO_{2max}:Maximum oxygen consumption.

VO_2 kg^{-1}: Relative oxygen consumption.

VT_1: Ventilatory threshold 1.

VT_2: Ventilatory threshold 2.

ABSTRACTS



ABSTRACT (SPANISH)

La aplicación de la termografía infrarroja en el deporte es un tema reciente y existen aspectos a resolver en relación a la metodología, así como a su aplicación en el contexto de la evaluación del rendimiento deportivo en el ciclismo. En este sentido, los objetivos de esta tesis fueron los siguientes: 1) analizar la validez de la utilización de la termografía infrarroja como medida de la temperatura de la piel en el ciclismo, 2) estudiar su aplicabilidad en el análisis de la eficiencia del ciclista, 3) evaluar su aplicabilidad como técnica complementaria para el ajuste de la postura del ciclista y 4) utilizar técnicas estadísticas para adaptar el estudio termográfico al ciclismo. Cinco estudios fueron desarrollados para responder a dichos objetivos. Un total de 62 hombres participaron en los estudios. De manera general, la temperatura de la piel fue determinada mediante termografía infrarroja antes de cada test de ciclismo, inmediatamente después de cada test y 10 min después. Otras medidas realizadas en los diferentes estudios fueron el análisis cinemático 2D, el cálculo de la tasa de sudoración corporal global, la medida de la temperatura de la piel mediante sensores de contacto, la medida de la temperatura interna mediante un sensor interno ingerible, medidas de intercambio de gases, y el análisis del confort, dolor y fatiga del ciclista. Las conclusiones más relevantes obtenidas en esta tesis fueron las siguientes. La termografía infrarroja demostró ser una tecnología válida para medir la temperatura de la piel en el ciclismo. Participantes con una mayor activación neuromuscular global con un menor componente de bajas frecuencias en el vasto lateral, presentaron una mejor respuesta termorreguladora a partir de menores aumentos de su temperatura de la piel tras un test incremental. De la misma manera, participantes con una mayor condición física (a partir de una mayor potencia) presentaron una mayor producción de calor interno y con ello una mayor temperatura de la piel. Sin embargo, la aplicación de la termografía infrarroja para estudiar los efectos del cambio de la altura de sillín no pareció ser adecuada. La variación de la temperatura de la piel puede ser una variable válida para estudiar el efecto de una intervención de ejercicio físico, pero es importante tener en cuenta las variables antropométricas durante el reclutamiento de los participantes con el fin de reducir su variabilidad. Finalmente, mediante el análisis factorial, se obtuvieron regiones de interés las cuales presentaron diferencias entre ellas como resultado de la diferente composición de su tejido, actividad muscular y capacidad de sudoración. Todo el contenido de esta tésis ha sido publicado en diferentes artículos científicos y capítulos de libros.

ABSTRACT (ENGLISH)

The application of infrared thermography in sports is still a recent topic and there are many fundamental discussions concerning its different methodological aspects and applications in the context of cycling performance assessment. The aims of this thesis were therefore 1) to analyse the validity of infrared thermography in the measurement of skin temperature while cycling, 2) to study its applicability in the assessment of a cyclist's efficiency, 3) to assess its applicability, as a complementary technique for adjusting the posture of the cyclist and 4) to use statistical techniques aimed at adapting thermographic studies to the sport of cycling. Five studies were developed in order to respond to the general aims. A total of 62 male participants volunteered to participate in the experimental studies. In general, skin temperature was determined using infrared thermography before each cycling test, immediately after, and then 10 min later. Other measurements performed in the different studies were kinematic 2D analysis, whole body sweat rate, skin temperature through thermal contact sensors, core temperature through an ingestible sensor, surface electromyography, gas exchange measurements, and analysis of the comfort, pain and fatigue of the cyclist. Different conclusions were obtained from the studies. Infrared thermography has proven to be a valid technology to measure skin temperature in cycling. Participants with larger overall activation and reduced low frequency component for vastus lateralis activation presented a better adaptive response in their thermoregulatory system by showing fewer changes in skin temperature after the incremental cycling test. In addition, participants of greater physical fitness (i.e. higher peak power output) presented higher heat production and higher skin temperature. However, application of infrared thermography for studying the effects of different saddle heights does not appear to be valid. Skin temperature variation can be a valid measure of the effect of an exercise intervention, but it is important to take into account anthropometrical variables during the recruitment of participants so as to reduce variability. Finally, by using a factorial analysis, coherent ROIs were obtained and presented differences between them as a result of their different tissue composition, muscular activity and sweat capacity. All the contents referred to in this dissertation have been published in international articles and chapters of books.

EXTENDED SUMMARY (SPANISH)

Introducción

La termografía infrarroja es una técnica de imagen no invasiva y a distancia que permite captar la radiación infrarroja emitida por los cuerpos, y con ello estimar su temperatura superficial. La termografía infrarroja es utilizada en muchos ámbitos, siendo algunos de los más importantes el sector militar y el industrial, seguida de otros sectores como el médico y el veterinario.

Aunque los primeros estudios utilizando termografía infrarroja en ciencias del deporte datan de los años 70 del siglo pasado, ha sido en la última década cuando su uso se ha incrementado exponencialmente. Las principales aplicaciones de la termografía infrarroja en este campo han sido en la medicina deportiva como medio de prevención y seguimiento de lesiones, y en la fisiología del ejercicio para la medida de la temperatura de la piel en estudios de evaluación termorregulatoria.

Sin embargo, hay excasos estudios científicos que analicen su posible aplicabilidad en el ciclismo. Estos estudios, únicamente presentan resultados preliminares sobre su posible uso en el estudio de la eficiencia del ciclista. Sin embargo, no existen estudios que hayan analizado otras posibles aplicaciones, como por ejemplo su uso como herramienta en el ajuste de la postura del ciclista.

Hipótesis y objetivos

En este contexto, la presente tesis doctoral tiene la siguiente hipótesis general: la termografía infrarroja puede ser una técnica útil para la evaluación de la eficiencia, rendimiento y postura del ciclista.

Para comprobar dicha hipótesis, se plantearon una serie de objetivos específicos englobados en cuatro objetivos generales:

1. **Objetivos de validación:** Analizar la validez de la utilización de la termografía infrarroja como medida de la temperatura de la piel del deportista en el ciclismo.
    - 1.1. Comparar los resultados de medición de la temperatura de la piel de la termografía infrarroja con los obtenidos con otra de las técnicas más utilizadas (sensores térmicos de contacto) durante la práctica del ciclismo.

1.2. Analizar el efecto del sudor en las medidas termográficas tras la realización de un ejercicio aeróbico de ciclismo.

2. **Objetivos de eficiencia:** Estudiar la aplicabilidad de la termografía infrarroja en la evaluación de la eficiencia del ciclista.

2.1. Determinar el efecto de la intensidad del ejercicio en la temperatura de la piel del deportista.

2.2. Determinar la relación entre la temperatura interna y la temperatura de la piel tras la realización de la práctica ciclista.

2.3. Estudiar la relación entre la actividad neuromuscular y la temperatura de la piel durante el ciclismo.

2.4. Estudiar la relación entre la temperatura de la piel, el rendimiento, y medidas predictivas de rendimiento (como puede ser el consumo máximo de oxígeno).

2.5. Comparar la temperatura de la piel de los ciclistas y los no ciclistas tras la actividad deportiva.

3. **Objetivos sobre la postura:** Evaluar la aplicabilidad de la termografía infrarroja como técnica complementaria en el ajuste de la postura del ciclista.

3.1. Analizar el grado de percepción de confort, dolor y fatiga de las distintas alturas de sillín que se analizarán termográficamente.

3.2. Analizar si las diferentes alturas de sillín se ponen de manifiesto en la temperatura de la piel del ciclista.

4. **Objetivos metodológicos:** Utilizar técnicas estadísticas para adaptar el estudio termográfico al ciclismo.

4.1. Determinar las regiones de interés (ROIs) a analizar en el ciclismo.

4.2. Examinar qué parámetros de la temperatura superficial (absolutas, variaciones pre-post) medidas en las ROIs resultan más adecuadas para analizar los efectos del ejercicio.

Para desarrollar estos objetivos, se han llevado a cabo 5 estudios. La figura S1 muestra un esquema de los objetivos llevados a cabo por cada estudio así como un resumen de las variables analizadas y el protocolo utilizado. A continuación se expondrá un resumen del método, resultados y discusión de cada uno de ellos.

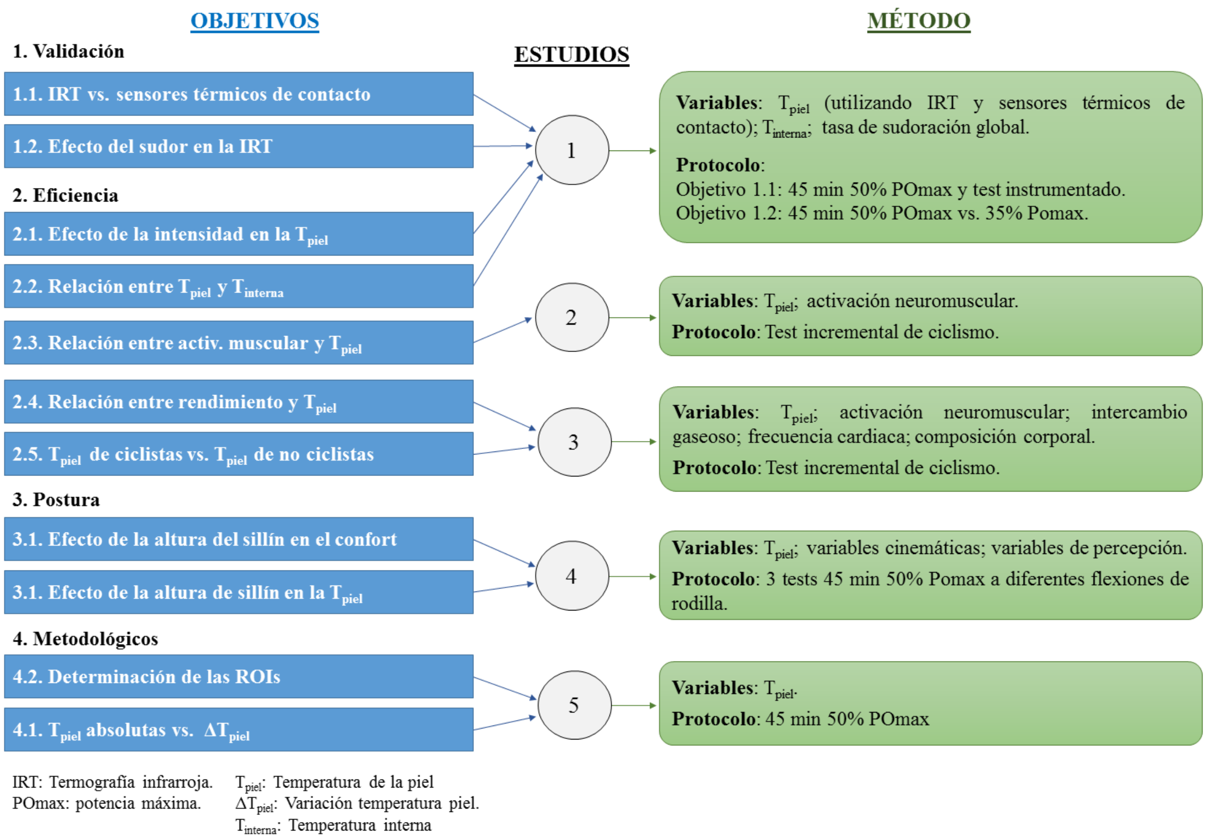


Figura S1. Esquema de los objetivos desarrollados por cada uno de los estudios.

Estudio experimental 1

Objetivos llevados a cabo:

1.1 Comparar los resultados de medición de la temperatura de la piel de la termografía infrarroja con los obtenidos con otra de las técnicas más utilizadas (sensores térmicos de contacto) durante la práctica del ciclismo.

1.2 Analizar el efecto del sudor en las medidas termográficas tras la realización de un ejercicio aeróbico de ciclismo.

2.1. Determinar el efecto de la intensidad del ejercicio en la temperatura de la piel del deportista.

2.2. Determinar la relación entre la temperatura interna y la temperatura de la piel tras la realización de la práctica ciclista.

Publicaciones obtenidas:

- Priego Quesada, J. I., Martínez Guillamón, N., Cibrián Ortiz de Anda, R. M., Psikuta, A., Annaheim, S., Rossi, R. M., … Salvador Palmer, R. (2015). Effect of perspiration on skin temperature measurements by infrared thermography and contact thermometry during aerobic cycling. Infrared Physics & Technology, 72, 68–76. https://doi.org/10.1016/j.infrared.2015.07.008
- Priego Quesada, J. I., Martínez, N., Salvador Palmer, R., Psikuta, A., Annaheim, S., Rossi, R. M., … Pérez-Soriano, P. (2016). Effects of the cycling workload on core and local skin temperatures. Experimental Thermal and Fluid Science, 77, 91–99. https://doi.org/10.1016/j.expthermflusci.2016.04.008

Método. 14 ciclistas hombres (edad 29.9 ±8.3 años, IMC 23.6 ±2.8 kg/m^2, potencia máxima 282 ±38 vatios) realizaron dos tests de 45 minutos al 35% y al 50% de la potencia máxima en diferentes días. Ambos tests se realizaron a una cadencia constante de 90 revoluciones por minuto. La potencia máxima de los ciclistas se obtuvo mediante un test de carga incremental en una sesión previa. La temperatura interna fue medida de manera continua durante todo el test mediante un sensor ingerible. La temperatura de la piel se midió mediante termografía infrarroja y sensores térmicos de contacto antes del test, inmediatamente después y 10 minutos después. Se analizaron ROIs adyacentes al sensor de dos tamaños, pequeñas de un tamaño similar al sensor (4 x 4 cm), y grandes cubriendo toda la parte corporal próxima al sensor.

Para valorar la adecuación de la termografía para medir la temperatura de la piel en el ciclismo, se compararon los resultados obtenidos con la termografía y con los sensores térmicos. Se utilizó para ello los datos respectivos al test al 50% de intensidad. Además, se realizó un test in vitro con un plato de calor, denominado en la presente tesis como “test instrumentado”, en condiciones secas y de mojado, en el que se compararon también las diferencias entre la termografía infrarroja y los sensores térmicos.

Por otro lado, para evaluar el efecto de la intensidad sobre la temperatura de la piel, se analizaron las diferencias entre ambas intensidades (50% y 35%) en dicha variable, además de en la temperatura interna, percepción de esfuerzo, y tasa de sudoración corporal. Para este objetivo, se utilizó un modelo de cuerpo completo de 17 ROIs: deltoide, pecho, abdomen, dorsal, lumbar, vasto lateral, recto femoral, vasto medial, abductor, rodilla, tibial anterior, tobillo, bíceps femoral, semitendinoso, poplíteo, gastrocnemio y Aquiles.

Resultados y discusión

Comparación entre la temperatura de la piel determinada con sensores térmicos de contacto y con termografía infrarroja.

Ambos métodos mostraron una alta correlación antes del test de ciclismo (r=0,92), disminuyendo dicha correlación inmediatamente después del test (r=0,82) y mucho más 10 min después de finalizar el test (r=0,59). La alta correlación inicial y la igualdad de los valores medios de la temperatura en situación basal (FIG. S2.A), permite afirmar que ambos métodos determinan la misma temperatura basal sobre la piel del ciclista ya que se puede afirmar que el 85% de la variación de la temperatura medida con la termografía se puede explicar por la variación de la temperatura determinada con los sensores. Ahora bien, inmediatamente después del test de ciclismo, la termografía infrarroja presentó valores más bajos que los sensores térmicos de contacto, pero además se perdió la correlación, lo que implica que en este caso es el 67% de la temperatura medida con la termografía la que se puede explicar por la temperatura determinada con los sensores, frente al 85% en la situación basal. 10 minutos después la termografía presentó valores más altos que los determinados con los sensores y en ese momento solo el 35% de la variación entre ambas medidas de la temperatura sería explicable (Figura S2.A).

Para determinar qué factores podrían estar alterando la correlación existente en la situación basal entre ambos métodos de medida de la temperatura superficial, se diseñó el estudio “in vitro”, para que no hubiese interferencia de factores humanos, consistente en una placa de calor de temperatura controlada con un tejido de algodón encima y que hemos denominado test instrumentado. En las condiciones de seco, la termografía obtuvo valores similares que los sensores térmicos de contacto no cubiertos, pero en la condición de mojado también se muestra una disminución de la temperatura medida con termografía respecto al sensor, pero la diferencia entre ambos métodos es mayor que en el caso de los ciclistas y no se observa el aumento de temperatura determinado con termografía al cabo de 10 minutos que se mostró en los ciclistas (Figura S2.B).

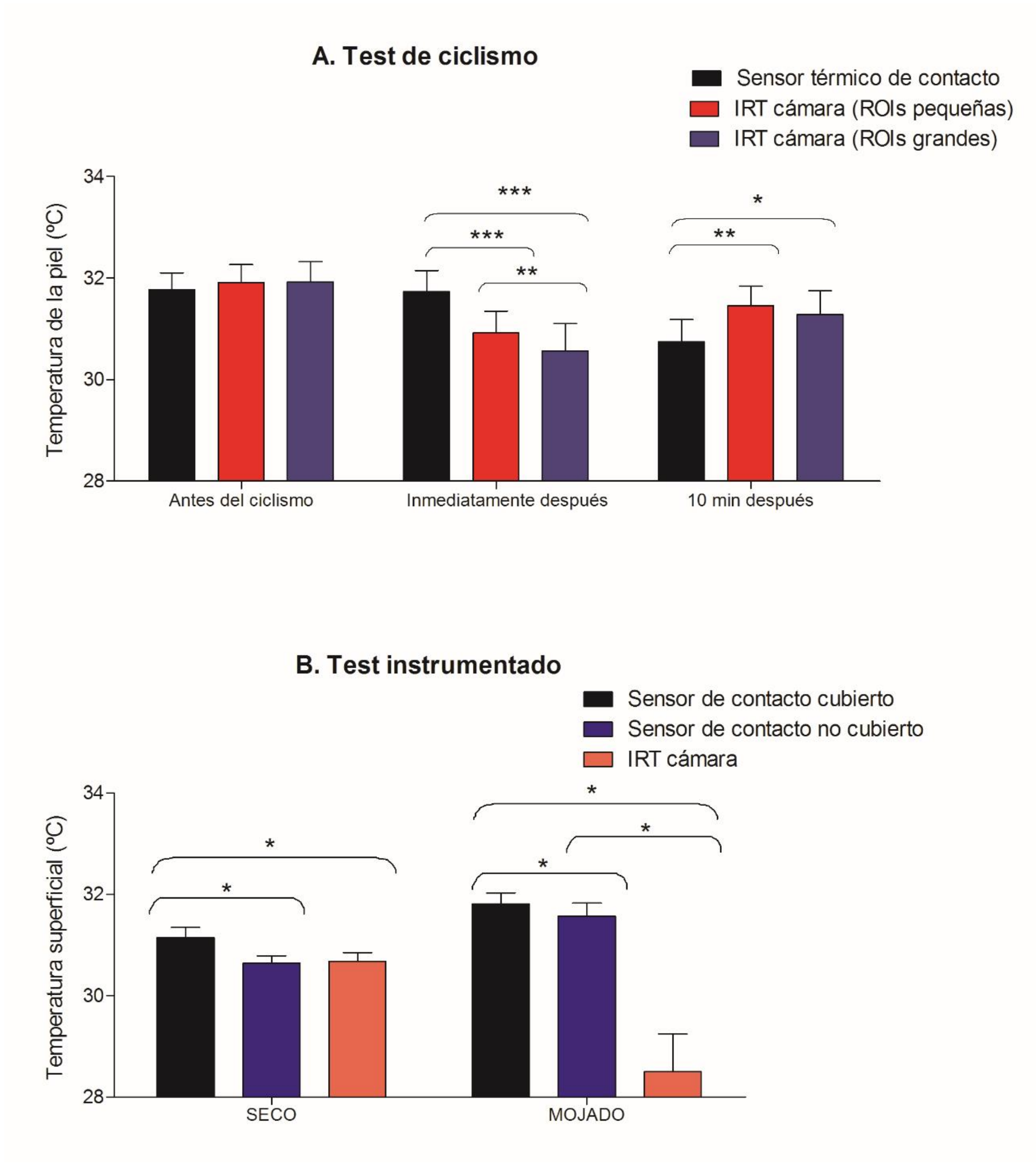


Figura S2. A. Resultados de la comparación entre la temperatura de la piel determinada con sensores térmicos de contacto y con termografía infrarroja (IRT) en los ensayos con ciclistas, y **B**. en los realizados con el test instrumentado.

La comparación de los resultados de los tests con ciclistas con los del test instrumentado (en los que la termorregulación no intervenía y no se formaban capas de agua sobre el textil medido) permitió discutir con mayor seguridad los resultados obtenidos.

Antes del ejercicio, cuando no se había activado el sistema termorregulatorio de los ciclistas, y en la situación de seco, no existió diferencia entre ambos métodos de medida. Sin embargo, tras el ejercicio y en la condición de mojado en el test instrumentado, sí que se observaron diferencias entre ambos métodos de medida de la temperatura, presentando los sensores térmicos una mayor temperatura que la termografía infrarroja. Esta situación sería explicable debido principalmente a que el sensor con su sistema de fijación a la piel (cinta médica adhesiva) redujeron la capacidad de disipación de la temperatura, ya sea por disminución de la radiación emitida al ambiente como por la reducción de la evaporación del sudor, debido a su condensación en la cinta. En el caso del test instrumentado, el proceso de evaporación justificaría también la disminución de la temperatura. Sin embargo, 10 minutos después del test, la termografía muestra mayor temperatura que los sensores sobre los ciclistas. Esto podría ser explicado porque en el caso de los sensores, el sudor absorbido por la cinta se acumuló, formando una capa de agua que hizo que se perdiese calor por conducción entre la piel y la capa de agua, mientras que la piel no tapada por la cinta el sudor ya estaba seca y podia estar aumentando su temperature por vasodilatación capilar. Sin embargo, en el test instrumentado, seguía mojado el tejido y por tanto continuaba la refrigeración por evaporación.

Influencia de la intensidad del ejercicio en la temperatura de la piel.

La temperatura interna promedio de los ciclistas durante el test al 50% de intensidad fue entre 0.2 y 0.3ºC mayor que la correspondiente al test con la intensidad al 35%, acorde con una mayor percepción de esfuerzo por parte de los cilistas y una mayor tasa de sudoración global.

Respecto a la temperatura de la piel determinada por termografía para el tibial anterior, tobillo y Aquiles, estas regiones presentaron mayores reducciones de la temperatura de la piel respecto de la situación basal en la intensidad del 50% que en la del 35%, y la rodilla presentó un menor incremento.

Aunque la intensidad de ciclismo aumentó la temperatura interna, esta no tuvo ningún efecto en la variación de la temperatura de la piel en la mayoría de las regiones de interés debido a una mayor tasa de sudoración. Sólo las regiones con menor producción de calor metabólico y perfusión sanguínea (mayormente constituidas por tejidos conectivos, oseos y grasos) se vieron afectadas, según la región analizada, con mayores reducciones o menores aumentos de la temperatura de la piel respecto a la temperatura basal a mayor intensidad. Estos resultados sugieren que estas regiones (rodilla, tibial anterior, tobillo, Aquiles) se ven afectadas por una disminución de la temperatura debido a la mayor tasa de sudoración en la intensidad más alta, en lugar de aumentar la temperatura a través del aumento de la temperatura interna.

La temperatura interna y la temperatura de la piel mostraron correlaciones débiles o moderadas, siendo negativas para la mayoría de las regiones corporales (Figura S3.A), pero otras como la rodilla, el tobillo o el Aquiles presentaron correlaciones positivas (Figura S3.B).

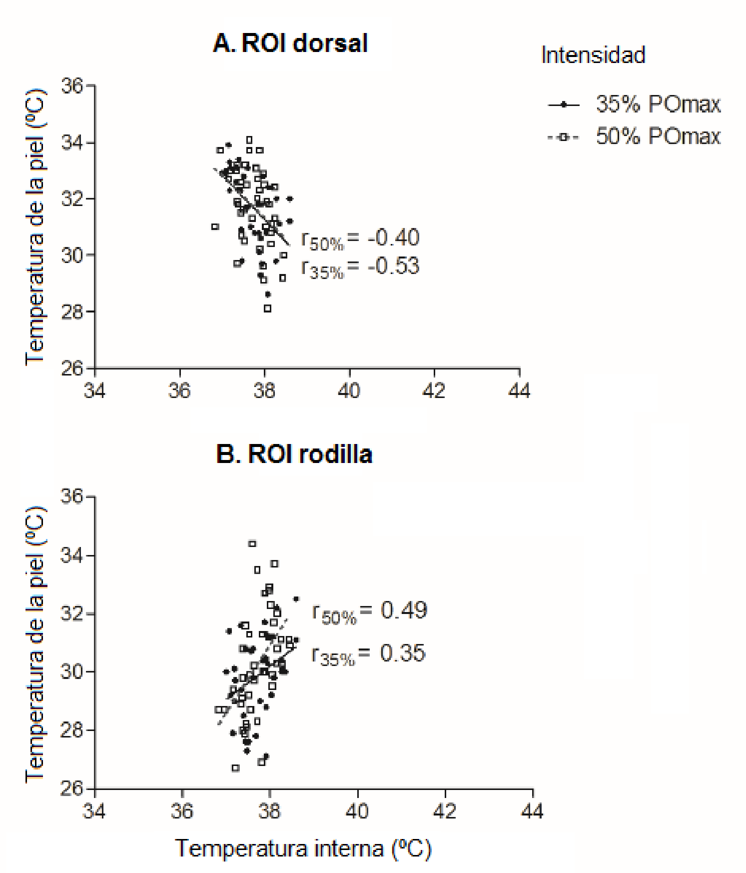


Figura S3.A Ejemplo de relación positiva entre temperatura de la piel y la temperatura interna en la zona dorsal, y **B.** de relación postiva en la rodilla.

Estudio experimental 2

Objetivo llevado a cabo:

2.3.Estudiar la relación entre la actividad neuromuscular y la temperatura de la piel durante el ciclismo.

Publicaciones obtenidas:

3. Priego Quesada, J. I., Carpes, F. P., Bini, R. R., Salvador Palmer, R., Pérez-Soriano, P., & Cibrián Ortiz de Anda, R. M. (2015). Relationship between skin

temperature and muscle activation during incremental cycle exercise. Journal of Thermal Biology, 48, 28–35. https://doi.org/10.1016/j.jtherbio.2014.12.005

Método. 10 participantes hombres no ciclistas pero físicamente activos (edad 24.6 ±4.0 años, IMC 24.5 ±2.3 kg/m^2, potencia máxima 253 ±36 vatios) realizaron un test de ciclismo de carga incremental hasta el agotamiento. Durante el test se registró la activación neuromuscular (mediante electromiografía) de 4 músculos: recto femoral, vasto lateral, bíceps femoral y gastrocnemio medial. Se tomaron imágenes termográficas antes, inmediatamente después y 10 minutos después de finalizar el test en las cuatro regiones correspondientes a los músculos citados. Para analizar el reclutamiento muscular de las unidades motoras se utilizó un análisis de bandas de frecuencia de la señal de electromiografía. Se estudiaron las correlaciones entre la variación de la temperatura de la piel respecto a la situación basal y las bandas de frecuencia de la electromiografía en los cuatro músculos.

Resultados y discusión. Se obtuvo una relación significativa e inversa entre la variación de la temperatura de la piel y la variación de la señal global de la electromiografía en el vasto lateral (r<-0,5 y p<0,04), y una relación significativa y positiva entre la variación de la temperatura de la piel y los componentes de baja frecuencia de la EMG en el vasto lateral (r>0,7 y p<0,01) (Figura S4).

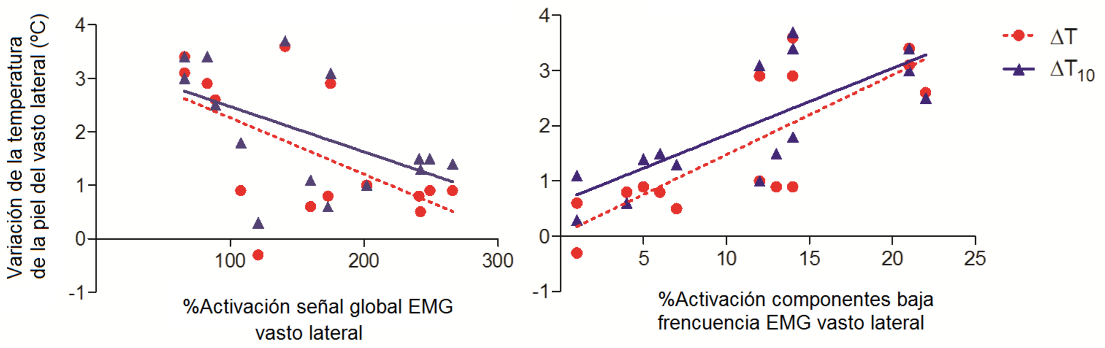


Figura S4. Resultados relación electromiografía (EMG) y variación temperatura de la piel entre antes del ejercicio y después (ΔT), y 10 min después (ΔT_{10}), en el vasto lateral.

Una mejor condición física, está asociada a lograr una mayor activación de la señal global de la electromiografía durante el ejercicio y un reclutamiento en menor proporción de unidades motoras pequeñas frente a unidades motoras grandes (menor activación de la banda de frecuencia baja). Por lo tanto, los resultados del presente estudio muestran como los sujetos con una mayor activación global y una menor activación de la banda de frecuencia baja en el vasto lateral, son los que tuvieron una menor variación de la temperatura de la piel en dicha zona y por lo tanto una mejor disipación del calor.

<u>Estudio experimental 3</u>

Objetivos llevados a cabo:

2.4. Estudiar la relación entre la temperatura de la piel, el rendimiento, y medidas predictivas de rendimiento (como puede ser el consumo máximo de oxígeno).

2.5. Comparar la temperatura de la piel de los ciclistas y los no ciclistas tras la actividad deportiva.

Publicaciones obtenidas:

4. Priego Quesada, J. I., Sampaio, L. T., Bini, R. R., Rossato, M., & Cavalcanti, V. (2017). Multifactorial cycling performance of Cyclists and Non-Cyclists and their effect on skin temperature. Journal of Thermal Analysis and Calorimetry, 127(2), 1479–1489. https://doi.org/10.1007/s10973-016-5971-z

Método. 11 ciclistas (edad 31.0 ±7.4 años, IMC 26.7 ±3.0 kg/m^2, potencia máxima 268 ±33 vatios) y 11 no ciclistas (edad 27.2 ±6.6 años, IMC 26.3 ±4.1 kg/m^2, potencia máxima 198 ±23 vatios), todos hombres, realizaron un test incremental hasta el agotamiento. Se midió a cada participante su composición corporal, potencia, consumo de oxígeno, frecuencia cardiaca, activación neuromuscular, y la temperatura de la piel del vasto lateral, recto femoral, bíceps femoral y gastrocnemio medial. Se calculó la producción de calor a partir de la diferencia entre el trabajo mecánico y el consumo metabólico medido mediante análisis de gases

Resultados y discusión

Relación entre la temperatura de la piel, el rendimiento y variables predictivas de rendimiento.

Las principales relaciones observadas fueron que la temperatura de la piel estuvo negativamente correlacionada con el porcentaje graso y positivamente correlacionada con la potencia máxima y la producción de calor. El tejido graso tiene propiedades aislantes lo que reduce la capacidad de dispación entre la temperatura interna y la piel, explicando la correlacion negativa existente entre la temperatura de la piel y el tejido graso. Por otro lado, los participantes que desarrollaron una mayor potencia máxima en el test incremental, también obtuvieron mayores valores de producción de calor, explicando por qué dichas variables estuvieron correlacionadas positivamente con la temperatura de la piel.

Diferencias entre ciclistas y no ciclistas en la temperatura de la piel.

Los ciclistas presentaron un menor porcentaje graso, mayor potencia máxima, y mayor consumo de oxígeno máximo que los no ciclistas, resultando en una mayor producción de calor y por tanto mayores temperaturas de la piel en vasto lateral, recto femoral y bíceps femoral (Figura S5).

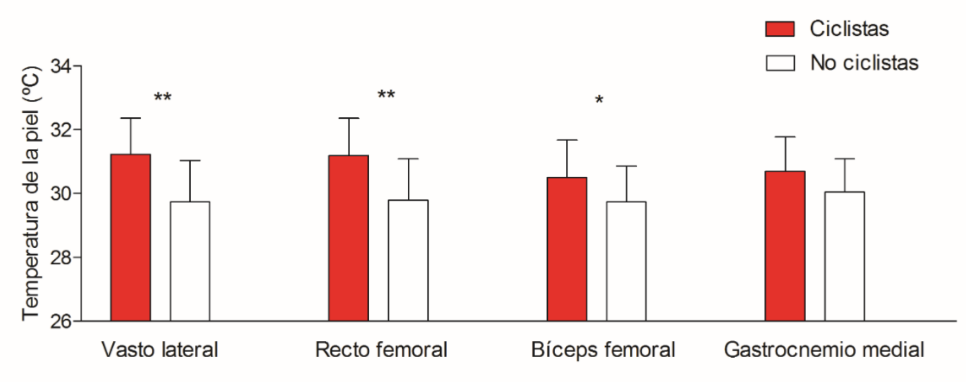


Figura S5. Diferencias en temperatura de la piel entre ciclistas y no ciclistas.

Aunque diferentes estudios han observado menores aumentos o mayores reducciones de la temperatura de la piel en participantes con mejor condición física tras la realización de ejercicio, en el presente estudio, los ciclistas con mayores valores de potencia máxima y consumo máximo de oxígeno, y por lo tanto mejor condición física que los no ciclistas, obtuvieron mayores temperaturas de la piel que estos últimos. Estos resultados se explican mediante la mayor producción de calor de los ciclistas al haber alcanzado mayores potencias. Por lo tanto, se remarca la importancia de tener en cuenta la producción de calor en el análisis de la temperatura de la piel.

Estudio experimental 4

Objetivos llevados a cabo:

3.1. Analizar el grado de percepción de confort, dolor y fatiga de las distintas alturas de sillín que se analizarán termográficamente.

3.2. Analizar si las diferentes alturas de sillín se ponen de manifiesto en la temperatura de la piel del ciclista.

Publicaciones obtenidas:

5. Priego Quesada, J. I., Pérez-Soriano, P., Lucas-Cuevas, A. G., Palmer, R. S., & Anda, R. M. C. O. de. (2017). Effect of bike-fit in the perception of comfort, fatigue and pain. Journal of Sports Sciences, 35(14), 1459–1465. https://doi.org/10.1080/02640414.2016.1215496

6. Priego Quesada, J. I., Carpes, F. P., Salvador Palmer, R., Pérez-Soriano, P., & Cibrián Ortiz de Anda, R. M. (2016). Effect of saddle height on skin temperature measured in different days of cycling. SpringerPlus, 5(1), 205–214. https://doi.org/10.1186/s40064-016-1843-z

Método. 16 ciclistas hombres (edad 29.3 ±10.0 años, IMC 24.1 ±3.1 kg/m^2, potencia máxima 273 ±48 vatios) realizaron 3 test aleatorizados de 45 minutos de pedaleo al 50% de su potencia máxima (cadencia 90 rpm), cada uno con una flexión de rodilla diferente (20º, 30º, 40º cuando la biela está a 180º). La flexión de rodilla fue determinada de manera dinámica mediante fotogrametría 2D. La temperatura de la piel fue obtenida en 16 regiones de interés en tronco y miembros inferiores (pecho, abdomen, dorsal, lumbar, vasto lateral, recto femoral, vasto medial, abductor, rodilla, tibial anterior, tobillo, bíceps femoral, semitendinoso, poplíteo, gastrocnemio y Aquiles), mediante termografía, antes, inmediatamente después y 10 minutos después del pedaleo. Además, dichas posturas fueron validadas mediante el estudio del comfort, y la percepción de fatiga y dolor tras el pedaleo. Por último, se analizó la reproducibilidad de las temperaturas absolutas y de las variaciones de la temperatura.

Resultados y discusión. En primer lugar, se obtuvieron diferencias en el análisis de la percepción de las tres posturas. La posición intermedia (30º) fue valorada como la más comfortable por los ciclistas. Por otro lado, la postura con la mayor flexión de rodilla fue la más incomfortable, además de percibir mayores niveles de fatiga y dolor en muslo anterior y rodilla. Los resultados de percepción de las tres posturas sugirieron que las diferencias entre ellas eran suficientes para producir diferencias térmicas, si éstas podían existir.

Las diferentes flexiones de rodilla no tuvieron efecto en la temperatura de la piel de la mayor parte de las regiones. Únicamente se observó una mayor temperatura en poplíteo a 20º de flexión respecto a 40º (32,2 ±0,7ºC vs 31,6 ±0,7ºC, $p<0,01$) y un menor incremento de temperatura (diferencia entre 10 min después y antes del pedaleo) en tibial anterior a 20º respecto a 30º (-0,2 ±0,8ºC vs 0,3 ±0,9ºC, p<0,01). La mayor temperatura de la zona poplítea en la posición más extendida podría explicarse por un mayor volumen sanguíneo en los tendones, mientras que el menor incremento de la temperatura del tibial podría deberse a un menor rango de movimiento del tobillo. Sin embargo, no se observó un efecto de la postura en la temperatura de las regiones conjeturadas como más susceptibles (por ejemplo cuádriceps). Estos resultados parecen indicar que la termografía infrarroja no sería útil en el ajuste de la postura en ciclismo. Las temperaturas tras el ejercicio obtuvieron una buena reproducibilidad, mientras que las variaciones de temperatura obtuvieron menores valores de reproducibilidad, lo que podría indicar que el análisis de las variaciones de temperatura tiene una mayor sensibilidad a la intervención realizada que el análisis de las temperaturas absolutas.

Estudio 5

Objetivos llevados a cabo:

4.1. Determinar las ROIs a analizar en el ciclismo.

4.2. Examinar qué parámetros de la temperatura superficial (absolutas, variaciones pre-post) medidas en las ROIs resultan más adecuadas para analizar los efectos del ejercicio.

Publicaciones obtenidas:

7. Priego Quesada, J. I., Lucas-Cuevas, A. G., Salvador Palmer, R., Pérez-Soriano, P., & Cibrián Ortiz de Anda, R. M. (2016). Definition of the thermographic regions of interest in cycling by using a factor analysis. Infrared Physics & Technology, 75, 180–186. https://doi.org/10.1016/j.infrared.2016.01.014

8. Priego Quesada J.I; Salvador Palmer R.; Pérez-Soriano P.; Izaguirre J.; Cibrián Ortiz de Anda R.M. (2017). Multi regression analysis of skin temperature variation during cycling exercise. VipIMAGE 2017. ECCOMAS 2017. Lecture Notes in Computational Vision and Biomechanics (Editors João Manuel R.S. Tavares and R.M. Natal Jorge). pp. 962-969. Cham (Switzerland): Springer International.

Método. De 19 participantes de los estudios experimentales previos, se seleccionaron 52 tests para el análisis del estudio 5. Estos tests consistieron en 45 minutos a 90 revoluciones por minuto al 50% de la potencia máxima. Se utilizaron el mismo modelo de 16 ROIs que en el estudio anterior. Se realizaron principalmente dos análisis:

1) análisis factorial con el objetivo de identificar grupos de regiones de interés, tanto para cada momento de medida, como para cada variación de temperatura. 2) Análisis de regresión múltiple en los que la variable respuesta fue la variación de temperatura de la piel debido al ejercicio (diferencia entre la temperatura inmediatamente después y antes del ciclismo), y las variables predictoras fueron la potencia máxima, la masa corporal, la altura, la superficie corporal, el índice de masa corporal, el volumen de entrenamiento de ciclismo (kilómetros a la semana), los pliegues corporales, la temperatura ambiente, la humedad relativa, y la temperatura antes del ejercicio.

Resultados y discusión.

Determinación de las regiones de interés en el ciclismo.

Todos los análisis factoriales realizados para cada momento de medida y variación de temperatura explicaron más del 80% de la varianza. Diferentes grupos de regiones de interés fueron obtenidos para cada análisis. Sin embargo, algunas regiones fueron siempre agrupadas en todos los análisis (por ejemplo las regiones del tronco y las del muslo anterior), mientras que otras regiones fueron agrupadas de manera diferente en cada análisis. El análisis factorial sugiere que una división de las áreas del cuerpo en 9 regiones sería suficiente para estudiar la termorregulación en el ciclismo: tronco, muslo anterior, muslo posterior, rodilla, poplíteo, tibial anterior, gastrocnemio, tobillo anterior y Aquiles (Figura S6). Las diferencias térmicas entre regiones pueden explicarse por las diferencias en la composición de los tejidos, la actividad muscular y la capacidad de sudoración. En primer lugar, se observaron las temperaturas más altas en el tronco. El tronco contiene los órganos internos que producen una gran cantidad de calor como resultado de sus procesos metabólicos. Por otro lado, las regiones con una gran proporción de tejidos conectivos y óseos (por ejemplo, rodilla, tobillo anterior, Aquiles y tibial anterior) presentaron las temperaturas más bajas. Estas temperaturas más bajas son probablemente el resultado de la menor producción de calor metabólico y la perfusión sanguínea de estas regiones. Además, son regiones más periféricas, y estudios previos han encontrado que la temperatura de la piel disminuye desde el tronco hasta las regiones periféricas.

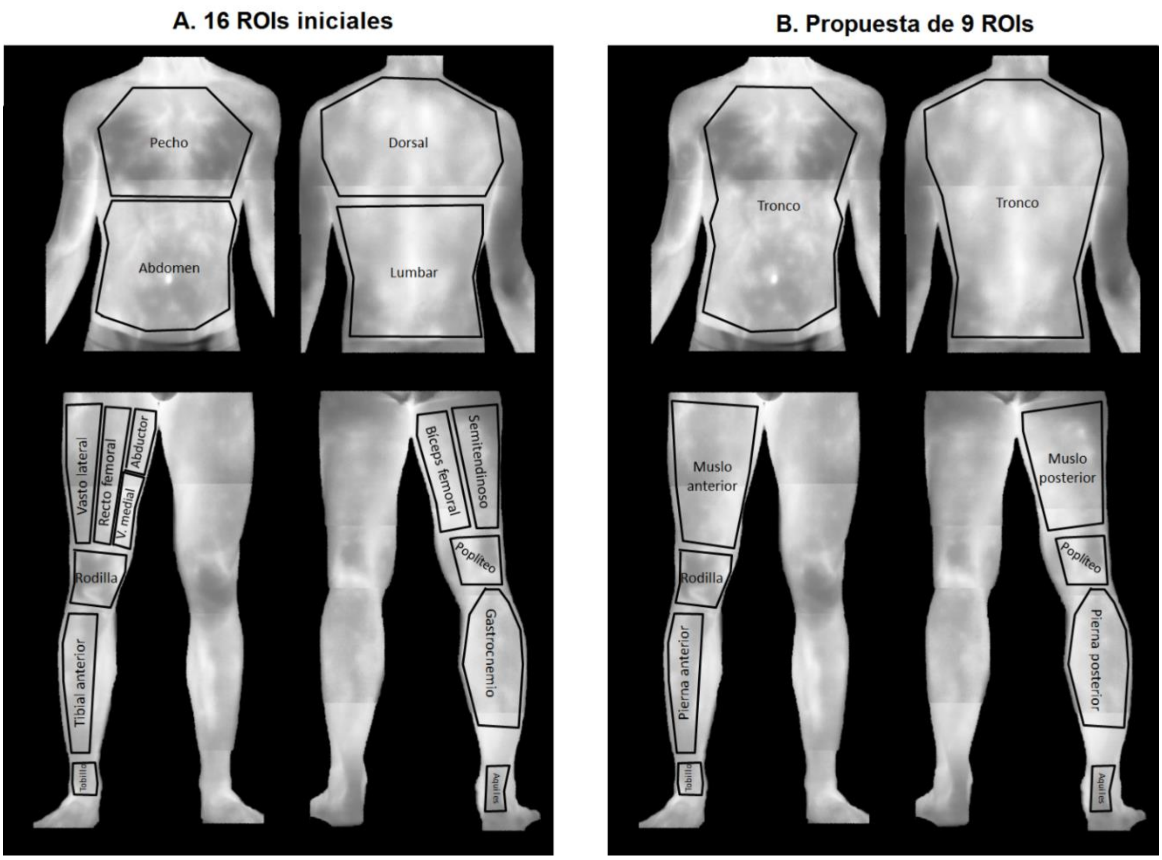


Figura S6. Propuesta de 9 ROIs para el estudio termográfico del ciclismo (B) a partir del análisis factorial de 16 ROIs (A).

Factores que afectan al análisis de la variación de temperatura.

Los modelos obtenidos para cada región de interés explicaron, en la mayoría de los casos, al menos el 60% de la varianza. Las variables antropométricas (masa corporal, superficie corporal e índice de masa corporal) fueron los predictores más importantes explicando cada uno de ellos más del 15% de la varianza. La variación de la temperatura se vio afectada principalmente por variables antropométricas. Sin embargo, el efecto fue diferente dependiendo de las variables. En primer lugar, la masa corporal y los pliegues cutáneos presentaron una relación inversa. Este efecto podría explicarse porque estas variables están relacionadas con la composición corporal (por ejemplo, grasa corporal), siendo debido a la capacidad de aislamiento de estas variables. Por otro lado, la superficie corporal y el índice de masa corporal presentaron una relación positiva. A pesar de que la superficie del cuerpo está comúnmente relacionada con una mayor capacidad de disipación del calor, en el presente estudio los participantes con mayores valores de superficie corporal fueron también los participantes con valores más altos de índice de masa corporal y pliegues cutáneos. Estos participantes podrían ser también los participantes con un nivel de condición física peor, por lo tanto con menor capacidad de evaporación del sudor durante el ejercicio, resultando en mayores valores de variación de temperatura.

Conclusiones obtenidas de la tesis doctoral

Tras la realización de la tesis doctoral, se obtuvieron diferentes conclusiones, que han sido divididas acordes a los objetivos específicos.

Conclusiones de validación:

1.1. La termografía infrarroja es una tecnología válida para medir la temperatura de la piel en la evaluación ciclista, teniendo como principales beneficios respecto a los sensores térmicos de contacto que es capaz de analizar grandes regiones y es una técnica a distancia que no interfiere en la termorregulación.

1.2. La sudoración durante el ciclismo no alteró los resultados térmicos significativamente, sugiriendo que la termografía infrarroja es una herramienta válida para medir durante y después de un ciclismo aeróbico en condiciones ambientales moderadas.

Conclusiones de eficiencia:

2.1. La intensidad de la carga en el ciclismo no tuvo ningún efecto en la temperatura de la piel de la mayoría de las regiones corporales debido a una mayor disipación del calor producida por el sistema termorregulatorio, y solo se vieron afectadas regiones que estaban constituidas principalmente por tejidos conectivos, oseo y graso.

2.2. En general, la temperatura interna y la de la piel mostraron correlaciones negativas débiles o moderadas en las regiones que presentaban mayores tasas de sudoración en el cuerpo, mientras que se observaron correlaciones positivas en las regiones en las que la capacidad de sudoración era baja. Estos resultados destacan la dificultad de relacionar temperatura de la piel con la intensidad del ejercicio y la temperatura interna, debido a la eficiencia del sistema termorregulatorio en incrementar el gradiente térmico entre el interior del organismo y la piel, además de la dependencia multifactorial de la temperatura de la piel.

2.3. Participantes con una mayor eficiencia neuromuscular del vasto lateral (mayor activación neuromuscular global y menor componente de bajas frecuencias) presentaron una mejor respuesta de su sistema termorregulatorio durante la práctica del ciclismo teniendo menores incrementos de la temperatura de la piel. Entre los diferentes músculos, el vasto lateral presentó la mejor asociación entre los cambios en la actividad neuromuscular y la temperatura de la piel durante un test incremental.

2.4. La composición coportal y el rendimiento del ciclista (potencia máxima producida) fueron los aspectos más importantes que influenciaron la respuesta de la temperatura de la piel. Con el objetivo de mejorar la disipación del calor, es importante para los ciclistas tener un bajo componente graso, que puede ser reducido a partir del control de la dieta y una correcta periodización del entrenamiento.

2.5. Los ciclistas presentaron mayores temperaturas que los no ciclistas durante y después de un test incremental de ciclismo. La producción de calor es una variable importante a tener en cuenta en la interpretación de los resultados de la temperatura de la piel durante y después del ejercicio.

Conclusión sobre el ajuste de la postura:

3.1. Diferentes flexiones de rodilla, que tras 45 minutos de ciclismo presentaron diferencias en el análisis de la percepción de confort, fatiga y dolor, no presentaron diferencias en la temperatura de la piel en la mayoría de las regiones de interés. Por ello concluimos que el análisis de la temperatura de la piel mediante termografía infrarroja para estudiar el efecto de diferentes alturas de sillín no parece ser de interés.

Conclusiones de metodología:

4.1. El análisis factorial permitió agrupar de forma coherente regiones de interés en las que se observarón diferencias térmicas entre dichas regiones, pudiendo explicarse en función de los diferentes tejidos que las componían, su actividad muscular y su capacidad de sudoración. Además, los resultados del estudio indicaron que regiones grandes como el tronco pueden ser medidas como una sola, mientras que regiones pequeñas pertenecientes a las piernas y las articulaciones deberían ser medidas de manera individual.

4.2. La reproducibilidad de la medida de la temperatura en cada sujeto en diferentes días fue buena, pero el análisis de la variación de la temperatura respecto a la situación basal resultó un mejor indicador para estudiar el efecto de una intervención sobre el ciclista (en este caso el efecto de modificar la altura de sillín en los diferentes días).

4.3. Aunque el análisis de las variaciones de temperatura parece tener ventajas respecto a las temperaturas absolutas como la minimización del efecto de las condiciones ambientes en los resultados, es importante tener en cuenta las variables antropométricas durante la selección de los participantes con el objetivo de reducir la variablidad de la medida.

Los estudios realizados en la presente tesis doctoral tienen algunas limitaciones que conviene comentar para que se tengan en cuenta en la interpretación de los resultados y conclusiones.

Limitaciones:

- Una de las principales limitaciones de esta tesis estriba en que los estudios se realizaron en laboratorio y no en condiciones reales de campo. La temperatura radiante así como el comportamiento de viento son aspectos muy diferentes entre ambos escenarios. Sin embargo, las condiciones de laboratorio permiten estandarizar un gran número de factores que en campo son difíciles de controlar (por ejemplo las condiciones ambientales, la intensidad del ejercicio, la postura del ciclista, etc.).
- Aunque el uso de electromiografía de superfice permite obtener una valiosa información de la activación neuromuscular, esta técnica tiene algunas limitaciones asociadas como la distancia existente entre las unidades motoras y los electrodos, o el movimiento de las fibras musculares respecto a los electrodos.
- Una limitación del estudio experimental sobre el ajuste de la postura del ciclista fue que no se midió la activación neuromuscular durante el test de ciclismo. Esto hubiese permitido comprobar las diferencias en la

activación neuromuscular producidas a partir de diferentes alturas de sillín hipotetizadas a partir de la revisión de la literatura.

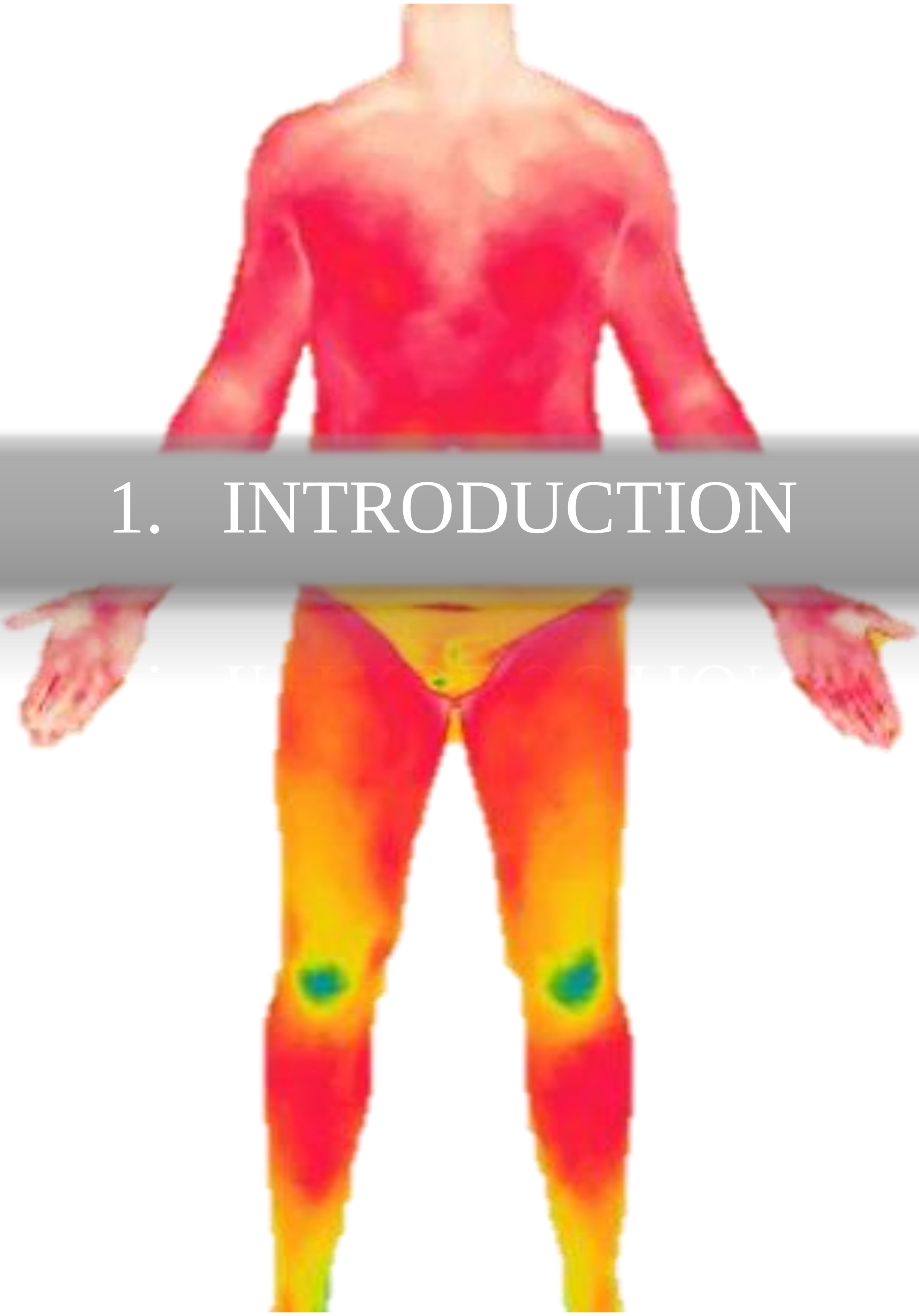
- La presente tesis doctoral se ha realizado únicamente con hombres, lo que es una limitación en cuanto al estudio del efecto del género. Futuros estudios deberían tener en cuenta tanto a hombres como a mujeres.

A partir del análisis del trabajo realizado en esta tesis doctoral, se puden proponer futuros estudios de investigación.

Futuros estudios:

- Explorar el efecto de una tasa alta de sudoración durante el ciclismo en las medidas termográficas (en un ambiente de calor y una intensidad alta).
- Para analizar el efecto de la intensidad, se evaluaron dos intensidades: 35% y 50% de la potencia máxima. Estas intensidades fueron escogidas con el objetivo de llevar a cabo un test aeróbico. Será de interés que futuros estudios evaluen intensidades con mayores diferencias entre ellas a partir de tests más cortos.
- Explorar la relación entre la temperatura de la piel y factores de rendimiento en ambientes de calor, donde la eficiencia del sistema termorregulatorio es clave a la hora de reducir la pérdida de rendimiento y el riesgo de un golpe de calor durante el ciclismo.
- Investigar la reproducibilidad de los datos térmicos (temperaturas absolutas y variaciones de temperatura) tras el ejecicio sin haber realizado ninguna intervención.
- Aplicar la termografía infrarroja en un equipo o club de ciclismo, con el objetivo de prevenir lesiones a partir del análisis de la simetría térmica.

1. INTRODUCTION



1. INTRODUCTION

1.1. Infrared thermography

1.1.1. Introduction, origins and applications

Infrared thermography (IRT) is a safe and non-invasive image technique used to record infrared radiation, and, in particular, the infrared radiation emitted by the human body, which permits estimation of body´s surface temperature (Figure 1.1)[9,111]. Any object at a temperature above absolute zero (0K or -273.15ºC) emits energy -electromagnetic radiation- depending on its temperature[125,224]; for the ~37 ºC of the human body, the emitted energy is in the infrared region of the electromagnetic spectrum (thermal radiation)[111,161].

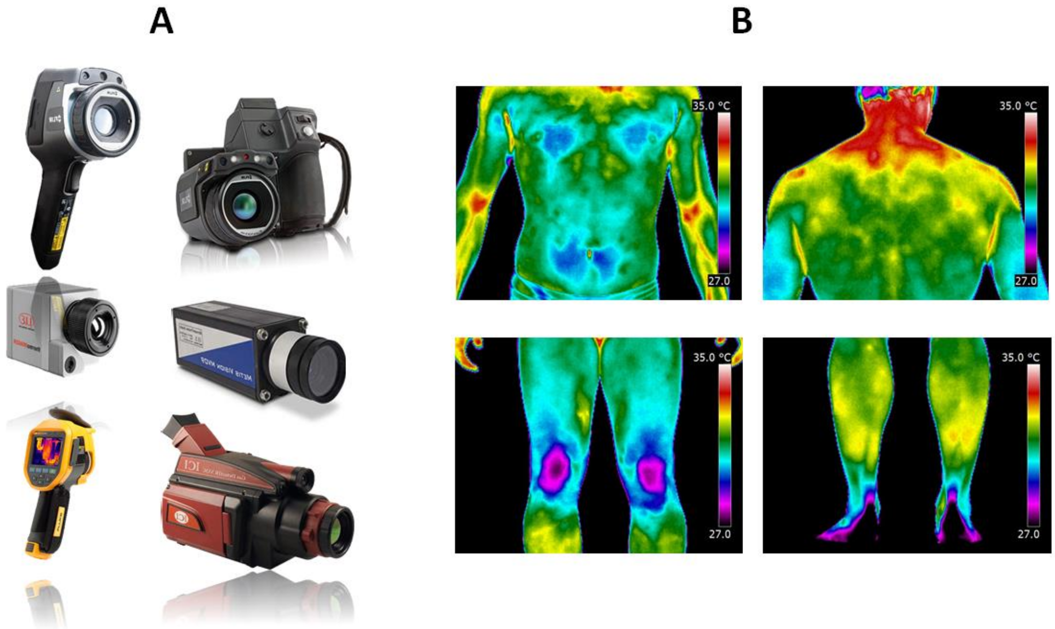


Figure 1.1. (A) Example of different thermographic cameras and (B) body thermographies of one cyclist before exercise.

The first step of the invention of the IRT cameras can be considered the discovery of infrared radiation. Infrared radiation was discovered in 1800 by Sir Frederick William Herschel (1738 Hannover, Germany; 1822 Slough, England), an English–German astronomer. Herschel was interested in learning how much heat passed through the different colors by watching the sun filters. He found that the heat increased from the violet to the red color of the spectrum. However, he also observed that next to the red spectrum, when there was no light, the temperature was higher[109]. This experiment from Herschel was very important because it marked the first time that someone had demonstrated that there were types of energy that are invisible to our eyes. Herschel called this radiation "Calorific Rays", a name quite popular throughout the nineteenth century that finally was giving the modern term "infrared radiation".

After the death of William Herschel, his son, John Frederick William Herschel (1792 Slough, England; 1871 Collingwood, England), repeated the experiments of his father and made an image using solar radiation in 1840[184]. This image was achieved by focusing solar radiation onto to a suspension of carbon particles in alcohol using a lens, a method known as evaporography[184]. He obtained an image that he called a "thermogram" (Figure 1.2), a term that is still in use. After John Herschel, some of the most important advances were related to the development of infrared detectors. Figure 1.3 presents some thermographies that show the evolution of the technique over time, related with the improvements added in the IRT cameras.

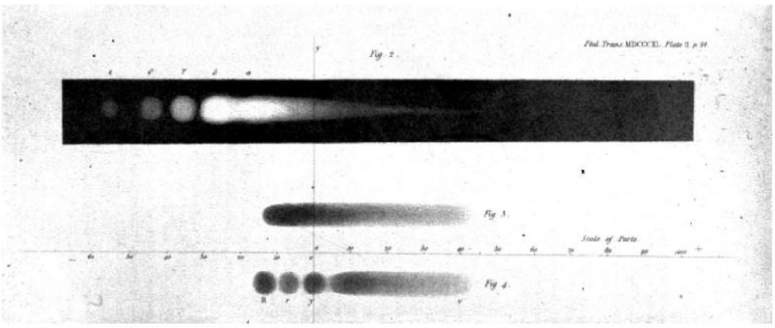


Figure 1.2. Thermogram performed by John Herschel using the evaporography method. Figure obtained from Ring[184].

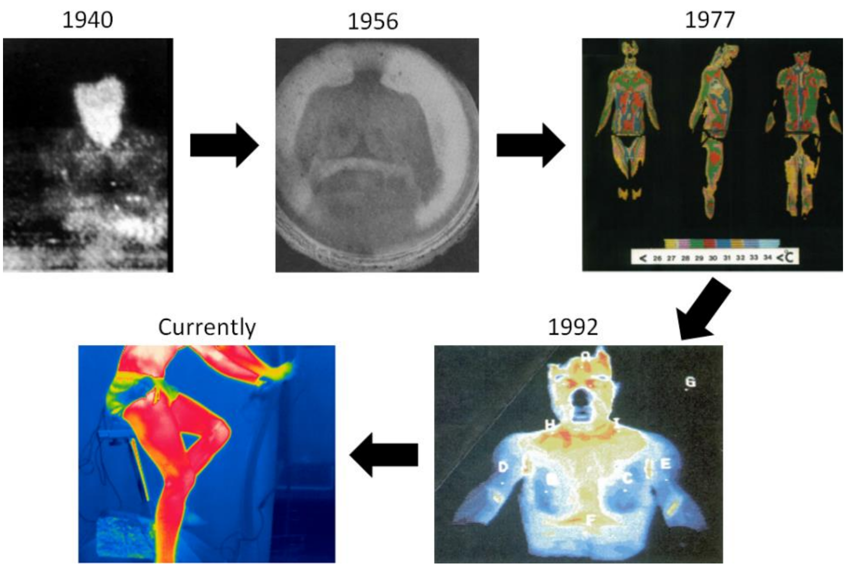


Figure 1.3. Quality evolution of infrared thermography. Figures were obtained from Ring[184] (1940), Lawson[135] (1956), Clark and Mullan[52] (1977) and Torii et al.[217] (1992).

Modern infrared detectors were developed during World War II[184,187]. The sensors were developed in this period for its military applications[133,161,224]. Its main use in the military field was, and remains, night vision. This utility is also highlighted when the objective is to detect people in dark environments and complex spaces. After IRT had been used in military applications, the technology was released for civilian uses[125,133].

In 1934, human skin was described to be a good emitter of infrared radiation[103], After that, IRT started to be considered as a potential technique for skin temperature measurement without contact and, then, as a possible way to enable diagnostic imaging in medical science[133]. A current overview of all the applications that IRT has in medicine is provided by the interesting reviews performed by Ring and Ammer[185], and Lahiri and colleagues[133], both of which were published in 2012. These reviews extracted the following applications of IRT in medicine: assessment of the thermoregulation, breast cancer detection, diagnosis of diabetic neuropathy and vascular disorder, fever screening, dental diagnosis, dermatological applications, blood pressure monitoring, diagnosis of rheumatic diseases, diagnosis of inflammatory arthritis, assessment of fibromyalgia, diagnosis of dry eye syndrome and ocular diseases, diagnosis of liver diseases, complementary test in the treatment of kidney, gynecology applications, and assessment of the psychological state[133,185]. Of the above applications, cancer detection was one given a higher priority in the hope that it could be a valid screening technique[184].

IRT is used in other applications related to medicine (e.g., veterinary science) but also in other fields such, as engineering. Some examples of representative and diverse applications are commented on below (Figure 1.4):

- **Veterinary science**. IRT has, in this area, a similar utility as in medicine. However, due to some characteristics, it has become very important in veterinary science. The difficulty of knowing the pain and the patient's condition without invasive techniques is higher in veterinary science than in medicine, and thus IRT is a low-cost, fast, efficient and simple method that allows knowledge of the status of the animal's injury[154]. Furthermore, it is considered that, in the veterinary field, IRT assessment can be useful to estimate the physiological state of animals in situations of stress, fertility, welfare, metabolism, health and disease detection[154].
- **Predictive maintenance of factories**. This application is widely used in electrical and nuclear facilities, and in different factories. This kind of application is

particularly important when the factories need to work continuously without stoppages occurring in their activity due to breakdowns. In this context, IRT helps routine inspections, where it is possible to visualize abnormalities in the components[172]. This display of anomalies would be able to repair or replace components before they produce serious damage to the operation of the factory. In addition, IRT in this context allows the person to carry out inspection at a safe distance from hazardous components (e.g., those with high temperature or radioactivity) and to measure the temperature without contact.

- **Building Inspection**. IRT is considered to be an excellent tool for diagnosing the state of buildings. Evaluation of insulation of different materials and/or the location of water leaks, and thus humidity, are specific uses of IRT in this field[90]. One of the techniques used is the evaluation of heat flow, which consists of the generation of a thermal gradient between the inside and outside of the building. An example of this is that in the winter heaters heat the inside. Thus, through IRT inspection from the outside of the building, it is possible to visualize whether there are hot areas. These hot areas are associated with heat transfer from inside to outside and therefore represent a problem with insulation in the walls or windows. If the whole outside surface of the building is a similar temperature, it means that the inside is properly isolated from the outside.

- **Gas detection industry**. Infrared cameras are able to visualize gases in a specific range of the infrared spectra[195]. Because of this, using the appropriate camera, it is possible to visualize specific gases such as the ethanol, carbon dioxide, propanol or sulfur hexafluoride, among others. This provides interesting applications of IRT in the industry. Two of the main applications are: (1) to check whether factories are not producing toxic gases or if the levels of the gases expelled are adequate; and (2) to check if there are leaks in the structures to store or transport gas.

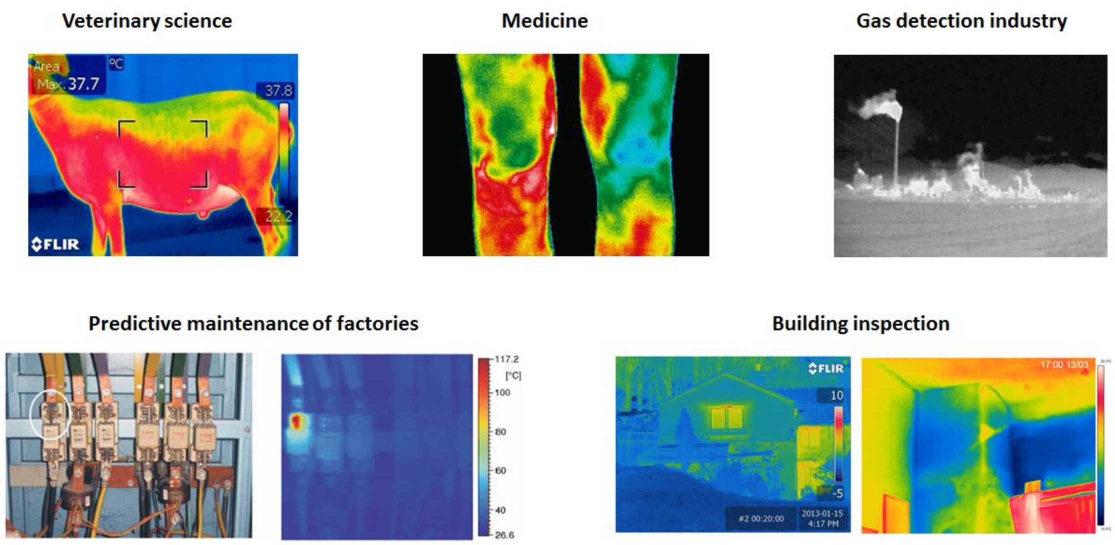


Figure 1.4. Different applications of infrared thermography. Figures were obtained from McManus et al.[154] (Veterinary), Hildebrandt[111] (Medicine), Sedlák et al.[195] (Gas detection) Petar et al.[172] (Factories) and Fox et al.[90] (Building).

The knowledge of IRT, which provides the basis for the relationship between the infrared radiation emitted and temperature, is presented below.

1.1.2. Physics principles of infrared thermography

Heat transfer

Heat is energy in transit that passes from a warm body to a cold body and temperature can be defined as the "measure" of the average kinetic energy of one body[168]. There are different scales for measuring temperature and the most well known are the degree Celsius, Kelvin and degree Fahrenheit. The degree Celsius is used by most countries in the world. However, in the international system of units, the temperature is expressed using the Kelvin scale (K). This scale is called absolute, because it is not possible, by imperative of the laws of thermodynamics, to have bodies with lower values than the 0 K (−273.16°C). The Kelvin scale is used in all aspects related to the physics of IRT.

The term heat, therefore, should be understood as heat transfer, called heat flow or heat flux, and only occurs when there is a temperature difference between two bodies. Therefore, when two bodies are at the same temperature, they are in thermal equilibrium[224]. In addition, when one body has a constant temperature, it is considered that it is in a thermal equilibrium, and it could be a result of the environment being at the same temperature as the body, or because it has a constant supply of heat that keeps it at a constant temperature even though the environment is different (as in the case of the internal temperature of the human body).

Furthermore, the transference of heat is based on three mechanisms: conduction, convection and radiation.

- **Conduction**: heat transfer by the contact of two solid bodies at different temperatures. The amount of heat transferred by conduction is given by Fourier's law. This law states that the heat flow is proportional to the temperature gradient existing in the body, being the proportionality constant material conductivity.
- **Convection**: heat transfer by the contact of a solid body with a liquid or gaseous element. The convective heat exchange between the body and the fluid is given by the Newton's cooling law. This law states that the heat flow per time depends on the temperature gradient and surface contact area of both, and the convective heat transfer coefficient (determined by the density, heat capacity, thermal conductivity and velocity of the fluid)[57].
- **Radiation**: heat transferred by the body by emission of electromagnetic radiation. All of the objects with temperature above absolute zero (0 K or −273.16 °C) emit electromagnetic radiation according to the Plank law, which indicates that the energy radiated is proportional to the fourth power of its temperature. Furthermore, objects absorb electromagnetic energy emitted by the environment. Since the emission of energy implies a decrease in internal energy and thus the temperature of the object, if the object maintains a constant temperature (thermal equilibrium), it is because the energy emitted is compensated by the energy absorbed, but if a body is at a higher or lower temperature than the environment, the net radiative heat transfer is the difference between the absorbed and the emitted radiation. As will be shown in the following section, the emitted radiation of the human body temperature is in the range of infrared radiation in the electromagnetic spectrum and is called thermal radiation.

Electromagnetic spectrum and infrared radiation

Electromagnetic radiation is a way of energy propagation through a vacuum or a material medium without mass transport. An electromagnetic wave can be defined as the propagation of the vibration of an electric field (E) and magnetic field (B), which together form an angle of 90° (Figure 1.5 A). The quantities that characterize the electromagnetic waves are the amplitude of the electric and the magnetic fields and the frequency of the wave.

The electromagnetic spectrum comes from the concept that electromagnetic radiation has different characteristics depending on its wavelength and frequency. The electromagnetic spectrum is a representation of the frequency distribution of all the electromagnetic waves (Figure 1.5 B). Regarding a body, the electromagnetic spectrum is all the electromagnetic radiation that is emitted (emission spectrum) or absorbed (absorption spectrum). The electromagnetic spectrum extends from the radiation of lower energy (or longer wavelength) such as the radio waves, the microwaves, the infrared rays or the visible light, to electromagnetic radiation with higher energy (and shorter wavelength) such as ultraviolet light (UV), X rays and gamma rays.

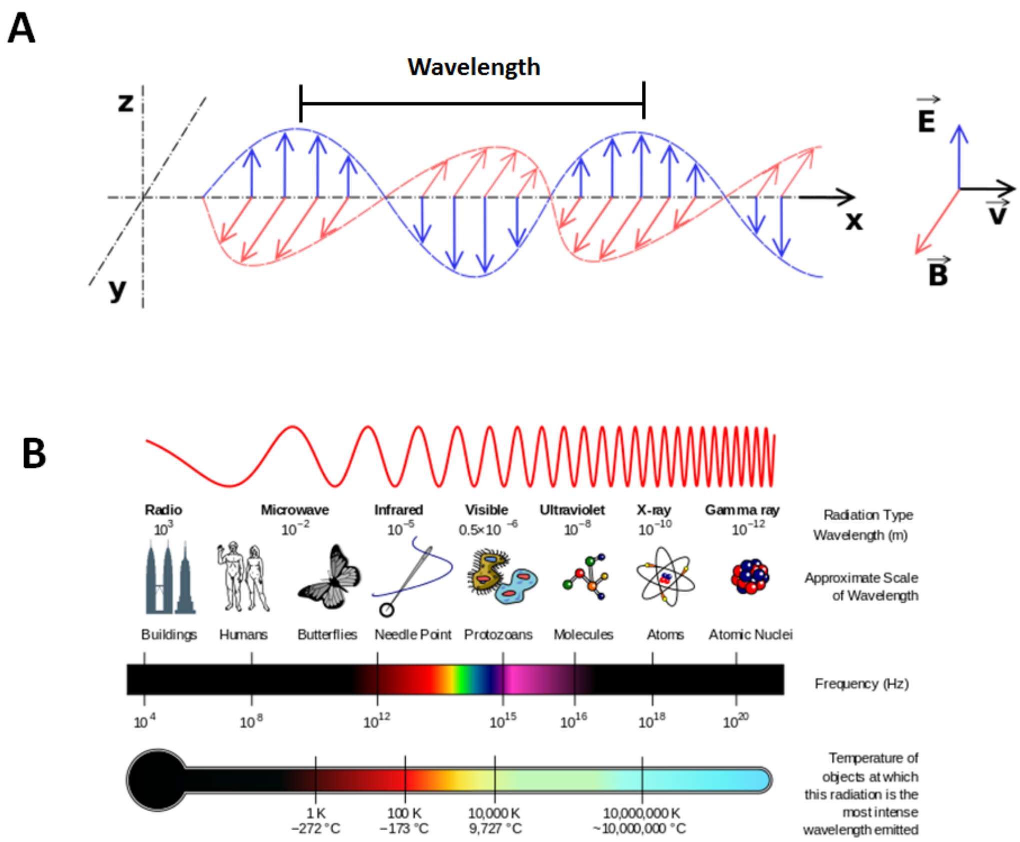


Figure 1.5. A. Representation of an electromagnetic wave with the vibration of the electric field (E) and magnetic field (B) and the velocity (v) and direction of the propagation of the wave. **B.** Representation of the electromagnetic spectrum (Figure modified from the free media repository of Wikimedia Commons).

The area of the electromagnetic spectrum involved in the IRT is infrared radiation. This radiation is also known as thermal radiation, because there is a relationship between the infrared radiation emmited by the bodies and its temperature, and its wavelength range is from 760 nm to 1 mm (Figure 1.6).

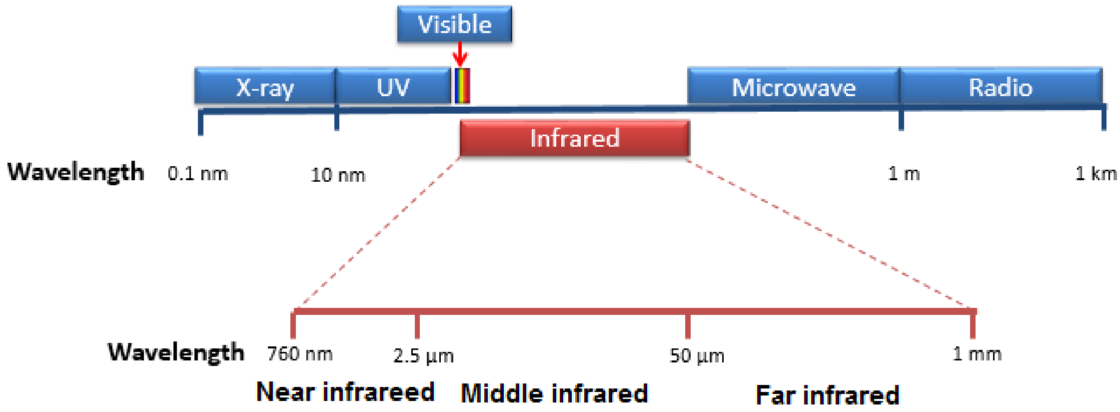


Figure 1.6. Electromagnetic spectrum focusing on the infrared radiation spectrum.

Physical laws of infrared radiation

The physical laws of infrared radiation and its relationship to temperature are based on the theory of the black body. The concept of the black body was introduced by Gustav Kirchhoff in 1860. A black body is a theoretical object that absorb all incident electromagnetic radiation, and its absorption is equal to its emission[227]. None of the incident radiation is reflected or passes through the black body. The black body also has a uniform surface and a uniform temperature. The black body is therefore an ideal perfect emitter of infrared radiation[227].

The laws that govern the IRT are considered the Wien´s displacement law, the Stefan-Boltzmann's law and the Planck's law.

Planck's law established that the spectral emissive power depends on temperature and the wavelength. Its equation is:

$$E_{\lambda}(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{1.1}$$

where $E_\lambda(\lambda,T)$ is the spectral radiance as a function of temperature and wavelength, λ is the wavelength of emission in meters, T is the temperature in kelvin, h is the Planck constant ($6.6256*10^{-34}$ Js), c is the speed of light in the medium ($3*10^8$m/s), and k is the Boltzmann´s constant ($1.38054*10^{-23}$WsK^{-1}).

Although Stefan-Blotzmann law and Wien's displacement law were empirically demonstrated prior to Planck's law, they can both be deduced from the latter.

Wien's displacement law was established by Wilhelm Wien in 1893. This physical law established that the wavelength of the peak of the blackbody radiation curve decreases as the body temperature is increased. The equation of Wien's displacement law is:

$$\lambda_{max} = \frac{a}{T} \qquad (1.2)$$

where λmax is the wavelength of emission peak in meters, a is the Wien's displacement constant ($2.897 * 10^{-3}$ m K), and T is the absolute temperature in kelvin.

After the Wien´s law, it is important to understand that bodies with very high temperature are capable to emit other radiations (visible and even UV), and bodies are heated during the absorption of their radiation. For example, the sun, because it is at a temperature between 5000 and 6000 K, emits its radiation in the ultraviolet, visible and infrared spectrum; however, its emission peak is in the range of visible radiation (526 nm, corresponding to the green–yellow colors of the visible light). However, in bodies in which the temperature is close to the environmental temperature, the energy radiated is from the infrared wavelength of the electromagnetic spectrum[12] (Figure 1.7). Thus, it is understood that for the 37°C of human body (370 K), the maximum emitted energy is 9.3 µm, and therefore all its radiation is infrared radiation; more specifically, the 90% of the emitted infrared radiation is in the far infrared[111,161].

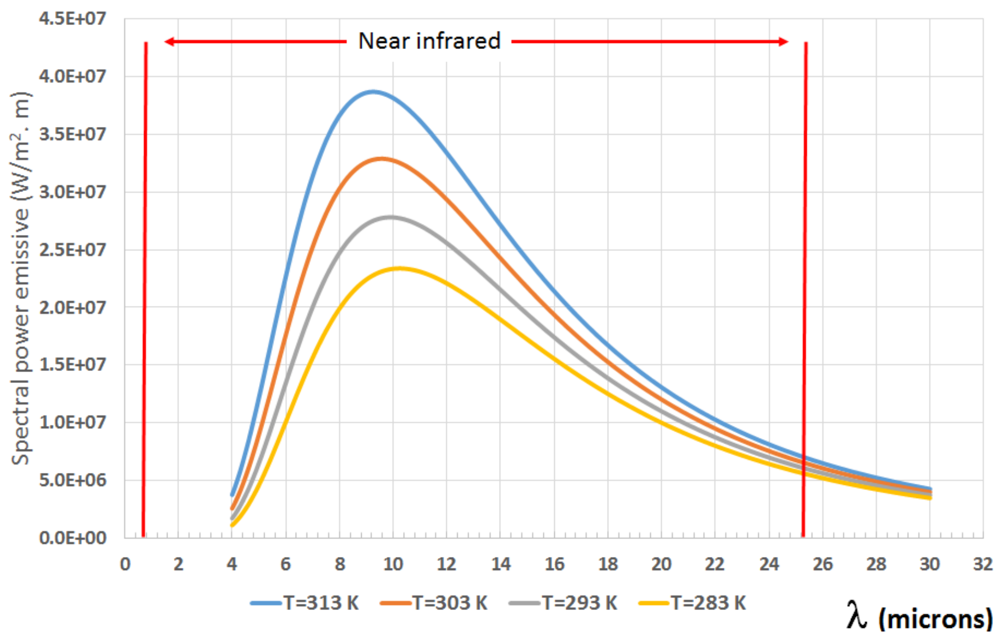


Figure 1.7. Spectral emissive power of the black body at the following temperatures: 313 K (40°C), 303 K (30°), 293 K (20°) and 283 K (10°). At these temperatures, all spectral emissive power is inside of the infrared spectrum

Stefan-Boltzmann's law was deduced by Josef Stefan in 1879 on the basis of experimental measurements made by John Tyndall and was derived from theoretical considerations by Ludwig Boltzmann in 1884. Stefan-Boltzmann's law expresses that the total emissive power or radiated energy from a black body is proportional to the fourth power of its absolute temperature:

$$E = \sigma * T^4 \tag{1.3}$$

where E is the total emissive power (W/m^2), σ is the Stefan-Boltzmann´s constant (5.67*10^{-8} W m^{-2}*K^{-4}), and T is the temperature in kelvin.

Small changes in temperature resulted in big changes in the emissive power. This is really easy to see in the Stefan-Boltzmann's equation because the temperature is expressed as the fourth power. This relationship is very important because it explains how the calculation of the temperature from the emissive power is very sensitive and allows differentiation of areas at different temperatures, as they will have different emissive powers. It can be considered that the Stefan-Boltzmann's law is the fundamental law that governs IRT.

For real surfaces, the Stefan-Boltzmann's equation is modified with the incorporation of emissivity (equation 1.4). The concept of emissivity and also the consequence of this parameter in the equation will be explained in the next section. Most of the infrared cameras and radiation thermometers made the calculations using the modified Stefan-Boltzmann's equation[224]:

$$E_0 = \varepsilon * \sigma * T^4 \qquad (1.4)$$

where ε is the value of the emissivity (ε).

After knowing the physical laws that explain the calculation of the temperature using infrared radiation, it is important to understand the radiative characteristics of one body in terms of its absorptivity, emissivity, reflectivity and transmissivity.

Radiative Characteristics of the Bodies

Infrared radiation that arrives on a body can be absorbed, reflected or can pass through the body, depending on its physical characteristics (Figure 1.8). These characteristics define the behaviour of one body in relation to the infrared spectrum:

- Absorptivity (α): capacity of one body to absorb infrared radiation.
- Emissivity (ε): capacity of one body to emit its own infrared radiation. This parameter corresponds to the absorptivity (α = ε).
- Reflectivity (ρ): capacity of one body to reflect the infrared radiation that comes from the environment.
- Transmissivity (τ): capacity of one body to let pass through it the radiation. If radiation is not transmitted through the body, this body it is therefore called opaque.

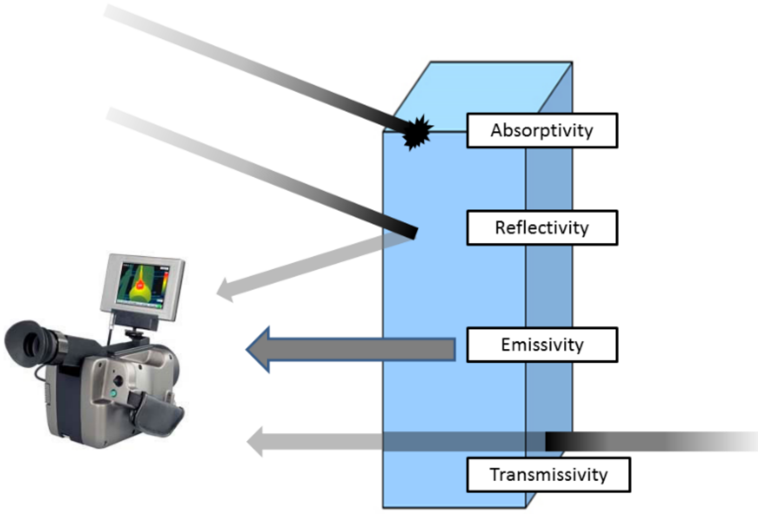


Figure 1.8. Radiative characteristics of a body.

The proportion of these components in a body are expressed by the following equations:

$$\alpha + \rho + \tau = 1 \quad (1.5)$$

Destinations of the incident radiation in a body, where α is the absorbed, ρ is the reflected (ρ) and τ is the transmitted radiation.

$$\varepsilon + \rho + \tau = 1 \quad (1.6)$$

Sources of the outgoing radiation of a body where ε is the emitted, ρ is the reflected and τ is the transmitted radiation.

As we discussed in the previous section, a black body is an ideal body with values of emissivity and absorptivity equal to 1, and without reflectivity and transmissivity, and is therefore considered to be the perfect infrared emitter surface.

In the calculation of the temperature of a body, it is essential, in order to have an accurate calculation, that the body presents a zero transmissivity and an emissivity as close as possible to 1. Bodies with high values of reflectivity will result in temperature calculations with many errors because most of the outgoing radiation comes from the environment.

Behaviour of different bodies can be different in the visible region compared with the infrared and for this reason it is essential to know the radiative characteristics of the bodies. One important example is water. In the visible region, water is more transparent and reflective. However, in the infrared, the characteristics of water are different. In the infrared, the water is opaque, with a higher emissivity than 0.9[157]. In this sense, knowing the emissivity of a body is of vital importance. Emissivity is a number ranging from 0 to 1, and it can be interpreted as the ratio of the actual amount of infrared energy emitted compared with the theoretically perfect amount that could be emitted (black body)[19].

In sports science, the most important "material" is usually the skin. Skin emissivity was determined with values between 0.97 and 0.99 with an standard deviation of 0.01 by different studies[191,207,214]. In scientific studies, an emissivity of 0.98 is commonly established[77,158]. This means that the skin is a good emitter of infrared radiation and it is possible to accurately calculate its temperature.

After all these physical concepts, it is possible to better understand how IRT cameras can measure temperatures from the detection of infrared radiation. The next section of the introduction will focus on the use of IRT in sports science.

Key Points

- Infrared thermography has a large number of applications in different fields: military, factories, medicine, veterinary, etc.
- All the bodies that present a temperature above absolute zero emit infrared radiation and infrared cameras are capable of capturing this radiation.
- Radiated energy from a black body is proportional to the fourth power of its absolute temperature. This relationship explains the high sensitivity of thermal cameras.
- Skin is a good emitter of infrared radiation (emissivity of 0.98), which is important in sport science studies, because it is commonly the "material of interest".

1.2. The use of infrared thermography in measuring thermoregulation in sports science

1.2.1. Thermoregulation

Concepts about thermoregulation are essential for the prediction and/or the interpretation of the thermographic results of an experiment. Human thermoregulation can be defined as the integrative physiological responses of the body with the aim of maintaining core temperature within a few tenths of a degree of 37°C, despite a wide range of activities and environments[43,224]. These responses are coordinated mainly by the hypothalamus[43,128,139]. The hypothalamus integrates inputs from the temperature of the hypothalamus itself, the core and the thermoreceptors in the skin[41,43,128].

In this section, the three heat transfer processes detailed previously (Sect. 1.1.2; convection, conduction and radiation) are explained putting in context how they occur in the human body (Figure 1.9). Also, it is necessary to add human body thermoregulation in terms of the sweat evaporation and respiration.

- **Conduction.** In the human body, the conduction transference is between the different structures of the body, and also between the human body and clothing. Regarding heat transference through the human body tissues, it is a slow process; in the limbs, it is mainly dependent on the temperature gradient between muscle and skin and the thermal conductivity of muscle[95]. For this reason, transference of heat by conduction is facilitated when the temperature gradient between the muscle and the skin is increased, occurring mainly by sweat evaporation during exercise or during exercise in cold environments[59,95]. Breathability and insulation properties of clothing will have an effect on this type of heat transfer. However, conduction heat loss is usually considered negligible unless the skin is in contact with highly conductive surfaces for a prolonged duration[57].
- **Convection**. In the human body, this convection could be explained by the heat dissipation via the blood flow; when blood flow through the core is heated, and that blood in turn heats the skin as it passes through. Convection also explains the effect of the wind on the skin. Wind convection also facilities sweat evaporation[57]. This heat transfer system is very important when the body is immersed in water. In this setting, it is considered that the 100% of heat loss occurs via convection due to the contact between the skin and the water. In the sports world, it is of

interest to consider clothing insulation because it can promote or reduce convective heat loss.

- **Radiation.** Commonly, the human body emits more heat radiation than it absorbs, due to the environment being cooler. However, in close proximity to warm objects or hot environments (e.g.,a fire), this radiation is absorbed by the body, resulting in the body heating[224]. During outdoor exercise, the most common source of radiation is the sun[57]. Radiation is heat transfer that detects IRT, while conduction and convection are important for proper IRT protocols. Furthermore, conduction and convection could affect skin temperature, and therefore human radiation.

- **Sweat evaporation** is considered to be the main mechanism of heat dissipation during exercise. Evaporation results in a temperature decrease of the skin surface[111]. It is important to note that it is the evaporation of sweat that is responsible for the temperature decrease and not the sweat production itself. Sweat rate is related to the ambient temperature, exercise intensity and absolute heat production[57]. In addition, the amount of evaporation is inversely proportional to the relative humidity of the air[224]. In an environment with 100% relative humidity, humidity could be condensed in the body resulting in a heat gain, at the same time as heat is lost by evaporation[224].

- **Respiration.** During respiration (specifically in the expiration), heat is lost to the environment via convection and evaporation[57]. Heat loss by respiration is higher in cold and dry environments; however, there is a low contribution of respiration in whole-body heat loss[57].

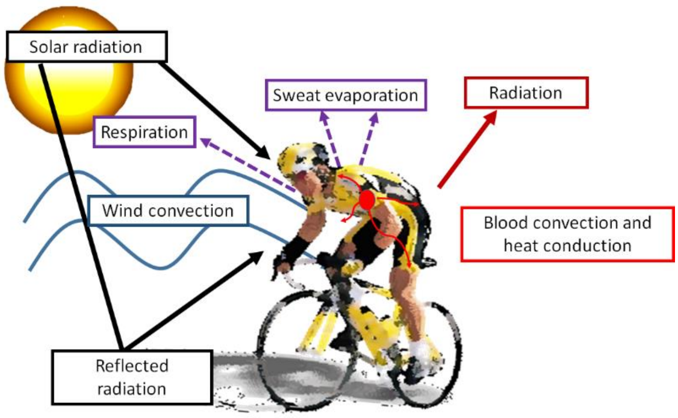


Figure 1.9. Heat exchange between the body and the environment during exercise.

All these concepts and the concept of heat production are expressed together in the heat balance equation (first law of the thermodynamics), which is commonly used in thermoregulation studies:

$$M\text{-}W = (K + C + R + ESK) + S \quad (1.7)$$

where M is the rate of metabolic heat production, W is the rate of mechanical work, K is the rate of conductive heat loss, C is the rate of convective heat loss from the skin, R is the rate of radiative heat loss from the skin, ESK is the rate of evaporative heat loss from the skin, and S is the rate of body heat storage.

Heat production is the difference between metabolic heat production and the rate of mechanical work (M-W). Metabolic heat production was defined by Cramer and Jay[57] as “the rate of free energy released from the catabolism of carbohydrate, fat, and amino acids to resupply adenosine triphosphate (ATP) for cellular activities such as biosynthesis, transport, and muscular contractions”. Some of this energy is converted in external work (W) and the rest is converted into heat[57]. For this reason, heat production is the difference between all the energy produced (M) and the energy used for external work (W). The body is very inefficient in transforming the energy in mechanical work, and between 30–70% of the energy produced, depending on activities, results in thermal energy [95]. Heat production is usually calculated by the combination of ergometers, which measure the work and indirect calorimetric measurements (gas exchange) that measure metabolic heat production[57]. Exercise results in an increment in heat production that the body needs to dissipate. It is possible to exemplify how heat production increases with the intensity of the activity using different values of heat production. The heat production of sleeping, walking, cycling at 250 W and running at 16 km/h are 1.0, 4.0, 13.3 and 20.0 W/kg, respectively. Thermoregulation usually aims to eliminate the excess of heat produced.

Thermoregulatory responses are different depending on the thermal environment (neutral or moderate, cold and warm/hot)[43]. Exemplification of the two most extreme scenarios help us to better understand human thermoregulation.

In **warm/hot environments**, the main objective of human thermoregulation is heat dissipation. This heat dissipation is mainly produced by two mechanisms, cutaneous vasodilation and sweat evaporation[43,224]. Cutaneous vasodilation consists of the increase of skin blood flow in order to transfer the heat from the core to the body by the blood[43]. It is important to considerer that during exercise in hot environments, there is a "competition" between the active muscles and the skin for the available cardiac output, resulting in an increase in cardiovascular stress[97]. In sweat evaporation, the evaporation reduces the skin temperature. It increases the heat transfer from the core to the skin[43]. In addition, heat acclimation (heat exposure during a time) produces adaptations in these mechanisms[171]. Core temperature is reduced due to an increase in skin blood flow and sweating[171]. Furthermore, the volume of plasma is increased in order to minimize dehydration during exercise[171].

In cold environments, the main objective of human thermoregulation is heat conservation. Two of the main mechanisms of heat conservation are cutaneous vasoconstriction and thermogenesis[43,224]. Cutaneous vasoconstriction is reduced in order to avoid heat dissipation via convection. Thermogenesis (increase of the body heat production) is produced mainly by shivering. Shivering consists of involuntary contractions of skeletal muscle with the aim of producing more heat[43]. Cooling acclimatization is a complex process with different patterns depending on the type and severity of chronic cold exposure[41]. The first adaptation is habituation, consisting of a less pronounced physiological responses (e.g., vasoconstriction and shivering)[41]. The second adaptation is an increase in heat production due to an exaggerated shivering or development of nonshivering thermogenesis[41]. Finally, there are insulation-related adjustments resulting in an enhanced vasoconstrictor response to cold exposure[41].

Physical exercise and repetitive effort is a challenge to thermal homeostasis[95,139,164]. It is well established that physical activity induces complex thermoregulatory processes where part of heat in excess is dissipated through the skin to the external environment[95]. While the increase in core temperature occurs proportionately to the exercise intensity, skin temperature is mainly related to environmental conditions and the heat loss capacity[93,194,204]. An increase in core temperature during exercise affects also skin temperature, as heat in excess is transferred from the inner to the superficial parts of the body via cutaneous vasodilation, where is dissipated thorough the skin[92]. Although during the initial phases of the exercise, skin temperature tends to decrease due to the cutaneous vasoconstrictor response to exercise[217], after that, skin temperature primarily increases when blood flow shifts from internal tissues to the skin, thus dissipating heat in excess related to an increased metabolic activity[129,190]. Therefore, an isolated increment in skin blood flow accompanies an increment in skin temperature[45]. However, this increment in skin blood flow is commonly accompanied by other processes of heat dissipation, such as convection, radiation and sweat evaporation[48,204]. As in many situations, skin temperature can result in a decrease instead of an increase.

During exercise, **clothing** affects heat exchange. Clothing increases insulation and reduces the convective and evaporative heat loss[94]. Furthermore, if the clothing is excessive, it can increase sweat production in response to decreasing core temperature, but this is not accompanied by efficient sweat evaporation[94]. Sweat or vapor may travel through clothing and it may be sorbed and desorbed by the textile fibers, or may condensate in the outer layer if these are colder than the skin[106]. This could result in an increase of the skinwetness and then a lower thermal comfort. For these reasons, usually the demands for sport clothing are based on allowing sweat evaporation[94]. However, these demands will be different for each kind of environment.

After exposing the basis of thermoregulation, now it is possible to show the different application of IRT in sport science.

1.2.2. Application of infrared thermography in sport science

In recent years, IRT has become a popular technique to determine the temperature of human skin during exercise[1,3,9,87]. In order to know the trend of the number of publications performed in sport science using IRT, it was performed a search in two databases: PubMed (Medline) and ScienceDirect. The key words used in the online search included “thermography”, “thermovision” or “thermal imaging”, and “exercise” or “sport”. Boolean operators, ‘OR’ and ‘AND’ were used to combine within and between the search terms of the subject areas.

Figure 1.10 shows the result of this online search. Although there had already been a gradual increase in the number of publications in the past, this rate of publication has increased considerably in recent years. In this sense, the number of publications in the first 7 years of the current decade (2011–2017: 37 articles published in PubMed and 57 in ScienceDirect) is more than the double that in the previous decade (2001–2010: 14 articles published in PubMed and 6 in ScienceDirect). The progressive increase in the number of studies using IRT in sport science could be explained by some of the technique’s advantages. IRT is a non-invasive method that can be used at a distance, and does not interfere in human thermoregulation, unlike other skin measurement methods[9,111] (Table 1.1). Additionally, this important increase in the number of studies in the last 7 years could be explained by the great decrease in the price of infrared cameras in the last years.

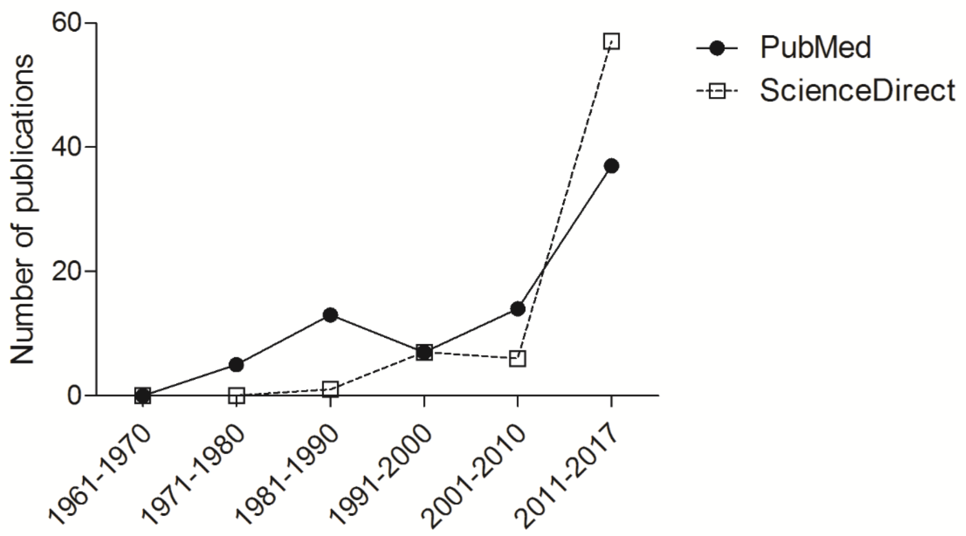


Figure 1.10. Number of papers published in PubMed (Medline) and ScienceDirect using infrared thermography in sport science.

Table 1.1. Advantages of the infrared thermography in the human assessment (modified from De Andrade Fernandes et al.[9]).

ADVANTAGES	Why is it an advantage?
1. Non-invasive method.	1. There is no physical interaction with the subject.
2. Distance method.	2. It is possible to take the measures without interference in the actual performance of the subject.
3. It does not interfere in the human thermoregulation	3. There is no interaction that can affect skin temperature during measurement (e.g. isolation and reduction of sweat evaporation due to tape attachment of contact sensors).
4. Freedom of movement during exercise.	4. Being able to measure without additional contact with the subjects (or with wires), means that movement patterns have more chances of occurring naturally.
5. Possibility to define the region of interest with small or large regions.	5. As many different regions as desired can be measured and monitored. Not just a single point is measured as with thermocouples, for example.
6. High sensitivity, accuracy and reproducibility.	6. Can provide very good and reliable results, if the experiment is performed accordingly to the methodological requirements.
7. Possibility of video recording with some camera models.	7. Measurements can be taken at different times or even during an entire performance that can significantly result in variation of skin temperature.

In addition to the number of publications, it is important to know in which fields or applications the studies were published, in order to see which are the most important uses of IRT in sports science. In this sense, in this search, it was defined the following categories:

- **Thermophysiology**: IRT studies focused on the assessment of human thermoregulation. All the studies that assessed the effect of exercise on skin temperature, the skin temperature distribution in relation to the sport or exercise, the differences in skin temperature between different groups (e.g., trained vs. untrained; young vs. old; woman vs. men), the effect of sport performance (e.g., VO_{2max} on skin temperature), and so on, were included in this category.
- **Sports medicine**: IRT studies related to the assessment of the effect of injury or disease in humans. In addition, this category included all studies that presented a clinical/medical perspective.
- **Animals and Sport**: IRT studies conducted with animals that are involved in an exercise or a sport. Papers with a clinical perspective involving animals were also included in this category. In this sense, this category would include the previous two categories, but with an animal focus.
- **Clothing**: IRT studies focused on the assessment of clothing in a specific sport or during exercise.
- **Methodology/developments**: studies that investigated the methodological aspects of the IRT and developments of the technique. Studies that compared IRT with other techniques (e.g., thermocouples), analysis of the data, determination of the regions of interest, guidelines, and so on, were included in this category.
- **Reviews**: reviews and overview papers about IRT in sport science were included in this category.

Papers obtained in the online search in PubMed and ScienceDirect (Figure 1.10) were categorized into the defined applications or fields (Figure 1.11). During the approximately 40 years that IRT has been used in sports science, the application that has been most used is sports medicine and thermophysiology, representing each category the 36% of the total number of papers. In other application fields, the percentage of published articles is much smaller. It is important to comment that only papers that are focused on sports science were included in the methodology and review categories. If all studies related to IRT in human assessment were included in these categories, without a focus on sport science, these sections would probably have higher frequency of papers. Sports medicine, thermophysiology and clothing were the categories selected to exemplify the application of IRT in sports science.

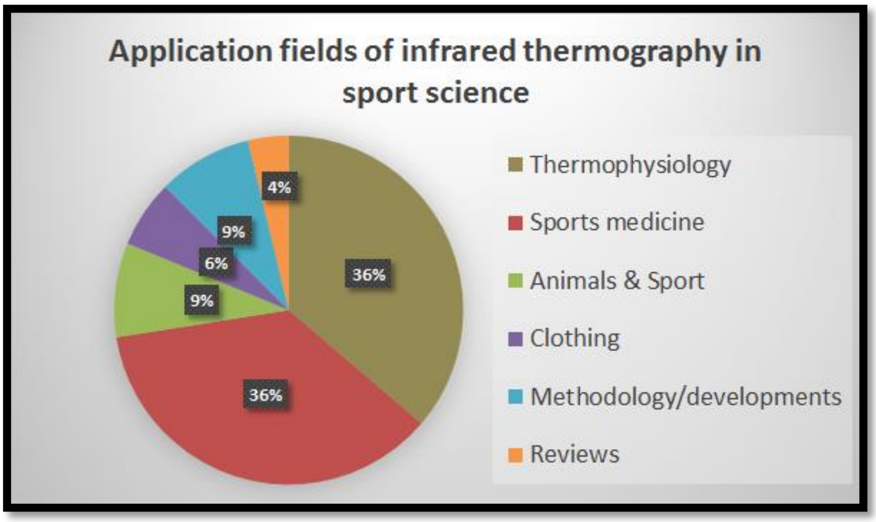


Figure 1.11. Percentage of the papers published using infrared thermography in sport science in the different applications or fields.

Infrared thermography in sports medicine

In sports science, IRT studies began approximately 10 years after those of medicine. Furthermore, the first IRT studies in sports science focused on its application in sports medicine. The first IRT study in sports science, entitled "Thermography in sport injuries and lesions of the locomotor system due to sport" by Keyl and Lenhart, was published in 1975 in the German journal Fortschritte der Medizin[130] and was written in German. In this study, the authors examined 82 patients and 50 athletes with different injuries. The main result of the study was the observation of hyperthermia in the injured area.

Currently, sports medicine is probably one of the most important fields of application for IRT, certain data exemplifying the importance of IRT in sports medicine. Gomez Carmona observed a reduction of 60% in injuries per season of a professional football team by applying IRT in their daily routine[37]. With this injury reduction, it was estimated that the use of IRT could save 7.5 million euros for the Spanish First Division League in medical expenses due to injuries[76].

Applying IRT in sports medicine is mainly based on the identification of thermal asymmetries by comparing bilateral body areas[78]. Thermal symmetries were explored in different studies assessing the normal thermal behaviour of the participants or the risk of injuries[20,200,222]. Vardasca et al.[222] defined thermal symmetry as "the degree of similarity between two areas of interest, mirrored across the human body's longitudinal main axes which are identical in shape, identical in size and as near identical in position as possible". Thermal symmetry assessment is considered a valuable method to assess the physiological normality/abnormality in sports medicine[111,222], as asymmetries higher than 0.5–0.7°C are usually associated with a dysfunction in the musculoskeletal system[163,220,222]. An injury is often related to variations in regional blood flow. Changes in blood flow affect skin temperature, which can increase in the case of an inflammation, or decrease in the case of tissues with poor perfusion, degeneration or reduced muscular activity[111,185,234] (Figure 1.12). Individuals with overuse and traumatic injuries could present an alteration of skin temperature and thermal symmetry[111,185].

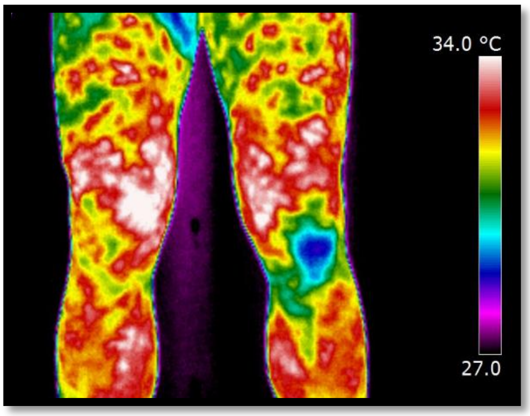


Figure 1.12. Example of the presence of undiagnosed injury in the left knee.

Thermal asymmetries could appear before other indicators such as pain, which is extremely useful for reducing injury risk[78]. However, IRT can also be useful after an injury occurs, given that it is possible to monitor how thermal asymmetry evolves in order to check the evolution of the rehabilitation process[78,177] (Figure 1.13).

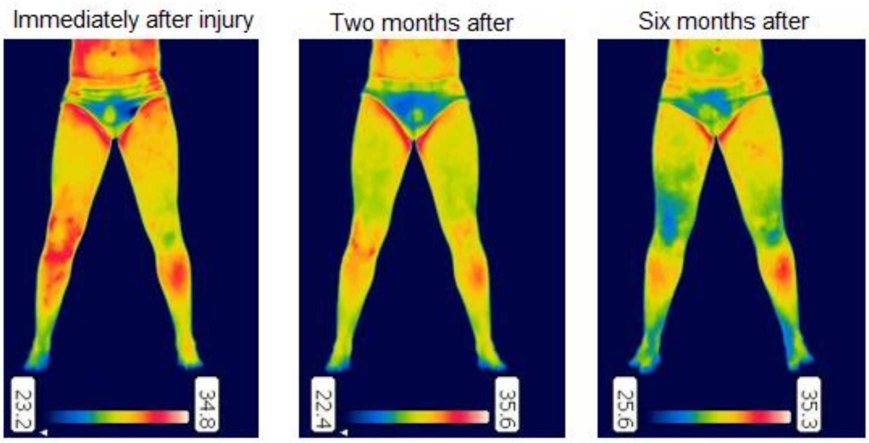


Figure 1.13. Evolution of an anterior cruciate ligament injury in the right knee. Figure adapted from Fernández-Cuevas et al.[78].

Infrared thermography in sport thermophysiology

Assessing thermoregulation through skin temperature analysis can be widely applied using IRT. Firstly, some studies analysed the effect of exercise on skin temperature. Relevant investigations were the studies of Clark and Mullan[52], Zontak et al.[236] and Merla et al.[156].

The study of Clark and Mullan[52] is an important paper because it was the first study using IRT in sport science in an English language, published in The Journal of Physiology in 1977. The study was titled “Skin temperature during running–a study using infra-red colour thermography.” Although the main limitation of this study is that was performed with only two participants, the study deals with different relevant aspects of IRT, that keep being topics of interest until the present, such as the effect of wind, the comparison of infrared thermography with thermocouples, the comparison between performing exercise in a laboratory or outdoors, the effect of the curvature of the body or sweat on thermal data, etc. Clark and Mullan analysed the body temperature distribution before running[52]. They described that the body temperature distribution depended on the following factors: body composition (i.e., body structures or regions with a higher proportion of fat presented lower temperatures), cutaneous blood flow (related to the warming of the hands), sweat rate evaporation, and muscle role (i.e., higher skin temperatures were recorded in the regions of the active muscles). In addition, they observed a decrease in the skin temperature during running. Although this variation was different in each body region, an average value could be considered 5°C. This decrease was associated with the sweat evaporation.

Another relevant piece of research was the study performed by Zontak et al.[236]. In this research, they had the objective of characterizing skin temperature response to cycling exercise using infrared thermography. They decided to measure the skin temperature of the hand because this area has a high skin blood innervation, resulting in a high variation of the skin temperature due to exercise (Figure 1.14.A). Two experimental protocols were assessed, an incremental workload and a stable workload. In the incremental workload, they observed a decrease in skin temperature during all exercise; and in the stable workload, a decrease in the skin temperature was first observed with a posterior increase in the skin temperature in the middle of the test (Figure 1.14.B)[236]. The authors suggested that these results depend on the vasodilator/vasoconstrictor balance of the skin blood flow, which depends mainly on the blood requirements for the active muscles and the skin (heat loss requirements)[236].

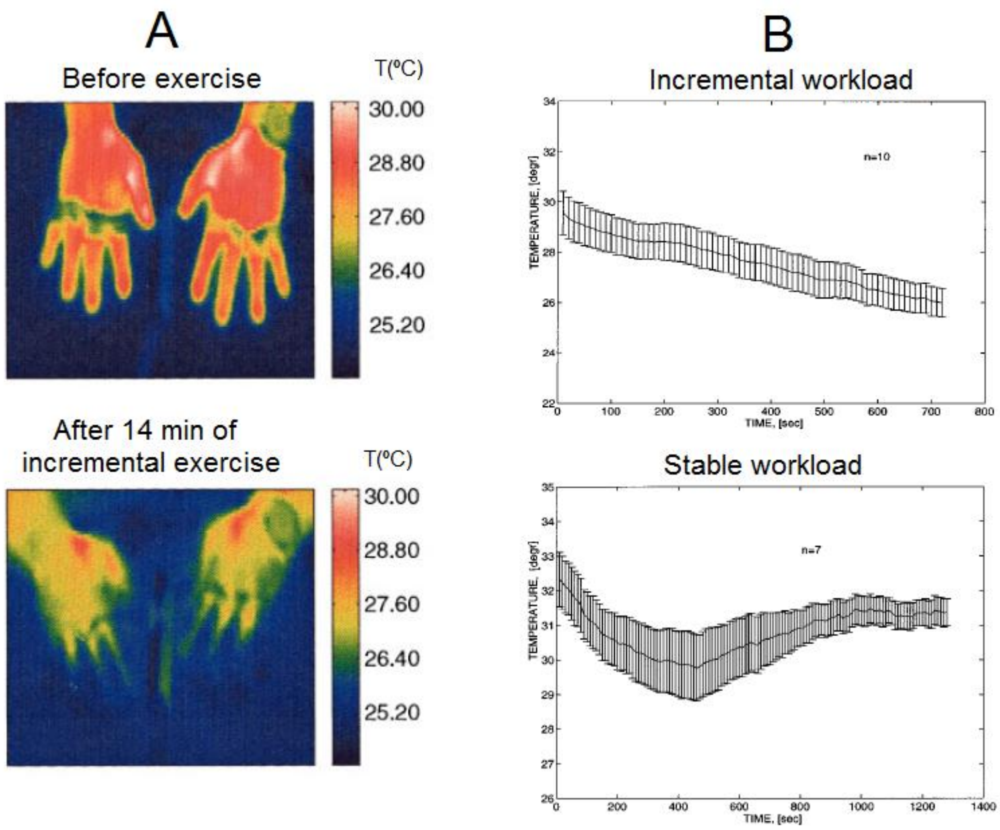


Figure 1.14. A. Example of hands thermographies from the study of Zontak et al.[236] corresponded to a cycling exercise. B. Graphs of the skin temperature dynamics during the incremental and the stable workload of their cycling tests. Figure adapted from the figures of Zontak et al.[236]

Merla et al.[156] investigated the whole body anterior skin temperature modifications in well-trained subjects during an incremental running test until exhaustion. They observed a continuous skin temperature decrement occurred during exercise, which was attributed to the continuous vasoconstrictor response (Figure 1.15). Also, they observed an increment until basal values in the recovery phase. Results were very similar to those of Zontak et al.[236].

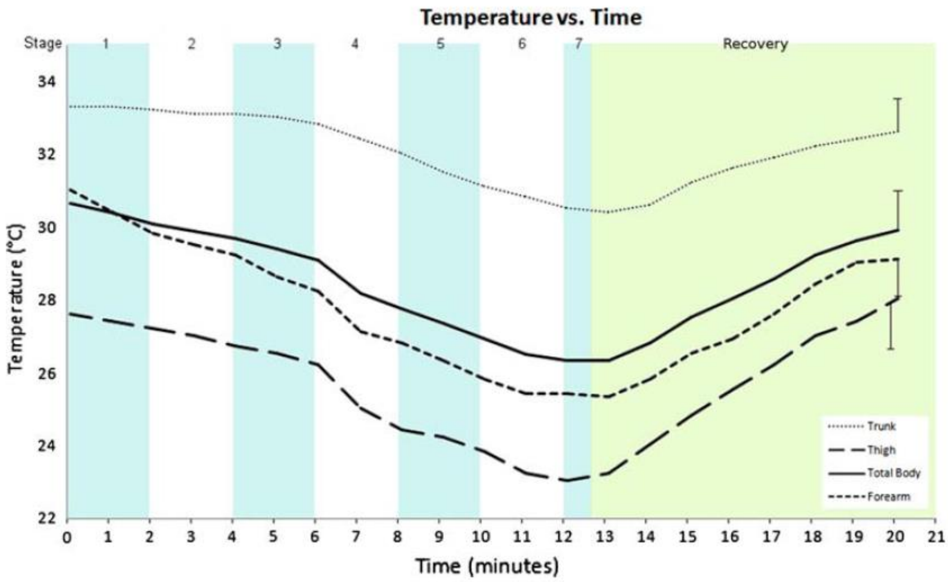


Figure 1.15. Results obtained in the study of Merla et al. Figure obtained from Merla et al.[156]

Although different studies observed reductions of skin temperature during and after exercise[1,11,51,80,88,156], other studies observed increments[87,121,180]. Different factors could explain these differences. Firstly, the Region of Interest (ROI) analysed. De Andrade Fernandes[9] observed a decrease of the mean skin temperature of the body after running, but an increase in the thigh. Also, increases could be produced on the foot during running due to the repetitive friction between the foot and the footwear, the footwear insulation, and a higher vascularization of the foot[180,196]. On the other hand, the type of the exercise could be an important factor. Resistance exercise with body weight studied by Formenti et al.[87] induced an increase in skin temperature of the calf area, and resistance exercise with very low load (i.e., 1 kg) studied by Ferreira et al.[80] did not produce any modifications on active muscles. Resistance exercises may have a lower sweat production (in some cases non-existent), contrary to what happens to other exercises (e.g., cycling and running) that result in a whole body sweating. However, other factors could be the explanation of these differences[77]: the duration of the exercise, environmental differences (i.e. differences in relative humidity and room temperature), differences between participants in fitness level, age, body composition, etc. Regard to environmental factors, James et al.[121] observed increments of skin temperature during exercise in a hot environment.

On the other hand, some studies assessed the relationship of the skin temperature with other thermoregulatory variables during exercise. Formenti et al.[88] studied the skin temperature response to two types of resistance exercises modulating the amount of skin blood flow. The rationale was that low intensity resistance training with slow movement and tonic force generation has been shown to create blood flow restriction within muscles. They observed that the slow movement exercise resulted in a lower rate of change of skin temperature which could be associated with the lower skin blood flow of this exercise[88]. On the other hand, different studies observed a negative relationship between heart rate and skin temperature during exercise[11,160]. Authors suggested that the increase of heart rate with the intensity is related with a reduction of skin temperature due to a higher skin vasoconstriction and sweat rate[11,160]. Finally, a recent study aimed to validate the indirect measure of the core temperature using the inner canthus of the eye temperature using IRT during exercise, by the comparison with the intestinal core temperature[75]. The authors observed poor agreement between both methods, suggesting that the measurement of the inner canthus of the eye temperature is a not a valid method to measure core temperature during exercise[75].

To conclude this summary of the literature, some studies assessed the effect of fitness level on skin temperature. Chudecka and Lubkowska[48] studied a team of handball players, and they obtained a regression model when the participants with a higher fitness level (by VO_{2max}), higher percentage of the maximum heart rate during the training season, and lower skin-fat fold on the arm, presented a higher decrease in skin temperatures after exercise. The reduction in the skin temperature after the training session was primarily attributed to the efficacy of sweat evaporation mechanism[48]. Merla et al.[155] observed that trained participants presented a higher decrease of skin temperature than untrained during an incremental cycling test. Formenti et al.[87] observed during a calf rise exercise that trained subjects had a higher and more quickly increase of their skin temperature with respect to untrained subjects. Finally, Abate et al.[1] observed that with respect to baseline, trained subjects exhibited a significant temperature decrement, while no difference was observed in untrained subjects.

Key Points

- Skin temperature during exercise is influenced by the thermoregulation processes: heat loss mechanisms (conduction, convection, radiation, respiration and sweat evaporation) and heat production. In addition, these processes are dependent of other important factors: environmental conditions (temperature, humidity, wind speed and radiation), clothing, exercise characteristics (type, duration and intensity), etc.
- It is possible to consider the 1970s as being the beginning of the use of IRT in sport science; since then, the number of scientific publications has gradually increased, and the number of studies published between 2011 and 2017 is more than the double that the amount published in the whole previous decade.
- Advantages of IRT in the measure of skin temperature during exercise are: non-invasive and distance method that not interfere in human thermoregulation and human movement, high sensitivity, accuracy and reproducibility, and possibility to record thermography video.
- Almost of the sport research has been performed in two kinds of applications: sport medicine and thermophysiology. The use of IRT in sports medicine is mainly based in the identification of thermal asymmetries by comparing bilateral body areas. Thermophysiology application was mainly focused on assess the effect of exercise on skin temperature, the relationship of the skin temperature with other thermoregulatory variables during exercise, and the effect of fitness level on skin temperature dynamics.

1.3. Application of infrared thermography in cycling

1.3.1. Biomechanic and physiologic magnitudes of cycling

Before explaining how IRT can be applied to cycling, it would be useful to discuss some cycling concepts that are relevant to this PhD thesis. These concepts are peak power output, maximal oxygen uptake, cycling mechanical efficiency and neuromuscular activation during cycling.

The mechanical power delivered by the cyclist is the amount of mechanical energy produced, and, in cycling, this is usually expressed in watts[235]. In this sense, **peak power output** (PO_{max}) is usually used as a measurement to evaluate the cyclist's performance, using an incremental test in which the load increases over time until the cyclist cannot continue; the workload at that point is considered the PO_{max}[73]. PO_{max} is influenced by physiological parameters such as exercise economy, anaerobic capacity, and muscle power[206].

Maximal oxygen uptake (VO_{2max}), obtained from cycling incremental tests, is also another important predictor of performance[54,73,206]. Successful professional cyclists have high values of VO_{2max} [54,79]. In addition, metabolic thresholds are important data to analyse in order to know the fitness level of the cyclist and to prescribe training[167]. It has, therefore, been observed that the anaerobic threshold is an important predictor of endurance performance[54,167].

There are several calculations to be made relating to cycling efficiency, **gross efficiency** being one of the most commonly used[73,235]. Gross efficiency can be defined as the ratio of work generated compared to total metabolic energy cost[73,122,235]. Here, our organism is quite inefficient, since over 75-90% of the energy produced dissipates in the form of heat, while only 10-25% is used[235]. Although more research into this parameter is required, it has been suggested that gross efficiency is a key determinant of endurance cycling performance, and can be improved by training[73,122]. Other factors that have been observed to have an important effect on gross efficiency are cycling intensity and cadence[44,74,122].

Finally, the assessment of **neuromuscular activation** in cycling is an important methodology in order to analyse whether the cyclist’s activation pattern is correct, and if all the muscles are working correctly[26]. Neuromuscular activation is usually measured by surface electromyography and is affected by different factors such as workload, cadence, body posture, and fatigue among others[26,72]. The activation pattern that is commonly followed in cycling is showed in figure 1.16.

However, different studies have observed that muscles play different roles in cycling[27,126,178]. In this sense, it has been suggested that vastus lateral, vastus medial, rectus femoris, and gluteus are the muscles that are the main producers of power[27,126,178]. In contrast, the gastrocnemius is a muscle whose function is considered as an energy transference and movement control muscle[27,126,178].

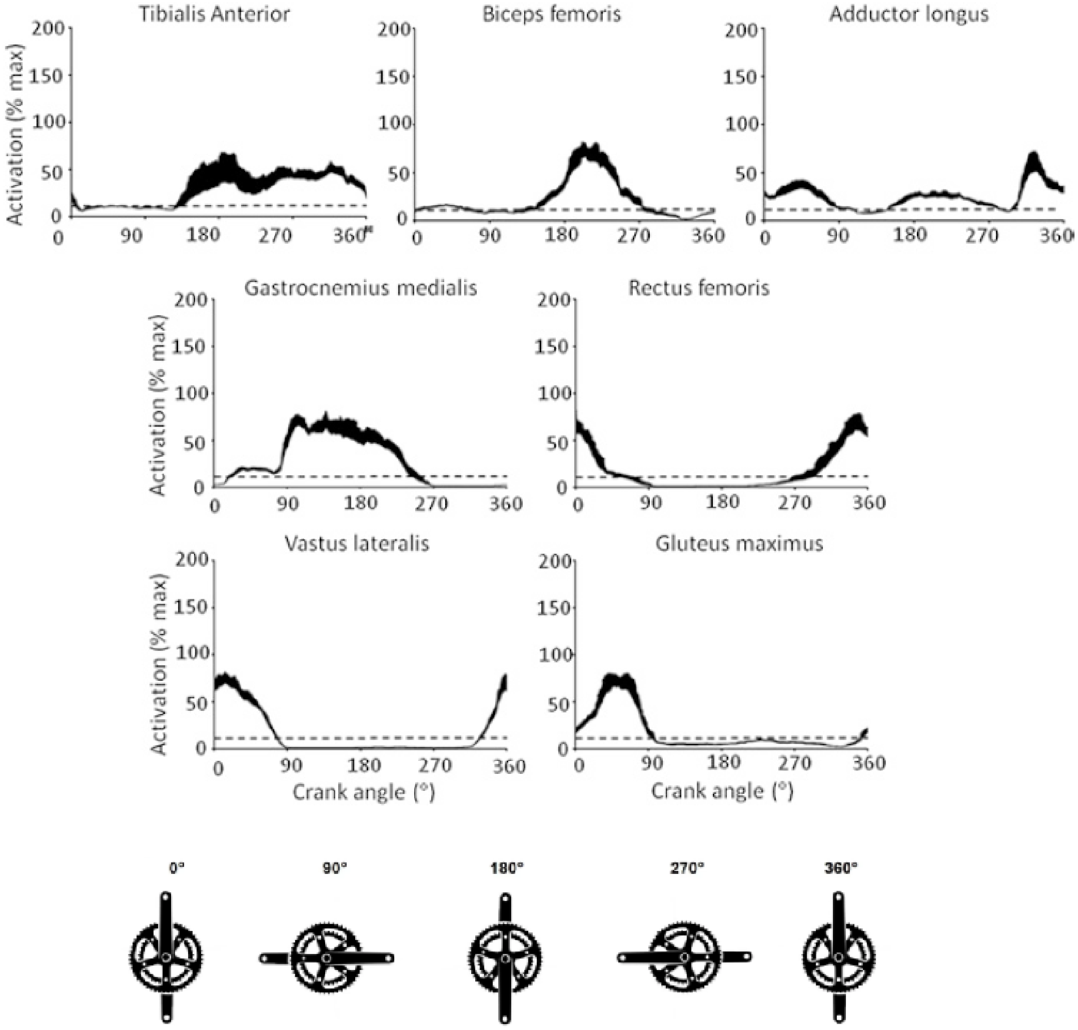


Figure 1.16. A cyclist's muscular activation pattern. Figure modified from Bini and Carpes[26]

1.3.2. IRT and cycling

This section will focus on IRT studies specifically aimed at cycling. Studies that have used cycling as a form of exercise, regardless of its characteristics as a sport, are not going to be taken into account[1,3,217]. These studies could have chosen another type of exercise like running without affecting their objectives.

There are few IRT studies focused on cycling. In relation to the areas of application mentioned in the previous section, it is important to note that no scientific studies related to the applicability of IRT in the prevention of cycling injuries have been found. The closest study to this area was the study performed by Arfaoui and colleagues[11], one of the objectives of which was to analyse the relationship between muscle mechanical imbalance and skin temperature imbalance in master cyclists[11]. The authors selected the calf for this analysis. They did not observe differences in skin temperature between both legs, concluding that mechanical imbalance does not necessary lead to a thermal imbalance[11]. Apart from this study, the few other studies found in the literature are related more with the field of thermophysiology.

In the study of Ludwig et al., similar response of skin temperature was observed for elite cyclists during the incremental cycling test as the results of the study of Merla et al.[156] on runners (Figure 1.15): a reduction in skin temperature during cycling, followed by a temperature increment after completing the exercise[144] (Figure 1.17).

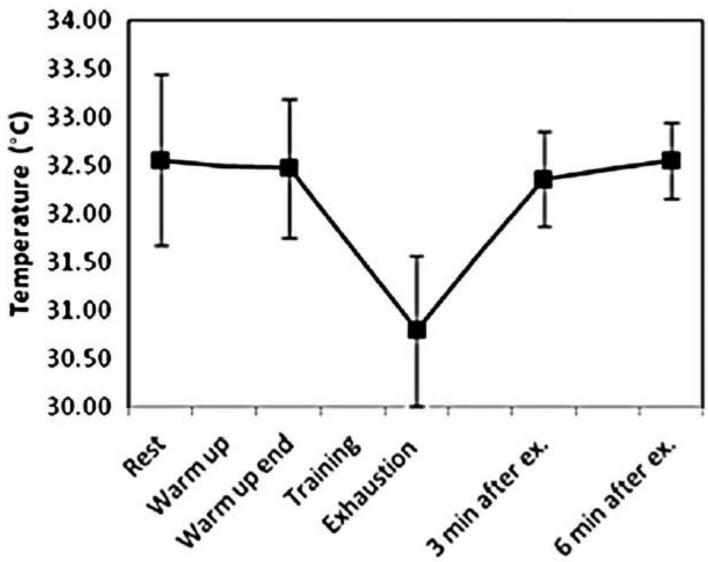


Figure 1.17. Results obtained in the study of Ludwig et al. Figure obtained from Ludwig et al.[144]

Some studies highlighted the presence of a hot-spotted pattern in participants during cycling exercise[11,144] (Figure 1.18). It was suggested that this pattern was the result of the presence of capilar vessels reaching the surface of the skin[11].

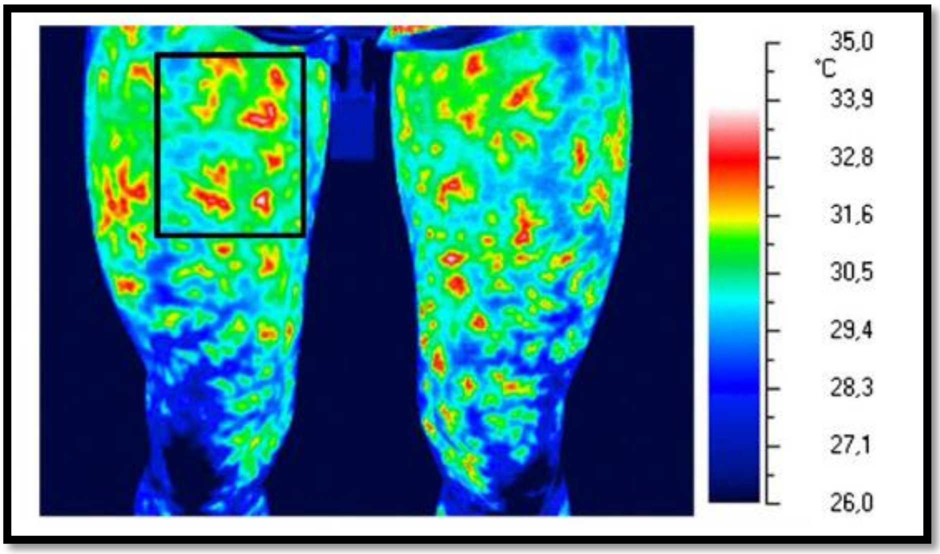


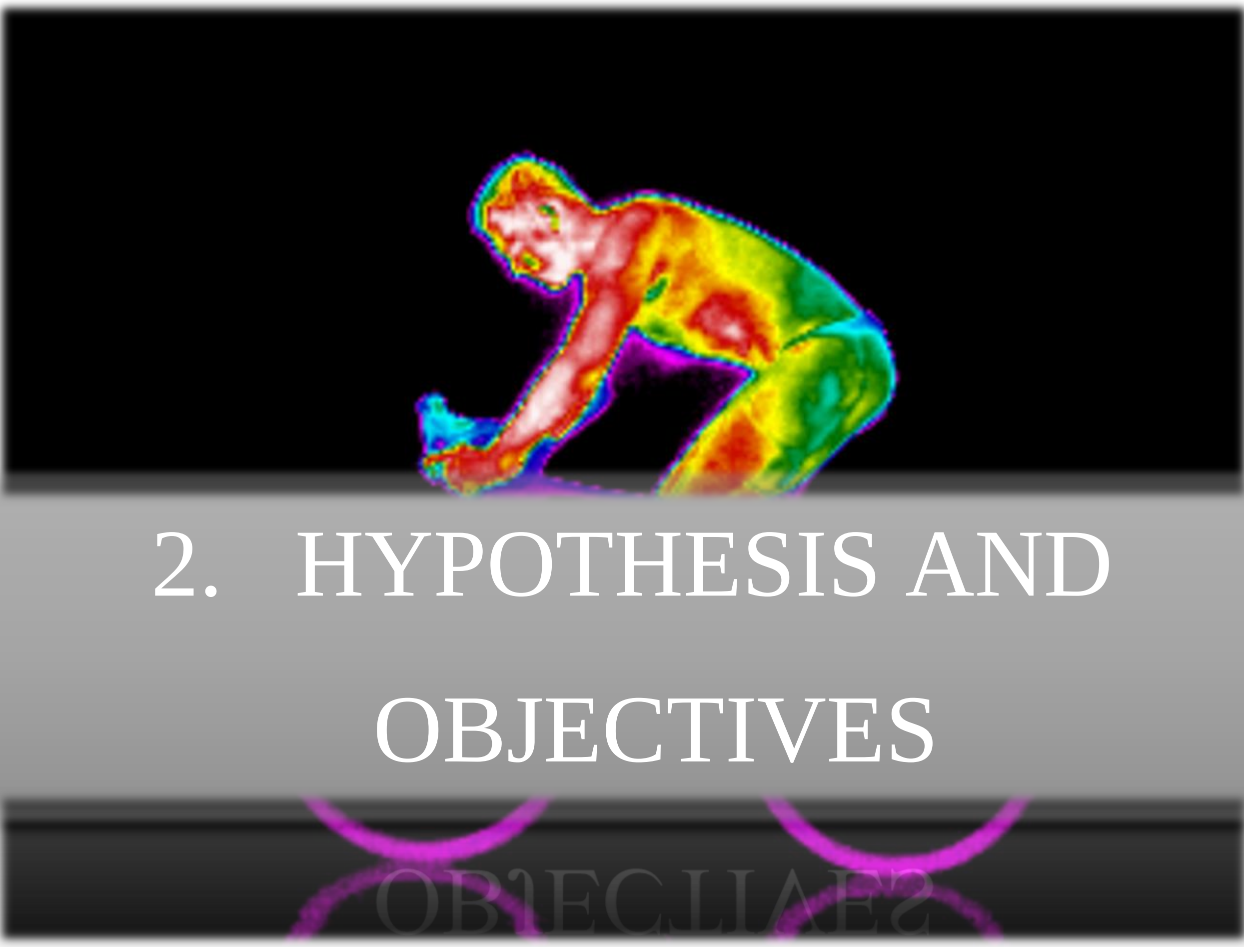
Figure 1.18. Example of a thermography presenting of a hot-spotted pattern. Figure obtained from Ludwig et al.[144]

Various studies have presented preliminary results with regard to the assessment of cycling efficiency by IRT. The research group of Bertucci, Duc and colleagues performed some experiments assessing the relationship between skin temperature and efficiency[21,68]. They observed that different values of cycling efficiency (gross efficiency, net efficiency and delta efficiency) were inversely correlated with changes in the skin temperature of vastus lateralis[68]. These results suggested that cyclists with higher efficiency presented a better capacity to decrease their skin temperature during a grade-cycling test, and showed that vastus lateralis can be an important ROI for measuring skin temperature in cycling. In addition, Cholewka et al.[47] assessed the relationship between the mean skin temperature of the body and cycling efficiency parameters (VO_{2max}, ventilation and workload). Their main result was that they observed an inverse correlation between workload and skin temperature[47]. The authors suggested that IRT could be a method helpful for assessing cycling efficiency[47].

There are many fields of cycling where the benefits of applying IRT have not yet been studied. One example is the assessment of the cyclist posture during cycling, which is a relevant topic in this sport[22,81,86,225]. Bike fitting aims to adjust the geometry of the bike to the body characteristics of the cyclist in order to maximize performance and to reduce injury risk[13,66,86,215]. Although the effect on injury risk and cycling performance of different posture variables such as knee flexion and trunk flexion during cycling have been extensively studied by the literature[14,22,174,216,221], there are no studies of the effect of these postures on skin temperature. Moreover, it is important to mention that bike fitting professional assessments are a growing industry providing a high quality service to cyclists[24].

Key Points

- There are not many thermographic scientific studies specifically aimed at applying it to the sport of cycling.
- Some preliminary results were obtained about the relationship between skin temperature and cycling efficiency, mainly showing that the more efficient cyclists presented a higher capacity of skin temperature reduction during exercise.
- There are many fields of cycling where the benefits of applying IRT have not yet been studied, for example its application in bike fitting assessments.



2. HYPOTHESIS AND OBJECTIVES

2. HYPOTHESIS AND OBJECTIVES

As presented in the introduction, IRT has been used in sports science as a method to measure skin temperature in the application fields of thermophysiology and injury prevention. However, there is a lack of information about whether IRT can be used in cycling to provide data on efficiency, performance and as a complementary technique in posture adjustment. More studies on these topics are required to evaluate the possible benefits of applying IRT in this field (e.g., cycling clubs and medical centres).

Moreover, although IRT was introduced in sports science approximately 40 years ago, its use in research laboratories has become more widespread in recent years, while still remaining a fairly new technique in sports science compared with other instruments such as electromyography, photogrammetry or indirect calorimetry. For this reason, more research is necessary to improve all the research stages: the methodology, image acquisition, data analysis, and the interpretation of the results.

The **general hypothesis** is that IRT may be a useful technique for assessing the efficiency, performance and posture of the cyclist.

This dissertation therefore has four **general aims,** which can be broken down into different specific objectives. These objectives were developed through five experimental studies, accounted for in the methodology section.

1. **VALIDITY AIMS:** To analyse the validity of IRT in measuring skin temperature in cycling.

   1.1. To compare IRT with the other most used method to measure skin temperature (thermal contact sensors) in a moderate cycling scenario (experimental study 1).

   1.2. To analyse the effect of sweat on thermographic measures after carrying out an aerobic cycling exercise (experimental study 1).

2. **EFFICIENCY AIMS:** To study the applicability of IRT in the assessment of a cyclist´s efficiency.

   2.1. To determine the influence of cycling intensity on skin temperature (experimental study 1).

2.2. To determine the relationship between skin temperature and core temperature after cycling exercise (experimental study 1).

2.3. To assess the relationship between neuromuscular activation (measured using surface electromyography) and skin temperature (measured using IRT) during cycling exercise (experimental study 2).

2.4. To assess the relationship between skin temperature, performance (power output), and predictive performance measures (e.g., VO_{2max}) (experimental study 3).

2.5. To compare the differences in skin temperature between two different groups (Cyclists vs. Non-Cyclists) (experimental study 3).

3. **POSTURE AIMS:** To assess the applicability of IRT as a complementary technique technique in adjusting the posture of the cyclist.

3.1. To assess the level of perception of comfort, fatigue and pain in the different saddle heights that will be analysed by IRT (experimental study 4).

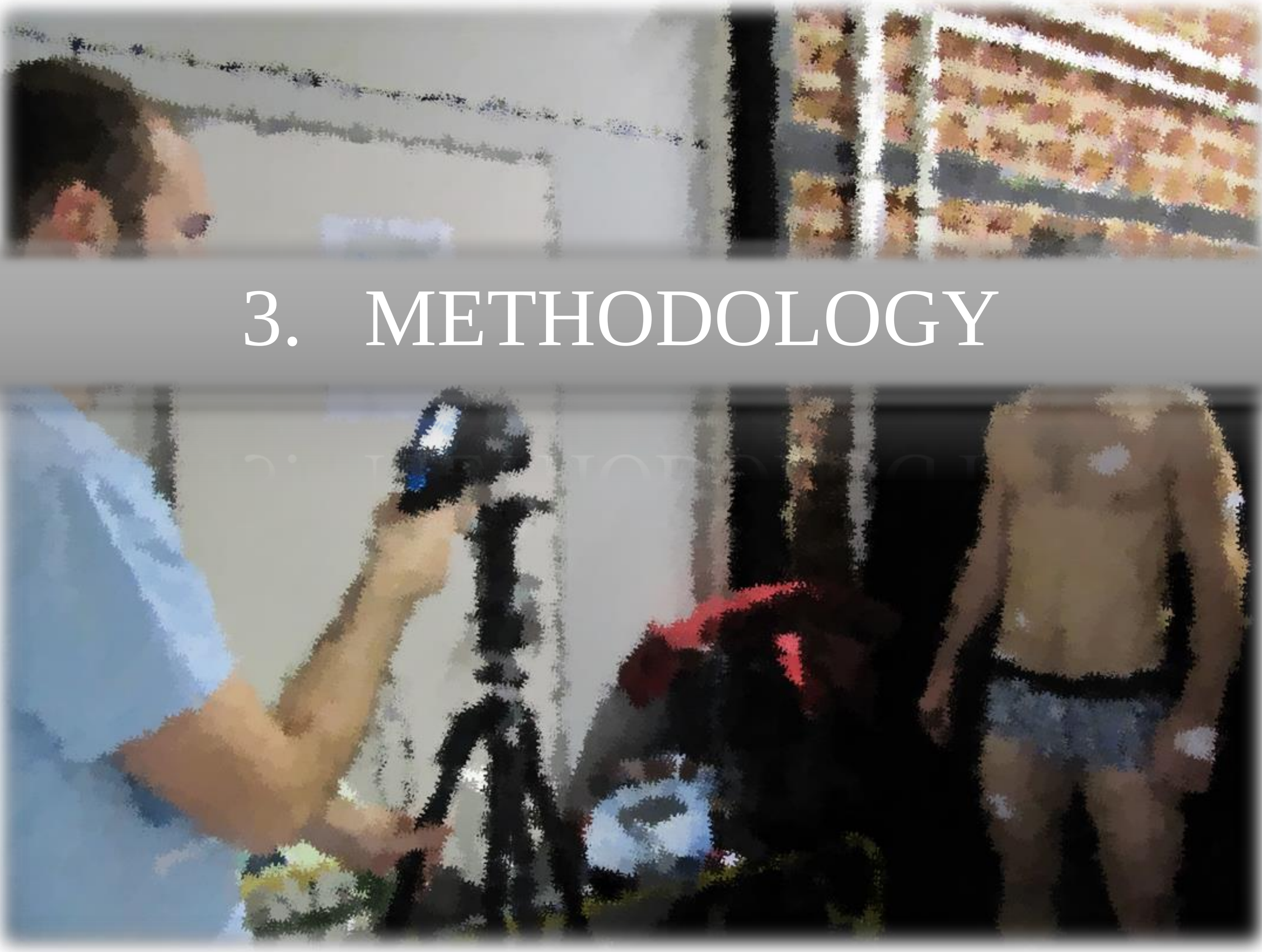
3.2. To examine if different saddle heights have an effect on the skin temperature of the cyclist (experimental study 4).

4. **METHODOLOGICAL AIMS:** to use statistical techniques aimed at adapting the thermographic study to the sport of cycling.

4.1. To determine the thermographic ROIs to be analysed in cycling (study 5).

4.2. To examine which parameters of skin temperature (absolute, pre-post variations) measured in the ROIs are more appropriate for analysing the effects of the exercise (study 5).

3. METHODOLOGY



3. METHODOLOGY

In order to fulfil the aforementioned objectives, the present thesis was divided into 5 studies. These studies were approved by the Committee of Ethics in Research with Humans at the University of Valencia (approval number H1384344515519, Appendix 1), and in agreement with the Declaration of Helsinki.

3.1. Participants

The table below shows all the characteristics of the male participants who volunteered to participate in the experimental studies (Table 3.1). All were physically active, some being cyclists and others non-cyclists. All the cyclist participants were categorized as club level, in accordance with the recommendations of Ansley and Cangley[10]. Eligibility criteria required participants to be: 18 years or older; healthy and have no history of lower-extremity injuries within the previous year. All participants signed an Informed Consent Term (Appendix 2). Participants followed some instructions in order to control some of the factors affecting skin temperature[77,158]. They were asked to:

(a) not smoke, drink alcohol, coffee, or any other stimulant beverage for at least 12 h before the test;

(b) avoid sunbathing or being exposed to UV rays and refrain from using sunscreen;

(c) avoid high-intensity or exhaustive exercise for at least 24 h before the test;

(d) refrain from having heavy meals before the test.

Table 3.1. Mean ± SD of demographics of the male participants.

Study	N	Age (years)	Body Mass (kg)	Height (cm)	BMI (kg/m^2)	Cycling training volume (km/week)	PO_{max} (W)
1	14 cyclists	29.9 ±8.3	72.8 ±10.6	175.8 ±8.0	23.6 ±2.8	162 ±77	282 ±38
2	10 non-cyclists	24.6 ±4.0	76.6 ±8.9	176.7 ±6.2	24.5 ±2.3	-	253 ±36
3	11 cyclists	31.0 ±7.4	80.8 ±13.0	174.9 ±6.1	26.7 ±3.0	265 ±116	268 ±33
3	11 non-cyclists	27.2 ±6.6	84.3 ±12.2	175.0 ±9.0	26.3 ±4.1	-	198 ±23
4	16 cyclists	29.3 ±10.0	77.0 ±9.4	178.8 ±6.5	24.1 ±3.1	230 ±133	273 ±48
5	19 cyclists	29.5 ±9.8	76.6 ±9.2	179.2 ±6.6	23.9 ±3.1	229 ±150	274 ±52

BMI: Body Mass index
PO_{max}: Peak power output

3.2. Thermographic Protocol

Skin temperature was determined in most of the studies (except study 3) using the camera FLIR E60, an IRT camera with infrared resolution of 320x240 pixels and thermal sensitivity <0.05°C (*FLIR E60, Flir Systems Inc., Wilsonville, Oregon, USA*) (Figure 3.1.A). For the study 3, camera FLIR T420 with an infrared resolution of 320x240 pixels and thermal sensitivity of <0.045ºC was used (*FLIR T420, Flir Systems Inc., Wilsonville, Oregon, USA*) (Figure 3.1.B).

Figure 3.1. Infrared thermography cameras used for the experimental studies: FLIR E60 (A) and FLIR T420 (B).

Prior to each experimental study, a black body (*BX-500 IR Infrared Calibrator, CEM, Shenzhen, China*) was used to ensure a correct calibration of the camera (Figure 3.2). This calibration consisted in the following steps:

1. Set the black body source at a higher temperature than the room temperature (80º).
2. After 30 min, for the stabilization of the black body, it was recorded a thermal image of the black body surface.
3. The difference between the temperature of the black body source in the thermography and the set temperature of the black body source was analyzed. If the difference was inside of the accuracy of black body source (±0.5ºC), it was considered that the camera was measuring correctly.

Figure 3.2. Black body used.

Skin temperature was measured three times in each study:

1) before the cycling test, after participants had adapted for 10 minutes to the laboratory room temperature[150] (15 min for the experimental study 1 because the difference between external and laboratory environmental conditions were more diferent than in the other studies);
2) immediately after the cycling test; and
3) 10 minutes after the cycling test.

In addition, in the experimental study 3, right thigh skin temperature was measured throughout the test by infrared video recording.

The thermal images were taken always by the PhD student of this dissertation (certified as thermography technician, level I thermographer, by the Infrared Training Center). Thermal images were taken while the participant was standing up wearing underpants. The camera was located 1 m away from the participant and the thermal images were taken perpendicular to the ROIs (Figure 3.3).

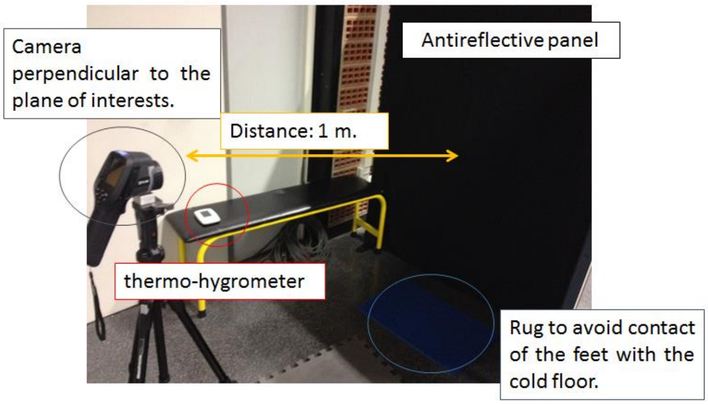


Figure 3.3. Space of measurement.

The camera was turned on 10 minutes before each measurement in order to ensure the electronic stabilization of the camera. This time was determined as a result of a previous experiment, where the thermographic camera recorded water at constant temperature measured with a platinum thermometer. Since the camera measurements became stable after 5 minutes of turning on the camera, a 10-min stabilization period was allowed to ensure this process.

Different environmental conditions were controlled to ensure the proper acquisition of the thermal images:

a) thermal images were taken with the lights off;

b) only the thermography technician and the participant were in the measurement space;

c) no electronic equipment was located within a 5 meter range of the measurement space;

d) an antireflective panel was placed behind the participant to avoid the effects from radiation reflected by the wall[112] (Figure 3.3); and

e) for all measurements, air temperature, relative humidity and reflected temperature were measured and were set in the camera settings. Air temperature and relative humidity were measured using a thermo-hygrometer with an accuracy of ±1ºC and ±3% of relative humidity (*Digital thermo-hygrometer, TFA Dostmann, Wertheim-*Reicholzheim, Germany) (Figure 3.3).

f) Reflected temperature was measured according to standard method in ISO 18434-1:2008. This method consists of:

1. Informing the following parameters to the camera: distance with a value of 0 and an emissivity with a value of 1.
2. Positioning cardboard with aluminum foil at the same level as the participant (Figure 3.4.A).
3. Measuring the average temperature of the aluminum foil with the camera (using a rectangle ROI) (Figure 3.4.B).
4. Introducing the thermal average temperature obtained as the reflected temperature.

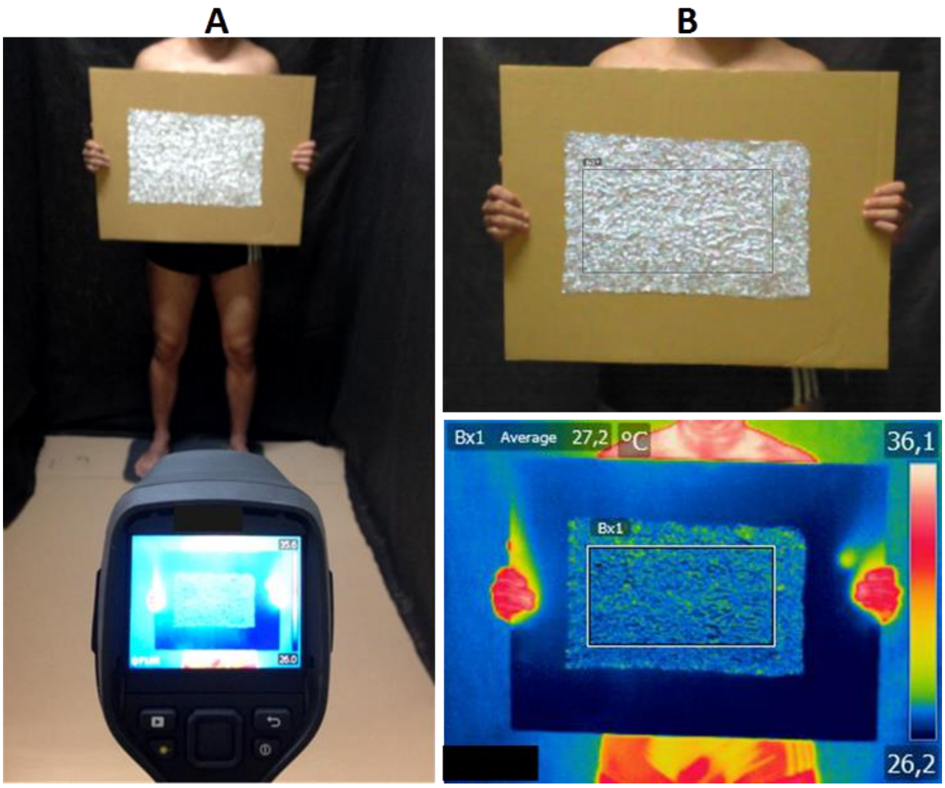


Figure 3.4. Reflector method.

ROIs were defined and analysed for all participants by the PhD student of this dissertation with the aim to ensure its consistency. ROIs were defined according for the objectives of each study. Therefore, ROI definition is described in the description of the methodology of each experimental study.

Mean temperature of each ROI was obtained using a thermography software (*Thermacam Researcher Pro 2.10, FLIR, Wilsonville, Oregon, USA*). The emissivity of skin was set at 0.98[207]. Then, skin temperature variations were calculated for each ROI in ºC:

- ΔT: difference between temperature immediately after the cycling test and before.
- ΔT10: difference between temperature 10 min after the cycling test and before.
- ΔTafter: difference between temperature 10 min after and immediately after the cycling test.

Positive values of these variables indicate increments of skin temperature, whereas negative values indicate decreases of temperature.

3.3. Specific methodology of each study

This section has been divided up in accordance with the studies performed. In order to facilitate the reading of this PhD thesis, a schematic guide has been developed, objectives being associated with the experimental studies undertaken (Appendix 3).

3.3.1. Experimental study 1

This experimental study was developed with three aims: 1) to compare IRT and thermal contact sensors for measuring skin temperature in a moderate cycling scenario, 2) to determine the influence of cycling workload on the variation of skin temperature of the different body regions, and 3) to study the relationship between core and skin temperature.

Protocol

Participants completed one pre-test, aimed at individualizing the cycling posture and the workload for a subsequent test, and two main tests with different workloads of 35% and 50% peak power output (PO_{max}).

Cycling posture was determined for each participant using a sagittal plane kinematic 2D model by Kinescan/IBV system (*IBV, Valencia, Spain*) and a high-definition video camera (*Sony Handycam HDR-FX1, Sony Corp., Tokyo, Japan*) with a sampling rate of 50 Hz. Reflective markers were attached to the lateral malleolus, the lateral femoral condyle, the greater trochanter of the left lower limb, the left acromion and the olecranon tuberosity (Figure 3.5). This posture was defined by maximum knee extension angle between 25º and 30º, horizontal saddle position defined by the plummet method[233], trunk flexion angle between 40º and 45º related to the transverse plane, and an arm extension angle related to the trunk between 75º and 90º (Figure 3.5). More detail about kinematic procedures were exposed in the kinematics section of experimental study 4 (section 3.3.4).

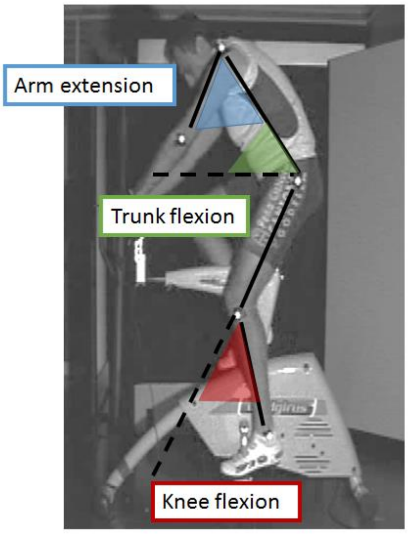


Figure 3.5. Marker´s placement and angles measures in the kinematic analysis.

Participants underwent an incremental cycling test to exhaustion using a stationary cycle ergometer (*Cardgirus Medical, Bikemarc, Sabadell, Spain*) (Figure 3.6). The incremental cycling test started with an initial workload of 50 W during 5 minutes and was followed by increments of 25 W/min until exhaustion as described elsewhere[39]. Pedaling cadence was controlled at 90 ±3 revolutions/minute (rpm) by visual feedback from the cycle ergometer head unit. Exhaustion was defined as the moment when cyclists were no longer capable of maintaining the pedaling frequency of 87 rpm. PO_{max} was defined as the workload of the last stage completed with the requested pedaling rate.

Figure 3.6. Cycle ergometer used.

The two main tests were performed on different days separated by one week. In these tests, participants warmed up during 3 minutes at 50 W before cycling for 45 minutes at 50% or 35% PO_{max} with pedaling cadence 90 ±3 rpm at the cycling posture determined in the pre-test. Cycling workloads (35% and 50% of the PO_{max}) were randomized. Average cycling workload was 98.6 ±14.0 W and 140.8 ±19.8 W for 35% and 50% PO_{max} test, respectively. Environmental conditions during the tests were 21.8 ±0.7ºC and 39.4 ±4.5% for 35% PO_{max} test and 21.2 ±0.8ºC ambient temperature and 39.0 ±4.9% relative humidity for 50% PO_{max} test (no statistically significant differences in room environmental conditions between both tests). Participants were wearing their own cycling short pants and cycling shoes (same in the both tests) while upper body was undressed. Drinking during the test was not allowed for the participants as this could influence the core and skin temperature.

Whole body sweat rate

Whole body sweat rate was estimated with the changes in body mass between before and after cycling test and their values were reported in milligrams per square centimetre per minute ($mg/cm^2/min$). Body mass was measured before cycling and at the end of the cooling down phase using a digital scale (*Edge YB02, Tecnovita by BH, Vitoria-Gasteiz, Spain*) and body surface area was calculated with the height and body mass of the participant with the Du Bois and Du Bois formula[67]. Participants were not towelled down prior to body mass measurements in order to ensure that mass changes better reflected the quantity of sweat that evaporated[56].

Thermal contact sensors

Local skin temperatures were recorded at nine locations using iButton sensors (Type DS1922L, *Maxim Integrated Products, San Jose, CA, USA*) attached to the skin with Hypafix™ clinical tape (*BSN Medical GmbH, Hamburg, Germany*) (Figure 3.7.A). These sensors consist of a digital thermometer with an accuracy of ± 0.5°C enclosed in a 16mm steel can. Thermal contact sensors were located at: left upper chest (A), right abdomen (B), back of the neck (C), right scapula (D), left paravertebral (E), right anterior thigh (F), left posterior thigh (G), right shin (H) and left calf (I) (Figure 3.8). Thermal contact sensors continuously recorded throughout the test and the averaged temperature values of the minute corresponding to the end of the thermal adaptation phase, immediately after the cycling phase and to the end of the cooling-down phase were taken for inter-method comparison.

Core temperature

Core temperature was registered at intestine-site using a core body thermometer enclosed in an ingestible pill (*CorTemp, HQ Inc., Palmetto, Florida, USA*) that transmits a continuous low-frequency radio wave signal in which wavelength varies according to the temperature to an external data logger (Figure 3.7.B). Participants ingested the pill between 6 and 8 h before coming to the laboratory, to ensure the pill would be located at the intestine during the cycling test. Absolute core temperature values were recorded every 10 seconds and averaged for each minute during the test. Similarly as observed in previous studies[136,212], at the beginning of exercise, most of the participants responded with a latency period of approximately 5 minutes consisting of an initial slight decrease in the core temperature after which, it started to increase. With the aim of properly examining the differences in the temperature increase between the two cycling workloads, the average core temperature during 10 minutes (5 minutes before starting exercise and the initial 5 minutes of exercise phase) was calculated and defined as the reference line to account for core temperature changes. Variation in core temperature was calculated as the difference between core temperature at each minute throughout the registration time and the defined core temperature reference line.

A. Thermal contact sensor

B. Core body thermometer (ingestible pill)

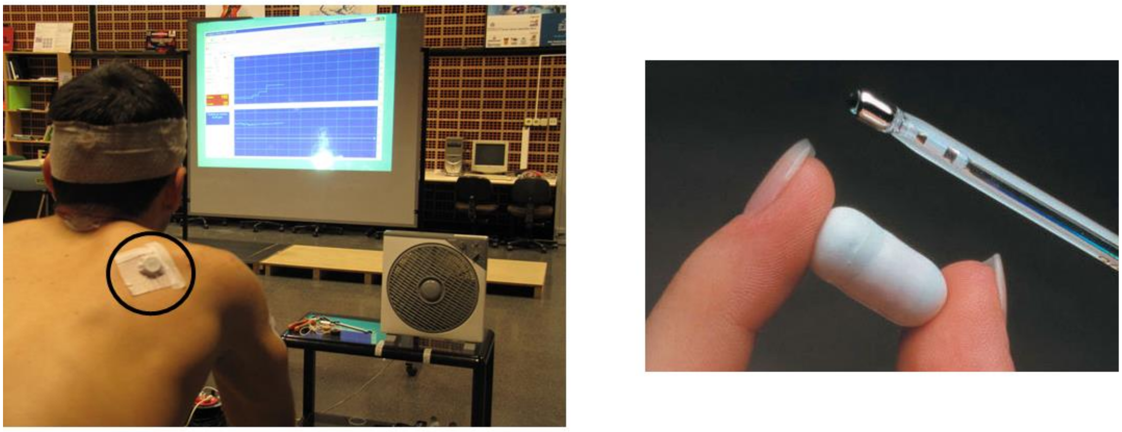


Figure 3.7.A. Thermal contact sensor. **B.** Core body thermometer.

Instrumented test

On the other hand, well controlled heat transfer processes excluding human thermoregulatory responses that could affect the skin surface temperature were simulated on a hot plate system. This setup allowed researchers to investigate the effect of the attachment method that used (clinical tape) on the temperature recording. For this purpose, a horizontal hot plate (Empa, *St. Gallen, Switzerland*) was covered with a 40x40 cm piece of cotton fabric (212.5 g/m^2). Six iButton temperature sensors of the same type as used in the human trials were placed on the surface of the fabric. Three of these thermal contact sensors were covered with Hypafix™ clinical tape, and three remained non-covered. An IRT camera was placed 40 cm above the center of the plate. Three areas of approximately the same size than those occupied by the thermal contact sensors were defined between each pair of covered and non-covered thermal contact sensors. Emissivity of the cotton fabric was 0.95, which was in agreement with previous studies[40,82] for dry and wet conditions.

The hot plate surface temperature was set at 35.00 ±0.05°C. Two kinds of tests were carried out under this configuration: a 30-minutes dry test by applying the cotton fabric in dry state on the hot plate and a 60-minutes wet test in which the cotton fabric was homogeneously wetted with 507.7 ± 45.3 g/m^2 of water using a domestic washing machine after spinning phase. Wet test aimed at simulating evaporation from the hot plate surface but ensuring no water layer was formed. Each test was repeated three times and the iButton sensors were removed and placed again in the same locations before each test. Average values of the 20-minutes steady-state (defined by a maximum temperature variation of 0.25°C) of each covered thermal contact sensor, of each non-covered thermal contact sensor, and of the areas defined for the infrared camera measurements were calculated.

ROI definition

For the main of this study related with the comparison of IRT data with the data of the contact sensors, nine small ROIs (4 x 4 cm area next to the sensor) and nine large ROIs (large surface covering almost the whole body part but avoiding its edges and the sensor) related to each of sensor location were defined out of the IRT images (Figure 3.8).

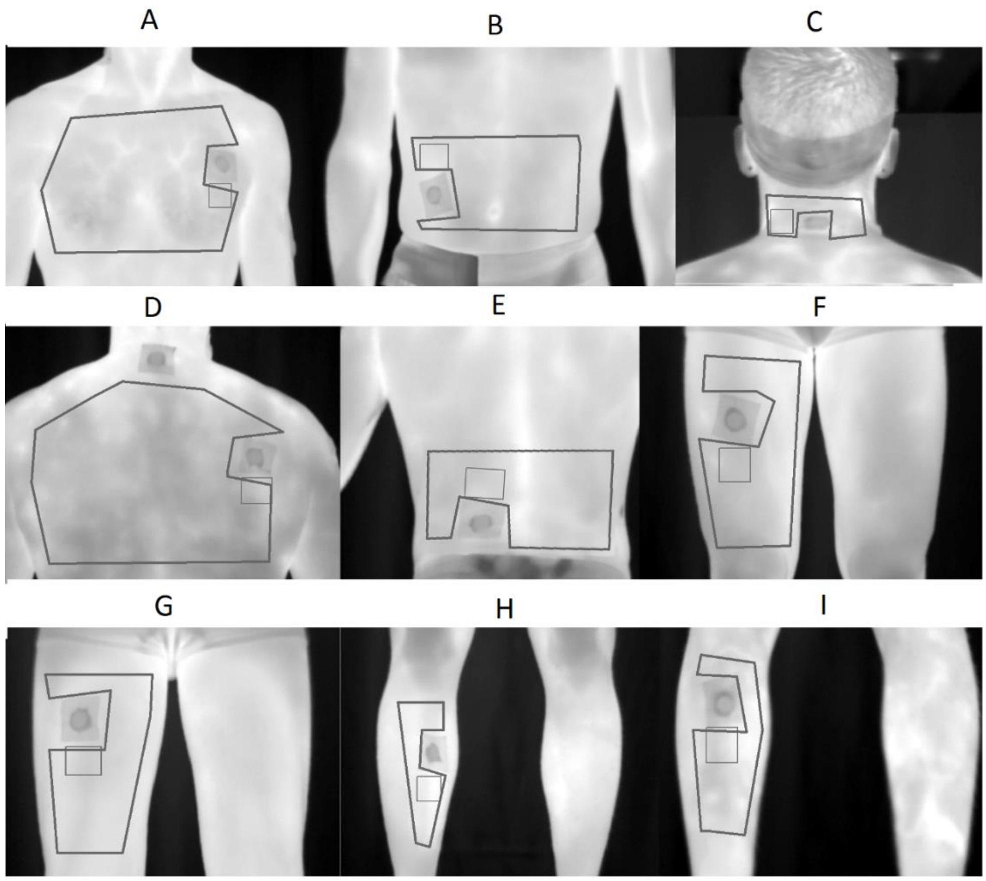


Figure 3.8. ROIs for objectives 1.1 and 1.2. ROIs: left upper chest (A), right abdomen (B), back of the neck (C), right scapula (D), left paravertebral (E), right anterior thigh (F), left posterior thigh (G), right shin (H), and left calf (I).

For the analysis of the effect of the cycling intensity on skin temperature, a full body model of ROIs was defined (Figure 3.9).

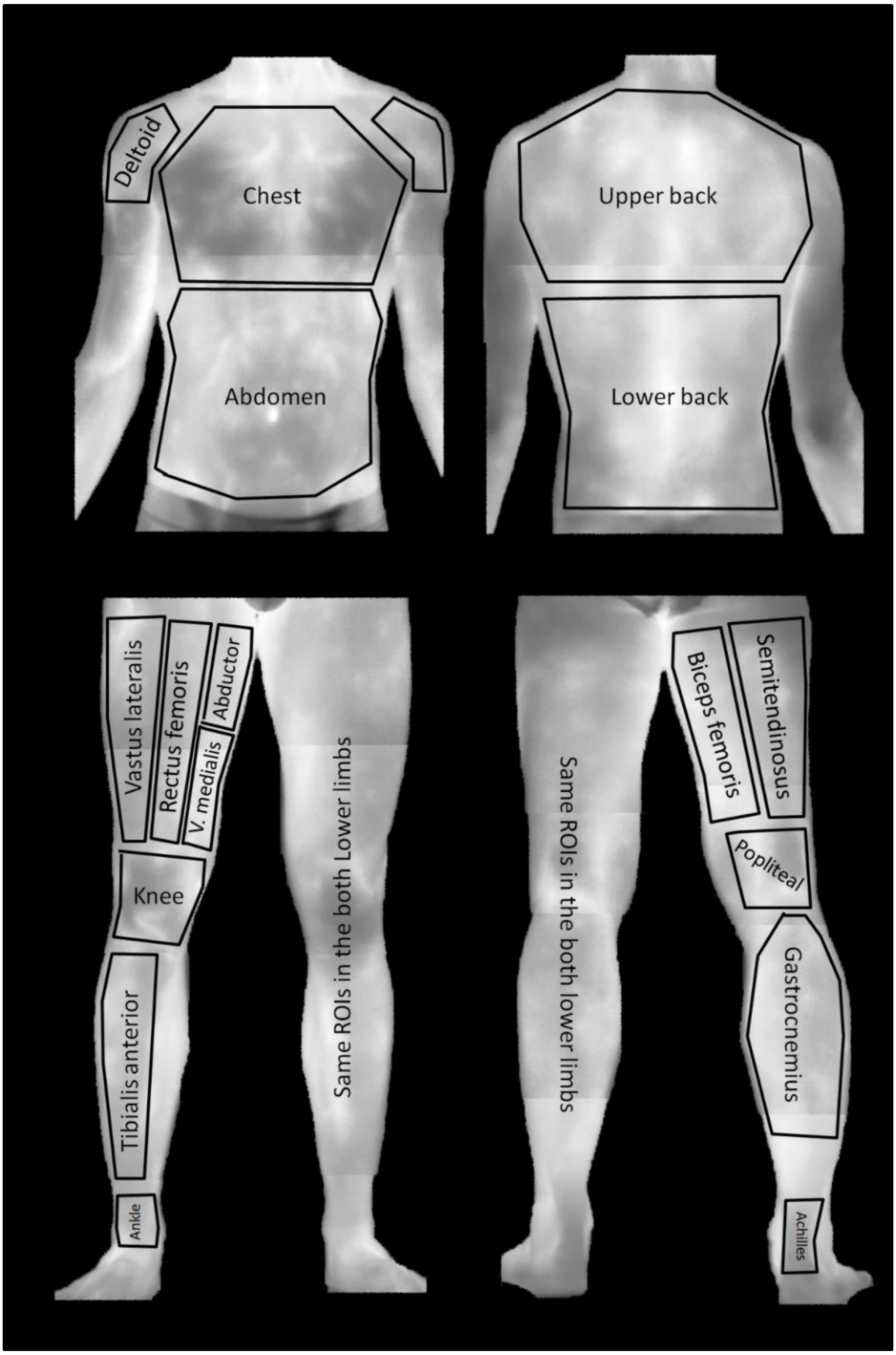


Figure 3.9. Full body model of ROIs defined for main 2.1 of the experimental study 1.

3.3.2. Experimental study 2

This experimental study was developed with the aim to assess the relationship between neuromuscular activation and skin temperature during cycle exercise.

Protocol

Participants underwent an incremental cycling test to exhaustion using a stationary cycle ergometer (*CG4, Inbrasport Co., Porto Alegre, Brazil*). The exercise protocol consisted on the same incremental cycling test described in the experimental study 1.

All participants performed the test with a similar position on the bike, having a maximum knee extension during cycling between 25º and 30º, horizontal saddle position defined by the plummet method[233], flexion of the trunk in relation with the transverse plane of about 55º, and an arm extension in relation to the trunk, defined by an angle between 75º and 90º. Posture was defined by manual procedures.

Environmental conditions during the tests were 19.5 ±1.3ºC and 62.9 ±3.2% relative humidity during all trials.

Surface electromyography

Neuromuscular activation was monitored by means of surface electromyography (EMG) from the right and left rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF) and gastrocnemius medialis (GM) during the incremental cycling tests (Figure 3.10). Pairs of Ag/AgCl electrodes (bipolar configuration) with a diameter of 22 mm (*Kendall Meditrace, Chicopee, Canada*) were positioned 22 mm apart on the skin after careful shaving and cleaning of the area with an abrasive cleaner and alcohol swabs to reduce the skin impedance[61]. A reference electrode placed over the skin of the olecranon served as a neutral site. The electrodes were placed over the belly of the muscles, parallel with the muscle fiber orientation[108] and taped to the skin using micropore tape (*3M Company, St Paul, MN, USA*) to minimize movement artifact. Encapsulating tape and electrodes were placed at the skin after the thermography measurement before exercise. For thermography measures acquired after exercise, sweat and electrode were removed right after exercise was finished. Sweat was removed from the skin with gentle friction using paper towel. Afterwards, thermography measurements post-exercise were recorded.

Figure 3.10. Surface electromyography measurement during cycling.

Muscle activation signals were amplified and recorded at a sampling rate of 2000 Hz with 14-bit resolution using an analog to digital converter (*Miotool 400, Miotec Biomedical, Porto Alegre, RS, Brazil*) and recorded using a commercial software (*Miograph, Miotec Biomedical, Porto Alegre, RS, Brazil*) for off-line signal processing. EMG signals were windowed for 10% of the total time for each participant at two instants of the test (10 and 90% of the total time of the test)[115].

The procedures of EMG analysis to compute discrete analysis of band-pass filtering are described elsewhere[65]. Briefly, each muscle's EMG signal was filtered (fifth order, zero leg Butterworth) using each of the nine combinations of high (193.45-300.80 Hz) and low (26.95-48.45 Hz) band stop (frequency bands). EMG signals of each of the nine frequency bands that resulted from the filtering process were then rectified. The sum of the nine average frequency bands was calculated for the analysis of the overall activation of each muscle (i.e. activation of all frequency bands of the EMG signal). The fifth, sixth and seventh bands were averaged to compute the high frequency components (147-300 Hz) of the signals, which would potentially represent the response of greater motor units[228]. The first and the second bands were averaged to compute the low frequency components (27-76 Hz) of the signals, which would represent the response of smaller motor units[228]. The same analyses were used to compare bilateral activation for a given muscle. High and low frequency pairs were normalized by individual muscle overall activation in order to represent the percentage of contribution of each frequency component. Overall muscle activations were normalized by muscles' individual responses at the 10% of the test, where fatigue would be expected to be minimal, in order to minimize between-subjects differences in electrode position to the muscles belly[147]. This normalization was performed instead of an isometric contraction, in order to avoid the low reliability for normalization of RMS during dynamic contractions[4]. All signal processing were conducted using custom made scripts in MATLAB® (*Mathworks Inc., Natick, Massachusetts, USA*).

The variation of the muscle activation (90% - 10% of the total time of test) was averaged for the ten participants for the overall (ΔOverall), high (ΔHigh) and low frequency bands (ΔLow).

ROI definition

For this study, ROIs were more related with muscular fascicles because the objective was to compare skin temperature data with the electromyography results (Figure 3.11).

3.3.3. Experimental study 3

This experimental study was developed with two aims: 1) to assess the relationship between varying performance factors and skin temperature, and 2) to compare differences in skin temperature between Cyclists and Non-Cyclists.

Protocol

The protocol involved a preliminary evaluation and a main test. In the preliminary evaluation, percentage of body fat was measured using the air displacement plethysmography (*BOD POD; Life Measurement Instruments, Concord, USA*) following the criteria defined by Fields et al.[83].

The main test consisted of an incremental cycling test until exhaustion on a cycle ergometer (*CG4, Inbrasport, Porto Alegre, Brazil*). For cyclists, the components of the cycle ergometer were configured in order to replicate the configuration used in each cyclist's bicycle. For non-cyclist, the posture was defined as experimental study 2. The incremental test consisted of a 3-min warm-up phase at an initial workload of 105 W followed by 3-min phases in which the workload was increased in steps of 35 W until exhaustion[64]. Pedaling cadence was controlled at 55 ±5 rpm, and exhaustion was defined as the moment when the cyclist was no longer able to maintain a pedaling cadence of 50 rpm. The slow cadence used in the incremental test was chosen in order to properly record pedaling motion with the video from the thermography camera (30 frames per second).

Tests were performed with air room at 23.5 ±1.2°C and 49.9 ±3.9% of relative humidity. Drinking during the test was not allowed for the participants in order to avoid their effect in the skin temperature data.

Cardiorespiratory and metabolic data

Gas exchange measurements were registered with an indirect calorimeter (*VO2000, MGC Diagnostics, Saint Paul, USA*) (Figure 3.12). Standard calibration procedures were performed before each test. Gas exchange data were analyzed to define the two ventilatory thresholds (VT_1 and VT_2)[210]. Heart rate was measured during the incremental cycling test using a heart rate monitor (*T31 CODED, Polar Electro, Kempele, Finland*). Mean heat production during the entire test (H_{pro}) was calculated in order to assess its relationship with the skin temperature. H_{pro} was calculated as the difference between the rate of metabolic energy expenditure and power output and it was converted into W/kg [58]. The rate of metabolic energy expenditure (M) was calculated with the following equation:

$$M = VO_2 \times \frac{\left[\left(\frac{RER - 0.7}{0.3}\right) e_c\right] + \left[\left(\frac{1.0 - RER}{0.3}\right) e_f\right]}{60} \times 1000 \qquad (2.1)$$

where VO_2 is expressed in L min_{-1} and M in watts, *RER* is the respiratory exchange ratio; e_c and e_f are the energetic equivalents of carbohydrate (21.13 kJ/L of O_2) and fat (19.62 kJ/L of O_2), respectively.

H_{pro} was averaged for the entire test and relative oxygen consumption (VO_2/kg), percentage of the maximum relative oxygen consumption (%VO_{2max}), heart rate (HR) and relative power output (PO/kg) at the VT_1, VT_2 and PO_{max} were selected for further analyses.

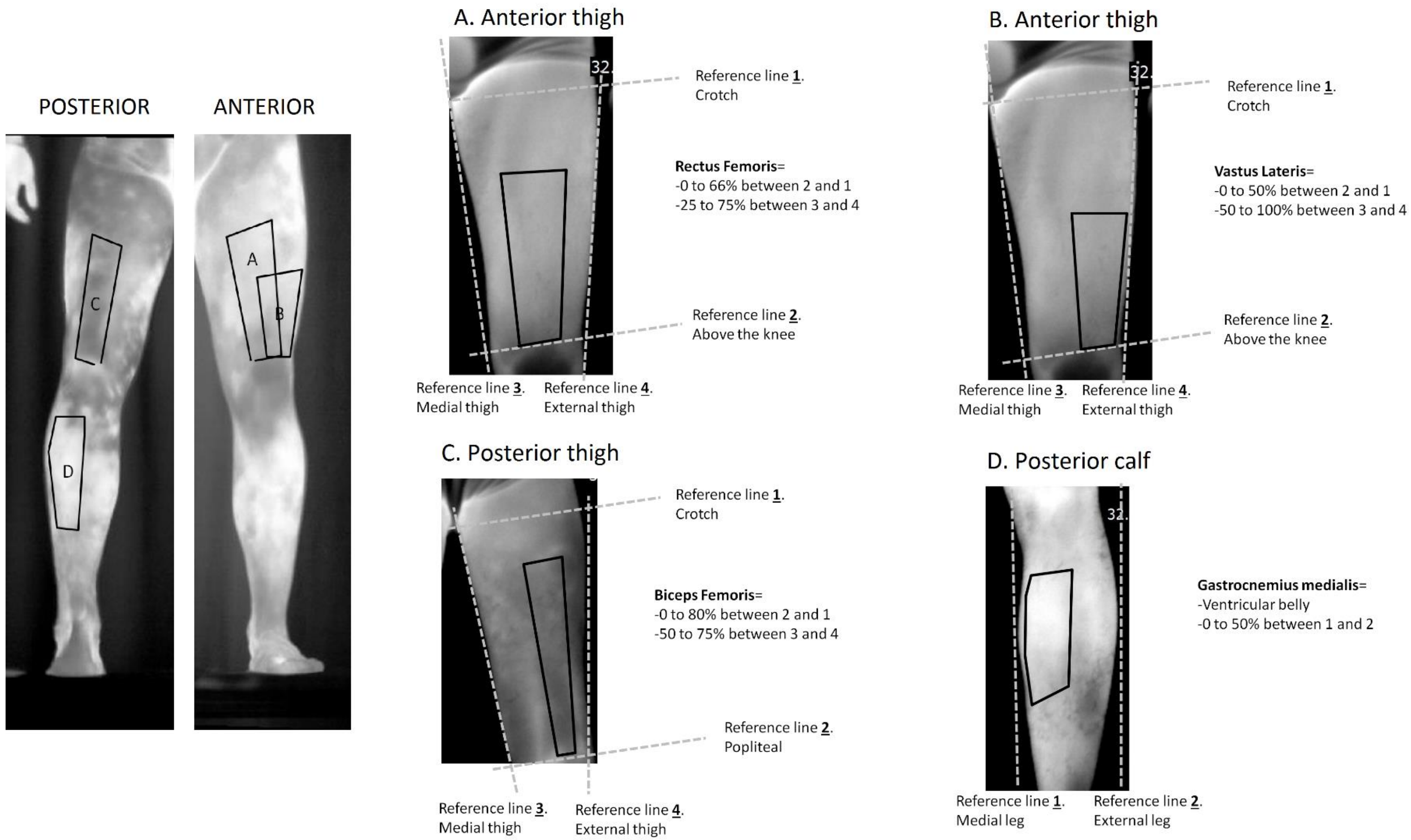


Figure 3.11. ROIs defined in the experimental study 3 and 4: A) rectus femoris, B) vastus lateralis, C) biceps femoris and D) gastrocnemius medialis.

Surface electromyography

Similar procedures as experimental study 2 were performed and only particularities of this experimental study are detailed.

EMG was recorded at a sampling rate of 1.5 kHz during 60s in the last minute of each stage of the cycling incremental test (Figure 3.12).

EMG signal analysis was performed using a commercial EMG software (*MyoResearch XP Basic 1.07.1, Noraxon, Scottsdale, USA*). EMG signal was filtered with a digital Blackman band-pass with frequencies between 20 and 450 Hz. The raw signal was smoothed with a root mean square algorithm (RMS) with 100 ms windowing. After this, signals were normalized by muscles' individual peak RMS at the first 3-minute stage of the cycling incremental test, where fatigue would be expected to be minimal, in order to minimize between-subjects differences in electrode position to the muscles belly[147]. This normalization was performed, instead of an isometric contraction, in order to avoid the low reliability for normalization of RMS during dynamic contractions[202]. The mean value of the EMG signal during stages of the two ventilatory thresholds and at the PO_{max} was calculated for each muscle.

Figure 3.12. Gas exchange and EMG measurements during cycling.

ROI definition

ROIs definition was the same as the previous study (Figure 3.11). In addition, for the thermography video analysis performed in this experimental study, a vastus lateralis ROI in the anterior thigh was assessed (Figure 3.13).

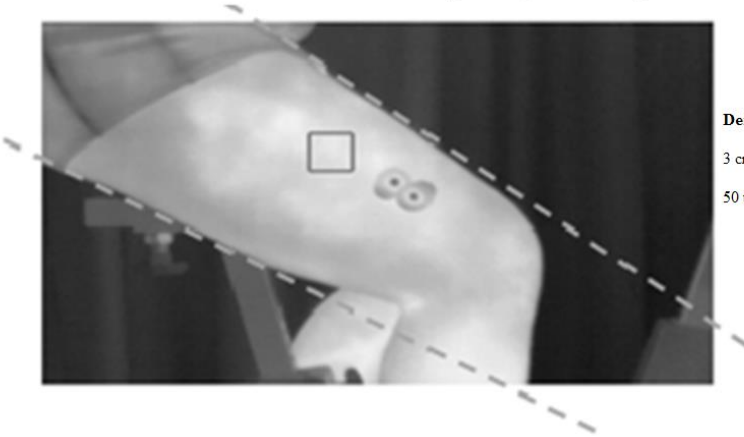


Figure 3.13. Vastus lateralis ROI defined in the experimental study 3 for the thermography video.

For the analysis of this thermographic video, variation in skin temperature (ΔSkin temperature) of VL was calculated as the difference between the temperature at each moment and skin temperature measured before the incremental cycling test.

3.3.4. Experimental study 4

This experimental study was developed with the aim to examine whether different cycling postures, elicited by different knee flexion angles, could influence skin temperature and perception of comfort, fatigue and pain.

Protocol

The participants completed one pre-test and three main tests carried out on different days. The differences between the main tests were the knee flexion and extension amplitudes. All trials were performed on a stationary cycle ergometer (*Cardgirus Medical, Bikemarc, Sabadell, Spain*).

In the first visit, all participants performed an incremental cycling trial into determine PO_{max} (same incremental cycling test as experimental studies 1 and 2). The three main tests began with a 3-min warm-up at 50 W and 90 rpm. The participants then cycled for 45 min at 50% PO_{max} at 90 ±2 rpm while maintaining a specific cycling posture. Each main test was performed with a specific knee flexion angle (40º [Knee40º], 30º [Knee30º], or 20º [Knee20º]) when the pedal crank was at 180° (Figure 3.14.A), and the order of the tests was randomized.

Environmental conditions during the test with the knee flexion angle at 40°, 30° and 20° were 23.4 ±1.1°C and 45.4 ±12.5%, 23.6 ±1.2°C and 40.7 ±11.3%, and 24.0 ±1.2°C and 50.8 ±11.2% relative humidity, respectively.

Kinematics

Kinematic procedures and analysis were performed in all tests by the same evaluator (the PhD student of this dissertation) to reduce between-evaluators variability in marker placement.

The knee angle was defined as the angle of knee flexion relative to the anatomical reference posture (static upright standing posture) taken as zero degrees (offset posture) (Figure 3.14.B)[175,179]. Trunk flexion (maintained between 40° and 50° between the transverse plane and the union of the left acromion and the olecranon tuberosity), arm extension (maintained as 75°–90° angle between the arms and the trunk), and the horizontal posture of the saddle, as defined by the plummet method[233], were controlled throughout the tests.

Posture was determined before each main test. Participants cycled at 50 W and 90 rpm, with knee flexion angle (obtained by changing the saddle height) using a 2D kinematic analysis system (*IBV, Valencia, Spain*) with a high-definition video camera sampling at 50 Hz with an image resolution of 1440 x 1080 pixels (*Sony Handycam HDR-FX1, Sony Corp., Tokyo, Japan*) placed 3 m perpendicular to the motion plane and 1 m height from the floor. Before measurements, optical distortion of the camera lens and calibration of the space were performed using a square object of known dimensions in which four space references were attached. Calibration was performed via 2D direct linear transformation using the motion analysis software. Spline smoothing method was used automatically in the motion analysis software[230]. Reflective markers were attached to the lateral malleolus, lateral femoral condyle, greater trochanter, left acromion, and olecranon tuberosity from the left body side. A bidimensional kinematic model of three markers (lateral malleolus, lateral femoral condyle and greater trochanter) defining two segments (thigh and shank) was used. Knee flexion angle was calculated by the projected β angle between these two segments[86] (Figure 3.14.A). A correction factor consisting of adding 2.2° to the measurements was performed[86]. Measurements of knee angle at the static upright position were performed before exercise (Figure 3.14.B). After that, adjusted knee flexion angle during cycling was calculated subtracting the static upright flexion knee angle from the dynamic flexion knee angle.

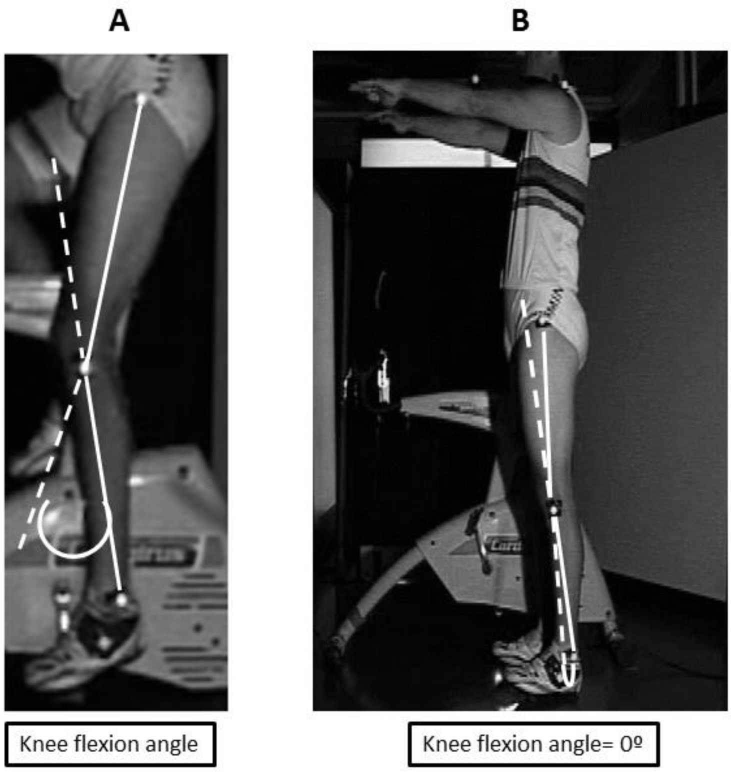


Figure 3.14.A. Knee flexion angle during pedaling with the crank at 180º (6 o'clock). **B.** Static upright posture and flexion knee angle. Solid lines illustrate thigh and shank while dashed lines illustrate their projections. Figure obtained from Priego Quesada et al.[179]

Perception study

Participants reported their perception of comfort, fatigue and pain one minute before the end of the test. They were not told under which bike-fit condition they were cycling. Figure 3.15 shows the questionnaire used.

Cyclists rated the comfort of the limbs and trunk on a 5-point Likert scale ranging from very uncomfortable (-2) to very comfortable (+2). Comfort was defined as the state of well being[176]. Limb and trunk comfort during cycling was based on this definition. A Borg CR-10 Scale[30], with scores ranging from 0 (none) to +10 (very, very strong), was used to rate the fatigue and pain experienced on different body areas: shoulders, dorsal back, pectoral, abdominal, lower back, buttocks, posterior thigh and popliteus, anterior thigh and knee, posterior leg, anterior leg, and foot and ankle. In this study, trunk fatigue and trunk pain were defined as the mean of the ratings reported in the fatigue and pain questionnaires on shoulders, dorsal back, pectoral, abdominal and lower back for fatigue and pain, respectively. Limb fatigue and limb pain were defined as the mean of ratings reported in the fatigue and pain questionnaires on buttocks, posterior thigh and popliteus, anterior thigh and knee, posterior leg, anterior leg, and foot and ankle for fatigue and pain, respectively.

	Comfort in	
	Trunk	Limbs
-2 Very uncomfortable		
-1 Somewhat uncomfortable		
0 Neither comfortable nor uncomfortable		
+1 Somewhat comfortable		
+2 Very comfortable		

Body areas	Fatigue	Pain
1.Shoulders		
2.Dorsal back		
3.Pectoral		
4.Abdominal		
5.Lower back		
6.Buttocks		
7.Posterior thigh and popliteus		
8.Anterior thigh and knee		
9.Posterior leg		
10.Anterior leg		
11.Foot and ankle		

Borg Scale

PAIN AND FATIGUE SCORE	SCORE
NOTHING	0
VERY, VERY WEAK (JUST NOTICEABLE)	0.5
VERY WEAK	1
WEAK	2
MODERATE	3
SOMEWHAT STRONG	4
STRONG (HEAVY)	5
	6
VERY STRONG	7
	8
	9
VERY, VERY STRONG (ALMOST MAXIMUM)	10

Figure 3.15. Questionnaire used for the perception study.

ROI definition

A full body model of 16 ROIs was used (the same as in the study 1 for the analysis of the effect of the cycling intensity on skin temperature, but without the deltoid region, Figure 3.9).

3.3.5. Study 5

This study consisted on two analysis of the thermographic data with the aims to determine the ROIs to evaluate in cycling studies and to assess the factors that affect the skin temperature variation.

Data used

From all the tests performed in this PhD thesis, 52 of the tests were used for the analysis of the data of the experimental study 5. These tests consisted of a 3-minute warm up at 50 W at 90 ±2 rpm, followed by 45 minutes at 50% PO_{max} at 90 ±2 rpm.

Temperature and relative humidity of the 52 remaining tests was 23.7 ±1.4ºC and 45.1 ±12.0%, respectively.

ROI definition

A full body model of 16 ROIs was used (the same as in the study 1 for the analysis of the effect of the cycling intensity on skin temperature, but without the deltoid region, Figure 3.9).

3.4. Statistical analysis

All the studies were analyzed with SPSS statistics software package (*SPSS Statistics 21.0, IBM, Armonk, New York, USA*). Data are reported as mean ±SD within 95% confidence intervals (95%CI). The level of statistical significance was determined for $p<0.05$.

3.4.1. Experimental study 1

Shapiro-Wilk test was performed to confirm a normal distribution of core temperature, skin temperature, effort perception and whole body sweat rate data ($p>0.05$). Repeated measures

Thermal contact sensors vs. thermography analyses: For the comparison between thermal contact sensors and skin temperature, only data of the test at 50% PO_{max} was used. ANOVA analysis was applied to analyze the differences in skin temperature determined by the different measurement methods (thermal contact sensors vs. IRT camera defined by small ROIs vs. IRT camera defined by large ROIs), at the three measurement times. Linear regression with a Pearson’s correlation coefficient was used to examine the relationships between thermal contact sensors and IRT camera defined by the small ROIs at the three measurement times for the averaged skin temperatures of all body locations. A moderate relationship was defined for $r>0.5$ or $r<-0.5$[166]. The agreement between skin temperature measurement methods was analysed using Bland–Altman plots.

Instrumented test: Due to non-normally distributed hot plate data (Shapiro-Wilk test, $p<0.05$), one-factor Kruskal-Wallis analysis with U-Mann-Whitney post-hoc test was applied to detect statistical differences in temperature measurements between methods in dry and wet conditions.

35% vs 50% PO_{max} and core vs. skin temperature analyses: Dependent Student's t test was used to examine differences in effort perception and whole body sweat rate between both tests. For core temperature, a repeated measures ANOVA with Bonferroni post-hoc test was applied with two factors: measurement time and cycling workload. Same analysis but with three factors (measurement time, cycling workload and ROI) was applied for each skin temperature variable assessed (absolute temperature measured at three times and the corresponding three temperature variation for each ROI). Finally, a Pearson's correlation coefficient analysis was used to examine the relationships between core and skin temperature in the three measurement moments. Significant correlations ($p<0.05$) were classified as weak ($0.2<|r|<0.5$), moderate ($0.5\leq|r|<0.8$), or strong ($|r|\geq0.8$)[166].

3.4.2. Experimental study 2

For analysis, data from both limbs of participants were used. Temperature data from the right leg of one subject was excluded because a varicose vein was detected which could affect surface temperature measures. EMG signal from vastus lateralis was removed after visual inspection in two participants due to poor signal quality. After all, 19 pairs of data were used for comparison between electromyography and temperature for rectus femoris, biceps femoris and medial gastrocnemius, and 15 pairs were used for the vastus lateralis.

Relationship between skin temperature and neuromuscular activation: After confirmation of normal distribution ($p>0.05$ in Shapiro-Wilk test), bivariate correlations tests with a Pearson correlation coefficient was used to examine the relations between peak power output and temperature variables (ΔT and $\Delta T10$), and between temperature variables and electromyography variables (ΔOverall, ΔHigh and ΔLow) for each muscle/body region of interest. Statistical significance of the correlations was defined when $p<0.05$ and a moderate relationship of $r>0.5$ or $r<-0.5$[166] for all analyses. Differences between the variables of skin temperature for each body region of interest and EMG variables for each muscle where assessed using one-way ANOVA and Bonferroni Post-hoc corrections.

3.4.3. Experimental study 3

Shapiro-Wilk's test was used to confirm the normality distribution of each variable ($p>0.05$).

Relationship between skin temperature, performance, and predictive performance measures: Stepwise multiple linear regressions for all participants, and for Cyclists and Non-Cyclists in separate, were performed to examine the relationship between temperature measures (skin temperature immediately after finishing the test and Δskin temperature) and all performance related measures (Body fat, PO_{max}, VO_{2max}, $\%HR_{max}$ at VT_2, and neuromuscular activation at the end of the test). A second multiple linear regression assessed the relationship between VL temperature from the thermography video and performance parameters at VT_1 and VT_2 (Body fat, PO, $\%VO_{2max}$, $\%HR_{max}$ and VL neuromuscular activation). Pearson's correlation coefficient analysis was used to examine the relationships between H_{pro} with skin temperatures at the end of the test and the PO_{max}.

Cyclists vs. Non-cyclists: Student's t test was used to examine differences in H_{pro} and body fat composition, and in PO, skin temperature and Δskin temperature of vastus lateralis, VO_2/kg, $\%VO_{2max}$, $\%HR_{max}$ and neuromuscular activity between the two groups (Cyclists vs. Non-Cyclists) in the stages corresponding to the two ventilatory thresholds (VT_1 and VT_2) and in the end of the test (PO_{max}). Then, a two-way ANOVA was used, with two within-subjects factors [the ROI (VL, RF, BF and GM) and the measurement moment (pre-cycling, post-cycling, 10-min post-cycling), and one between-subjects factor (Cyclists vs. Non-Cyclists] followed by post-hoc Bonferroni correction when main effects and interactions were observed. A one-way ANOVA was carried out to analyze the variation in skin temperature with only one within-subject factor (the ROI) and for each group (Cyclists vs. Non-Cyclists), when main effects were observed at the two-way test.

3.4.4. Experimental study 4

Knee40° vs. Knee30° vs. Knee20°: The normality of each variable was confirmed by the Shapiro–Wilk test ($p>0.05$). After this, differences between the three knee flexions for absolute temperatures and temperature variations in each ROI were examined by applying repeated measures ANOVA. Same analysis was performed for limb and trunk comfort, and fatigue and pain in each body area. For all these analyses, Bonferroni post hoc tests were used for pairwise comparison if applicable.

Intraday reproducibility analysis: Intra-class correlation coefficient (ICC) from model "2,1"[197] was calculated to determine the intraday reproducibility of each ROI. To assess reproducibility, the following classification of ICC values was used[229]: values 1.00–0.81 (excellent reproducibility), 0.80–0.61 (very good), 0.60–0.41 (good), 0.40–0.21 (reasonable) and, from 0.20–0.00 (poor). The typical error of the measurement was calculated to represent absolute consistency across the tests[113,229].

3.4.5. Study 5

The normality of the thermal data was confirmed by the Kolmogorov-Smirnov test (p>0.05).

Multi regression analysis of skin temperature variation: The statistical analysis of this section was performed using the software RStudio[183]. Stepwise multiple linear regressions in both directions were performed to find the best combination of predictor variables to explain the variable response (ΔT) for each ROI. The predictor variables were: age, PO_{max}, body mass, height, body surface area, BMI, cycling training volume, skinfolds, room temperature, relative humidity, and baseline temperature (skin temperature before cycling). The model obtained with the stepwise method was adjusted by removing the non-significant variables (p>0.05). Variance accounted for by each predictor was calculated using the follow equation:

$$Variance\ A = \frac{standarized\ \beta_A}{\sum all\ \ standarized\ \beta\ of\ the\ model} * R^2 \qquad (2.2)$$

Normality of the final model residuals was confirmed by the Lilliefors test (p>0.05). Finally, Pearson correlations between body surface area and other anthropometric measures (BMI and skinfolds) were assessed in order to explain the relationships obtained in the models.

ROIs study using factor analysis: A factor analysis (principal component and varimax rotation of the orthogonal rotation method) was used to identify groups of ROIs highly correlated between them based on the skin temperature of each moment of measurement and on the skin temperature variation parameters (ΔT, ΔT10 and ΔTafter).

After the different groups of the factor analyses were identified, the temperature of each group was calculated using a weighted average based on the size of each ROI within their specific group. Tucker´s coefficient of congruence (K) of each model was calculated and values greater than 0.93 were considered as an indication of acceptable congruence[218]. Then, repeated measures ANOVA were performed to examine the differences between groups in each moment of measurement and between the temperature variation parameters.

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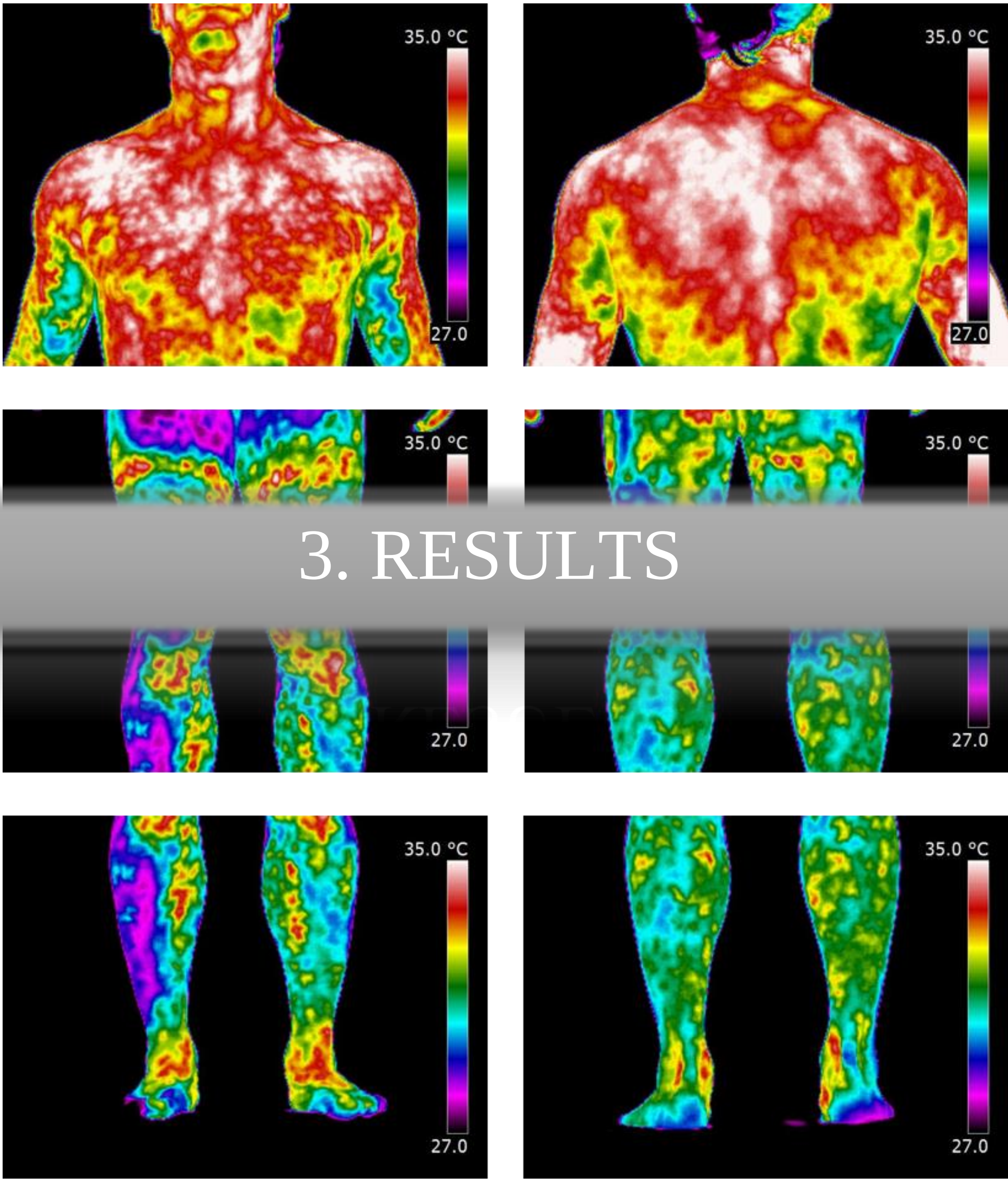
3. RESULTS



4. RESULTS

4.1. Validity results

4.1.1. Infrared thermography vs. thermal contact sensors (experimental study 1)

Figure 4.1 shows skin temperature for all the body locations. The temperature values are presented according to the measurement method. Before cycling, no differences were observed between the three measurement methods ($p>0.05$). Immediately after cycling, temperature was lower with the infrared camera in either small or large ROIs compared to the thermal contact sensors, whereas 10 min after cycling, the opposite was observed, providing IRT higher values than thermal contact sensors for both ROIs definitions.

Interestingly, comparing small and large ROIs, large ROIs presented lower temperature values than small ROIs immediately after cycling. However, no differences were found between both IRT camera measurement definitions before cycling and 10 min after cycling. Table 4.1 shows confidence intervals for temperature differences between the measurement methods and corresponding p-values of the differences shown in Figure 4.1.

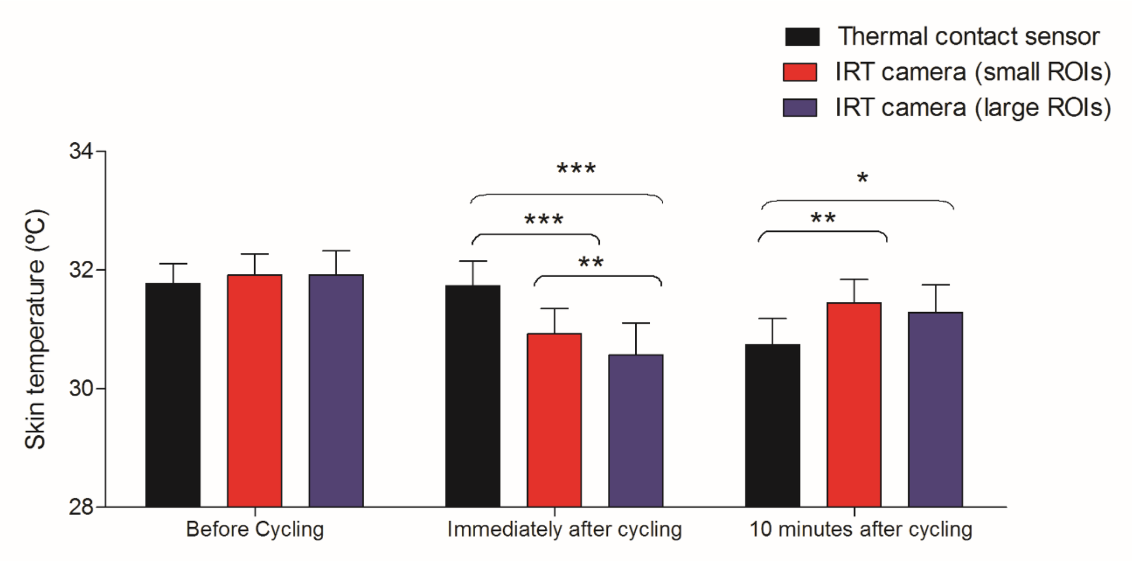


Figure 4.1. Mean with 95%CI for skin temperature of the all body locations analyzed in each measurement time. Significant differences between measurement methods (thermal contact sensors and infrared thermography camera (IRT) defined by small and by large ROIs) for each measurement time are indicated using * when p<0.05, **when p<0.01, and ***when p<0.001.

Table 4.1. Confidence intervals at 95% (95%CI) for temperature differences between the three measurement methods. Significant differences (p<0.05) are indicated using bold italics. IRT= infrared thermography.

Measurement time		Thermal contact sensors - IRT defined by small ROIs [ºC]	Thermal contact sensors - IRT defined by large ROIs [ºC	IRT defined by small ROIs - IRT defined by large ROIs [ºC]
1. Before cycling	95%CI	[-0.30,0.01]	[-0.35,0.04]	[-0.11,0.09]
	Significance	(p=0.06)	(p=0.16)	(p=1.00)
2. Immediately after cycling	95%CI	[0.61,1.01]	[0.79,1.54]	[0.13,0.58]
	Significance	***(p<0.001)***	***(p<0.001)***	***(p=0.003)***
3. 10 min after cycling	95%CI	[-1.12, -0.29]	[-1.07,- 0.01]	[-0.04, 0.36]
	Significance	***(p=0.001)***	***(p=0.04)***	(p=0.13)

Bland–Altman plots show the agreement between measurement methods in Figure 4.2. The Bland–Altman plots showed that the differences between thermal contact sensors and IRT were higher immediately after cycling and 10 min after than before cycling.

The linear regression analysis between measurement methods (thermal contact sensors and IRT camera defined by small ROIs) for averaged skin temperature for all the ROIs is presented separately for each measurement time in Figure 4.3. The linear regression analysis showed that before cycling, the temperature values obtained by each method were similar, therefore, the pairs of values were on line of identity (95%CI [0.9, 1.1]) and an y-intercept of 0.5ºC (95%CI [-1.9, 2.9]), resulting in a positive significant relationship between both methods ($r=0.92$ and $p<0.001$). The agreement between both methods was reduced immediately after cycling ($r=0.82$ and $p<0.001$); the slope had a value of 0.7 (95%CI [0.6, 0.8]) and the y-intercept a value of 9.4ºC (95%CI [6.7, 12.1]). The agreement between both methods was the lowest among the three measurement times 10 min after cycling ($r=0.59$ and $p<0.001$); the slope was 0.4 (95%CI [0.3, 0.5]), and the y-intercept 18.5ºC (95%CI [15.3, 21.6]). It can be observed that the differences between both methods were higher at lower temperatures of the thermal contact sensor.

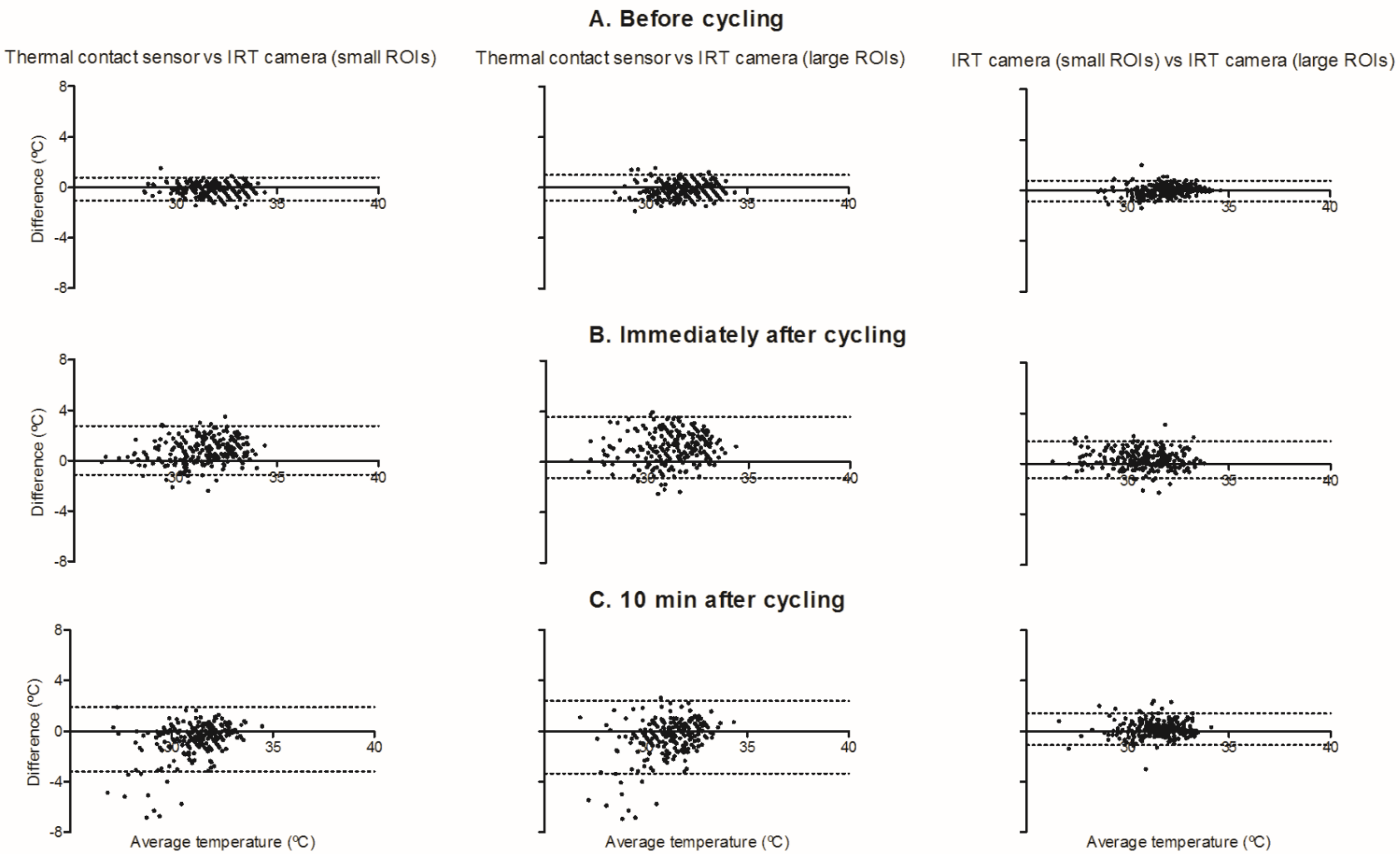


Figure 4.2. Bland–Altman plot with 95% limits of agreement illustrates the difference in skin temperature measurements between values obtained by thermal contact sensor vs. infrared thermography (IRT) defined by small ROIs vs IRT defined by large ROIs.

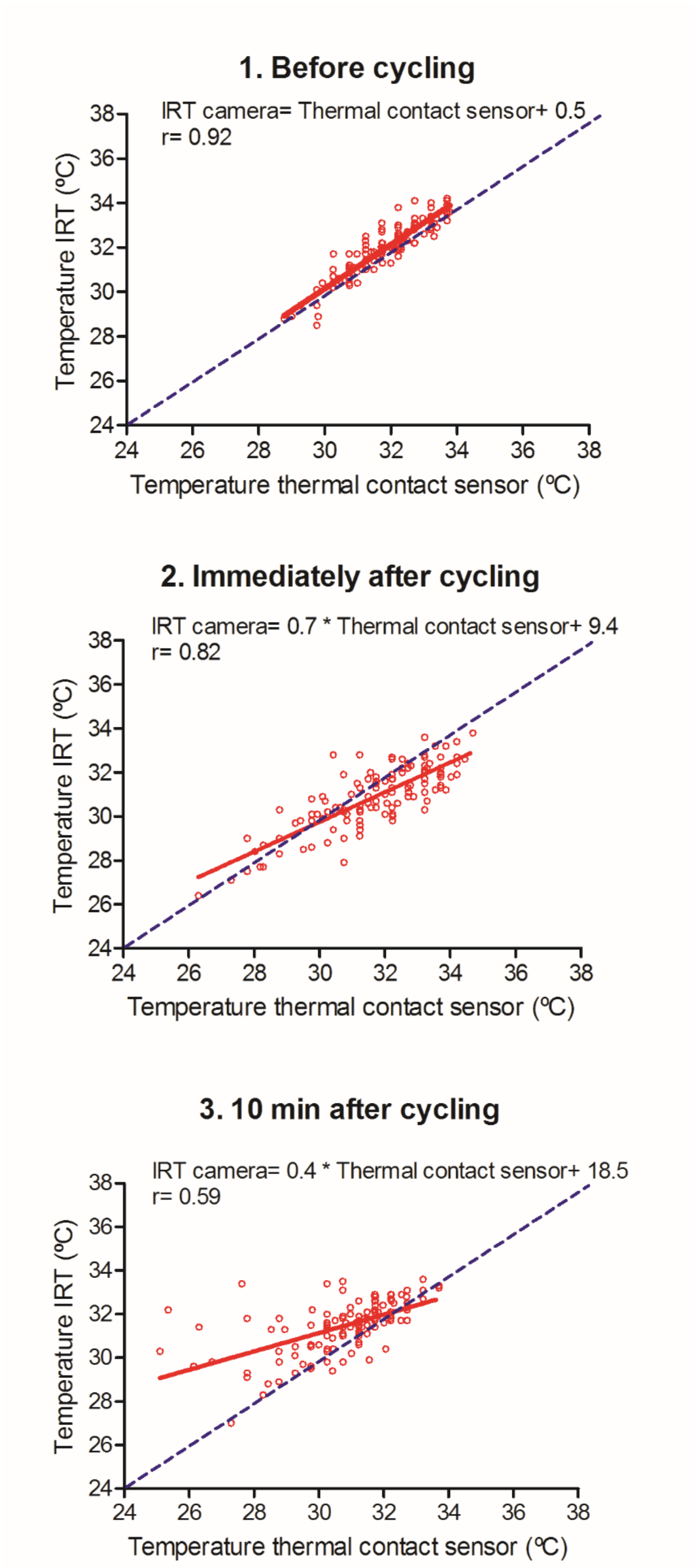


Figure 4.3. Linear regression between thermal contact sensors and infrared thermography camera (IRT) defined by small ROIs in each measurement time. All the regression were significative ($p<0.001$). Blue lines correspond with the line of identity, and red lines with the lines fitted with the regression equation.

In the assessment of temperature in the individual body locations (Figure 4.4), the agreement observed for all body locations together between methods was observed before cycling at left upper chest, right scapula, left paravertebral, right anterior thigh and left calf. Immediately after cycling, the temperature of thermal contact sensors was higher than the other two methods in all locations, except at the back of the neck and the left calf. 10 min after cycling, the temperature of the thermal contact sensors was lower than the other methods at left upper chest, right abdomen, and back of the neck.

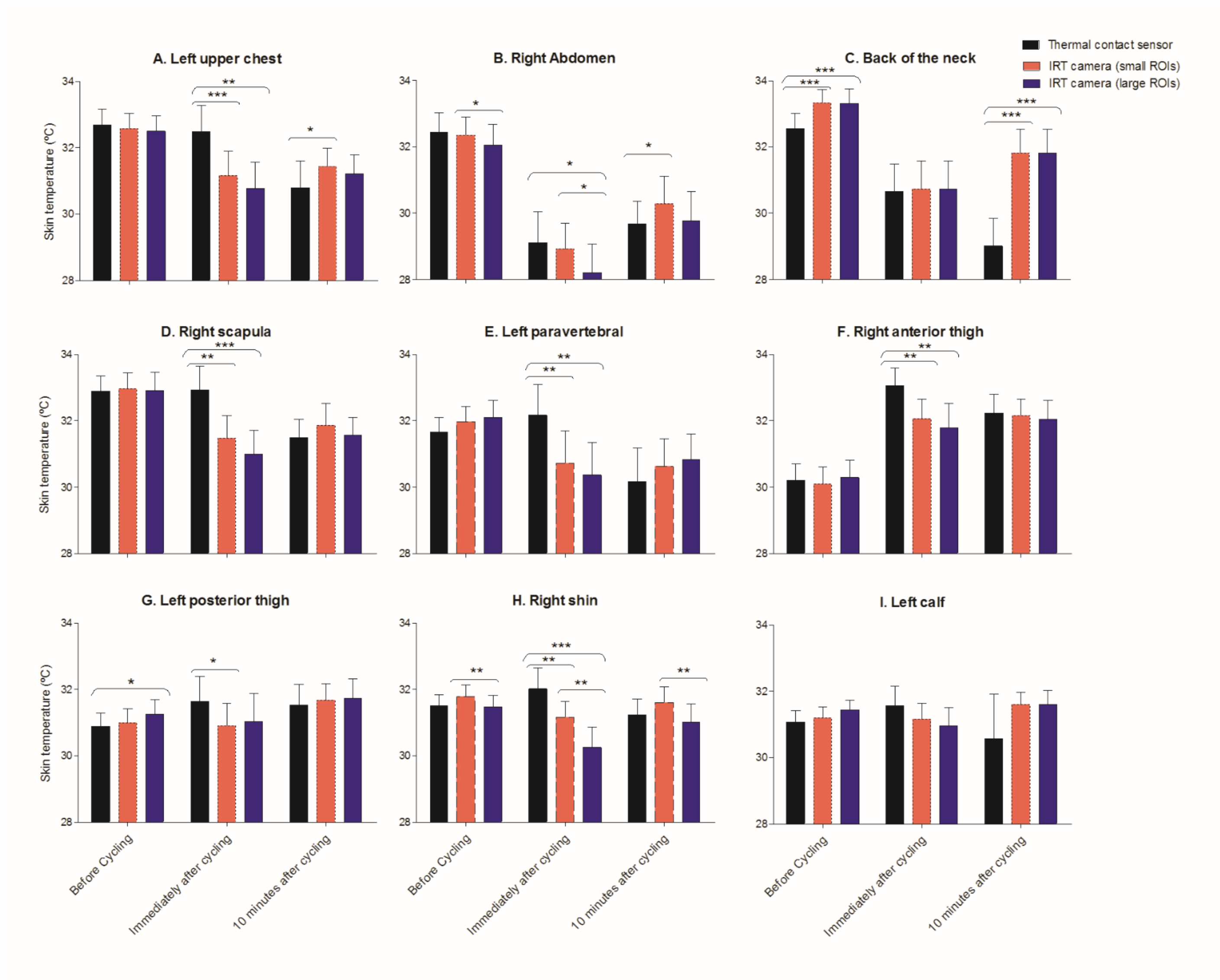


Figure 4.4. Mean with 95%CI temperature of the nine body locations in each measurement time. Significant differences between measurement methods (thermal contact sensors and infrared thermography camera (IRT) defined by small and large ROIs) for each time are indicated using *when $p<0.05$, **when $p<0.01$, and ***when $p<0.001$.

4.1.2. Results of the instrumented test (experimental study 1)

Figure 4.5 shows the mean and standard deviation values for each group of temperature measurement methods. Covered sensors measured a higher temperature than non-covered in dry (95%CI [0.4, 0.6ºC]; p=0.04) and wet conditions (95%CI [0.05, 1.16ºC]; p=0.04). The differences between covered sensors and IRT camera were 0.5ºC for dry conditions (95%CI [0.4, 0.6ºC]; p=0.04) and 3.7 ºC for wet conditions (95%CI [3.1, 4.2ºC]; p=0.04). In the case of non-covered sensors, no differences between sensors and IRT camera were found for dry conditions (p=0.26), but 3.0ºC difference was observed for wet conditions (95%CI [2.5, 3.6ºC]; p=0.04).

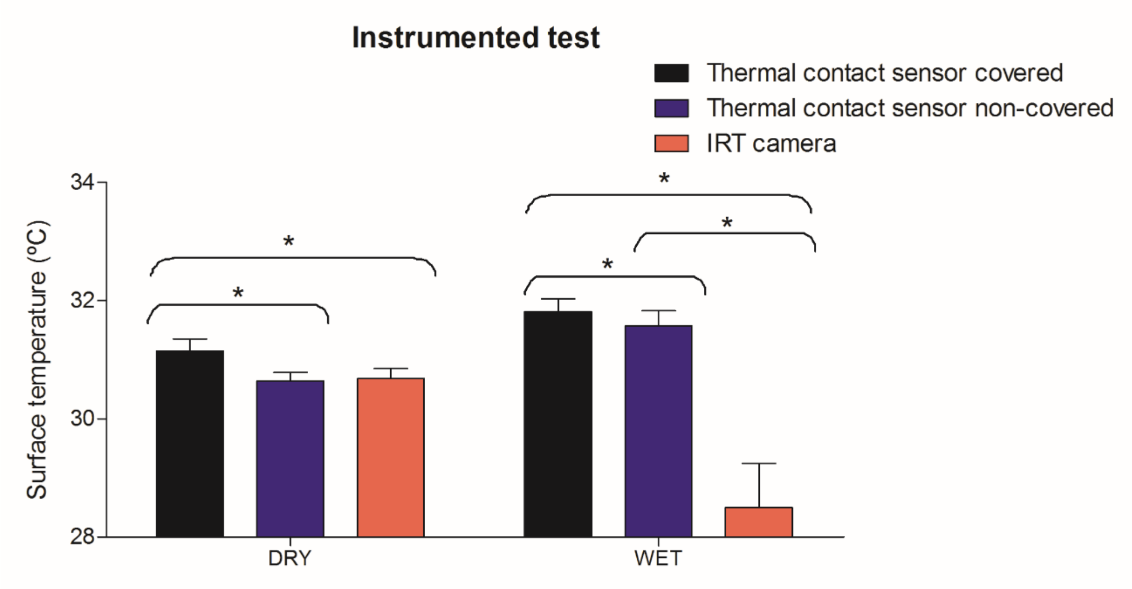


Figure 4.5. Comparison of temperature measurements by different instruments on the surface of the cotton fabric placed on top of the hot plate in two different conditions (cotton fabric dry and wet) Significant differences between measurement methods (thermal contact sensors covered, thermal contact sensors non-covered and IRT camera (IRT)) are indicated using * when p<0.05.

4.2. Efficiency results

4.2.1. Influence of cycling intensity on core and skin temperature and the relationship between both temperatures (experimental study 1)

Effort perception in the 20-point Borg scale differed between workloads (p<0.01; 95%CI of the difference [1.0, 3.0]) being 11.2 ±1.0 (light effort) and 13.2 ±1.5 (somewhat hard effort) for 35% and 50% PO_{max}, respectively. Whole body sweat rate was higher at 50% PO_{max} than at 35% PO_{max} (0.47 ±0.22 mg/cm^2/min in the 35% PO_{max} and 0.69 ±0.19 mg/cm^2/min in the 50% PO_{max}; 95%CI of the difference [0.04, 0.39 mg/cm^2/min]; p=0.02).

The maximum increase in core temperature with regards to the corresponding reference line was observed at the end of the exercise for both tests with an increase of 0.5ºC (95%CI [0.4, 0.7ºC]) and 0.8ºC (95%CI [0.7, 0.9ºC]) for tests at 35% and 50% PO_{max}, respectively. Core temperature increase was greater at 50% than at 35% PO_{max} test during the whole exercise bout and until 5 minutes after finishing the activity ($p<0.05$) (Figure 4.6). During the time course of the exercise sessions, temperature difference between the both intensities ranged from 0.1ºC to 0.3ºC, with the maximal difference between tests found at the end of the exercise (95%CI of the difference [0.1, 0.5ºC). After exercising at 50% PO_{max}, core temperature decreased faster than exercising at 35% PO_{max}, resulting in no significant differences between tests from minute 60 onwards.

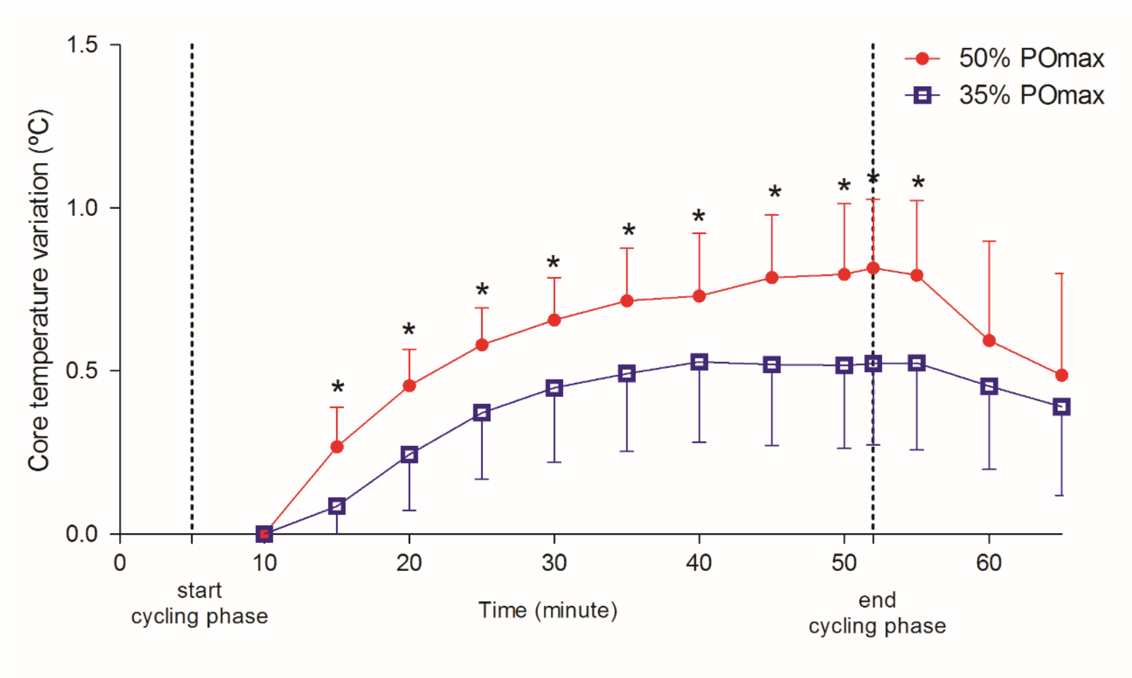


Figure 4.6. Mean variation in the core temperature ±SD with regard to core temperature reference line for the two cycling workloads (50% and 35% PO_{max}). Differences between both tests are indicated using * ($p<0.05$).

Table 4.2 shows skin temperature data at each ROI. Skin temperature measured immediately after the cycling test was significantly higher ($p<0.01$) for both exercise workloads in ROIs located in the anterior thigh (vastus lateralis, rectus femoris, abductor and vastus medialis) and knee, but remained unchanged for the remaining ROIs of the leg (biceps femoris, semitendinosus, popliteal, gastrocnemius, Achilles and ankle anterior). However, ROIs located on the trunk (deltoid, chest, abdomen, upper back and lower back) and tibialis anterior revealed decreases in skin temperature ($p<0.05$).

Ten minutes after completion of the cycling test, temperature in areas of the trunk (deltoid, abdomen), posterior thigh (biceps femoris and semitendinosus) and leg (tibialis anterior and gastrocnemius) increased with regard to the corresponding temperatures immediately after test completion. Conversely, the anterior thigh area excluding the vastus lateralis (rectus femoris, abductor and vastus medialis) and Achilles showed no change in temperature for both workloads. Simultaneously, some ROIs of the trunk (chest, upper back, lower back) and some included in the lower limb (vastus lateralis, knee, and ankle anterior) showed an increase in their temperature in the test at 35% PO_{max} ($p<0.05$), but they remained unchanged at 50% PO_{max}.

No differences in absolute values of skin temperature between workloads at any ROI were observed ($p>0.05$). Furthermore, cycling workload did not have any effect in variation of the skin temperature (ΔT, ΔT10 and ΔTafter) in the most ROIs ($p>0.05$). However, higher reductions in the skin temperature due to exercise (ΔT, ΔT10) were observed at 50% rather than 35% PO_{max} at the abdomen, tibialis anterior, ankle anterior and Achilles, alongside smaller increases at knee (Table 4.3 and Figure 4.7). 10 minutes after cycling (ΔTafter), knee and ankle anterior showed smaller increases in the 50% PO_{max} test compared to the 35% PO_{max} test, though tibialis anterior temperature increased more at 50%.

Table 4.2. Absolute temperature values obtained from the 17 ROIs (Regions of Interest) at the three measurement times in the two Tests: 35 and 50% of peak power output (PO_{max}).

ROI	*Mean ±SD skin temperature (ºC)*					
	Test 35% PO_{max}			*Test 50% PO_{max}*		
	before cycling	*immediately after cycling*	*10 min after cycling*	*before cycling*	*immediately after cycling*	*10 min after cycling*
Trunk						
Deltoid	33.1 ±0.5	31.1 ±1.1**	32.1 ±0.7**##	32.9 ±0.7	31.0 ±1.6**	32.0 ±1.1**##
Chest	32.7 ±0.7	30.4 ±1.3**	31.2 ±1.2**##	32.5 ±0.8	30.8 ±1.4**	31.2 ±1.0**
Abdomen	32.5 ±0.7	29.7 ±1.5**	31.0 ±1.4**##	32.1 ±1.1	28.2 ±1.5**	29.8 ±1.5**##
Upper back	33.2 ±0.5	30.6 ±1.3**	31.5 ±0.8**##	33.0 ±1.0	31.0 ±1.2**	31.6 ±0.9**
Low back	32.5 ±0.6	30.2 ±1.7**	30.8 ±1.2**#	32.1 ±0.9	30.4 ±1.7*	30.8 ±1.3*
Thigh						
Vastus lateralis	30.3 ±0.9	31.8 ±1.1**	32.3 ±1.1**#	30.2 ±1.0	31.7 ±1.5**	32.1 ±1.1**
Rectus femoris	30.2 ±0.9	32.0 ±1.1**	32.0 ±1.1**	30.0 ±0.9	31.7 ±1.4**	31.9 ±1.1**
Abductor	31.6 ±1.2	32.0 ±1.0**	32.0 ±1.2**	30.5 ±1.0	31.6 ±1.3**	31.8 ±1.1**
Vastus medialis	30.6 ±0.9	32.4 ±0.9**	32.6 ±0.9**	30.5 ±1.0	32.2 ±1.2**	32.4 ±1.0**
Biceps Femoris	31.1 ±0.8	31.0 ±1.4	31.6 ±1.1#	31.0 ±0.9	30.8 ±1.5	31.5 ±1.1#
Semitendinosus	31.5 ±0.7	31.4 ±1.3	32.0 ±0.9#	31.4 ±0.7	31.2 ±1.4	31.9 ±1.0#
Knee						
Knee	28.8 ±1.1	30.6 ±1.8**	31.1 ±1.6**##	28.9 ±1.0	30.5 ±1.5**	30.4 ±1.1**
Popliteal	32.0 ±0.3	32.2 ±0.9	32.5 ±0.7*	31.9 ±0.6	32.0 ±0.9	32.3 ±0.6**
Leg						
Tibialis anterior	31.5 ±0.6	30.7 ±0.9*	31.1 ±0.9#	31.5 ±0.6	30.3 ±1.1**	31.0 ±1.0##
Gastrocnemius	31.5 ±0.6	31.3 ±1.0	31.8 ±0.7#	31.4 ±0.5	31.0 ±0.9	31.6 ±0.7##
Ankle anterior	29.7 ±1.4	29.3 ±1.9	30.4 ±1.6##	29.9 ±1.0	29.2 ±1.7	29.7 ±1.4
Achilles	27.8 ±0.9	27.7 ±1.5	28.0 ±1.3	28.1 ±0.8	27.4 ±1.6	27.3 ±1.4

Differences between the measurement times are indicated using different symbols (* differences if compared with before cycling test ($p<0.05$), ** differences if compared with before cycling test ($p<0.01$), # differences if compared with immediately after cycling test ($p<0.05$), ## differences if compared with immediately after cycling test ($p<0.01$)).

Table 4.3. Differences between the tests at 35 and 50% of peak power output (PO_{max}) in the temperature variations[a].

	ΔT (ºC)				**ΔT10 (ºC)**				**ΔTafter (ºC)**			
ROI	35% PO_{max} (Mean ±SD)	50% PO_{max} (Mean ±SD)	35% vs 50% PO_{max}		35% PO_{max} (Mean ±SD)	50% PO_{max} (Mean ±SD)	35% vs 50% PO_{max}		35% PO_{max} (Mean ±SD)	50% PO_{max} (Mean ±SD)	35% vs 50% PO_{max}	
			p	95%CI			p	95%CI			p	95%CI
Abdomen	-2.7 ±1.0	-3.8 ±1.4	***<0.01***	0.4, 1.8	-1.5 ±0.9	-2.3 ±1.3	***0.01***	0.2, 1.5	1.3 ±0.7	1.6 ±1.0	0.33	-0.3, 0.8
Knee	1.8 ±1.8	1.6 ±1.7	0.53	-1.1, 0.6	2.3 ±1.6	1.5 ±1.3	***<0.01***	0.3, 1.3	0.5 ±0.5	-0.1 ±1.2	***0.03***	0.0, 1.1
Tibialis	0.9 ±0.9	-1.2 ±1.2	***0.02***	0.1, 0.7	-0.4 ±0.9	-0.5 ±1.0	0.52	-0.2, 0.1	0.5 ±0.5	0.8 ±0.6	***0.03***	0.0, 0.6
Ankle	-0.4 ±2.1	-0.7 ±1.9	0.20	-0.8, 0.2	0.8 ±1.8	-0.2 ±1.6	***<0.01***	0.3, 1.5	1.1 ±0.5	0.5 ±1.2	***0.04***	0.0, 1.1
Achilles	-0.1 ±1.7	-0.8 ±1.5	0.09	-1.3, 0.1	0.2 ±1.5	-0.8 ±1.3	***<0.01***	0.3, 1.7	0.3 ±0.6	0.0 ±0.8	***0.03***	0.0, 0.6

Only regions of interest with significant differences are showed. Significant differences are indicated when $p<0.05$ using bold italics in the p value.

[a]ΔT: Difference between temperature before and immediately after the cycling test. ΔT10: Difference between temperature before and 10 min after the cycling test. ΔTafter: Difference between temperature immediately after and 10 min after the cycling test.

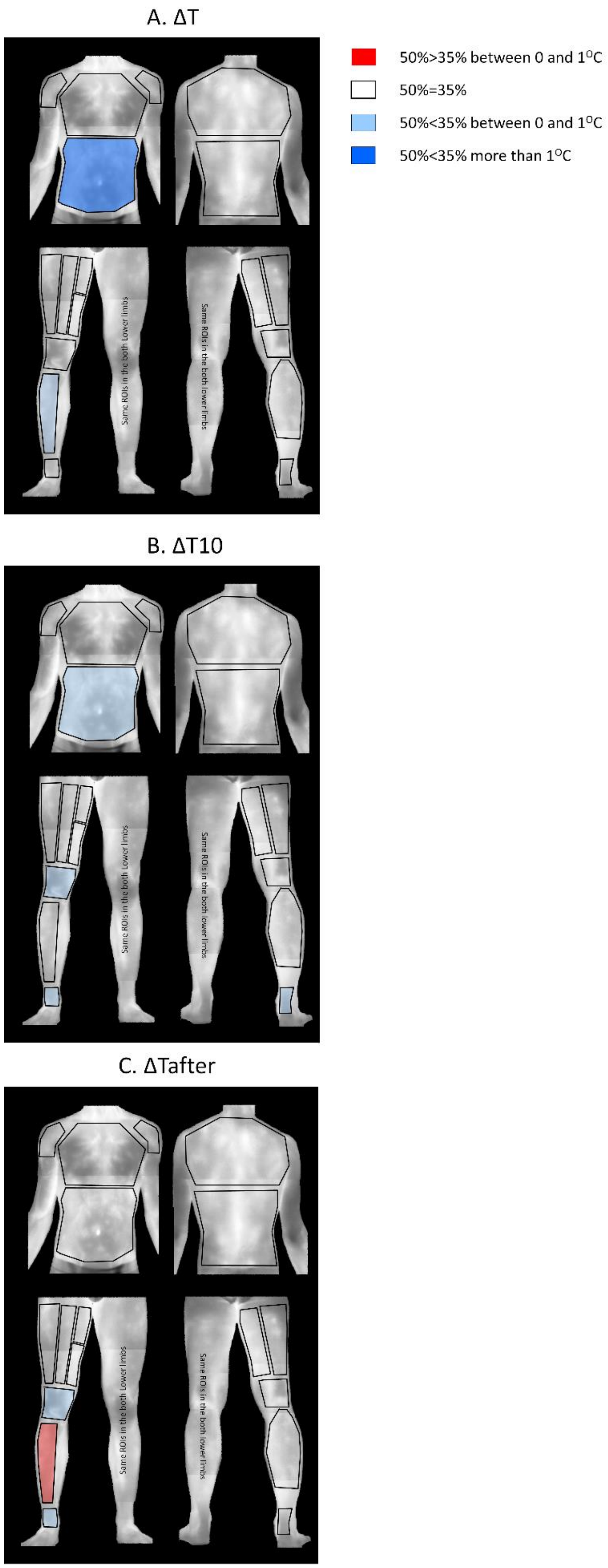


Figure 4.7. Representation of the differences in the variation of skin temperature between 50 and 35% PO_{max} in the 17 regions of interest considered in this study ($p<0.05$).

In general, weak and moderate negative correlations ($r<-0.5$ and $p<0.05$) were observed between core and skin temperature in the trunk (deltoid: $r=-0.34$ and $p<0.001$; chest: $r=-0.49$ and $p<0.001$; abdomen: $r=-0.58$ and $p<0.001$; upper back: $r=-0.46$ and $p<0.001$; low back: $r=-0.37$ and $p<0.001$) and in some ROIs of the lower limb (semitendinosus: $r=-0.22$ and $p=0.04$; tibialis anterior: $r=-0.41$ and $p<0.001$; gastrocnemius: $r=-0.25$ and $p=0.02$). In the knee alone, a weak positive correlation was observed ($r=0.42$ and $p<0.001$).

When data were analyzed separately for each cycling workload, stronger negative correlations ($p<0.05$) were observed for the lower workload (35% PO_{max}) compared to 50% PO_{max} in the trunk, biceps femoris, semitendinosus, tibialis anterior and gastrocnemius (Figure 4.8). However, the general positive correlation observed for the knee was stronger at 50% PO_{max} test ($p<0.05$). Positive relationships were also observed for ankle anterior and Achilles at 50% PO_{max} tests ($r=0.43$ and $p<0.01$, and $r=0.31$ and $p=0.04$, respectively), whereas no significant correlations were observed for tests at 35% PO_{max}.

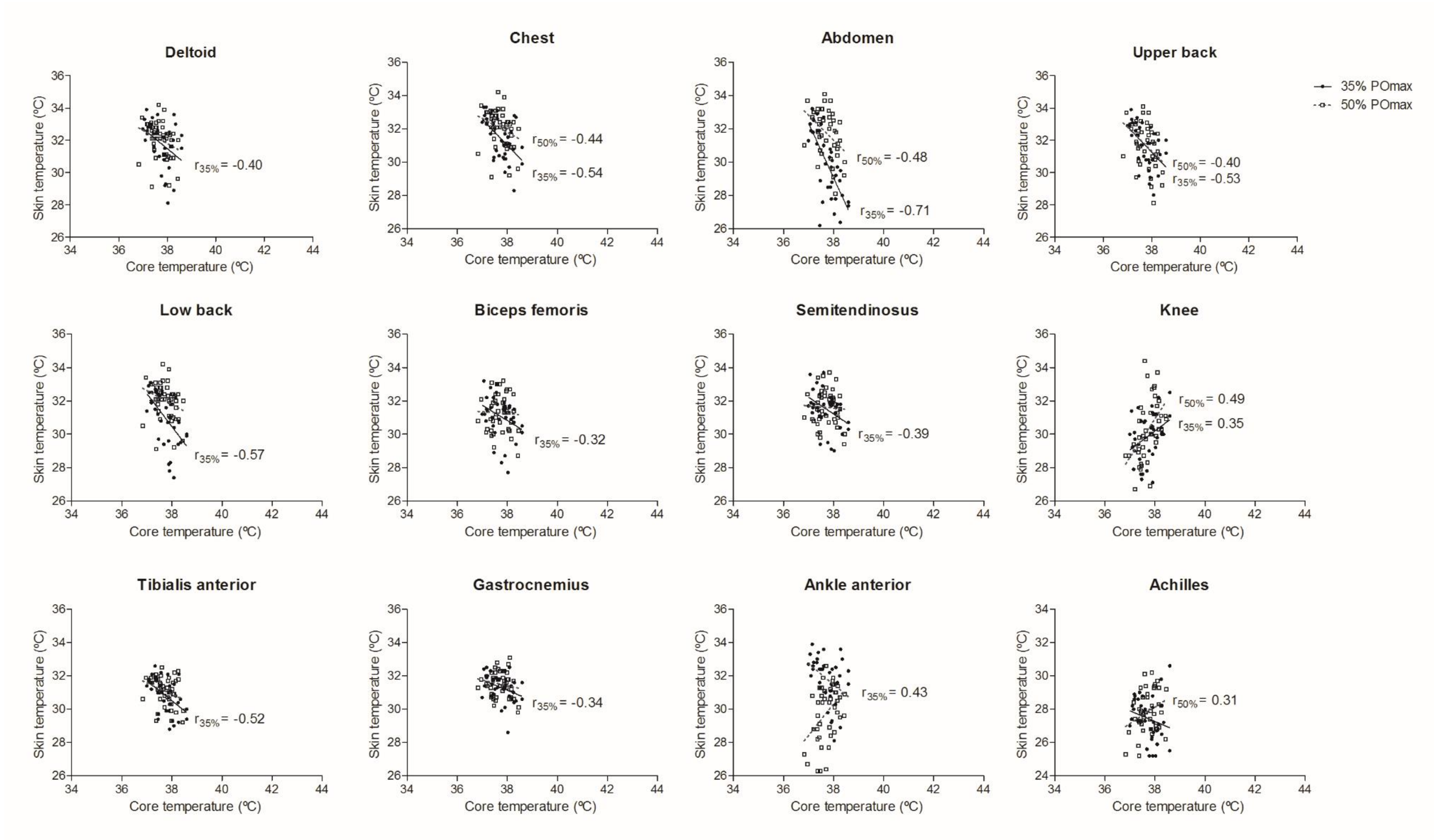


Figure 4.8. Relationships observed between core and skin temperature. Data are grouped by cycling workload (35% and 50% PO_{max}). Pearson's correlation coefficient is presented only if significant ($p<0.05$) for the 35% (r35%) and 50% tests (r50%).

4.2.2. Relationship between skin temperature and neuromuscular activation (experimental study 2)

Table 4.4 shows the thermal results obtained in each of the body regions of interest.

Table 4.4. Absolute temperature values obtained in the four body regions of interest (rectus femoris, vastus lateralis, biceps femoris and gastrocnemius medialis) at the three measurement moments.

	Temperature (ºC)					
	Before the cycling test		Immediately after cycling test		10 min after finishing the cycling test	
ROI	Mean ± SD	95%CI	Mean ±SD	95%CI	Mean ±SD	95%CI
Rectus femoris	29.4 ±1.6	28.7 - 30.1	31.0 ±1.8	30.1 - 31.8	30.1 ±1.7	30.3 - 31.9
Vastus lateralis	28.8 ±1.4	28.0 - 29.6	30.4 ±1.6	29.5 - 31.3	30.7 ±1.6	29.9 - 31.6
Biceps femoris	30.9 ±0.9	30.5 - 31.3	30.4 ±1.5	29.7 - 31.1	30.9 ±1.4	30.2 - 31.6
Gastrocnemius medialis	31.2 ±0.9	30.8 - 31.6	31.1 ±1.2	30.5 - 31.7	31.0 ±1.3	30.4 - 31.6

Knee extensors presented significant increases in temperature after exercise (rectus femoris: 95%CI of ΔT [0.9, 2.0ºC] and ΔT10 [1.2, 2.2ºC], and vastus lateralis: 95%CI of ΔT [0.9, 2.3ºC] and ΔT10 [1.4, 2.6ºC]; $p<0.05$) (Figure 4.9). Biceps femoris and gastrocnemius medialis did not present changes in temperature after the incremental cycling test ($p>0.05$).

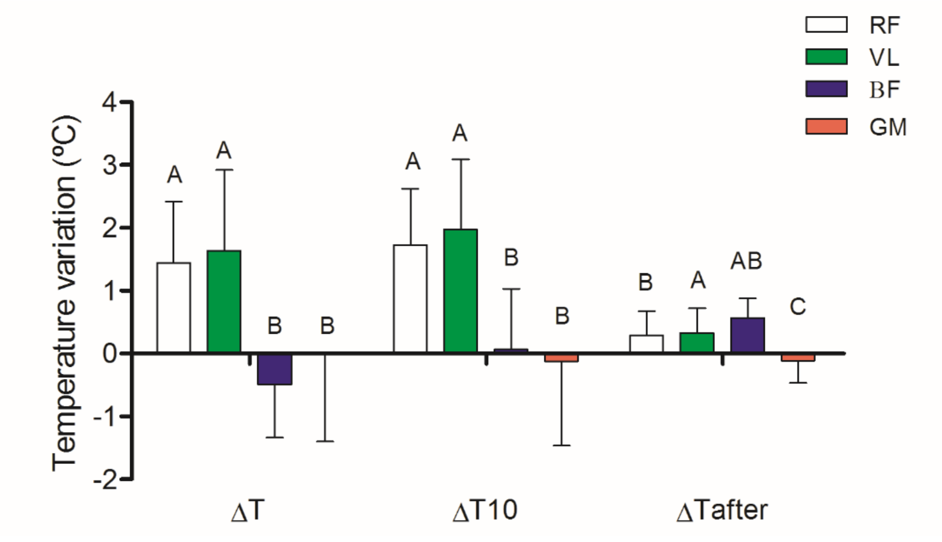


Figure 4.9. Variation in temperature at four body regions of interest (RF – rectus femoris, VL - vastus lateralis, BF – biceps femoris, and GM - gastrocnemius medialis) for each temperature variation (ΔT, ΔT10 and ΔTafter). Differences between muscles for each temperature variation are indicated when $p<0.05$ using different letters (A>B>C).

Overall activation of rectus femoris, vastus lateralis and biceps femoris increased during the incremental cycling test, without changes in high frequency components of any muscle (Figure 4.10). Low frequency components increased for vastus lateralis

(95%CI [7, 15%]), biceps femoris (95%CI [8, 18%]), rectus femoris (95%CI [5, 9%]) and gastrocnemius medialis (95%CI [1, 7%]).

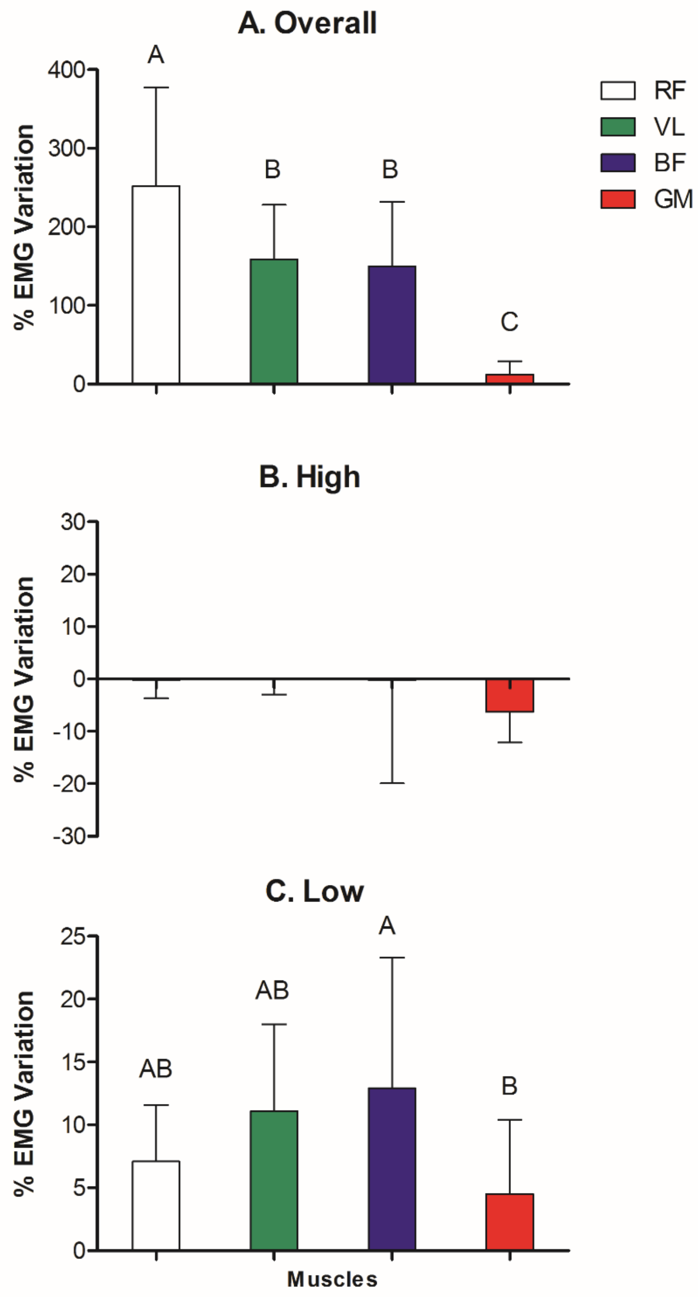


Figure 4.10. Changes in EMG (% of 10% of the total time of the test) for Overall, High and Low frequency components from the four muscles (RF – rectus femoris, VL - vastus lateralis, BF – biceps femoris, and GM - gastrocnemius medialis) during the incremental cycling test. Differences between muscles are indicated when $p<0.05$ using different letters (A>B>C).

Significant relationships between changes in skin temperature and changes in overall and low frequency components of neuromuscular activation were observed for vastus lateralis (Table 4.5 and Figure 4.11). Significant inverse relationships were observed between ΔOverall and ΔT ($r=-0.58$ and $p=0.02$), and ΔT10 ($r=-0.53$ and $p=0.04$), and positive significant relationships were verified between ΔLow and ΔT ($r=0.79$ and $p<0.01$) and ΔT10 ($r=0.76$ and $p=0.01$).

Table 4.5. Correlation between variation in neuromuscular activation for overall (ΔOverall), high (ΔHigh) and low frequencies (ΔrLow) and variation in temperature (ΔT and ΔT10) for the assessed muscles (RF – rectus femoris, VL - vastus lateralis, BF – biceps femoris, and GM - gastrocnemius medialis). Significant relationships are indicated when $p<0.05$ and $r>0.5$ or $r<-0.5$ using bold italics.

		ΔOverall				ΔHigh				ΔLow			
		RF	VL	BF	GM	RF	VL	BF	GM	RF	VL	BF	GM
ΔT	r	.18	***-.58***	-.34	.17	-.11	.07	.05	-.17	.12	***.79***	.10	-.02
	p	.46	***.02***	.14	.49	.65	.79	.85	.48	.63	***<.01***	.68	.95
ΔT10	r	-.02	***-.53***	-.17	.20	-.20	.21	.05	-.17	-.03	***.76***	.07	.02
	p	.95	***.04***	.47	.41	.42	.46	.85	.48	.89	***<.01***	.76	.95

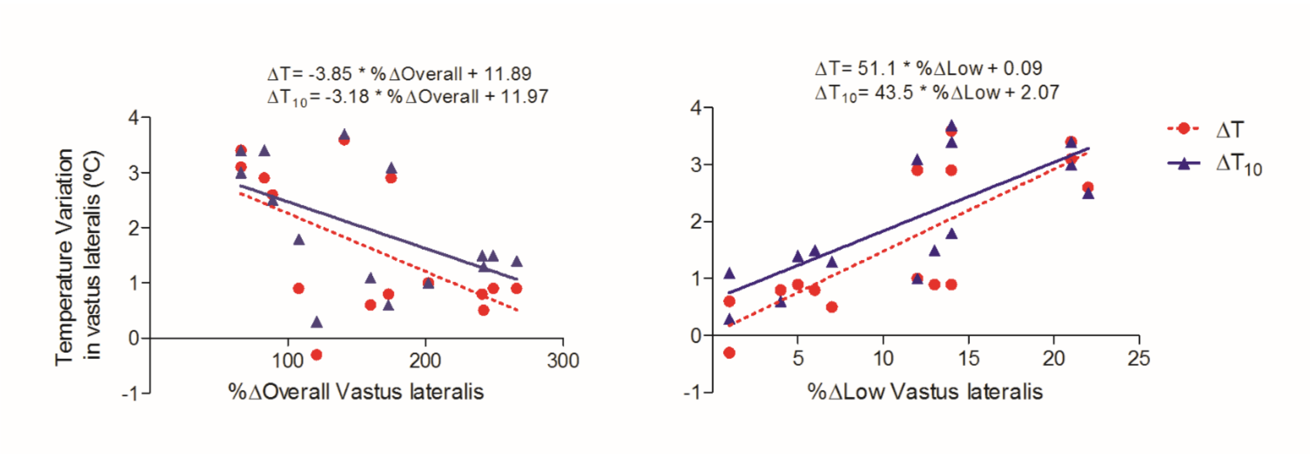


Figure 4.11. Significant inverse correlations for vastus lateralis ($p<0.05$ and $r<-0.5$) between changes in overall neuromuscular activation (ΔOverall) and changes in temperature measures (ΔT and ΔT10), and significant positive correlations for vastus lateralis ($p<0.01$ and $r=0.8$) between increment in low frequency activation (ΔLow) and changes in temperature between before and after exercise (ΔT).

Significant correlations were observed between peak power output and ΔOverall in rectus femoris ($r=0.61$ and $p<0.01$; Table 4.6). Inverse significant correlations were verified between peak power output and ΔLow in gastrocnemius medialis ($r=-0.54$ and $p=0.02$).

Table 4.6. Correlation between peak power output and variation in neuromuscular activation for overall (ΔOverall), high (ΔHigh) and low frequencies (ΔLow) and variation of temperature (ΔT and ΔT10) for the assessed muscles (RF – rectus femoris, VL - vastus lateralis, BF – biceps femoris, and GM - gastrocnemius medialis). Significant relationship are indicated when p<0.05 and r>0.5 or r<-0.5 using bold italics.

		Peak power output			
		RF	VL	BF	GM
Temperature					
ΔT	r	-.01	-.14	-.33	-.34
	p	.98	.63	.16	.16
ΔT10	r	-.16	-.17	-.33	-.40
	p	.50	.56	.16	.09
EMG					
ΔOverall	r	***.61***	.05	.09	.24
	p	***<.01***	.88	.72	.32
ΔHigh	r	.40	.35	.27	.11
	p	.09	.20	.25	.66
ΔLow	r	.30	.08	.39	***-.54***
	p	.22	.79	.09	***.01***

4.3.3. Relationship between skin temperature, performance, and predictive performance measures (experimental study 3)

The multiple linear regression (Table 4.7) indicated that the skin temperature at the end of the test was negatively correlated with body fat ($r>-0.5$ and $p<0.05$). Non-Cyclists presented a negative correlation between GM temperature and body fat and maximum oxygen consumption ($r=-0.8$ and $p=0.01$). ΔSkin temperature of GM presented a positive relationship with PO_{max} ($r=0.5$ and $p=0.04$), and similar association was observed for Cyclists in VL and RF ($r>0.7$ and $p<0.01$).

Table 4.7. Multivariate stepwise regression analyses between the skin temperature immediately after finishing the test and the different performance parameters analyzed (peak power output-PO_{max}, body fat, maximum oxygen consumption, percentage of the maximum heart rate at the second ventilatory threshold and neuromuscular activation at the end of the test).

Multiple Regression (Stepwise)			
Dependent variable	Variables included in the model Regression equation r		
	All participants	Cyclists	Non-Cyclists
Skin temperature at the end of the test			
VL(ºC)	Body Fat (%) Tsk VL = -0.1*Body Fat + 32.2 r = -0.63	Body Fat (%) Tsk VL = -0.1*Body Fat + 32.6 r = -0.79	Any variable was included
RF(ºC)	Body Fat (%) Tsk RF = -0.1*Body Fat + 32.0 r = -0.60	Body Fat (%) Tsk RF = -0.1*Body Fat + 32.2 r = -0.75	Any variable was included
BF(ºC)	Body Fat (%) Tsk BF = -0.1*Body Fat + 31.3 r = -0.60	Any variable was included	Body Fat (%) Tsk BF = -0.1*Body Fat + 32.9 r = -0.62
GM(ºC)	Body Fat (%) Tsk GM = -0.1*Body Fat + 31.2 r = -0.52	Any variable was included	Body Fat (%) and VO_{2max} Tsk GM = -0.2* Body Fat + - 0.1* VO_{2max} + 37.1 r = -0.82
ΔSkin temperature			
VL(ºC)	Any variable was included	PO_{max} (W/Kg) ΔTsk VL = 0.7* PO_{max} - 3.9 r = 0.77	Any variable was included
RF(ºC)	Any variable was included	PO_{max} (W/Kg) ΔTsk RF = 0.9* PO_{max} - 4.6 r = 0.82	Any variable was included
BF(ºC)	Any variable was included	Any variable was included	Any variable was included
GM(ºC)	PO_{max} (W/Kg) ΔTsk GM = 0.5* PO_{max} - 2.6 r = 0.45	Any variable was included	Any variable was included

In relation with the multiple linear regression analysis of the VL temperature during the test using the thermographic video (Table 4.8), skin temperature presented a positive correlation with PO ($r=0.5$ and $p=0.02$), and a negative relationship with body fat ($r=-0.5$ and $p<0.05$) and $\%VO_{2max}$ ($r=-0.5$ and $p=0.03$). Negative relationship was observed between ΔSkin temperature of the VL and its neuromuscular activation in Cyclist group at VT_2 ($r=-0.6$ and $p=0.04$).

Table 4.8. Multivariate stepwise regression analyses between the skin temperature of Vastus Lateralis (VL) and the different performance parameters analyzed (relative power output (PO), body fat, percentage of maximum oxygen consumption ($\%VO_{2max}$), percentage of the maximum heart rate and neuromuscular activation (EMG-RMS) at the two ventilatory threshold (VT_1 and VT_2).

Multiple Regression (Stepwise)			
Dependent variable	Variables included in the model Regression equation r		
	All participants	Cyclists	Non-Cyclists
Skin temperature of VL			
VT_1	PO (W/Kg) Tsk VL at VT_1 = 1.6*PO + 27.1 r = 0.50	Any variable was included	$\%VO_{2max}$ Tsk VL at VT_1 = -0.2* $\%VO_{2max}$ + 41.5 r = -0.66
VT_2	Body Fat (%) Tsk VL at VT_2 = -0.1*Body Fat + 31.6 r = -0.47	EMG-RMS VL (%) Tsk VL at VT_2 = -0.03*EMG_VL + 32.8 r = -0.62	Any variable was included
ΔSkin temperature of VL			
VT_1	Any variable was included	Any variable was included	Any variable was included
VT_2	Any variable was included	Any variable was included	Any variable was included

H_{pro} was correlated with the skin temperatures immediately after the test for VL ($r=0.47$ and $p=0.03$), RF ($r=0.49$ and $p=0.02$), and BF ($r=0.43$ and $p=0.04$), but not for GM ($r=0.28$ and $p=0.20$). H_{pro} was also correlated with PO_{max} ($r=0.70$ and $p<0.01$).

4.3.4. Cyclists vs. Non-Cyclists (experimental study 3)

Cyclists presented lower body fat percentage than Non-Cyclists (Cyclists 19.5 ±8.4%; Non-Cyclists 29.0 ±5.1%, $p<0.01$). At the three moments of the test (VT_1, VT_2 and PO_{max}), cyclists presented higher values of power output, higher skin temperature at the VL, and higher oxygen consumption ($p<0.05$). During all the test, no differences between groups were observed for ΔSkin temperature at the VL, relative values of oxygen consumption, heart rate, or neuromuscular activation ($p>0.05$), as shown in Table 4.9.

Table 4.9. Mean ±SD of the different outcomes analyzed during the incremental cycling tests at the two ventilatory thresholds (VT_1 and VT_2) and at the end of the test (PO_{max}), for the two groups (cyclists and non-cyclists). 95% confidence intervals (95%CI) and p value of the differences between cyclists and non-cyclists were showed.

	Cyclists	Non-Cyclists	Cyclists vs Non-Cyclists	
	Average ±SD	Average ±SD	p	Diff. (95%CI)
VT_1				
PO (W/Kg)	2.4 ±0.4	1.8 ±0.3	***<0.01***	***[0.3, 0.9]***
Skin temperature VL (ºC)	31.3 ±1.0	29.5 ±1.3	***<0.01***	***[0.8, 2.9]***
ΔSkin temperature VL (ºC)	0.1 ±0.7	-0.1 ±1.4	0.60	[-0.7, 1.2]
VO_2 (ml/min/kg)	24.2 ±6.1	17.5 ±2.8	***<0.01***	***[2.4, 10.9]***
%VO_{2max}	52.9 ±10.5	55.0 ±3.9	0.53	[-9.3, 4.9]
%HR_{max}	82.3 ±5.1	83.6 ±7.3	0.70	[-6.6, 4.5]
EMG (RMS)				
VL (%peak)	69.2 ±16.4	71.6 ±26.8	0.80	[-22.2, 17.3]
RF (%peak)	64.4 ±25.0	61.5 ±20.8	0.77	[-17.6, 23.4]
BF (%peak)	61.4 ±23.6	75.7 ±40.0	0.32	[-43.4, 14.8]
GM (%peak)	52.6 ±18.3	54.1 ±15.2	0.83	[-16.5, 13.4]
VT_2				
PO (W/Kg)	3.1 ±0.6	2.2 ±0.3	***<0.01***	***[0.6, 1.4]***
Skin temperature VL (ºC)	30.4 ±1.2	29.1 ±1.3	***0.02***	***[0.2, 2.4]***
ΔSkin temperature VL (ºC)	-0.8 ±0.6	-0.5 ±1.3	0.44	[-1.2, 0.6]
VO_2 (ml/min/kg)	32.5 ±8.2	23.7 ±4.3	***<0.01***	***[3.1, 14.7]***
%VO_{2max}	91.2 ±2.5	91.8 ±4.5	0.72	[-3.8, 2.7]
%HR_{MAX}	70.4 ±10.9	74.3 ±7.2	0.34	[-12.1, 4.4]
EMG (RMS)				
VL (%peak)	76.9 ±22.8	99.2 ±38.6	0.12	[-50.6, 5.8]
RF (%peak)	76.6 ±32.1	108.8 ±53.9	0.11	[-71.6, 7.3]
BF (%peak)	70.0 ±31.2	89.1 ±46.1	0.27	[-54.1, 16.0]
GM (%peak)	51.5 ±19.3	60.3 ±23.6	0.35	[-27.9, 10.4]
PO_{max}				
PO_{max} (W/Kg)	4.2 ±1.1	2.4 ±0.3	***<0.01***	***[1.1, 2.5]***
Skin temperature VL (ºC)	29.9 ±1.1	28.7 ±1.2	***0.03***	***[0.1, 2.1]***
ΔSkin temperature VL (ºC)	-1.3 ±1.0	-0.8 ±1.3	0.33	[-1.5, 0.5]
VO_{2max} (ml/min/kg)	46.1 ±8.6	31.9 ±5.4	***<0.01***	***[7.7, 20.5]***
HR_{max} (beats/min)	176.1 ±9.1	175.2 ±11.1	0.84	[-8.1, 10.0]
EMG (RMS)				
VL (%peak)	83.9 ±22.3	108.2 ±34.7	0.07	[-50.3, 1.6]
RF (%peak)	84.0 ±30.9	122.5 ±56.8	0.07	[-79.2, 2.2]
BF (%peak)	78.2 ±25.0	98.1 ±54.0	0.28	[-57.3, 17.5]
GM (%peak)	55.1 ±21.1	59.8 ±24.2	0.63	[-24.9, 15.5]

Differences between groups were indicated with bold italic letters when $p<0.05$.

Cyclists presented a higher H_{pro} than non-cyclists (cyclists 7.1 ±1.2 W/kg, non-cyclists 5.2 ±1.1 W/kg, $p<0.01$). In the two-way ANOVA analysis of the skin temperature, although the interaction between the two within-subjects factors and the between-subjects factor was not significant ($p>0.05$ for ROI*measurement moment* Cyclists vs. Non-Cyclists), the interaction between the ROIs and the between-subjects factor showed that cyclists presented higher skin temperature in knee extensors (VL: cyclists 31.2 ±1.1ºC, non-cyclists 29.7 ±1.3ºC, $p<0.01$; RF: cyclists 31.2 ±1.2ºC, non-cyclists 29.8 ±1.3ºC, $p<0.01$) and biceps femoris (cyclists 30.5 ±1.1ºC, non-cyclists 29.7 ±1.1ºC, $p=0.04$) (Figure 4.12). There was no difference on Δskin temperature for the different ROIs between Cyclists and Non-Cyclists, immediately after the incremental cycling test ($p=0.24$), and 10 min after the incremental cycling test ($p=0.13$). Δskin temperature immediately after the incremental cycling test was -0.6 ±1.4ºC, -0.6 ±1.4ºC, -1.6 ±1.2ºC and -1.4 ±1.0ºC for VL, RF, BF and GM, respectively, and 10 min after the incremental cycling test was 0.8 ±1.6ºC, 0.7 ±1.6ºC, -0.3 ±1.2ºC and -0.5 ±1.3ºC.

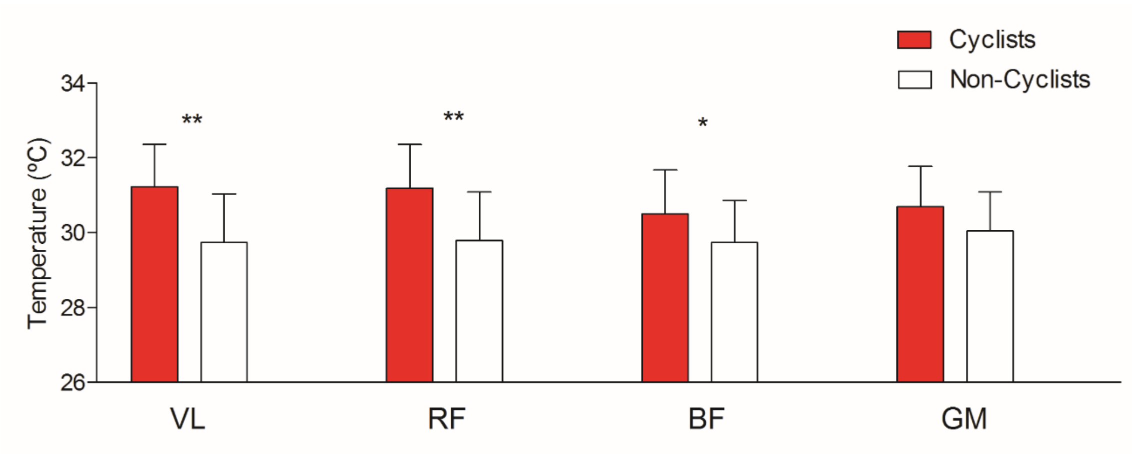


Figure 4.12. Mean ±SD of the skin temperature at four body regions of interest (VL - Vastus Lateralis, RF – Rectus Femoris, BF – Biceps Femoris and GM - Gastrocnemius Medialis). Differences observed between groups (Cyclists and Non-Cyclists) where showed by * ($p<0.05$) and ** ($p<0.01$).

4.4. Posture results

4.4.1. Validation of knee flexion postures by the perception study (experimental study 4)

Participants performed the three cycling tests in a specific knee flexion (Knee40°, Knee30°, and Knee20°) calculated from the offset position. The absolute knee angle values for Knee40°, Knee30° and Knee20° were 50.4 ±3.5°, 39.8 ±4.0° and 30.0 ±4.9°, respectively. These values correspond to the measurement when the pedal was in the bottom dead centre position.

Knee20° was reported to be "neither comfortable nor uncomfortable" (95%CI [−0.5, 0.6]) (Figure 4.13). This position was considered more comfortable than Knee40° (95%CI [−1.7, −0.9], $p<0.01$) but less comfortable than Knee30° (95%CI [0.6, 1.5], $p<0.01$).

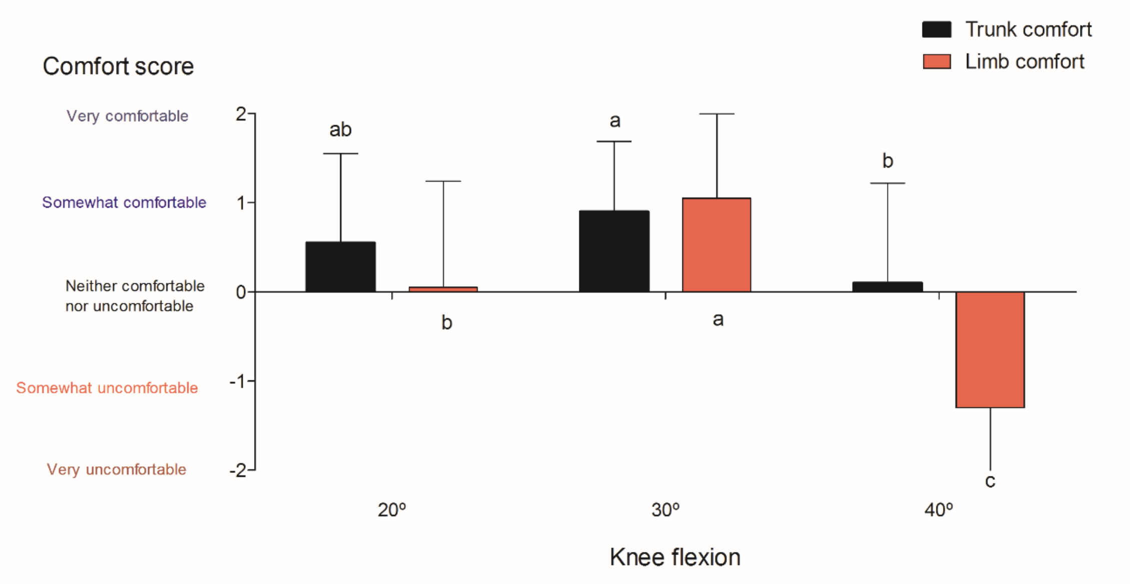


Figure 4.13. Ratings of limb and trunk comfort in terms of different knee flexion. Differences between knee-fits in trunk comfort and limb comfort are indicated using different letters (a>b, significance difference at $p<0.05$).

Mean limb fatigue and pain values ranged from 0 to 3 (none to moderate) and 0 to 2 (none to weak), respectively. Knee40° was reported to provoke more limb pain compared with all Knee30° ($p<0.01$) (Table 4.10).

The differences in fatigue and pain for each body region due to knee flexion were also analysed. Knee40° provoked higher fatigue than Knee30° in the anterior thigh and knee (95%CI of the difference [0.02, 2.9], $p=0.04$). Similarly, Knee40° also provoked higher pain than Knee30° in the anterior thigh and knee (95%CI of the differences [0.4, 2.7], $p<0.01$). Knee-fit had no effect on fatigue and pain in the trunk regions ($p>0.05$).

Table 4.10. Ratings of trunk and limb fatigue and pain for all knee flexions. Scores range from 0 (none) to +10 (very, very strong). Differences between all knee flexions are indicated using different letters (a>b, significance difference at p<0.05).

	Trunk fatigue		Limb fatigue		Trunk pain		Limb pain	
Knee flexion	Mean ±SD	95%CI	Mean ±SD	95%CI	Mean ±SD	95%CI	Mean ±SD	95%CI
20º	0.7 ±0.6	-0.3, 1.6	1.9 ±2.4	-2.0, 5.7	0.2 ±0.3	-0.3, 0.6	***0.2 ±0.3[ab]***	-0.2, 0.6
30º	0.3 ±0.4	-0.1, 0.6	1.2 ±1.4	0.0, 2.4	0.0 ±0.0	0.0, 0.0	0.1 ±0.1[a]	0.0, 0.2
40º	0.6 ±0.5	0.2, 0.9	1.8 ±0.5	1.4, 2.2	0.1 ±0.1[a]	0.0, 0.2	***0.7 ±0.4[b]***	0.0, 0.7

Groups with differences were indicated with bold italic letters when p<0.05

4.4.2. Effect of knee flexion postures on skin temperature (experimental study 4)

Table 4.11 shows the temperature values obtained in each ROI corresponding to the different knee angle during cycling. In the analysis of the absolute temperatures in the ROI, differences were obtained only in the popliteus. Immediately after the cycling test, Knee20° elicited higher temperature in popliteus than Knee40° (Knee20° vs Knee40°: 32.2 ±0.7 vs 31.6 ±0.7°C, 95%CI of the difference between conditions [0.1, 0.9°C]; p<0.01). No differences were obtained for absolute temperatures between the three flexion angles in the other fifteen ROIs (p>0.05).

In the temperature variation analysis, differences were observed only in the tibialis anterior (Table 4.12). Knee30° elicited higher ΔT10 in the tibialis anterior than Knee20° (Knee30° vs Knee20°: 0.3 ±0.9 vs −0.2 ±0.8°C, 95%CI of the difference between conditions [0.2, 1.1°C]; p<0.01). No differences were found between the three flexion angles for temperature variation in the other fifteen ROIs (p>0.05).

Table 4.11. Absolute temperature values ±SD obtained from the different body ROIs (regions of interest) in the three tests (20º, 30º and 40º knee flexion angle test).

	Before cycling			Immediately after cycling			10 min after finishing cycling		
ROI	Knee20º	Knee30º	Knee40º	Knee20º	Knee30º	Knee40º	Knee20º	Knee30º	Knee40º
Chest	32.8 ±1.2	32.6 ±0.9	32.6 ±0.6	33.6 ±0.8	33.2 ±0.9	33.1 ±1.2	32.6 ±0.8	32.4 ±1.1	32.5 ±1.0
Abdomen	32.5 ±1.5	32.3 ±1.2	32.3 ±0.9	32.2 ±1.3	31.5 ±1.4	31.5 ±1.3	31.8 ±1.2	31.5 ±1.6	31.8 ±1.3
Upper back	33.5 ±1.0	33.4 ±0.9	33.2 ±0.7	33.6 ±0.7	33.1 ±1.1	33.1 ±1.2	33.2 ±0.9	33.2 ±1.0	33.2 ±0.9
Lower back	32.7 ±1.4	32.5 ±1.2	32.4 ±0.8	33.4 ±1.0	32.7 ±2.0	32.5 ±2.4	32.5 ±1.3	32.3 ±1.6	32.4 ±1.5
Vastus lateralis	32.1 ±1.0	31.3 ±1.2	32.1 ±1.0	32.5 ±1.3	32.3 ±1.6	32.2 ±1.2	32.8 ±1.0	32.9 ±1.0	32.6 ±0.6
Rectus femoris	31.7 ±1.2	31.2 ±1.3	31.3 ±0.9	32.3 ±1.3	32.2 ±1.7	32.1 ±1.2	32.7 ±1.1	32.7 ±1.0	32.4 ±0.9
Abductor	31.8 ±1.6	31.3 ±1.4	31.6 ±1.0	31.6 ±1.6	31.7 ±1.3	31.6 ±1.0	32.1 ±1.2	32.2 ±1.1	32.0 ±1.2
Vastus medialis	32.1 ±1.3	31.6 ±1.3	31.8 ±0.8	32.9 ±1.4	32.8 ±1.5	32.7 ±1.2	33.2 ±1.0	33.2 ±1.0	33.0 ±0.8
Biceps femoris	32.1 ±1.3	31.6 ±1.3	31.8 ±0.8	31.6 ±1.0	31.2 ±1.4	31.1 ±1.0	32.3 ±0.9	31.9 ±1.1	31.9 ±0.9
Semitendinosus	32.5 ±1.3	31.9 ±1.4	32.1 ±0.8	32.0 ±1.1	31.5 ±1.5	31.4 ±1.0	32.8 ±0.9	32.4 ±1.1	32.3 ±0.8
Knee	30.9 ±1.4	30.3 ±1.8	30.4 ±1.3	32.2 ±2.0	31.6 ±2.3	31.4 ±2.3	32.1 ±1.7	32.1 ±1.8	31.8 ±1.6
Popliteus	32.8 ±1.1	32.3 ±1.0	32.5 ±0.7	**32.2 ±0.7***	31.9 ±1.0	**31.6 ±0.7***	32.8 ±0.8	32.7 ±0.7	32.5 ±0.6
Tibialis anterior	32.5 ±1.2	32.0 ±1.1	32.3 ±0.8	31.5 ±0.9	31.5 ±1.1	31.1 ±1.2	32.2 ±0.7	32.4 ±0.9	32.0 ±0.8
Gastrocnemius	32.5 ±1.0	32.1 ±0.9	32.2 ±0.7	31.8 ±0.9	31.6 ±1.3	31.2 ±1.0	32.6 ±0.7	32.4 ±0.9	32.1 ±0.8
Ankle anterior	31.6 ±1.2	30.9 ±1.4	31.2 ±0.8	32.1 ±0.9	31.4 ±2.0	31.3 ±1.7	32.2 ±0.8	31.9 ±1.5	31.6 ±1.2
Achilles	30.4 ±1.4	29.6 ±1.9	29.8 ±1.0	31.1 ±1.8	30.2 ±2.3	29.9 ±2.3	30.7 ±1.5	30.0 ±2.2	29.7 ±1.9

Statistical significant difference was observed in popliteus between the knee at 20º and 40º ($p<0.05$) and it is indicated with bold letters and *.

Table 4.12. Temperature variations values ±SD obtained from the different body ROIs (regions of interest) in the three tests (20º, 30º and 40º knee flexion angle test).

	ΔT			ΔT10			ΔTafter		
ROI	Knee20º	Knee30º	Knee40º	Knee20º	Knee30º	Knee40º	Knee20º	Knee30º	Knee40º
Chest	0.8 ±1.3	0.6 ±1.2	0.5 ±1.5	-0.2 ±1.1	-0.3 ±1.2	-0.1 ±1.1	-1.0 ±0.8	-0.8 ±1.1	-0.6 ±1.1
Abdomen	-0.3 ±1.3	-0.7 ±1.4	-0.8 ±1.3	-0.6 ±0.9	-0.8 ±1.2	-0.5 ±1.0	-0.4 ±1.1	-0.1 ±0.9	0.3 ±1.0
Upper back	0.1 ±1.3	-0.3 ±1.4	-0.2 ±1.5	-0.3 ±1.2	-0.2 ±1.1	-0.1 ±1.0	-0.4 ±0.7	0.1 ±0.8	0.1 ±0.8
Lower back	0.7 ±1.5	0.3 ±2.2	0.1 ±2.6	-0.2 ±1.6	-0.2 ±1.6	-0.0 ±1.5	-0.9 ±0.8	-0.4 ±0.9	-0.1 ±1.7
Vastus lateralis	0.7 ±1.2	1.0 ±0.9	0.8 ±0.9	1.0 ±1.0	1.6 ±0.8	0.6 ±0.8	0.3 ±0.7	1.2 ±0.6	0.5 ±0.7
Rectus femoris	0.6 ±1.2	1.0 ±0.9	0.7 ±0.9	1.0 ±1.0	1.5 ±0.8	1.1 ±0.7	0.4 ±0.6	0.5 ±0.8	0.4 ±0.6
Abductor	-0.2 ±1.1	0.4 ±1.0	0.0 ±0.8	0.3 ±1.0	0.9 ±0.9	0.5 ±0.7	0.5 ±0.7	0.5 ±0.7	0.5 ±0.6
Vastus medialis	0.8 ±1.2	1.1 ±0.8	0.9 ±0.8	1.1 ±1.1	1.5 ±0.7	1.3 ±0.5	0.3 ±0.7	0.4 ±0.8	0.3 ±0.7
Biceps femoris	-0.5 ±1.3	-0.4 ±0.9	-0.8 ±0.9	0.2 ±1.0	0.4 ±0.7	0.1 ±0.7	0.7 ±0.7	0.8 ±0.7	0.9 ±0.6
Semitendinosus	-0.5 ±1.2	-0.5 ±1.0	-0.7 ±0.9	0.3 ±0.8	0.4 ±0.8	0.2 ±0.7	0.8 ±0.7	0.9 ±0.7	0.9 ±0.5
Knee	1.3 ±2.0	1.4 ±2.1	1.0 ±2.3	1.3 ±1.7	1.8 ±1.8	1.4 ±1.4	-0.1 ±0.8	0.4 ±0.8	0.4 ±1.0
Popliteus	-0.6 ±0.9	-0.4 ±0.7	-0.8 ±0.6	-0.0 ±0.6	0.3 ±0.7	0.0 ±0.4	0.6 ±0.5	0.8 ±0.6	0.8 ±0.4
Tibialis anterior	-1.0 ±1.3	-0.6 ±1.1	-1.2 ±1.0	**-0.2 ±0.8***	**0.3 ±0.9***	-0.3 ±0.6	0.7 ±0.8	0.9 ±0.6	0.9 ±0.7
Gastrocnemius	-0.8 ±0.9	-0.6 ±0.8	-1.0 ±1.0	0.1 ±0.6	0.3 ±0.6	-0.1 ±0.6	0.9 ±0.6	0.9 ±0.5	1.0 ±0.5
Ankle anterior	0.5 ±1.4	0.5 ±1.6	0.0 ±1.6	0.6 ±1.1	1.0 ±1.3	0.3 ±1.0	0.1 ±0.8	0.5 ±0.9	0.3 ±0.7
Achilles	0.6 ±1.6	0.7 ±2.1	0.1 ±1.8	0.3 ±1.4	0.5 ±1.9	-0.1 ±1.4	-0.3 ±0.6	-0.2 ±0.8	-0.2 ±0.7

Statistical significant difference was observed in tibialis anterior between the knee at 20º and 30º ($p<0.05$) and it is indicated with bold letters and *.

4.5. Methodological results

4.5.1. Intraday reproducibility study (experimental study 4)

Table 4.13 shows the intra-class correlation coefficients of the absolute temperatures and temperature variations obtained from the three knee flexion tests. Before the cycling test, the different ROIs presented good and very good reproducibility. Immediately after cycling, the different ROIs continued showing good and very good reproducibility. Moreover, the ROI of the knee showed excellent reproducibility. Ten minutes after the cycling test all ROIs presented ICC values higher than 0.6 (very good reliability).

Regards to temperature variations, the ROI of the trunk presented good and very good reproducibility in the three temperature variations. However, the ROIs of the lower limbs presented lower values of ICC in temperature variations than in absolute values. ΔT values presented, in some ROIs, poor (rectus femoris) and reasonable reproducibility (abductor, biceps femoris, and popliteus). This tendency increased for ΔT10 values, more ROIs showing poor (vastus lateralis, rectus femoris, abductor and popliteus) and reasonable reproducibility (vastus medialis, biceps femoris and gastrocnemius). In the ΔTafter values, almost all ROIs of the limbs presented good reproducibility, and only three presented reasonable ICC values (popliteus, gastrocnemius and ankle anterior).

Table 4.13. Typical error and Intra-class correlation coefficient (ICC) was calculated to determine the intraday reproducibility for the absolute temperatures and temperature variations. Intraday reproducibility was measured from the three knee flexion tests.

	Absolute temperatures						Temperature variations					
	Before cycling		Immediately after cycling		10 min after finishing cycling		ΔT		ΔT10		ΔTafter	
ROI	TYPICAL ERROR	ICC	TYPICAL ERROR	ICC	TYPICAL ERROR	ICC	TYPICAL ERROR	ICC	TYPICAL ERROR	ICC	TYPICAL ERROR	ICC
Chest	0.21	0.69	0.22	0.63	0.22	0.69	0.30	0.74	0.24	0.67	0.22	0.67
Abdomen	0.28	0.80	0.29	0.60	0.31	0.75	0.28	0.56	0.21	0.46	0.22	0.63
Upper back	0.19	0.71	0.23	0.66	0.22	0.73	0.32	0.73	0.24	0.61	0.17	0.60
Lower back	0.25	0.70	0.41	0.63	0.34	0.79	0.48	0.70	0.35	0.69	0.24	0.43
Vastus lateralis	0.21	0.44	0.31	0.73	0.19	0.60	0.22	0.62	0.14	0.17	0.16	0.52
Rectus femoris	0.25	0.57	0.32	0.69	0.22	0.61	0.21	0.14	0.14	0.11	0.14	0.62
Abductor	0.31	0.72	0.31	0.66	0.25	0.62	0.18	0.33	0.15	0.14	0.13	0.54
Vastus medialis	0.26	0.65	0.32	0.79	0.21	0.74	0.20	0.60	0.14	0.22	0.16	0.68
Biceps femoris	0.25	0.60	0.25	0.64	0.21	0.65	0.19	0.26	0.15	0.32	0.14	0.56
Semitendinosus	0.27	0.66	0.27	0.69	0.22	0.68	0.21	0.47	0.15	0.44	0.14	0.66
Knee	0.31	0.53	0.53	0.85	0.40	0.85	0.48	0.73	0.34	0.52	0.19	0.60
Popliteus	0.20	0.63	0.17	0.54	0.15	0.61	0.14	0.32	0.09	0.11	0.09	0.27
Tibialis anterior	0.20	0.62	0.22	0.51	0.17	0.62	0.24	0.53	0.16	0.45	0.14	0.54
Gastrocnemius	0.19	0.63	0.25	0.70	0.18	0.63	0.18	0.45	0.11	0.21	0.10	0.36
Ankle anterior	0.24	0.50	0.33	0.52	0.26	0.65	0.33	0.58	0.23	0.51	0.16	0.38
Achilles	0.31	0.50	0.49	0.72	0.43	0.71	0.39	0.57	0.33	0.53	0.14	0.45

4.5.2. Determination of ROIs by using a factor analysis (study 5)

The results of the factor analyses and the definition of the different groups of ROIs in the body are presented in Table 4.14 and Figure 4.14. Different groups were obtained when the analysis focused on the mean skin temperature (Figure 4.14.A) or on the skin temperature variations (Figure 4.14.B). All the analyses performed for skin temperature at each moment (before, immediately after and 10 min after cycling test) and for each skin temperature variation (ΔT, ΔT10 and ΔTafter) explained more than 80% of the variance (Table 4.14). With respect to the moment of measurement, the factor analysis defined 3 principal components for the first moment (before cycling), 4 principal components for the second moment (immediately after cycling), and 3 principal components for the last moment (10 minutes after cycling). For each skin temperature variation, the factor analysis defined 5 principal components. In all of the analyses, the group 2 (defined mainly by the thigh, or the anterior thigh, depending on the analysis) was the principal component that explained most of the variance (>46%). Tucker´s coefficient showed an acceptable congruence in all moments and variations ($K>0.93$) except for the ΔT, which showed a lower value ($K=0.92$) (Table 4.15).

Before cycling (Figure 4.15.A), the mean skin temperature was significantly different between the three groups of ROIs ($p<0.001$). Group 1 (trunk) presented higher skin temperature, followed by group 2 (lower limbs without their joints), and group 3 (knee, anterior ankle and Achilles). Similarly, group 1 (trunk) and group 2 (thigh) exhibited the greatest mean skin temperatures immediately after cycling (Figure 4.15.B), whereas the rest of the groups were not affected ($p<0.05$). However, no differences were observed between groups 3 and 4 ($p=0.06$). Finally, for the measurement 10 minutes after cycling (Figure 4.15.C), group 3 (knee, tibialis anterior, anterior ankle and Achilles) presented the lowest skin temperatures ($p<0.001$). No differences were observed between group 1 (trunk) and group 2 (lower limb) ($p=1.0$).

With respect to the skin temperature variation ΔT (Figure 4.16.A), group 2 (anterior thigh) presented the highest increase of skin temperature ($p=0.01$ with group 1; $p<0.001$ with groups 3, 4 and 5). No differences in ΔT were found between groups 1, 3, 4 and 5 ($p>0.05$). Regarding ΔT10 (Figure 4.16.B), group 2 (anterior thigh) and group 3 (knee, anterior ankle anterior and Achilles) presented the highest increase of skin temperature, followed by group 5 (posterior thigh) ($p<0.001$). No differences were found between groups 1 and 4 ($p>0.05$). Finally, for ΔTafter, group 5 (posterior limb except the

Achilles) presented the highest increase of skin temperature, followed by group 2 (anterior thigh) and group 3 (knee, tibialis anterior and anterior ankle) ($p<0.001$). No differences were found between groups 1 and 4 ($p>0.05$) (4.16.C).

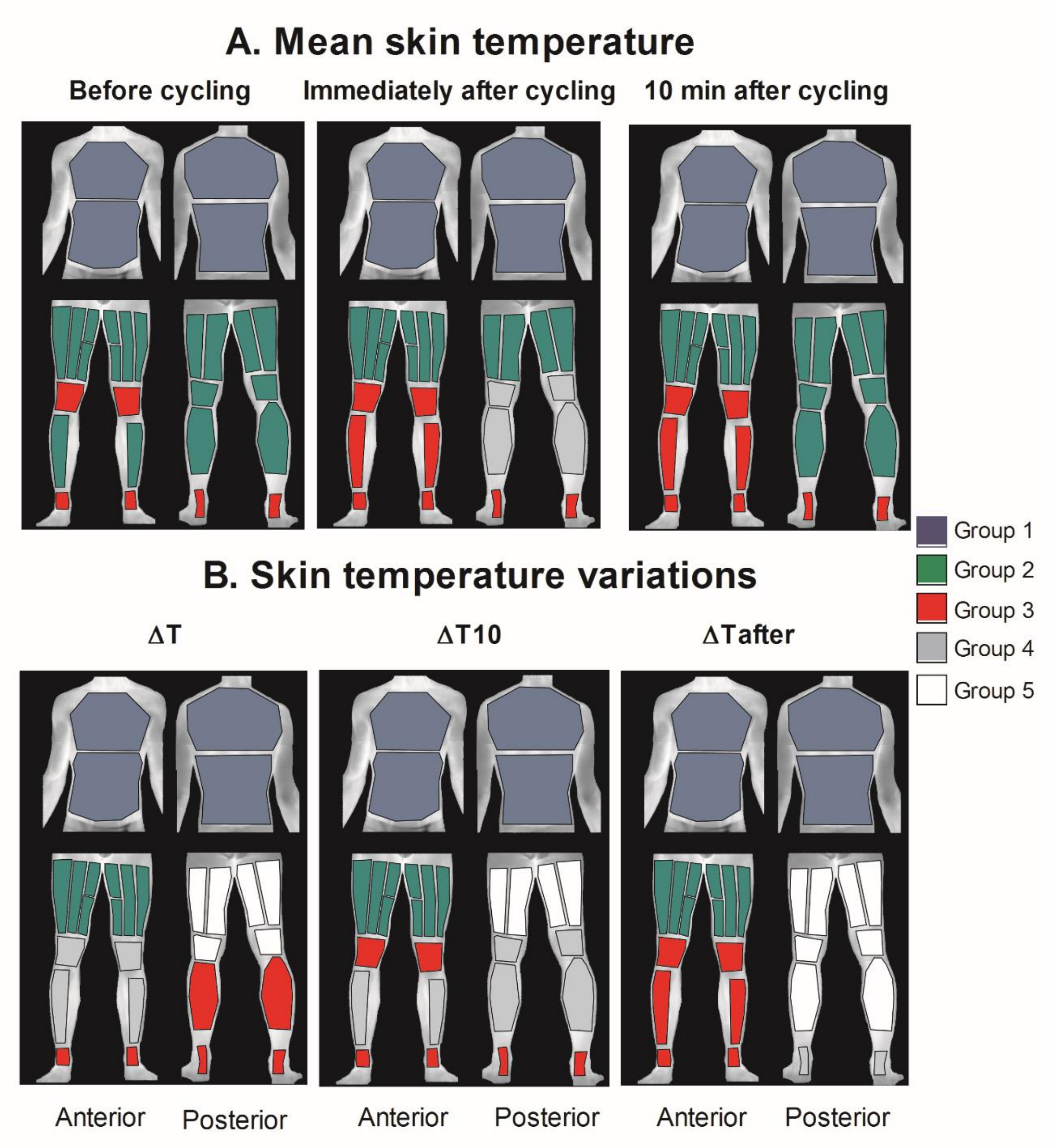


Figure 4.14. Representation of the groups of ROIs at each moment of measurement (A) and in each skin temperature variation (B) resulting from the factor analysis. ΔT (difference between temperature immediately after the cycling test and before), ΔT10 (difference between temperature 10 min after the cycling test and before) and ΔTafter (difference between temperature 10 min after and immediately after the cycling test).

Table 4.14. Description of the groups resulting from the factor analysis, percentage of the variance explained by each of them and Tucker´s coefficient of congruence (K). Abbreviations of the ROIs: chest (C), abdomen (A), upper back (UB), lower back (LB), vastus lateralis (VL), rectus femoris (RF), abductor (AB), vastus medialis (VM), biceps femoris (BF), semitendinosus (SM), knee (K), popliteus (P), tibialis anterior (TA), gastrocnemius (G), anterior ankle (AA), and Achilles (AC). ΔT (difference between temperature immediately after the cycling test and before), ΔT10 (difference between temperature 10 min after the cycling test and before) and ΔTafter (difference between temperature 10 min after and immediately after the cycling test).

	Mean skin temperature					
	Before cycling		**Immediately after cycling**		**10 min after cycling**	
	ROIs	**Variance explained (%)**	**ROIs**	**Variance explained (%)**	**ROIs**	**Variance explained (%)**
Group 1	C – A – UB - LB	4.2	C – A – UB – LB	5.9	C – A – UB – LB	10.5
Group 2	VL – RF – AB – VM – BF – SM – P – TA – G	78.4	VL – RF – AB – VM – BF – SM	58.3	VL – RF – AB – VM – BF – SM – P – G	54.1
Group 3	K – AA – AC	6.2	K – TA – AA – AC	10.9	K – TA – AA – AC	15.9
Group 4			P – G	10.4		
Total		**88.8**		**85.5**		**80.5**
	K = 0.98		K = 0.94		K = 0.94	
	Skin temperature variations					
	ΔT		**ΔT10**		**ΔTafter**	
Group 1	C – A – UB – LB	5.4	C – A – UB – LB	3.7	C – A – UB – LB	6.5
Group 2	VL – RF – AB – VM	51.4	VL – RF – AB – VM	51.9	VL – RF – AB – VM	46.8
Group 3	G – AA – AC	9.7	K – AA – AC	13.3	K – TA – AA	8.3
Group 4	K – TA	4.0	P – TA – G	8.6	AC	4.7
Group 5	BF – SM – P	12.9	BF – SM	6.4	BF – SM – P – G	14.6
Total		**83.4**		**82.9**		**80.9**
	K = 0.92		K = 0.94		K = 0.96	

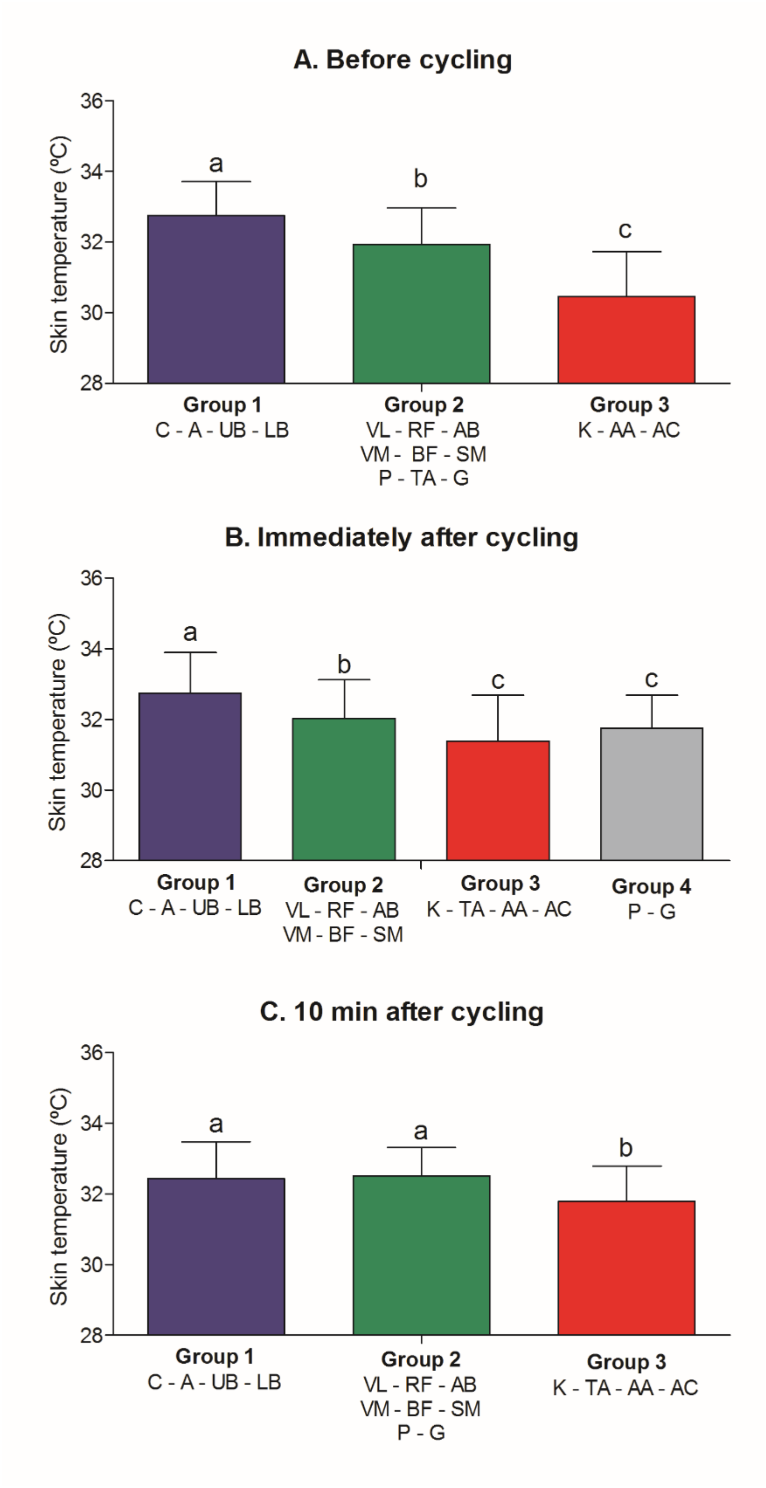


Figure 4.15. Mean ± SD of each group at the three moments: before cycling (A), immediately after cycling (B), and 10 minutes after cycling (C). Differences between groups are indicated with letters (A>B>C) when $p<0.05$. Abbreviations of the ROIs: chest (C), abdomen (A), upper back (UB), lower back (LB), vastus lateralis (VL), rectus femoris (RF), abductor (AB), vastus medialis (VM), biceps femoris (BF), semitendinosus (SM), knee (K), popliteus (P), tibialis anterior (TA), gastrocnemius (G), anterior ankle (AA), and Achilles (AC).

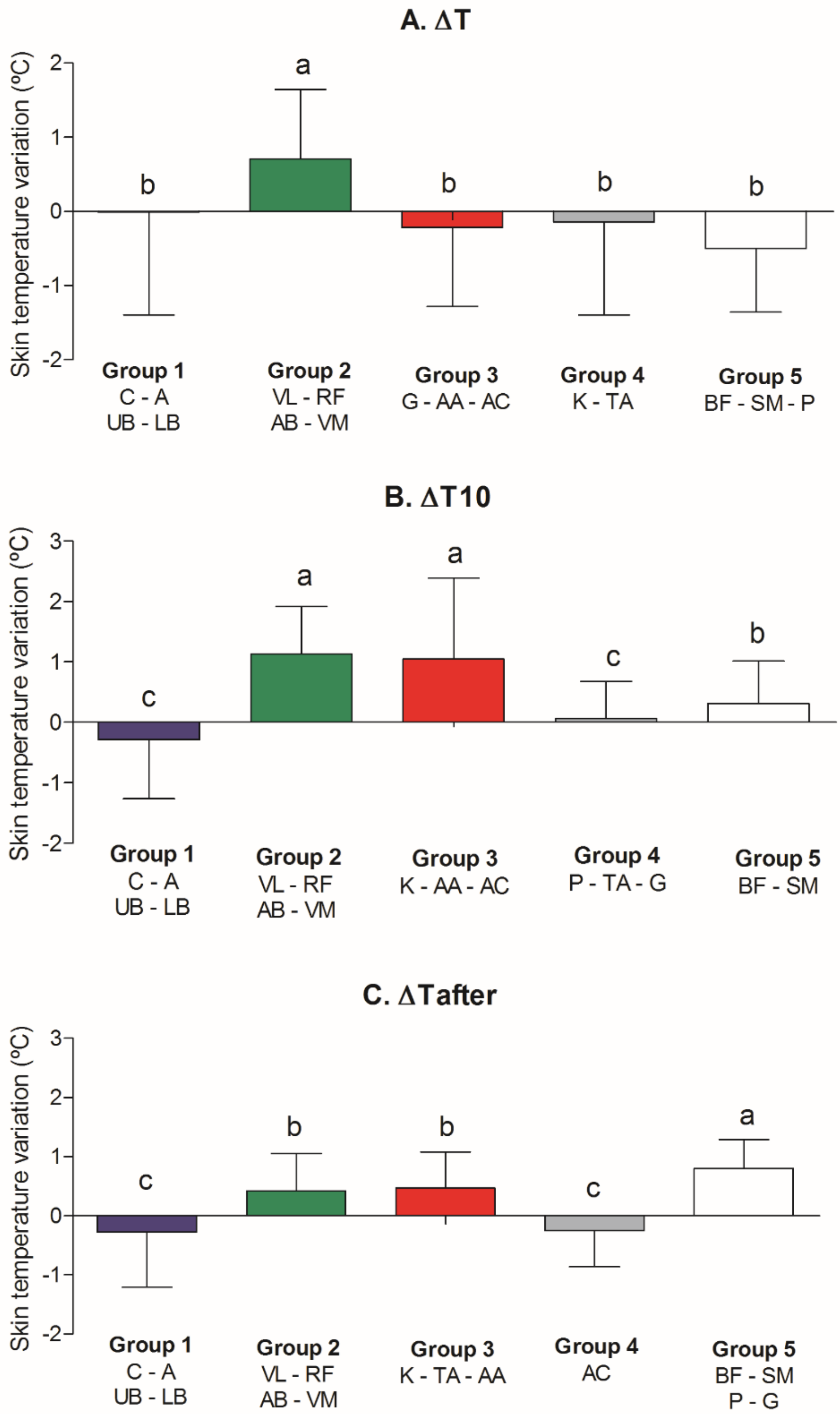


Figure 4.16. Mean ± SD of each group in the three skin temperature variations: ΔT, ΔT10 and ΔTafter. Differences between groups are indicated with letters (A>B>C) when p>0.05. Abbreviations of the ROIs: chest (C), abdomen (A), upper back (UB), lower back (LB), vastus lateralis (VL), rectus femoris (RF), abductor (AB), vastus medialis (VM), biceps femoris (BF), semitendinosus (SM), knee (K), popliteus (P), tibialis anterior (TA), gastrocnemius (G), anterior ankle (AA), and Achilles (AC). ΔT (difference between temperature immediately after the cycling test and before), ΔT10 (difference between temperature 10 min after the cycling test and before) and ΔTafter (difference between temperature 10 min after and immediately after the cycling test).

4.5.3. Multi regression analysis of skin temperature variation (study 5)

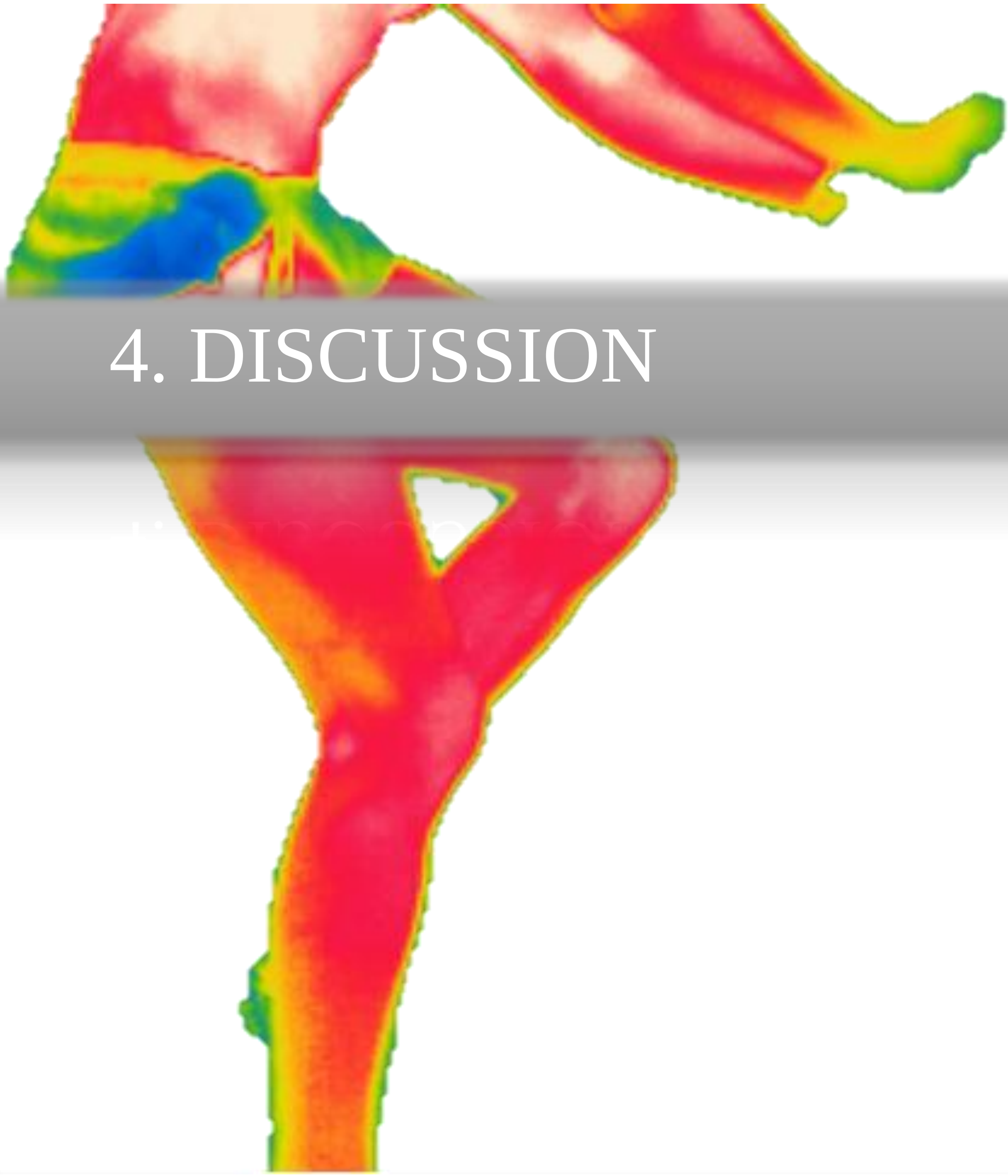
The multiple regression analyses obtained a model for each ROI which accounted for at least 60% of the variance of the ΔT, apart from for the anterior thigh where it accounted for 51% (Table 4.15). The anthropometric variables (body mass, body surface area and BMI) were the most important predictors explaining more than 15% of variance in most of the models. Other predictors, although of less importance (between 5 and 15% of the variance), were baseline skin temperature, height, skinfolds, and age. Although in some models, PO_{max}, relative humidity and room temperature were significant, they predicted less than the 1% of the variance.

Body surface area presented a positive relationship with BMI ($r=0.5$ and $p<0.001$) and the different skinfolds ($r>0.3$ and $p<0.05$).

Table 4.15. Summary of the regressions models obtained for the ΔT for each ROI.

Model	Quality of the model	Predictor variables	Coefficients	SE	p	Variance explained for by the predictor (%)
ΔT of the Trunk	R^2=0.63 (p<0.001) Residual standard error=0.90	Intercept	-110.46	37.25	<0.01	-
		Body mass	-2.36	0.68	<0.01	27.7
		Body surface area	122.91	35.03	<0.01	19.3
		BMI	3.48	0.98	<0.001	13.4
		Basal skin temperature	-1.15	0.18	<0.001	1.4
		Relative humidity	0.04	0.01	<0.01	0.7
		Abdominal skinfold	-0.05	0.02	0.02	0.6
		Room temperature	0.22	0.10	0.04	0.4
ΔT of the Anterior thigh	R^2=0.51 (p<0.001) Residual standard error= 0.68	Intercept	5.58	3.31	0.10	-
		Body surface area	5.50	0.91	<0.001	17.1
		Age	-0.06	0.01	<0.001	13.7
		Basal skin temperature	-0.41	0.10	<0.001	12.2
		Thigh skinfold	-0.09	0.03	<0.01	8.0
ΔT of the Anterior leg	R^2=0.62 (p<0.001) Residual standard error=0.81	Intercept	0.88	4.28	0.84	-
		BMI	0.17	0.05	<0.01	19.4
		Body surface area	3.68	1.19	<0.01	16.8
		Basal skin temperature	-0.36	0.12	<0.01	14.7
		Age	-0.03	0.01	0.03	10.8
ΔT of the Posterior thigh	R^2=0.62 (p<0.001) Residual standard error=0.57	Intercept	-90.62	24.93	<0.001	-
		BMI	2.08	0.51	<0.001	21.7
		Body mass	-0.60	0.16	<0.001	19.2
		Height	60.98	14.70	<0.001	13.8
		Basal skin temperature	-0.67	0.13	<0.001	2.5
		Thigh skinfold	-0.08	0.02	<0.001	2.5
		Age	-0.03	0.01	<0.01	0.9
		Relative humidity	0.02	0.01	0.01	0.9
ΔT of the Posterior leg and ankle	R^2=0.61 (p<0.001) Residual standard error=0.74	Intercept	-30.58	33.61	0.37	-
		Body mass	-1.82	0.54	<0.01	22.8
		Body surface area	129.73	33.79	<0.001	21.6
		BMI	1.77	0.77	0.03	7.2
		Height	-55.85	22.91	0.02	4.9
		Thigh skinfold	-0.11	0.02	<0.001	1.3
		Basal skin temperature	-0.64	0.16	<0.001	0.8
		Age	-0.06	0.01	<0.001	0.8
		PO_{max}	-0.01	0.00	<0.01	0.6
		Relative humidity	0.03	0.01	0.02	0.5

4. DISCUSSION



5. DISCUSSION

This section discusses the results of the PhD thesis following the same order proposed by the general objectives (validity, efficiency, posture and analysis objectives) and their specific aims.

5.1. Validity

5.1.1. Infrared thermography vs. thermal contact sensors

Background

Thermal contact sensors such as thermistors and thermocouples are widely used for skin temperature measurements. In case of wireless sensors, they provide test participants with great mobility as they do not interfere with their physical activity[9,203]. These sensors allow a continuous recording of the temperature in high-dynamic situations or below or in-between clothing layers[162]. Although the validity of wireless temperature sensors is accepted[151,203], determining temperature in just one single point can limit the understanding of human thermal response as the evaluated body part could be not properly represented. In addition, thermal interactions between sensor and environment can reduce the reliability of the measurement[203]. The attaching method to the skin (usually different types of clinical tapes) has been shown to affect the local heat transfer[33,181], and hence, the local thermal regulation and skin temperature[9,110,219].

IRT has been successfully applied for many clinical purposes[133]. It has become more popular in the last years in sports physiology research due to its non-contact and non-invasive character[3,9,89,156]. It generally shows a high reproducibility[153,234], although some variation was detected in measurements between different days for distal body parts[234], probably due the large number of the factors that can affect the skin temperature[77]. By IRT is possible to analyze skin temperature distribution on surface of the entire body or some specific ROIs[9]. Hence, IRT can provide a more representative temperature value of the body region than thermal contact sensors. However, in order to properly take infrared images of skin surface and to obtain correct values of temperature, some factors need to be controlled accurately[77,158]. They mainly concern the surrounding environment[111,185], the participant preparation for the test[8,150], the use of the camera[6,120,213], and the thermal images post-processing protocol[143].

Some attempts to validate IRT imaging by comparing with thermal contact sensors have been undertaken in the literature. Different studies observed higher temperature values measured by thermal sensors than by IRT at rest and during running exercise, and lower temperatures values for thermocouples compared to thermography measurements after exercise[9,110,121]. The authors suggested that the low agreement between methods could be mainly due to the fixation method of the thermal sensors on the skin and its effect on convective and evaporative heat loss in the region where the thermocouple was fixed.

Discussion of the results

The results obtained (section 4.1.1) showed that temperature values from thermal contact sensors and IRT camera differed depended on the measurement time. Hence, the findings from the human trials for each measurement time are discussed with the respective finding from the instrumented test (section 4.1.2).

Before cycling, when neither vasodilatation nor sweat mechanism are activated at their maximum, no difference between the methods was observed (Figure 4.1). Additionally, the linear regression analysis showed that the relationship between methods corresponded to the line of the identity (slope=1; y-intercept=0), representing a good agreement between methods when applied before exercise (Figure 4.3). Similar agreements were found for resting participants as well as for light exercising participants in cold, moderate and hot conditions by De Andrade Fernandes et al.[9], James et al.[121] and Buono et al.[31].

Psikuta et al.[181] showed in their study that the attachment method of the thermal contact sensors affected the readings of skin temperature. The instrumented test provided similar results when comparing non-covered thermal contact sensors and thermography camera measurements in dry conditions (Figure 4.5). However, slightly increased temperature values were found in cases where the sensors were covered with clinical tape. Covered sensors provided significantly higher temperature by 0.5ºC than the non-covered ones. This difference could be due to the thermal insulation offered by the Hypafix™ clinical tape. In accordance to these findings, Buono and Ulrich[33] attributed differences due to tape from 0.4ºC up to 1.3ºC depending on environmental conditions when comparing skin temperature measurements using covered and non-covered probes. These results support the idea that thermal contact sensors attached to the skin can interfere in the heat exchange process[9,110,181].

Immediately after cycling, the thermography camera, defined by small and large ROIs, recorded on average lower temperatures than thermal contact sensors by 0.8 and 1.2ºC, respectively. De Andrade Fernandes et al.[9] reported similar results when comparing IRT imaging and thermocouple measurements for an exercise phase. These differences were explained by the interference of the clinical tape covering the thermal contact sensor in heat exchange and evaporation of sweat[9,181]. Other possible explanation could be the effect of sweat on skin emissivity, which will be discussed in the section 5.1.2.

10 min after cycling, the difference between the methods turned into the opposite than observed at post-cycling. The temperature was 0.7 and 0.5ºC lower for thermal contact sensors compared to the thermography camera defined by small and large ROIs, respectively. It was more remarkable in the regression plots when it can be observed that the differences between methods were higher in the lower temperatures of the thermal contact sensor. This inversion of the difference between immediately after cycling and 10 min after cycling was also observed by De Andrade Fernandes et al.[9]. Either wiping off the sweat from the skin as the participants in the present study did or evaporation happening during 60 min after sweating stopped, seemed to provide dry skin conditions again. Nevertheless, it might happen that the remaining sweat absorbed by the clinical tape continued evaporating, and thus, further local cooling of the sensor could have happened, whereas no evaporation occurred on the rest of the skin.

Thermal contact sensors have some advantages over the thermography as they can measure temperature during movement easier, the possibility to measure when participants are clothed, when temperature need to be continuously registered or in case that required body posture or space do not allow having optimal conditions to take IRT images. However, the results of this dissertation showed that the contact method had a higher effect on the skin temperature. During exercise, the thermal contact sensors and their clinical tape interfere in the heat exchange and evaporation of sweat[9,181]. It probably produces higher temperatures to the adjacent skin. However, this local accumulation of the sweat in the location of the sensor produces lower temperature 10 min after the exercise because it continues to promote heat loss by sweat evaporation whereas the adjacent skin was drier. However, it is important to take into account that differences between both methods remained within the accuracy of the infrared camera (±2ºC).

The present study has shown some differences between analyzing small and large ROIs for each body part. Generally, large ROIs presented lower temperatures than small ROIs immediately after cycling (Figure 4.1 and 4.4). Due to exercise, muscles activity within one body part can be different and uneven temperature due to skin capillaries distribution can happen[7,87]. Hence, punctual skin temperature measurements (small ROIs) might be not representative of the whole body part (large ROIs) in these cases or might highly depends on the exact location of the punctual measurement for some particular activities.

5.1.2. Effect of sweat on thermographic measurements

Background

Scientific studies determining emissivity of the human skin have mostly agreed on the value of 0.98[19,207,214]. Bernard et al.[19] criticized that traditional clinical studies based on measuring skin temperature with IRT do not mention the emissivity they assumed for the skin. Some disinfectants, gels or lotions that are commonly applied on the skin surface for medical or cosmetic treatments could affect its optical properties due to their lower emissivity[19,207]. Additionally, moistening of the skin surface due to perspiration may lead to difficulties in evaluating the temperature of the skin. Although sweat emissivity has not been determined, a coating of dew presented emissivity values as high as human skin[157], and hence, a low potential to modify skin surface emissivity could be expected. Nevertheless, Ammer[5] suggested that a water coating on the skin due to ‘‘profuse’’ sweating might act as a filter for the emitted infrared radiation from the skin surface, even if the water layer is just a few microns as determined for other types of surfaces[157]. In such a case, IRT would be able only to measure the temperature of the outer surface of the sweat layer. This would produce a difference in temperature between wet and dry skin areas due to different heat transfer conditions. Removing the sweat or water from skin has been tried as a solution[223,232], however, temperature could increase as a consequence of touching or rubbing the skin surface. A sudden elimination of a heat sink such as evaporating sweat could lead to an increase in skin temperature. The application of IRT for measuring skin temperature in exercise could be limited by thermoregulatory perspiration. Nevertheless, to establish in which conditions IRT is providing reliable data remains still unclear.

Discussion of the results

Immediately after cycling, the thermography camera recorded lower temperatures than thermal contact sensors. James et al.[121] had similar results and they also suggested that sweat affecting the skin emissivity could contribute to these differences. Differences observed between thermal contact sensors and IRT camera presented a similar trend in the human trials and in the instrumented test. Nevertheless, in the instrumented test, the absolute difference in wet conditions was bigger than immediately after cycling in human trials where sweating occurred. Presumable reasons for this behaviour could be that the cotton fabric provided a fully-saturated water condition that did not represent the participant's skin. Therefore, the instrumented test reflected more a 'profuse' perspiration state. Furthermore, the blood circulation in the human skin might help to distribute the heat all over the entire skin surface whereas this effect is not present in case of the instrumented test.

In the instrumented test carried out (Figure 4.5), the cotton fabric was fully-saturated with water but due to its hygroscopic character no water layers were formed on the surface. In the case of human tests, if water would form a continuous layer, a higher temperature decrease than in the instrumented test could be expected due to infrared radiation shielding. However, the results from the wet condition tests pointed to a 3.7ºC higher temperature of the covered thermal contact sensors compared to the thermography measurements. This difference was much higher than the difference observed in the case of human trials after the cycling exercise (0.8ºC with regards to the thermography camera defined by small ROIs) at which the skin was partly wet. These differences might be due to the human adaptive thermoregulation mechanisms. The human body has a large capacity of temperature reduction from the continuous evaporation of sweat[18,211] but it also controls the heat transfer to the environment by adjusting vasomotion close to the skin surface in the process of thermoregulation[211].

Comprehensible results were observed between dry and wet states when comparing human trials and instrumented tests in which no water coating was present, suggesting that in the described exercising scenario in moderate environment, sweat delivery was not high enough to produce a continuous water layer on the skin as well (Figure 5.1).

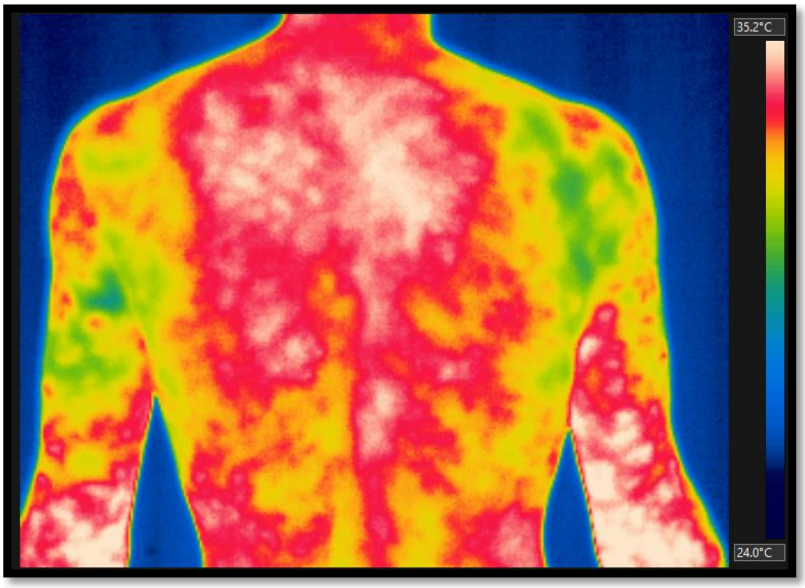


Figure 5.1. Example of a thermography: an upper back of a cyclist immediately after cycling 45 min. Sweat was not removed and, visually, layers of sweat were not appreciated.

Key Points

- Before exercise, when heat disipation mechanisms are not activated at maximum, good agreement between thermal contact sensors and IRT was observed.
- Immediately after exercise, thermal contact sensors presented higher skin temperature than IRT. This difference could be associated with the interference of the thermal contact sensor and its clinical tape on heat exchange process (increase of thermal insulation and reduction of sweat evaporation).
- 10 min after exercise, IRT presented higher skin temperature than thermal contact sensors. Sweat could be absorbed by the clinical tape during the exercise and this local accumulation of the sweat in the location of the sensor produces lower temperature 10 min after the exercise because it continues to promote heat loss by sweat evaporation whereas the adjacent skin was drier.
- Small ROIs presented higher temperature than large ROIS. The increase of skin capillarity due to exercise could produce hot spots, that had a higher effect on small ROIs.
- The comparison of the results of cycling tests and the instrumented test suggested that the sweat, during aerobic cycling in a moderate environment, did not have effect on IRT results.

5.2. Efficiency

5.2.1. Influence of cycling intensity on core and skin temperature and the relationship between both temperatures

Background

An efficient thermoregulation activity is important in sports, especially during prolonged exercises, such as cycling, and in hot environments[95,164]. A high thermal stress limits performance and may increase the risk of heat exhaustion and heat stroke during cycling[164]. Furthermore, high core temperatures (~40ºC) are associated with fatigue and performance impairment[98,165].

In this regard, core temperature measurements during exercise allow us to assess internal thermal state with the aim to reduce the risk of thermal stress, heat exhaustion and heat stroke[35,165]. At rest, core temperature presents small variation, whilst during physical exercise, core temperature increases due to the higher metabolic activity and convective heat transfer in the bloodstream from the exercising limbs[95,96]. Such increases in core temperature is moderated by cutaneous vasodilation and sweating[84,92]. However, core temperature requires an invasive method, which usually presents practical limitations during sports activities.

During the last years, skin temperature monitoring with IRT have gained attention in running and cycling for analyzing the effect of exercise[47,156,208]. In cycling, exercise workload produces greater power output[70] with higher muscle activation[146] resulting in an increased core temperature[63]. However, it is unclear how it affects skin temperature. Research about how workload affects skin temperature in each body region is necessary to determine the potential use of the IRT camera in the training assessment.

Discussion of the results

Changes in skin temperatures of the ROIs were found to be heterogeneous (Table 4.2). Skin temperature results from the balance between metabolic heat production and heat dissipation[95]. Furthermore, the balance between the skin vasodilation in order to increase heat dissipation and skin vasoconstriction in order to supply more blood flow to the muscle could affect differently in relation with the role of the muscles of the ROI[208,209,217]. It was observed different effects of cycling exercise on skin temperature across the investigated body regions. Skin temperature increased ~1.5ºC in the ROIs located in the anterior thigh and knee, decreased ~2.1ºC in the ROIs of the trunk and tibialis anterior and remained unchanged for the rest of the leg. One possible explanation for these results might be related with the combined effects of neuromuscular activation and sweat rates happening in each ROI[178,204] (Figure 5.2). ROIs next to muscles with greater neuromuscular activation during cycling can present higher skin temperatures due to higher heat production occurring underneath[129,190]. During cycling, knee extensor muscles (e.g. quadriceps) and hip joint extensor (e.g. hamstrings) play an important role for force production and present higher neuromuscular activation[178]. However, plantar flexors (e.g. gastrocnemius) mainly transmit this energy from the limbs to the crank[178]. Yet, trunk muscles sustain trunk position and stay mostly unchanged during pedalling[38]. In contrast, the trunk is one of the body regions presenting the highest sweat rate, whereas the lower limbs showed the lowest sweat rates[119,204]. As sweat evaporation is one of the main mechanisms for heat dissipation during exercise, a higher reduction in the temperature at regions located on the trunk could be expected.

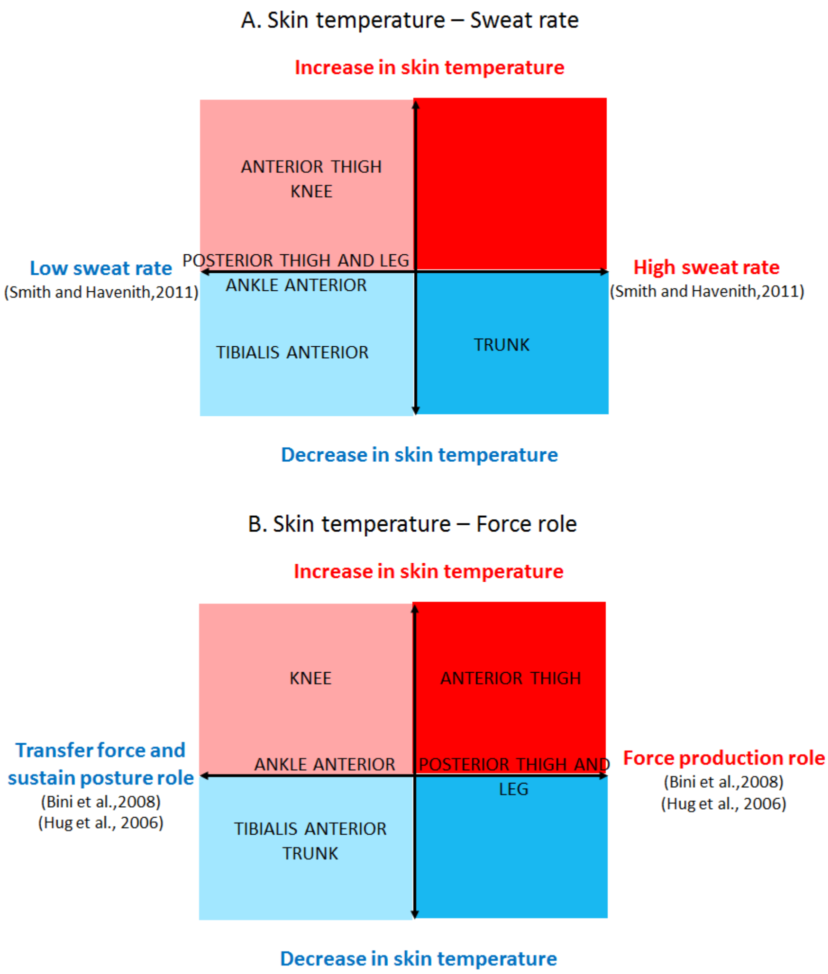


Figure 5.2. Schematic explanation for the variation in skin temperature at the different regions of interest immediately after cycling test, according to their sweat rate [204] and their force role [27,116].

It is important to take into account other factors that could affect the differences in the skin temperature between the body regions. One of them is the effect of the convective heat dissipation during cycling. The movement of the legs during pedaling causes air movement around them and could increase the heat dissipation and provide, therefore, lower local skin temperatures. In agreement with this, Defraeye et al.[62] observed one of the highest convective heat transfer coefficient at the lower limbs. Another factor is the additional thermal insulation and evaporative resistance due to the presence of clothing[53,94]. This effect could limit the evaporation of the sweat and increase the temperature on the body areas covered with textile during cycling.

As previously highlighted by other researchers, higher exercise workloads produced higher increase of the core temperature[47,63,95]. According to the results of this dissertation that represent situations in which thermal regulation system can work normally, it was observed that increasing workloads from 35% PO_{max} to 50% PO_{max} (difference in absolute workload of ~42.2 W) potentially results in increments of core temperature between 0.2 and 0.3ºC after 48-minute cycling performed at environment temperature of 21-22ºC (Figure 4.6). Similarly to other studies, the higher workload corresponded to higher effort perception and higher whole body sweat rate[32,114].

The cycling workload did not have any effect in the skin temperature in the most body regions probably due to the higher whole body sweat rate observed in the higher workload (Table 4.3). However, when cycling at 50% PO_{max}, skin temperature decreased more in the regions of the abdomen, tibialis anterior, ankle anterior, and Achilles compared to cycling at 35% PO_{max}, with knee temperature showing smaller increases (Figure 4.7). None of these regions were located on top of muscles with high neuromuscular activation during cycling. Moreover, tibialis anterior, knee, ankle anterior and Achilles are body regions mostly constituted by connective and bone tissues which involves a lower metabolic heat production and blood perfusion. The abdomen contains a greater percentage of fat tissue that insulates skin compared to other ROIs (e.g. ROIs of the lower limbs)[49,193]. Both mechanisms suggest that these regions are affected by a temperature decrease due to a slightly higher overall sweat rate according to a higher intensity observed in this work and in previous studies[32], rather than temperature increases through rising workloads. Due to cycling posture, sweat might accumulate more intensively in these low-heat-production regions, resulting in higher reduction or lower increment of skin temperature with increase of exercise intensity.

According to the aforementioned heat exchange conditions of each particular ROI, different skin temperatures at each region were observed. Consequently, the correlations found between skin and core temperature were either weak or moderate. Negative and positive relations were found, depending on the specific region analyzed (Figure 4.8). Different mechanisms of adaptation to exercise might explain this observation. While core temperature depends directly on the intensity of exercise, skin temperature has a multifactorial dependence[77]. Apart from dependence on the sweat production and heat conducted from muscles to skin, skin temperature is affected by local changes in environmental variables (e.g. local radiant temperature or local air movement) more so than core body temperature. Other factors (e.g. subcutaneous fat tissue, clothing or evaporation efficiency) vary over the body surface[77]. Most regions on the trunk, semitendinosus and tibialis anterior showed a negative relationship with core temperature. A higher core temperature produces a higher sweat rate[92], and thus, a more pronounced skin temperature reduction can be observed if sweat evaporation is not impaired. In addition, this mechanism helps to intensify the dissipation of the core body heat, because it increases the thermal gradient[59]. Nevertheless, areas such as the knee showed positive correlations between core temperature and its skin temperature most probably due to scarce presence of sweat.

When comparing between both cycling workloads, negative correlations between core and skin temperatures were higher for 35% compared to 50% PO_{max}, whereas positive correlations were higher for 50% rather than 35% PO_{max} (Figure 4.8). It can be explained due to the inter-participant differences in the efficiency of their thermoregulatory system. Different studies have found that the physical fitness greatly affects the efficiency of thermoregulatory system[3,48,87]. Participants with better physical fitness are more efficient in the heat elimination due the sweat evaporation, with larger decreases or lower increases of the skin temperature during exercise[3,48,87]. In this sense, the differences between participants in the efficiency in the heat elimination may increase resulting in a lower level of correlations at higher workloads. In the ROIs with a lower capacity of the sweat evaporation that presented positive relationships (e.g., knee), these physical fitness differences between participants were not affected showing an increase of the positive correlations at higher workload.

5.2.2 Relationship between skin temperature and neuromuscular activation

Background

Skin temperature during exercise could be related to muscular work, which reflects the efficiency in dissipating the heat produced and in turn depends on activity of circulatory system recruiting level and sweating rate[2,48,231]. A significant reduction in skin temperature is observed during or after an incremental workload or intense workload exercise[48,80,156,217,236], which can be related to sweat evaporation for heat dissipation during exercise[48,105].

EMG permits to estimate the magnitude of electrical neuromuscular activity during exercise[29,61]. A link between muscle activation and skin temperature could be valuable to ascertain on the efficiency of thermoregulatory system to dissipate muscle heat production. In this issue, only one study observed an inverse relationship between biceps brachii activation and skin temperature during fatigue isometric contractions[16]. Along these lines, an increase in temperature of biceps brachii during loading was associated to a decrease in median power frequency of the EMG signal, suggesting increased muscle fatigue[16]. Therefore, it is unclear if subjects performing aerobic exercise (rather than isometric contractions) with larger neuromuscular activation could optimally dissipate heat, and the relationship between muscular effort and skin temperature is still unknown.

Discussion of the results

In the present study, it was hypothesized that participants showing larger changes in neuromuscular activation would present better adaptive responses of their thermoregulatory system, which would be observed by lower increases in skin temperature after exercise. During cycling, vastus lateralis has been referred as a primary muscle contributing to power production[127]. Together with the present results (section 4.2.2), it is possible to suggest this muscle a potential site for assessment of efficiency of the thermoregulatory system and relationship between muscle activation and skin temperature. The present study showed that participants showing larger increases in overall activation and limited increases in low frequency content of neuromuscular activation in their vastus lateralis presented lower increments in skin temperature after an incremental cycling test (Figure 4.11).

Higher maximum overall activation is associated with improved fitness level[101,102] and low frequency content in neuromuscular activation has been associated to a greater proportion of small size motor units being recruited[182]. The present data suggest that participants with lower fitness level were less capable of recruiting their vastus lateralis maximally (lower increases in overall activation). Indeed, they may have used more small size (driven at lower frequencies) rather than large size motor units because small size motor units have improved fatigue-resistant profile[69] and are more efficient[142]. In contrary, participants with better fitness level could sustain the exercise longer by recruiting larger size motor units (driven at intermediate to high frequencies) which could be used to produce more power[100], resulting in lower increases in skin temperature. Larger increases in skin temperature for participants who presented increased low frequencies and limited overall activation of vastus lateralis during maximal aerobic exercise could then be associated to their reduced fitness level.

Previous studies were in agreement with the influence of fitness level on thermoregulation, as observed in the present study by significant relationships between changes in skin temperature and changes in neuromuscular activation. Abate et al.[1] observed that trained subjects presented a decreased trunk skin temperature after the beginning of the exercise compared with untrained subjects. Likewise, players with better fitness level presented a larger decrease in skin temperature after 90 min of exercise[48].

The present study did not observe significant correlations between skin temperature and cycling performance (peak power output) during the incremental workload test (Table 4.6). This result may indicate that the thermoregulatory system is related to neuromuscular activation of surface electromyography (vastus lateralis in this case) rather than with the peak power produced in the cycling test. This finding is reinforced by observations from a previous study which indicated that training affected more muscle activation than peak power production during isokinetic cycling[188]. Along these lines, peak power was positively related to the activation of rectus femoris, which is in line with the double role of this muscle as a main force producer and driver during pedaling due to its bi-articular attachment[159]. In contrary, an inverse correlation was observed between low frequency content in gastrocnemius medialis and power output. This could be related to the role of this muscle as force transfer to the cranks[27,91], which may involve a less pronounced contribution from small motor units, given these motor units may have lower strain-rates than larger ones[137].

5.2.3. Relationship between skin temperature, performance, and predictive performance measures

Background

Laboratorial cycling performance is usually tested with a maximal incremental test and PO_{max} is one of the best predictors of cycling performance[17,73]. Over the last decades, several studies have shown that cardiorespiratory and neuromuscular variables have a strong relationship with cycling performance[54,142]. Furthermore, cyclists with better performance also present lower percentage of body fat[170].

Cholewka et al.[47] reported an inverse relationship between average power displayed on the cycle ergometer and average skin temperature measured using IRT. However, the relationship between skin temperature and performance related variables, such as cardiorespiratory, neuromuscular, and power output, remains unclear.

Discussion of the results

Two main associations were found between skin temperature and performance measures (Table 4.7 and 4.8). The first was the negative correlation between body fat and skin temperature. Body fat tissue has an insulation capacity resulting in impairment in heat dissipation[48,193]. Furthermore, the level of physical fitness had an important influence on body composition (e.g. percentage body fat)[124,170]. This result highlights the important relationship between physical fitness, body composition and thermoregulation suggested by previous studies[1,48,87,155]. This result could help to explain that different studies observed better heat dissipation in participants with better performance[3,48] probably because these participants also presented a lower percentage fat.

The second main association with skin temperature was peak power output. Peak power output obtained during incremental cycling tests is considered one of the best predictors of cycling performance[73]. It could be expected that this parameter should have presented a negative association with skin temperature. However, it was observed that peak power output was positively correlated with skin temperature immediately after finishing the test and skin temperature variation. Although participants exercised at the same power output, those with higher level of physical fitness had lower values of skin temperature due to their larger capacity for heat dissipation[1,48] and presented a higher metabolic efficiency resulting in a lower heat production[58]. The present study assessed participants at power outputs equivalent in relation to their cardiorespiratory capacity

(VT_1 and VT_2) and at their maximum capacity (PO_{max}). Participants with higher values of peak power output presented higher values of heat production and then higher values of skin temperature.

Although much less frequent than body fat and peak power output, other associations were observed such as a negative correlation between $\%VO_{2max}$ and skin temperature for VL at VT_1 in non-cyclists, and a negative correlation between neuromuscular activation of VL and its skin temperature at VT_2 in cyclists (Table 4.8). Similar relationships were observed by a previous studies[48]. Chudecka and Lubkowska[48] obtained a regression model with a significant correlation when participants with a higher fitness level (by VO_{2max}), higher percentage of the maximum heart rate during the training season, and lower skin-fat fold on the arm, presented a higher decrease in skin temperatures after exercise. The reduction in skin temperature after a training session was primarily attributed to the efficacy of sweat evaporation mechanism[48]. These associations observed in non-cyclists and cyclists at VT_1 and VT_2, respectively, could be because there may be a reduced variability in heat production among participants. This enforces the relevance of the variability in predictive performance measures ($\%VO_{2max}$ and neuromuscular activation of VL) among participants of each group.

5.2.4. Cyclists vs. Non-Cyclists

Background

Different studies showed that better physical fitness, was related to a larger reduction or lower increment in skin temperature due to exercise[3,48]. This link between performance and skin temperature is based on larger heat loss, mainly through the evaporation of sweat during exercise[48,117]. Furthermore, athletes with better physical fitness have greater capacity of heat transference between the core and the skin due to higher blood flow and lower body fat[48,193,201]. Regards to cycling, a preliminary study performed by Bertucci et al.[21] showed that national level cyclists presented higher decreases in skin temperature during cycling than less trained cyclists. Although, these initial studies observed that participants with better physical fitness presented greater capacity for heat dissipation, there is need of more evidence about the differences in skin temperature between participants with different cycling training profiles.

Discussion of the results

The present study investigated the possible differences in skin temperature due to cycling training experience. In this sense, it is important to understand the functional differences between groups. Cyclists presented lower body fat, greater peak power output and higher oxygen consumption than non-cyclists (Table 4.9). These differences could be explained by the larger training volume for cyclists. Endurance training performed during cycling was associated with a reduction in body fat composition[170] and higher peak torque during the downstroke[54,55], resulting in a greater peak power output and cycling performance.

Different studies showed that there is a relationship between physical fitness and skin temperature dynamics[3,48]. Bertucci et al.[21] observed in a preliminary study a possible association between gross efficiency and the variation in skin temperature during incremental cycling tests. Furthermore, different studies suggested that participants with better physical fitness have a higher capacity of heat loss, resulting in lower skin temperatures during exercise[1,3,47,48,87]. This idea was reflected in the study of Cholewka et al.[47], which highlighted that higher power produced in the cycle ergometer results in higher heat loss and lower mean body skin temperature. However, in the present study, cyclists presented higher skin temperature than non-cyclists (Figure 4.12). This higher skin temperature could be explained by the higher aerobic capacity of cyclists and therefore higher heat production during an incremental cycling test. Cramer and Jay[58] indicated that in thermoregulatory studies is important to elicit the same heat production during exercise in order to prevent the introduction of systematic bias in the assessment of differences on core and skin temperature. The results of the present study are in agreement with this indication. Differences between previous studies and the present study could be explained by the heat production. In assessments conducted in controlled workloads, differences in heat production may be small and cyclists with better physical fitness could present lower skin temperature due to a better efficiency in heat dissipation. However, during an incremental cycling test, participants with better physical fitness could present higher skin temperature due to a high capacity of heat production. This is important to take into account in the interpretation of the skin temperature results in cycling assessments.

In the results of the experimental study 2 (section 4.2.2), it was observed increments in skin temperature for the quadriceps muscles in non-cyclists between 0.9

and 2.0ºC, which differs from the these results, where no changes were observed (-0.6 ±1.4ºC). The differences between both studies, in terms of skin temperature, could be explained by the cadences used. While in the experimental study 2 the incremental test was at 90 rpm, it was opted in this study for a cadence of 55 rpm. The lower cadence was chosen with the aim of monitoring the thermographic video of the vastus lateralis during the cycling test. This cadence may had some benefits compared to higher cadences, such as higher efficiency for the cardiovascular system, but also had some disadvantages such as larger torque and higher effort perception[10]. In relation to the effect of the skin temperature, the slower cadence could reduce muscle blood flow[99,237] resulting in a lower heat transference between the core and the skin. Future studies should explore the effect of cadence on skin temperature.

Key Points

- The effect of cycling exercise on skin temperature is different dependly of the ROI. These differences might be related with the combined effects of neuromuscular activation and sweat rates happening in each ROI.
- The cycling workload did not have any effect in the skin temperature in the most body regions probably due to the higher whole body sweat rate observed. Only the ROIs with lower metabolic heat production and blood perfusion were affected with higher reductions and lower increases of the skin temperature at higher workload due to a slightly higher overall sweat rate.
- Weak and moderate correlations were found between skin and core temperature. Most regions showed a negative relationship with core temperature: a higher core temperature produces a higher sweat rate, and thus, a more pronounced skin temperature reduction can be observed. Nevertheless, areas such as the knee showed positive correlations between core temperature and its skin temperature most probably due to scarce presence of sweat.
- Vastus lateralis was suggested as a potential muscle for assessment of efficiency of the thermoregulatory system by IRT. Participants with a suggested better fitness level (by larger increases in overall activation and limited increases in low frequency content of neuromuscular activation in their vastus lateralis) presented lower increments in skin temperature after an incremental cycling test.
- Two main associations were found between skin temperature and performance measures: 1) a negative correlation with body fat, explained by the insulation capacity of body fat tissue, and 2) a positive association with peak power output; participants with higher values of peak power output presented higher values of heat production and then higher values of skin temperature.
- Cyclists presented higher skin temperature than non-cyclists. This higher skin temperature could be explained by the higher aerobic capacity of cyclists and therefore higher heat production during an incremental cycling test.

5.3. Posture

5.3.1. Validation of knee flexion postures by the perception study

Background

The degree of knee flexion is considered the gold standard to determine saddle height in cycling[22]. A range between 25º and 30º of knee flexion in static conditions with the crank at 180º has been recommended to prevent injuries and optimize cycling efficiency[22,34,174]. Moreover, while greater knee flexion has been associated with patellofemoral pain[23,36,60] and anterior knee injuries[25], greater knee extension has been found to provoke excessive strain on the iliotibial and hamstrings muscles, leading to an increased risk of patellar tendinitis and muscle overload[25,60,198].

Bike-fit strongly influences the cyclist's performance[13,215] and perception of comfort[13,15,46,199]. Previous studies have stated that comfort has a strong effect on injury prevention and enhancement of performance in running[141,145], soccer[107,131] or basketball[134]. However, even though most studies find this relationship to be obvious in some sports, it is still unclear how different cycling postures influence the cyclist's perception of the bike during cycling.

Discussion of the results

Previous studies have recommended, during static assessment, a knee flexion angle of 25º to 30º when the pedal crank is at 180º to prevent overuse injuries and to improve performance[22,34,174]. However, Ferrer-Roca et al.[81] suggested that, during dynamic assessment, the recommended range of knee flexion angle should be between 30º to 40º. The present study assessed angles considering the anatomical reference position as zero degrees[175] to account for the different placement of markers between participants and trials. However, in order to analyze the results with the recommended dynamic range of Ferrer-Roca et al.[81], the absolute values are also presented. In the present study, an intermediate knee flexion (Knee30º with an absolute value of 39.8 ±4.0 which was within the recommended flexion range) and the most flexed posture (Knee40º with an absolute value of 50.4 ±3.5º which was outside the recommended flexion range) were considered the most comfortable and uncomfortable postures, respectively (Figure 4.13). These findings provide further evidence that comfort is indirectly related to improvements in performance and prevention of injuries, which is a relationship that has been previously suggested in other sports[131,141].

Higher ratings of fatigue and pain in the anterior thigh and knee were observed when cycling with the greatest knee flexion. This could be the result of different mechanisms. Firstly, high degrees of knee flexion have been found to produce patelofemoral compression that may result in knee pain[23,36]. Secondly, changes in muscle length, as a consequence of changing the position on the bike, could influence muscle activation[26]. It has been observed that greater angles of knee flexion result in higher neuromuscular activation of quadriceps[71,126] that could lead to greater perception of fatigue in the anterior thigh.

The greatest knee extension of the study was reported less comfortable but received similar pain and fatigue values as the recommend knee flexion fit. However, cyclists tend to prefer a greater knee extension rather than greater knee flexion. This finding could be explained by the fact that after 45 minutes of cycling, the cyclists reported more pain and fatigue in the anterior thigh and knee while cycling in the posture with the greatest knee flexion compared to the posture with the greatest knee extension. This may imply that injuries associated with greater knee extension may occur more in the long term compared to those injures associated with greater knee flexion.

In the present study, the saddle position with the highest knee flexion (40º) resulted in greater trunk discomfort (Figure 4.13). Previous publications have shown a strong interaction between the pelvis and the spine, the so called lumbar-pelvic rhythm[138]. Lumbar bone structures, ligaments, and the thoracolumbar fascia form an integrated system that transfers the load between the lower back and pelvis[138,226]. This interaction between the pelvis and the spine depends in part on the hip extensor muscles such as gluteus maximus and biceps femoris, whose muscle length-tension relationship is strongly influenced by changes in the hip flexion angle during exercise[123,215]. Studies where the saddle angle is modified[85,189] concur, therefore, with the mechanism explained. Salai and colleagues[189] observed that saddle angle strongly affects the lumbopelvic region. High saddle angle increases the tensile forces along the anterior longitudinal ligament of the lumbar spine and can be an important cause of back pain[189]. In agreement with these studies, Fonda et al.[85] observed that uphill cycling modified the timing and intensity of neuromuscular activation of the hip muscles and suggested that moving the saddle forward and changing its angle could counteract this effect.

The three knee flexions measured resulted in considerable differences on perception. Therefore, these results validated that theses knee positions were adequate to explore if IRT is useful in the assessment of their thermal differences.

5.3.2. Effect of knee flexion postures on skin temperature

Backgroung

Different studies showed that changes in saddle height affect neuromuscular activation during cycling. Sanderson and Amoroso[192] observed that greater knee flexion (differences of 17º) due to low saddle height decreased neuromuscular activation in the soleus and medial gastrocnemius. Jorge and Hull[126] found lower activation of quadriceps and hamstring when saddle height was set at 95% of trochanteric length compared to saddle height set at 100%. These differences in the neuromuscular activation can theoretically affect the heat production of the muscles, thus affecting skin temperature[129,190,211]. Considering the previously discussed relationship between muscle activation and heat production[129,190], IRT can be an additional tool to explore the effects of saddle height during cycling from a thermal point of view.

Discussion of the results

It was hypothesized the effects of different knee angles and saddle height positions on skin temperature, but no differences were observed. Although changes in the saddle height can increase the neuromuscular activation of specific muscles and thus increase their heat production[129,190], these were not reflected in increased skin temperature, probably due to higher sweat rate[32,92]. Higher sweat rate reduces the skin temperature and this favours its thermal gradient with the core[59]. Thus, the result of the skin temperature is the balance between metabolic heat production and heat dissipation[95].

Thermal effects produced by the different knee flexions were observed in poplitius and tibialis anterior (Table 4.11 and 4.12). The greatest knee extension (20º when the pedal crank is at 180°) showed a higher temperature in popliteus (ranged from 0.1 to 0.9ºC) than in the greatest knee flexion (Knee40º). Different authors have associated pain in popliteus with a too high saddle height[36,198]. It is possible that the higher tendon elongation produced by the greatest knee extension results in a higher tendon blood volume[132], and then an increase in skin temperature[112]. On the other hand, the greatest knee flexion (Knee40º) presented lower temperature variation ($\Delta T10$, ranged between 0.2

and 1.1ºC) in the tibialis anterior than intermediate knee flexion (30º). Tibialis anterior is an ankle stabilizer during pedaling[205]. A recent study observed lower range of ankle motion in an optimal saddle height (25º) than in low saddle height (45º)[28]. These results were in agreement with the present study, in which the lowest increase in the tibialis anterior skin temperature was found between the greatest (Knee40º) and the intermediate knee flexion (Knee30º). Lower range of ankle motion can result in lower muscular activation of tibialis anterior[205], resulting in a lower temperature variation. However, although higher differences between the greatest and the lowest knee flexion (Knee20º) could be expected, no differences were found between both postures.

Key Points

- Three knee flexions when the pedal crank is at 180º were assessed: 20º, 30º and 40º. The intermediate knee flexion (30º) and the most flexed posture (40º) were considered the most comfortable and uncomfortable postures, respectively. Furthermore, higher ratings of fatigue and pain in the anterior thigh and knee were observed when cycling at 40º.
- Although changes in the saddle height can increase the neuromuscular activation of specific muscles and thus increase their heat production, these were not reflected in increased skin temperature, probably due to higher sweat rate.
- The greatest knee extension showed a higher temperature in popliteus than in the greatest knee flexion. One possible explanation was that the higher tendon elongation produced by the greatest knee extension results in a higher tendon blood volume, and then an increase in skin temperature.
- The greatest knee flexion presented lower temperature variation in the tibialis anterior than intermediate knee flexion. Lower range of ankle motion at the greatest knee flexion can result in lower muscular activation of tibialis anterior, resulting in a lower temperature variation.

5.4. Methodological

5.4.1. Determination of ROIs by using a factor analysis

Background

Although the number of studies using thermography in the field of sport physiology has increased, some methodological aspects remain unclear. One of the most controversial aspects is the definition of the ROIs in the thermal images[77]. In this sense, The Glamorgan Protocol was published in 2008 and one of its main objectives was to standardize the ROIs for the thermographic studies[8]. However, researchers have developed their own criteria to define their ROIs, with different geometries and methodologies[77].

To address these issues, the identification of ROIs that are highly correlated could help researchers to decide how to select the ROIs. Depending on their thermal characteristics, a large number of ROIs can be grouped into a smaller number. Factor analysis could be used to group the ROIs according to their temperatures at different times of measurement. Moreover, if this analysis is performed on the temperature variations occurring as a result of physical exercise, it would enable researchers to observe the influence that exercise has on the temperatures of the different ROIs of the body.

Discussion of the results

The factor analysis used in the present study showed coherent groups that explained a high percentage of the variance (>80%) and in almost all of the cases the congruence was acceptable (K>0.93) (Table 4.14). This statistical grouping technique showed different groups of ROIs when the analysis focused on the moment of measurement or on the skin temperature variations before and after cycling. While the first analysis could define groups depending on their absolute skin temperatures, the second analysis could define groups depending on their thermal behaviour due to the cycling exercise. These differences between analyses must be taken into account in future studies when defining the ROIs, depending on the objective of the study.

The factor analysis performed on the skin temperature variations showed a greater discrimination of the body regions. While the definition of groups resulting from the moments of measurement consisted of 3-4 groups, the definition of groups from the skin temperature variations resulted in 5 groups. In this sense, whereas some studies observed differences in skin temperature variations after their interventions with no differences in absolute temperatures[87], other studies focused solely on the temperature variations[20,48]. These findings support the idea that temperature variations may have greater sensitivity to exercise interventions compared to absolute skin temperatures and highlight the importance of temperature variations when investigating thermoregulation in sport.

Some ROIs, such as the ROIs of the trunk, were always grouped together regardless of the time of measurement or temperature variation. In the same way, all the ROIs of the thigh were grouped together when the analysis was based on the moments of measurement, whereas anterior and posterior thighs are discriminated, but grouped together, when the analysis was based on the variation of temperature. However, ROIs of the legs (tibialis anterior and gastrocnemius) and their joints (knee, popliteus, anterior ankle and Achilles) were grouped in a different way depending on the time of measurement or the variation of temperature. This result suggest that sections of large regions such as the trunk and thigh could be grouped together regardless of the objective of the study, whereas other smaller regions (knee, popliteus, tibialis anterior, gastrocnemius, anterior ankle and Achilles) should be analysed independently due to the variability that they showed when were grouped according to the moment of measurement or temperature variation. In this sense, the factor analysis of the skin temperature variations of the 16 initial ROIs indicates that a division of the body areas into 9 ROIs would be enough to study thermoregulation in cycling: trunk, anterior thigh, posterior thigh, knee, popliteus, tibialis anterior, gastrocnemius, anterior ankle and Achilles (Figure 5.3).

In agreement with previous studies[148,204] and the previous discussion (section 5.2.1), thermal differences between ROIs or groups of ROIs can be explained by the differences in tissue composition, muscular activity and capacity of sweating. Firstly, the analysis of the skin temperatures based on the moments of measurement led to some general differences between the groups of ROIs (Figure 4.15). Similar to previous studies, the highest temperatures were observed in the trunk[50,149,234]. The trunk contains the internal organs which produce a great amount of heat as a result of their metabolic processes[50,95]. Also, during cycling, heat generated from the exercising limbs is transferred to the core through the bloodstream[96]. On the other hand, regions with a large proportion of connective and bone tissues (e.g. knee, anterior ankle, Achilles and tibialis anterior) presented the lowest temperatures. These lower temperatures are likely the result of the lower metabolic heat production and blood perfusion of these regions[112]. Also, they are more peripheral regions, and previous studies have found that the skin temperature decreases from the trunk to peripheral regions[50,149,234].

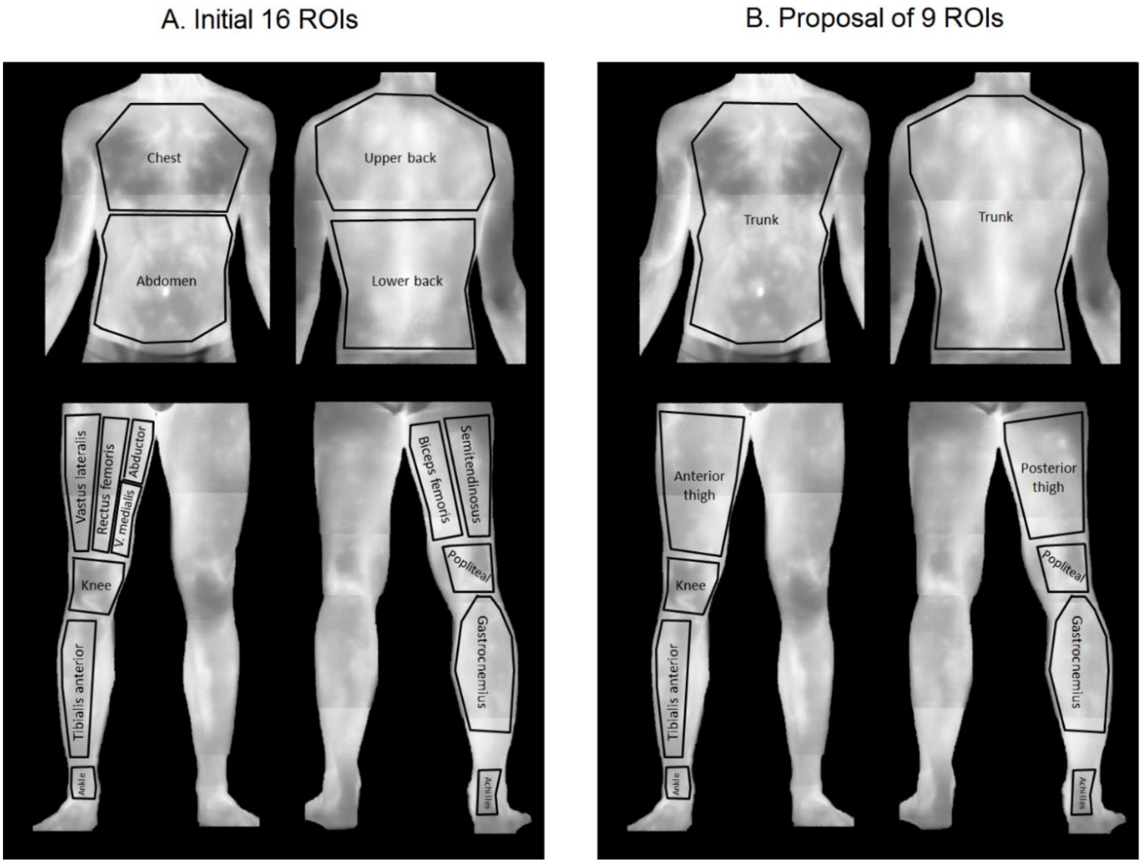


Figure 5.3. Determination of a propossal of 9 ROIs from the analysis of 16 initial ROIs.

Secondly, with respect to the temperature variation between before and immediately after cycling (ΔT), most groups showed no significant changes and presented the lowest value of congruence coefficient (K=0.92). Since the skin temperature variation results from the difference between the heat production and the heat dissipation[95], the maintenance of the skin temperature could show the correct functioning of the heat dissipation mechanisms (mainly the sweat evaporation). However, the skin temperature of the anterior thigh increased (Figure 4.16.A). This result could be explained by the greater neuromuscular activation of the quadriceps during cycling[26], which could lead to greater generation of heat[129]. Similar to previous results, the results of the experimental study 2 (section 4.2.2) observed an increase of the quadriceps skin temperature during cycling, whereas the skin temperature of other regions such as the hamstrings or gastrocnemius remained unchanged. As a result, the anterior thigh should be included as a ROI when assessing thermoregulation in cycling studies. On the other hand, the variation of the skin temperature during the 10 minutes after exercise (ΔTafter;

Figure 4.16.C) showed increases of skin temperature in the posterior lower limb. This result could imply that these areas continue generating heat after exercise, thereby resulting in a lower heat dissipation.

5.4.2. Intraday reproducibility study

Background

IRT is a technique that enables measurement of skin temperature, with valuable applications in the study of the thermal effects of physical exercise[1,87]. This technique provides some advantages to skin temperature measurement over other methods (e.g. thermocouples) since it is a non-invasive and non-contact technique with high sensitivity and accuracy[9]. However, to properly measure skin temperature it is necessary to control intervening factors[77,158] in order to reduce variability. Variability of skin temperature data on different days can be greater than the effect of changes in saddle height on skin temperature. In addition, reproducibility can be lower in ROIs affected by different saddle heights. For this reason, when research is focused on exploring different conditions on different days, such as in the present study, it is important to consider the reproducibility of skin temperature. McCoy et al.[153] observed excellent reproducibility between days for IRT images from the paraspinal region. However, Zaproudina et al.[234] found moderate reproducibility in the trunk and poor reproducibility in the extremities. The authors suggested that this result was probably due to physiological variability of blood flow in the distal parts of the body[234]. These studies were performed under baseline conditions but reproducibility data after exercise is still necessary.

Discussion of the results

The intraday reproducibility results (Table 4.13) obtained before cycling test in absolute temperature were better, except in the ROI of the knee, than those presented by Zaproudina et al.[234]. They presented a 0.76 ICC value for the trunk anterior (0.69 and 0.80 in chest and abdomen in the present study), 0.32 in the back (0.71 and 0.70 in upper and lower back) 0.42 in the thigh (0.60) 0.76 in the knee (0.53), and 0.52 in the calf (0.63). Differences between the results may be due to a number of reasons: differences in the ROI identification, different room adaptation (10 min lower in the present study) or/and differences in the variability of the blood flow of the participants[234]. In any case, thermography measurement has presented good and very good reproducibility following the rigorous methodology used by different authors and organizations[8,111,186]. Furthermore, the present study showed that reproducibility is still good after exercise. However, the temperature variation analysis showed similar reproducibility in the trunk, but worse in the lower limbs. This may be due to the fact that temperature variations can be more sensitive to changes in the saddle height than absolute temperatures. Hence, Formenti et al. showed significant results in their temperature variations after their interventions, but no differences in absolute temperatures[87]. Similarly, different studies focus their significant results on temperature variations, probably because absolute temperatures do not reflect the effect of their interventions[20,48].

5.4.3. Multi regression analysis of skin temperature variation

Background

IRT in sports is still a recent topic and there are many fundamental discussions concerning different methodological aspects, one of these being the analysis of thermal data.

Different variables can be obtained from analysing IRT data during exercise such as average temperature, maximum temperature, minimum temperature and standard deviation. Although average temperature is the most commonly used skin temperature variable[1,48,89], temperature variation resulting from exercise (ΔT) has been suggested as a valid measurement for determining the effect of exercise intervention.

Skin temperature depends on several individual factors (e.g. gender, age, body composition or physical fitness level), environmental factors (e.g. room temperature, relative humidity and wind speed) and the characteristics of the exercise (duration and intensity)[48,77,80,89]. However, it is unknown which factors affect the ΔT.

Discussion of the results

ΔT was affected mainly by anthropometrical variables (Table 4.15). However, the effect was different depending on the variables. Firstly, body mass and skinfolds presented an inverse relationship with ΔT. This effect could be accounted for by the fact that these variables are related with body composition (e.g. body fat). Body fat has an insulation capacity resulting in impairment in heat dissipation between the core and the skin[48,193], so resulting in lower ΔT. On the other hand, body surface and BMI presented a positive relationship. Although, body surface is commonly related with greater capacity of heat dissipation[104], in the present study the participants with greater values of body surface were also the participants with higher BMI and skinfold values. These participants could also be the participants with the lowest physical fitness level, and, therefore, with a lower capacity of sweat evaporation during exercise, resulting in higher values of ΔT

Baseline skin temperature affects the ΔT. The results suggested that if the participant presented a lower skin temperature before exercise, its increase would be greater. The importance of these parameters differed per ROI, explaining between 0.8 and 14.7% of the variance. Although the present study did not assess ROIs in the foot, their lower baseline skin temperatures and greater variability between participants could increase this variable's importance in these cases. Further research should explore the potential of standardizing ΔT through baseline skin temperature.

Age presented a negative relationship with ΔT in line with previous studies[80,173]. This lower response with age may be related to a lower metabolic rate resulting in a lower core temperature[42,118], and the lower capacity of heat dissipation via vasodilation and sweat rate[118,173]. While in the anterior ROIs of the lower limb, age accounted for 10% of the variance, in the posterior ROIs, it only accounted for 1% of variance. However, it is important to note that the present study was not carried out with any great variation in ages (mean age 29.5 ±9.8 years); so, with greater variability its importance could increase.

Environmental conditions were suggested as one of the main factors that affect skin temperature[77]. Skin temperature is directly related with room temperature[140,169] and relative humidity affects the sweat evaporation rate during physical activity and sport performance[152]. Previous data of our group suggested that an increase of 1ºC in the room temperature results in 0.35ºC higher skin temperature, but ΔT analysis minimizes this influence. This finding is in agreement with the results of the present work, which showed that environmental conditions accounted for a lower percentage of the variance (<1%). However, it is important to mention that room temperature was controlled in the present study, presenting low variation in environmental conditions (23.7 ±1.4ºC and 45.1 ±12.0%).

Finally, the lower variability accounted for by performance factors such as PO_{max} and cycling training volume suggested that tests matched by a percentage intensity of the PO_{max} provides a good approach for analysing the effect of an intervention on ΔT.

Key Points

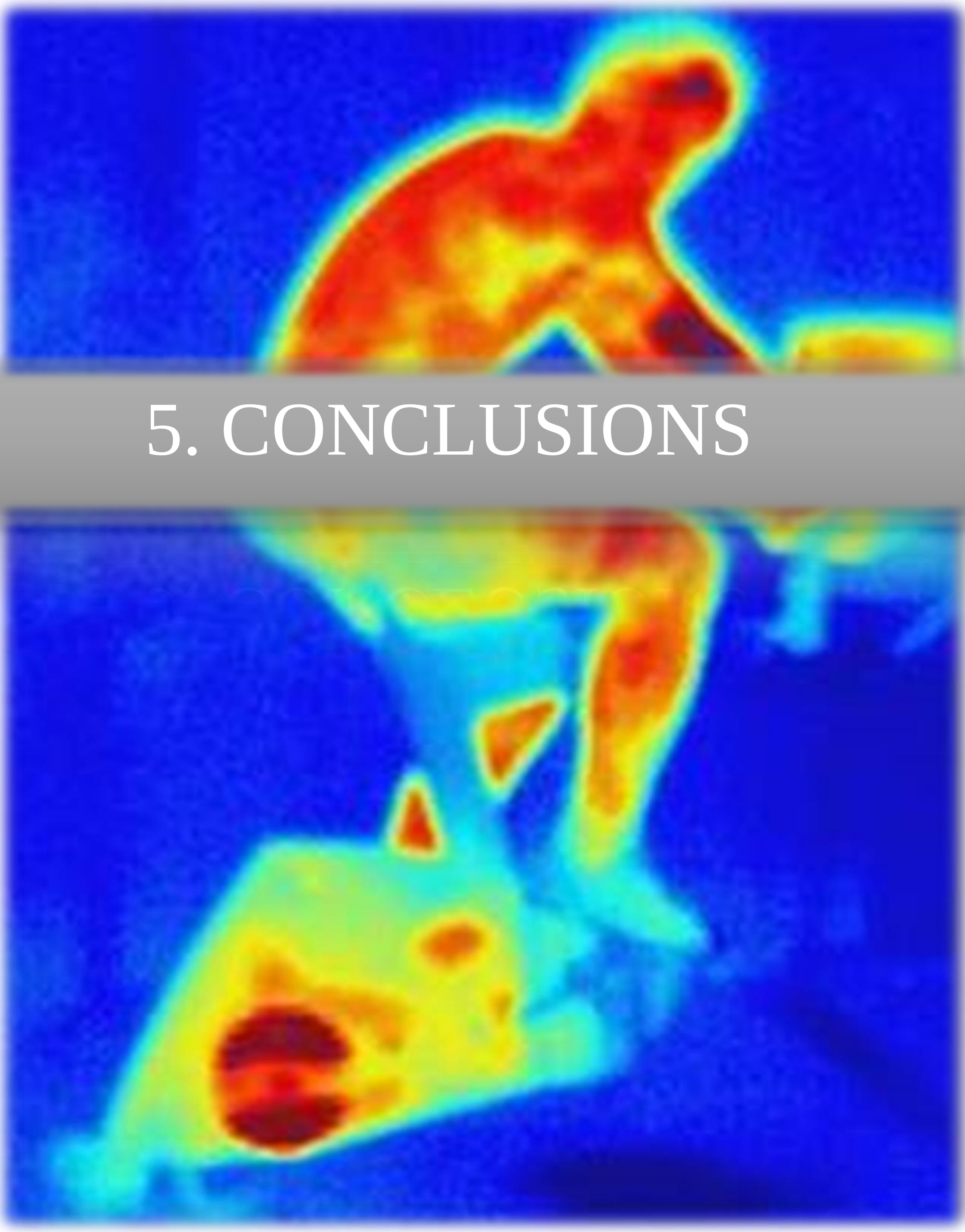
- The factor analysis results suggested 9 ROIs to assess thermoregulation in cycling: trunk, anterior thigh, posterior thigh, knee, popliteus, tibialis anterior, gastrocnemius, anterior ankle and Achilles. Thermal differences between these ROIs can be explained by their differences in tissue composition, muscular activity and capacity of sweating.
- IRT measurement presented a good and very good reproducibility before exercise. After exercise, absolute temperatures presented good reproducibility. However, reproducibility of skin temperature variations in the lower limbs was less effective, perhaps due to the fact that temperature variations can be more sensitive to an intervention (changes in the saddle height) than absolute temperatures.
- Skin temperature variation was affected mainly by anthropometrical variables.

5.5. Limitations of the study

Several limitations have been accounted during the development of the experimental studies and need to be mentioned and taken into account during the interpretion of the results.

- One of the limitations of the present thesis is related with the inherent differences between studies performed in a laboratory and real conditions in the field. Radiant temperature and the behaviour of the wind are very different in these two scenarios. However, a laboratory study allows one to control a large number of factors that, in a field study, could be uncontrollable (e.g. environmental conditions, workload, bike posture, etc.).
- It should be noted that muscle activation signals recorded through surface EMG provides valuable information on muscle recruitment; however; there are inherent limitations (i.e. distance from muscle fibers to electrodes, movement of activate fibers in relation to the electrodes, etc). Control of these issues was intended following recommendations from ISEK-Seniam on preparing the skin before electrodes position.
- One limitation of the posture study was that neuromuscular activation was not measured during the cycling test. Surface electromyography could had validate the differences in the neuromuscular activation due to different saddle heights reported by the literature[126,192].
- This thesis has been undertaken only on males, which is a limitation. Future studies should take the effect of gender on results more into account.

5. CONCLUSIONS



6. CONCLUSIONS

The conclusions of the study will be presented in separate sections in accordance with the aims (section 2).

1. **Validity conclusions**

   1.1. IRT is a valid technology to apply in cycling for assessing skin temperature, the main advantages in comparison with contact sensors being that is capable of analysing large areas on the body surface and that it is distance technique which does not interfere in the processes of heat exchange.

   1.2. Sweating during cycling did not alter the thermographic measurements, so suggesting that IRT is a valid measuring method both during and after aerobic cycling in a moderate environment.

2. **Efficiency conclusions**

   2.1. Cycling workload did not have any effect on the skin temperature in most body regions due to the higher heat loss of the thermoregulatory system, and only those ROIs that are mostly constituted by connective, bone and fat tissues were affected.

   2.2. In general, core and local skin temperatures showed a weak to moderate negative correlation for regions presenting the highest sweat rates over the body, whereas some positive correlations were observed in regions where sweat production was low. These findings highlight the difficulty of linking skin temperature with cycling workload and core temperature due to the efficiency of the thermoregulatory system in the increase of the thermal gradient, together with the multifactorial dependence of skin temperature.

   2.3. Participants with a suggested improved neuromuscular efficiency (higher overall neuromuscular activation and lower frequency content in activation for vastus lateralis) presented a better adaptive response of their thermoregulatory system by presenting limited increases in skin temperature. Among the assessed muscles, vastus lateralis presented the clearest association between changes in neuromuscular activation and skin temperature during incremental cycling exercise.

2.4. Body composition and cycling performance (peak power output) were the most important aspects influencing skin temperature dynamics. In order to improve heat dissipation, it is important that cyclists have a low body fat percentage, which can be reduced by controlling the diet and a correct training schedule.

2.5. Cyclists presented higher skin temperature compared to non-cyclists during and after the incremental cycling test. Heat production is an important variable to take into account in interpreting the skin temperature results during and after exercise.

3. Posture conclusion

3.1. Different knee flexions, which after 45 minutes of cycling presented differences in the perception of comfort, fatigue and pain, did not present differences in skin temperature in most of the ROIs. Therefore, it was concluded that the application of skin temperature analysis using IRT for studying the effects of different saddle heights does not appear to be valid.

4. Methodological conclusions

4.1. By using a factorial analysis, coherent ROIs were obtained, the differences between them resulting from their different tissue composition, muscular activity and sweat capacity. Furthermore, the results of this study indicate that sections of large regions such as the trunk or the thigh could be grouped together, whereas other smaller regions such as the ROIs of the legs and joints should be analysed independently.

4.2. Reproducibility of the absolute temperatures after exercise on different days was good, but temperature variations in the lower limbs presented a lower level of reproducibility. This could mean that skin temperature can be measured on different days by IRT, but temperature variation analysis may be better for studying the effects of an intervention.

4.3. Although the assessment of temperature variations could have advantages in its use such as the minimization of the effect of environmental conditions on results, it is important to take anthropometrical variables into account during the recruitment of the participants so as to reduce its variability.

7. FUTURE RESEARCH

7. FUTURE RESEARCH

Throught the development of this PhD thesis, questions and hypothesis have aroused for further analysis. Therefore, future studies of interest have been proposed to solve the new research questions:

- To explore the effect of high rate of sweating during cycling (in hot environment and high intensity cycling) on thermographic measurements.
- The effect of workload was assessed by the differences between 35% and 50% PO_{max} (difference in absolute workload of ~42.2 W) on core and skin temperature in a moderate environment. These intensities were chosen with the aim of carrying out a moderate aerobic intensity test. Further studies could potentially evaluate greater differences between workloads in shorter tests.
- To explore the associations between skin temperature and performance factors in hot environments when the efficiency of thermoregulation is challenged in order to reduce the impairment of performance and the risk of heat exhaustion and heat stroke during cycling.
- To investigate the reproducibility of temperature data (absolute and temperature variations) after exercise without any intervention.
- To explore the applicability of IRT, in a cycling team, for injury prevention by the thermal symmetry analysis.

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8. REFERENCES

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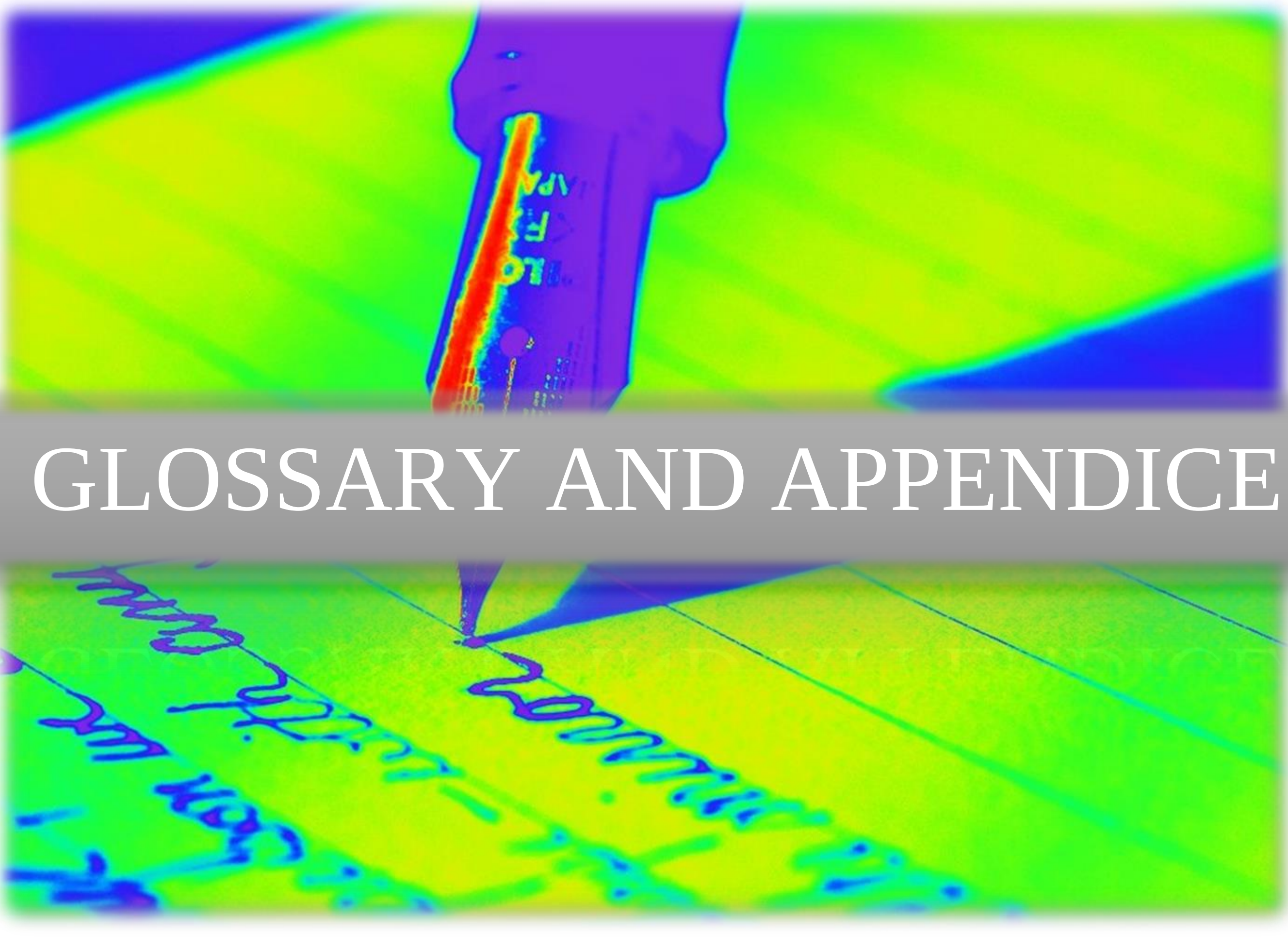

GLOSSARY AND APPENDICES

Glossary index

APPENDIX 1: Approval of the Committee of Ethics in Research with Humans of the University of Valencia

VNIVERSITAT D VALÈNCIA
Vicerectorat d'Investigació i Política Científica

D. Fernando A. Verdú Pascual, Profesor Titular de Medicina Legal y Forense, y Secretario del Comité Ético de Investigación en Humanos de la Comisión de Ética en Investigación Experimental de la Universitat de València,

CERTIFICA:

Que el Comité Ético de Investigación en Humanos, en la reunión celebrada el día 13 de enero de 2014, una vez estudiado el proyecto de tesis doctoral titulado:
"Uso de la termografía en la mejora del rendimiento, prevención de lesiones y aumento del confort térmico en el ciclismo", número de procedimiento H1384344515519,
cuyo doctorando es D. José Ignacio Priego Quesada, bajo la dirección de Dña. Rosa Mª Cibrián Ortiz de Anda, Dña. Mª Rosario Salvador Palmer y D. Pedro Pérez Soriano,

ha acordado informar favorablemente el mismo dado que se respetan los principios fundamentales establecidos en la Declaración de Helsinki, en el Convenio del Consejo de Europa relativo a los derechos humanos y cumple los requisitos establecidos en la legislación española en el ámbito de la investigación biomédica, la protección de datos de carácter personal y la bioética.

Y para que conste, se firma el presente certificado en Valencia, a quince de enero de dos mil catorce.

FERNANDO ALEJO|
VERDU|PASCUAL
2014.01.15
13:10:36 +01'00'

Carrer: Blasco Ibáñez, 13
VALÈNCIA 46071

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APPENDIX 2: Example of the Informed Consent Term of the experimental study 1

VNIVERSITAT DE VALÈNCIA
Facultad de Medicina y Odontología
Departamento de Fisiología
Biofísica y Física Médica

EMPA
Materials Science & Technology

G.I.B.D.
Grupo de Investigación en Biomecánica aplicada al Deporte

INFORMACIÓN Y DECLARACIÓN DE CONSENTIMIENTO

Estudio THERMOBIKE: "Evaluación de la carga física mediante termografía y sensores de temperatura"

INFORMACIÓN

La Unidad de Biofísica y Física Médica del Departamento de Fisiología y el Grupo de Investigación en Biomecánica Aplicada (G.I.B.D.), ambos de Universitat de València, junto al Laboratorio de Ciencia de los Materiales y Tecnología de Suiza (EMPA) están llevando a cabo un proyecto termofisiológico para la evaluación del pedaleo, estudiando el comportamiento térmico de los grupos musculares implicados.

El estudio constará de 3 pruebas de ciclismo realizadas sobre cicloergómetro, en días distintos, con la toma de la termografía de las zonas implicadas, antes y después de la prueba. En ellas se estudiará también el comportamiento térmico mediante sensores de temperatura superficiales y píldoras para la medición de la temperatura interna.

La termografía es una técnica de imagen consistente en captar, mediante una cámara sensible al infrarrojo, el calor emitido por los cuerpos. Los sensores de temperatura superficial son pequeños discos (aproximadamente 1.5 cm de diámetro) que se sitúan sobre la piel y permiten captar la temperatura y humedad superficiales. La píldora *CoreTempTM Core Body Temperature Sensor* es una cápsula que permite registrar la temperatura interna. No se degrada en el tracto digestivo y se elimina de forma natural sin problema durante la defecación. No es difícil de tragar (tamaño 22 x 11 mm) e incluso este proceso se puede facilitar si se ingiere acompañada de algún líquido.

- Antes de comenzar la primera prueba se anotarán los datos personales y la edad y se medirá la altura, el peso y la dismetría de los miembros superiores y de los inferiores. Asimismo, antes, inmediatamente después y 10 minutos después de cada prueba se tomarán las correspondientes termografías y en diferentes momentos de las pruebas se preguntará por el confort general y por partes del cuerpo.
- 1ª prueba: test incremental submáximo, comenzando con 5 minutos de pedaleo con una resistencia de 50W y aplicando seguidamente incrementos progresivos de 25W de resistencia cada minuto hasta no poder mantener la cadencia de 90 revoluciones/minuto. Esta prueba

servirá para individualizar la carga de trabajo de las pruebas 2 y 3. Tiempo total estimado de 60 min.

- Pruebas 2 y 3: pedaleo durante 45 minutos, cada día una intensidad diferente (35% y 50% de la máxima alcanzada en la primera prueba). En estas pruebas se utilizarán los sensores de temperatura superficiales y las píldoras de temperatura interna. Tiempo total estimado de cada prueba de 90 min

Las pruebas se realizarán en el laboratorio de Biomecánica de la FCAFE (Facultad de Ciencias de la Actividad Física y el Deporte. Universidad de Valencia), situada en la planta primera del Aulario V, C/ Gascó Oliag, 3, de Valencia.

INDICACIONES PARA REALIZAR LAS PRUEBAS

Vestimenta

- Se realizarán los tests sin camiseta. Mallot o pantalón corto; se aconseja traer cullot. Realizar todas las pruebas con la misma ropa.
- La termografía se realiza en ropa interior. Se ruega que dicha ropa también sea la misma en todos los ensayos.
- Las pulsaciones se medirán con una cinta cardiaca en el pecho (adecuado las mujeres traer top deportivo).

Cosmética

- No usar cosméticos en la piel ni tratamiento de rayos UVA antes de la prueba.

Hidratación y nutrición

- No tomar antes de la prueba una gran cantidad de sustancias excitantes (café/té, redbull, ...).
- No fumar ni beber alcohol en las 12 horas previas a la prueba.
- Según el ensayo se realice por la mañana o por la tarde, se recomienda ingerir previamente la siguiente cantidad de líquidos: ensayo por la mañana: 0.5 litros, ensayo por la tarde: 1.5 litros.
- No venir en ayunas.
- Deberá transcurrir un mínimo de 1h y 30’ entre la comida (no abundante) y la realización de la prueba. Según sea el ensayo por la mañana o por la tarde, desayunar antes de las 8:30 h o comer antes de las 14:30 h.

Descanso

Con el fin de que la fatiga percibida en cada prueba pueda ser equiparable en cada ensayo, es necesario establecer unas pautas para garantizar un descanso mínimo para la realización de una prueba óptima. Las directrices son:

- No realizar ejercicio extenuante durante las 24 horas anteriores a la prueba.
- Dormir la noche anterior un mínimo de 7 horas.

Ingestión de la cápsula de medición de la temperatura interna

- Si el ensayo se realiza por la mañana, ingerirla la noche anterior (entre las 23:00 h y las 24:00 h).
- Si el ensayo se realiza por la tarde, ingerirla a primera hora de la mañana (entre las 6:00 h y las 7:00 h).
- La cápsula de temperatura interna no es difícil de tragar. Se puede ingerir acompañada de líquido (agua o zumo).

RIESGOS

Dado que la termografía es una técnica de imagen en la que se registra, mediante una cámara termográfica y sin contacto, el calor emitido por los cuerpos, no lleva asociado ningún tipo de daño sobre la persona a la que se le toma la imagen termográfica.

Las pruebas de pedaleo no implican una demanda física excesiva puesto que se realizan con una intensidad adecuada e individualizada.

Las cápsulas no son difíciles de tragar (tamaño 22 x 11 mm) y este proceso se puede facilitar si se ingiere acompañada de algún líquido.

Debido al contenido de partes metálicas en el interior de la píldora, se deben cumplir las siguientes condiciones:

- Peso del individuo superior a 40 kg.
- No tener problemas de disfagia (dificultad para tragar), ni disminución del reflejo vomitivo.
- No tener problemas en el tracto gastroinstestinal.
- No haber sido sometido a cirugía gastrointestinal.
- No llevar implantado un marcapasos o cualquier otro equipo electromédico.
- No someterse a resonancia magnética desde que se ingiera la píldora hasta que se elimine.
- Evitar volar desde que se ingiera la píldora hasta que se elimine.

Confirmar que se está en disposición de cumplir estas condiciones.

PROTECCIÓN DE DATOS

Los datos personales que se solicitan para participar en este proyecto serán tratados siguiendo los principios de confidencialidad, de acuerdo con la ley 15/1999 de Protección de Datos de Carácter Personal, complementada por la ley 41/2002 del 14 de noviembre, básica reguladora de la autonomía del paciente y de derechos y obligaciones en materia de información y documentación clínica. En ninguno de los informes del estudio aparecerá su nombre y su identidad no será revelada a persona alguna, salvo para cumplir los fines del estudio y en el caso de urgencia médica o requerimiento legal. Los datos personales de los voluntarios serán recogidos en el estudio pero no serán publicados en ningún informe, memoria o artículo. Los datos serán confidenciales y estarán controlados exclusivamente por miembros del equipo de investigación.

CONTACTO

Para cualquier consulta relacionada con el estudio, problemas en el test, cambio de cita, etc., contactar con:

José Ignacio Priego (Doctorando responsable del proyecto): jpriegoquesada@gmail.com Tfno.: 645 988 299

PARTICIPACIÓN

Su participación en este estudio es voluntaria y, por tanto, puede comunicar su deseo de no continuar en cualquier momento.

Por participar en todo el estudio recibirá una tarjeta regalo para material deportivo por valor de 30 euros. Se entregará a la finalización de todas las pruebas.

CONSENTIMIENTO

Tras de leer este documento, manifiesto que las condiciones expuestas son satisfactorias, que me han explicado la prueba con claridad y contestado mis dudas y doy mi consentimiento para su realización y para que los resultados obtenidos puedan ser utilizados en el proyecto de investigación que sobre el tema se está realizando, asegurándose la confidencialidad de los datos.

Además, declaro que no tengo impedimento para tomar la cápsula de medida de la temperatura interna CorTemp™ porque estoy exento de TODAS las siguientes condiciones (a-h):

(a) Mi peso corporal es mayor de 40 kg.
(b) No experimento problemas de disfagia (dificultad para tragar).
(c) No presento ni he presentado en ninguna ocasión alteraciones o disminución del reflejo vomitivo.
(d) No padezco ni he padecido esofagitis.
(e) No padezco ni tengo sospecha de padecer ningún tipo de enfermedad obstructiva del tracto gastrointestinal: diverticulitis, inflamación intestinal, etc., ni motilidad reducida.
(f) Nunca he sido sometido a cirugía gastrointestinal.
(g) No tengo implantado un marcapasos ni cualquier otro equipo electromédico.
(h) No me voy a someter a resonancia magnética desde que ingiera la cápsula hasta que la elimine.

Valencia, _____ de ______________________ de __________

Firma:

Nombre y Apellidos____

DNI______________________

APPENDIX 3: Schematic guide