Manuscript Details

Manuscript number	JTV_2018_117_R1
Title	Comparison of different wheelchair seating on thermoregulation and perceptual responses in thermoneutral and hot conditions in children
Article type	Research Paper

Abstract

We examined the effects of 4 different wheelchair seatings on physiological and perceptual measures in 21 healthy, pre-pubertal children (9±2 years). Participants were able-bodied and did not regularly use a wheelchair. Participants sat for 2 h in Neutral (~22.5°C, ~40%RH) and Hot (~35°C, ~37%RH) conditions. Four seating technologies were: standard incontinent cover and cushion (SEAT1); standard incontinent cover with new cushion (SEAT2) were tested in Neutral and Hot; new non-incontinent cover with new cushion (SEAT3); new incontinent cover and new cushion (SEAT4) were tested in Neutral only. Measurements included skin blood flow (SkBF), sweating rate (SR) and leg skin temperature (TlegB) on the bottom of the leg (i.e. skin-seat interface), heart rate (HR), mean skin temperature, tympanic temperature, thermal comfort, and thermal sensation. During Neutral, SkBF and TlegB were lower (~50% and ~1°C, respectively) and SR higher (~0.5 mg·cm-2·min-1) ($p<0.05$) with SEAT3 compared to all other seats. SkBF was ~30% lower ($p<0.05$) for SEAT2 and SEAT4 compared to SEAT1. No other differences were observed between SEATs (all $p>0.05$). During Hot, HR and temperatures were higher than in Neutral but there were no differences ($p>0.05$) between SEATs. New cover and cushion improved thermoregulatory responses during Neutral but not Hot. An impermeable incontinent cover negated improvements from cushion design. Seat cover appears more important than seat cushion during typical room conditions.

Keywords	Thermoregulation; Children; Wheel chair; skin blood flow; sweat, pressure injury
Corresponding Author	Bareket Falk
Corresponding Author's Institution	Brock University
Order of Authors	Gary Hodges, Matthew M. Mallette, Alan Rigby, Panagiota Klentrou, Stephen Cheung, Bareket Falk
Suggested reviewers	Brian Timmons, Vivian Mushahwar, Flavia Meyer, Anita Rivera-Brown

Submission Files Included in this PDF

File Name [File Type]

EEL 100 cover letter R1.pdf [Cover Letter]

EEL100 Reviewer Comments R1.docx [Response to Reviewers (without Author Details)]

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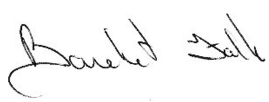
2019-03-27

Dear Editor,

Submitted online is the revised ms, titled Comparison of different wheelchair seating on thermoregulation and perceptual responses in thermoneutral and hot conditions in children - JTV_2018_117

We would like to thank the reviewers for their constructive comments. We have addressed all comments and believe they have served to improve our manuscript. We hope you will find it acceptable for publication.

Kindest Regards,



Bareket Falk, Ph.D.
Corresponding author
Professor
Brock University
bfalk@brocku.ca

Comments from the editors and reviewers:

-Reviewer 1

Summary: The methods and results are not appropriate for the stated objective to compare the different cushions and covers. Use of different participants to test the various seating types for an environmental condition is a major weakness and in my opinion not valid for the analyses performed and conclusions made. Repeated measures of all seat types for each participant for each environmental condition is needed. There is variation from person to person of the physiologic measures used.

We agree with the reviewer that it would have been preferable to examine all participants using all seating combinations in both environmental conditions. Indeed, that was our aim. This would have meant eight experimental sessions for each participant. As testing progressed, it was evident that the different SEATs had no effect in the hot environment. These data are presented in the manuscript. Therefore, we proceeded to examine the SEATs in the Neutral environment. Due to the ~3 h time commitment per experimental session, it was difficult to get the families to commit to the multiple sessions. Therefore, not all participants performed all sessions. Nevertheless, our comparisons were made within individuals. This is now clarified in the text.

And you did not normalize the data to baseline or use changes in measures, which would be more acceptable but still as ideal as a repeated measures design.

We agree. We now present the data for mean skin temperature, top and bottom of leg temperature, tympanic temperature, and skin blood flow as change from baseline. We have, however, kept the SR, HR, and BP presented in absolute units, as this may have clinical value. It is worth noting that the statistical analysis of either absolute values or change data resulted in a similar pattern and the same conclusions.

The study does contribute to knowledge by providing seating interface temperature and moisture data for the pediatric population with two cushion designs and three cover designs. It would be more appropriate to summarize in tables the mean temperatures and other measures obtained, with and without incontinence covers and for the two seat types, as this data appears to be needed for the pediatric population and the main contribution of this study.

We thank the reviewer for this suggestion. However, we feel that the data in graphical form are more informative – especially now that it has been converted to change rather than absolute values.

Introduction

Wheelchair-bound is not currently acceptable terminology. Use person-first language of "children who use a wheelchair" or "Individuals who use a wheelchair" throughout.

We have changed the terminology and updated the manuscript to person-first language.

"Pressure injury" is the most current terminology - pressure sore is deprecated

We have updated the terminology throughout the manuscript. We thank the reviewer for pointing this out.

In first paragraph you reference one article from Lahmann et al. to support the statement that current guidelines are adapted from adult care. Please reference actual guidelines to support this statement, such as the NPUAP/EPUAP prevention and treatment guidelines for pressure injuries.

We have updated this accordingly.

Missing a critical reference, "Microclimate: A critical review in the context of pressure ulcer prevention" by Jan Kottner, Joyce Black, Evan Call, Amit Gefen, Nick Santamaria (2018)

We have updated the manuscript (Introduction, 3rd paragraph) and included the suggested reference. We thank the reviewer for bringing it to our attention.

The statement, "Several studies have examined the effects of different seat cushions on pressure-sores development, with inconclusive results [11–13]." is inaccurate. The Brienza [11] and Geyer [13] clinical trials indicated that pressure reducing seat cushions had a significantly lower pressure injury incidence than standard foam cushions. This statement needs to be revised.

This sentence has been updated accordingly. We thank the reviewer for pointing this out.

Materials and Methods

It is clear that 5 participants completed all 6 test conditions. But the statement, "All other participants (n = 16) completed at least two conditions (identical SEAT in the Neutral and Hot condition)" is not clear. Since neutral and hot are not compared, it is not important if participants completed both for the same seat. It is more relevant how many tested more than one seat type for the same environmental condition, which are compared in your analyses.

In hindsight, we agree and thank the reviewer for pointing this out. We have added a table to clearly show how many children participated in each experiment.

This statement is not complete and spelling of Invacare incorrect, please rewrite. "Fabric provided to Invicare from Dartex coatings (Long Eaton, UK) and a standard order incontinence attached in fabrication by Invicare to the DartexTM Cover."

Define PSVF

Define "1816 cushion"3

The text has been updated and PSVF (Posture Seat Visco Foam) and 1816 (the name given based on the Imperial measurements 18 inches by 16 inches) have been explained.

Add more information to the last procedure paragraph. The total duration of each test condition/session (and data collection) is not stated. It is not clear if each of the six conditions tested were done on 6 different days. And if some were done the same day, how much time in between and what conditions to allow return to baseline.

We have updated the paragraph as requested. Data collection was 2 h in duration and all trials were performed on different days with at least 48 h between trials.

How was change in tympanic temperature calculated? Measured at 4 hz and previous data point subtracted? Change over a set time period?

The change value was based on 5 min of data collection during instrumentation. Each data point presented is 1 min of data from the corresponding time point e.g. 5 min, 10 min, etc. The manuscript has been updated with this information (Data collection subsection of Methods).

Major concern is that you did not have the same participants complete all 6 conditions. And you did not normalize the data. Some participants will have a lower baseline tympanic and skin temperature than others. Perception will vary. This negates the ability to compare the seating types as you have done.

We have provided a table to be clearer on the children's participation in the study. With regards to tympanic temperature, we have expressed the data as change, which should account any differences in basal body temperature between individuals. As noted above, we have also expressed other outcome variables as changes from baseline.

The statement "A repeated measures 2-way ANOVA was used with each seat, condition, and time (within subjects), for Neutral and Hot trials (separately), with a Bonferroni post-hoc correction for multiple comparisons." should be reworded, as condition (assuming you mean neutral, hot) is not part of the 2-way ANOVA and analyzed separately. Statement is not clear as written.

Text updated. Thank you for this comment.

Results

Figure 2 and 3 captions are reversed

Table 1 caption incorrectly states n=15

These have been corrected.

Why is Seat4 omitted from tympanic temperature results?

The tympanic temperature probes were generally not well received or tolerated by the children. We only had an n=6 for the SEAT4 as other participants were unwilling to use the tympanic probe. We chose to exclude those data to present a 'cleaner' data set. Nevertheless, in view of the reviewer's comment, we have added these data, updated figure 3 and the Results section accordingly, and noted the reduced sample for SEAT4.

Referenced in text to Figure 5 differ from captions. Say SR on leg bottom in neutral is 5A, but caption indicates this is 5C. Would be better to have included figures in the document with associated captions to improve ease of review. Especially since axes do not state top or bottom for SR.

Text and figure captions have been double-checked for accuracy. Figure has been updated to include lettering for each panel and the axis updated to include text referring to the data presented.

Discussion

The statement, "Pressure sore development is generally considered to be due to pressure-induced changes in skin wetness (SR) and SkBF" is incorrect in that pressure injuries are not DUE TO skin wetness, and pressure-induced changes in skin wetness does not occur. Skin wetness should be removed from this sentence and discussed separately as a risk factor. Skin moisture increases pressure injury risk two ways: increasing friction, which results in more tissue shear, and causing moisture associated skin damage, making tissue more susceptible to pressure injury.

We have modified this sentence and reframed the paragraph to discuss SR and SkBF responses, as suggested.

The statement, "These data indicate that seat covers rather than seat cushions are the most likely cause for potential problems with skin wetness and possibly, ulceration." is incorrect and a dangerous statement. Seat cushions play a major role in immersion, envelopment and thus pressure magnitude and distribution. Pressure is the cause of a pressure injury and other factors like moisture and temperature increase tissue susceptibility to pressure damage. The statement could be revised to state something like, "These data indicate seat covers play a significant role in skin temperature and moisture, both risk factors for pressure injury development."

We thank the reviewer for this comment and have updated the manuscript accordingly.

-Reviewer 2

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The current manuscript was aimed to compare 4 different wheelchair seatings (cushion and cover) on thermoregulatory and perceptual responses in pre-pubertal children. The purpose appears relevant considering the potential advantages of new types of seatings to prevent sores and optimize comfort to wheelchair-bound children.

I have listed below some general and specific suggestions, questions and corrections that - in my opinion - should improve the study rationale, clarify some methodological issues and understand the results .

Title:

Effect of different wheelchair seating technologies on physiological and perceptual measurements of thermal strain during normothermia and hyperthermia
I suggest to include “children”. You may even cut other words. As an example:
Comparison of different wheelchair seatings on thermoregulation and perceptual responses in thermoneutral and heat conditions in children.
We have updated the title, as suggested.

Abstract:

I suggest to specify that children were not wheelchair-bounded.

We have updated the text accordingly.

I suggest including some numbers (mean,sd), instead of only reporting if seatings were similar or not - or at least where significant differences occurred. This will help the reader "quantify" some outcomes.

We have added some values to the abstract to emphasize the differences between the seating types.

Introduction:

A stronger reason of focusing the experiment in children is lacking. I suggest adding some reference-based thoughts on few conditions (either related to health or physical features) that would make the pediatric group respond differently.

We have added some text to the introduction to address this. We have stated that children are characterized by higher skin temperature, yet lower sweating rate compared to adults. This is one of the fundamental bases for this study. We thank the reviewer for commenting on this.

In this following sentence how can poor nutrition affect pressure sore:

Exacerbating factors which increase the risk of pressure sore development include shear forces, poor skin hygiene, poor nutrition, hypohydration, elevated skin temperature, and importantly, skin-surface wetness [1,7,8].

I suggest listing only the factors that are controlled in the present study and briefly mention how they affect outcomes.

We agree and have updated the manuscript as suggested.

As a “key” sentence in the Introduction, I feel that the purpose needs to be rephrased. : “Therefore, we sought to determine whether different wheelchair seating technologies enhance thermoregulatory parameters in healthy, young children.”
The term enhance in this context is vague.
The authors used earlier and even in the title “physiological and perceptual responses” suggest keeping these terms.
We agree and have updated the purpose statement in the manuscript.

Another point - that I did not realize until later in the text - is the use of “healthy” for those who are not wheelchair-bounded children. I suggest being specific because the concept of “healthy” is wide-ranging and even inclusive.
We have updated the text to explicitly state that the participants in this study are not wheel-chair bound.

By the way, you shall write here - or somewhere at the beginning of the Methods - the reason (s) of not testing the target pediatric group in which the whole study rationale was built. Ideally, you should have used a specific age group of wheelchair bound children.
We agree with the reviewer that it would have been ideal to test children who regularly use wheelchairs. Unfortunately, despite our intense efforts, we were unable to recruit these children. Testing required multiple, lengthy visit to the laboratory. Parents and families with child(ren) who use a wheelchair were unable to make the commitment.

Materials and Methods:
Again, the term healthy should be specified.
We agree, the phrasing was vague. We have been specific that the children who participated in this study did not use a wheelchair.

Have you done any sample size calculation to achieve the number of 21 children?
No. We did not have any data to go on as we had no idea how effective (or not) the new seating technologies would be. We managed to recruit 11 participants per seating type (see

new Table 1) and based on the results, we feel that a greater sample size would not have altered the observed outcomes or the interpretations.

I bit confusing when you write that 5 participants completed all 6 conditions, Initially the understanding is that you will compared 4 conditions.

We have added a table (new Table 1) to more clearly present the participation in the study.

I found in the abstract – but not in the Methods - that altogether children sat for 2 hrs. What did children do during this whole time (they read, play with mobiles) ? Did you give any standard recommendation?

We have updated the methods stating that the children were seated for 2 h (final procedure paragraph in the Methods section). Children were able to read, watch a movie, or use cell phones/tablets. We have included this information in the Methods.

I suggest to elaborate a Table to better "visualize" the differences in a given feature among the 4 seats.

We have added a table (Table 3) that outlines the permutations we have used in the four seating types.

The choice of tympanic temperature (Tty) as an indication of core temperature was justified with a reference paper that studied adults (Nadel , 1970). I am not convinced that the self-inserted method by children have certainly reached the tympanic membrane as it can be painful. Better to have a specific methodological reference to cite here or give more details about this procedure.

This was difficult. We ensured that the temperature was steady before starting data collection and, because of the methodological difficulties, we examined the change in temperature, rather than the absolute temperature.

More details should also be given on how you calculated the sweating rate. Did you weight patches immediately after removing from skin? Result units are in mg per surface area per min. Did you correct by body surface area or patch surface area? I suggest reporting the body surface area in Table 1. How did you manage to correct by time (min)? Missing the specification and precision of the scale used to weight the patch.

Patches were sealed in an air-tight wrapping and weighed within 90 min of collection. Patches were on for exactly 15 min. Scale details have been provided and all information has been added to the manuscript.

Results:

"Tsk during the Neutral and Hot conditions (Fig 2)…"

According to the legend Fig 2 refers to Tty and not Tsk. Please check.

We have fixed figure legends.

" Cardiovascular responses   For SR on the bottom of the leg, during the Neutral conditions…"

Consider SR as physiological or thermoregulatory (not cardiovascular) response as you are using these terms in title and purpose.

We have updated the subheading to thermoregulatory

Discussion:

More insight should be given to the limitation of not testing wheelchair bound children, as there is a big individual variability on the extent that spinal cord injuries may affect thermoregulatory responses. I suggest deeper Discussion in this issue that was only briefly mentioning using one reference (Pritchett at al, 2015) related to adults who are athletes.

We agree and thank the reviewer for this suggestion. We have added to the Discussion regarding the limitation of using children that do not use wheelchairs and why an examination of such a population would be valuable.

EEL 100 – Highlights

- 4 different wheelchair seats on physiological and perceptual measures in children
- A newly designed seat is described, with improved thermoregulatory responses
- The seat is beneficial in neutral but not in hot conditions.
- An impermeable incontinent cover negated beneficial effect of breathable cushion

Comparison of different wheelchair seating on thermoregulation and perceptual responses in thermoneutral and hot conditions in children.

Gary J. Hodges[1], Matthew M. Mallette[1], Alan Rigby[2], Panagiota Klentrou[1,3], Stephen S. Cheung[1], Bareket Falk[1,3]

[1]Department of Kinesiology, Faculty of Applied Health Sciences, Brock University, St. Catharines, ON L2S 3A1, Canada.
[2]Niagara Prosthetics and Orthotics, St. Catharines, ON L2S 3A1, Canada
[3]Centre for Bone and Muscle Health, Faculty of Applied Health Sciences, Brock University, St Catharines, ON, Canada, L2S 3A1

Corresponding Author
Bareket Falk, Ph.D.
Professor
Department of Kinesiology,
Brock University,
St. Catherines, ON L2S 3A1
Canada

Comparison of different wheelchair seating on thermoregulation and perceptual responses in thermoneutral and hot conditions in children.

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Corresponding Author

[redacted]

Abstract

We examined the effects of 4 different wheelchair seatings on physiological and perceptual measures in 21 healthy, pre-pubertal children (9±2 years). Participants were able-bodied and did not regularly use a wheelchair. Participants sat for 2 h in Neutral (~22.5°C, ~40%RH) and Hot (~35°C, ~37%RH) conditions. Four seating technologies were: standard incontinent cover and cushion (SEAT1); standard incontinent cover with new cushion (SEAT2) were tested in Neutral and Hot; new non-incontinent cover with new cushion (SEAT3); new incontinent cover and new cushion (SEAT4) were tested in Neutral only. Measurements included skin blood flow (SkBF), sweating rate (SR) and leg skin temperature (T_{legB}) on the bottom of the leg (*i.e.* skin-seat interface), heart rate (HR), mean skin temperature, tympanic temperature, thermal comfort, and thermal sensation. During Neutral, SkBF and T_{legB} were lower (~50% and ~1°C, respectively) and SR higher (~0.5 $mg \cdot cm^{-2} \cdot min^{-1}$) ($p<0.05$) with SEAT3 compared to all other seats. SkBF was ~30% lower ($p<0.05$) for SEAT2 and SEAT4 compared to SEAT1. No other differences were observed between SEATs (all $p>0.05$). During Hot, HR and temperatures were higher than in Neutral but there were no differences ($p>0.05$) between SEATs. New cover and cushion improved thermoregulatory responses during Neutral but not Hot. An impermeable incontinent cover negated improvements from cushion design. Seat cover appears more important than seat cushion during typical room conditions.

Key terms: autonomic nervous system, sympathetic, parasympathetic, pressure injury

Introduction

Individuals who use a wheelchair spend long hours in a seated position and develop significant skin wetness (maceration) in regions contacting seating surface. This wetness increases the risk of developing pressure injuries. Presently, no data exist as to the extent to which sweating occurs in children who use a wheelchair. Current guidelines and prevention strategies for pressure injuries are adapted from adult care, but are not evidence-based towards children in general [1,2].

Pressure injuries are a source of preventable harm and discomfort in individuals who use a wheelchair. Once formed, pressure injuries can be debilitating, affecting comfort, mobility and daily-life functionality with infected sores potentially leading to infection and even death [3]. The annual cost of treating pressure injuries is in the billions of dollars [3–7], while the prevention of pressure injuries, even if labour-intensive, can be more cost-effective [6]. The ongoing discomfort is often associated with reduced physical function and negatively affects cognitive ability, leading to poor job or school performance. Wheelchair seat technology plays a crucial role in local heat dissipation and humidity management, both of which affect the development of pressure injuries.

Exacerbating factors which increase the risk of pressure injuries development include shear forces, elevated skin temperature, and importantly, skin-surface wetness [1,8,9]. Skin wetness is the product of unevaporated sweat, increasing its susceptibility to pressure injuries [10]. Indeed, the effects of humidity and temperature next to the skin surface are inextricably linked to concurrent soft tissue deformation [11]. However, extant data on skin wetness and thermoregulatory problems in children who use a wheelchair is extrapolated from data from adults with spinal cord injury. Importantly, children are characterized by higher skin temperature, yet lower sweating rate compared to adults [12,13]. As a result, this study aims to examine skin microenvironment and thermoregulatory mechanisms employed by children during different environmental conditions and using different wheelchair seating technologies.

Seat cushions greatly influence the microenvironment, resulting from an interaction between physiological responses, environmental conditions, and material properties of the cushion [14]. Several studies have examined the effects of different seat cushions on pressure-injury development, indicating that, in adults, pressure-reducing cushions resulted in a significantly lower pressure injury incidence than standard foam cushions [15–17]. Ferguson-Pell et al. [18] tested 32 available wheelchair cushions for their ability to dissipate heat and humidity and came to the conclusion that "Clearly, room for improvement exists in the design of cushion thermal dissipation performance" (p.954). Recently, intermittent electrical stimulation has been proposed as an approach to preventing deep tissue injury [19–22]. While this approach appears to be promising, it addresses the prevention of inside-out pressure injuries, rather than the common outside-in injuries. Importantly, all of the above studies were performed in adults and elderly individuals, and may not be applicable to children. Baharestani and Ratliff [23] highlight the need to develop age-specific measures for preventing pressure injuries in children.

Therefore, we sought to determine whether different wheelchair seating technologies affect physiological and perceptual responses in young children. To do this, we had four different seating systems that broadly-termed were: 1. Standard incontinent cover and cushion, 2. Standard cover, and newly designed cushion 3. Newly designed non-incontinent cover and newly designed cushion, and 4. Newly designed incontinent cover and newly designed cushion. We hypothesized that the newly designed cushion and covers would improve heat dissipation, as reflected by higher sweating rates and lower skin temperatures in the area in contact with the skin.

Materials and Methods

Participants

All participants and parents were fully informed of the experimental methods and risks prior to volunteering. Parents and children provided verbal consent and assent, respectively. The study was cleared by the Bioscience Research Ethics Board at [redacted]. All experimental protocols adhered to the guidelines set forth by the Declaration of Helsinki.

Twenty one healthy children (12 male/9 female) were recruited to participate in this study over 6 conditions with n = 11 for each condition (Table 1). Participants were able-bodied and did not regularly use a wheelchair. Physical characteristics are presented in Table 2. Participants were not diagnosed with any metabolic or cardiovascular disease, did not smoke and were not taking any medication. Participants were instructed to abstain from caffeine for 12 h and exercise for 24 h prior to testing. Additionally, the participants were instructed not to eat for 1 h prior to the testing session, but were encouraged to drink water *ad libitum*.

Seating types

Standard cushion and cover (SEAT1).

This assembly is comprised of a standard Invacare Matrx® Posture Seat Visco Foam (PSVF) cushion (Product ID: PSVF1816, Invacare, Mississauga, Canada) with standard Dartex™ fabric cover (Model: C-PSVF1816) (Table 3). Fabric provided to Invacare from Dartex™ coatings (Long Eaton, UK) and a standard order incontinence layer is attached in fabrication by Invacare to the Dartex™ Cover. Total dimension of the cushion and cover is 45.7 cm W x 40.6 cm D x 8.9 cm H.

Newly designed cushion, generic cover (SEAT2).

Custom made block style standard dimension 45.7 cm x 40.6 cm (18” x 16”) cushion alternative to the PSVF in SEAT 1. The cushion was made of 2.5 mm diameter full long-extrusion nylon 6,6 which was randomly wound to form a continuous sheet style material

8.9 cm thick. This sheet material was then heat cut to form closed ends on the cut extrusions. The seating block, as an alternative to the PSVF was cut to a 45.7 cm W x 40.6 cm D cushion, (Niagara Prosthetics & Orthotics, St. Catharines, Canada) (Fig. 1A) The same standard C-PSVF1816 Dartex™ cover with integrated incontinent cover was used to complete SEAT 2 (Table 3).

Newly designed cushion and newly designed cover (SEAT3).

The same 2.5 mm diameter full long-extrusion nylon 6,6 which was randomly wound to form a continuous sheet style material 8.9 cm thick (as used in SEAT2) was used again with a custom cotton/nylon blended cover. The custom cotton/nylon cover was fabricated without an integrated incontinence cover by sewing a standard shape 18" x 16" cushion cover from purchased woven bolt material 23% Nylon, 74% Cotton, and 3% Spandex with a 110 gsm weight (Niagara Prosthetics & Orthotics, St. Catharines, Canada) (Table 3). The new cushion and cover is easily washable and dry-able in short time frames such that there is no requirement for an impermeable incontinence cover to protect the cushion from damage.

Newly designed cushion and newly designed incontinence cover (SEAT4)

While the new cushion is easily washable, feedback from families at Niagara Prosthetics and Orthotics indicated that an incontinence cover was necessary. As such, SEAT 4 is a replica of SEAT 3 with the addition of a unique incontinence cover (Table 3). The cover was fabricated from bolt sheet material and sewn into a standard 18" x 16" cover. The material is designed to be unidirectionally water resistant (thus protecting the cushion) while breathable for air flow. The seams were sealed using Seam Seal™ thread treatment post fabrication. The bolt sheet material is a coated fabric similar to the material used in SEAT 3 (without Spandex due to the incompatibility with the stretch properties of the coating) with a polyurethane-based treatment to the inside surface of the fabric in a microscopic structure (Model number KBTRPM250P-F15-B16). Fabric is 75% Nylon and 25% Cotton and 115 gsm weight. The material is not a membrane based material such as Gore-Tex™.

Instrumentation and experimental procedures

Upon arrival at the laboratory children changed into provided clothes for the study (generic t-shirt and shorts of appropriate size) and completed a pubertal staging questionnaire (often with parental assistance). Body mass and standing stature were measured, along with skinfold thicknesses for the calculation of body fat percentage [24].

Participants were then instrumented with a 3-lead electrocardiogram (ECG; BioAmp, AD Instruments, Colorado Springs, CO, USA) to measure heart rate. Mean whole body skin temperature ($\overline{T}_{sk}$) was recorded from the weighted average of 4 T-type thermocouples (PVC-T-24-190, Omega Environmental Inc., Laval, QC, CA) placed on the chest, forearm, thigh, and calf [25]. Temperature from the top of leg (quadriceps, T_{legT}) and bottom of leg (hamstring, T_{legB}) was recorded from T-type thermocouples (PVC-T-24-190, Omega Environmental Inc., Laval, QC, CA). An index of core temperature was obtained from tympanic temperature (T_{ty}) using a thin and small flexible probe (Smiths Medical, ASD) on the left side. These were self-inserted until the probe touched the tympanic membrane, moved slightly away from it, and held in place with cotton wool and taped in place with hypoallergenic surgical tape (Transpore, 3M Canada). Tympanic temperature has been related to both skin and environmental temperatures [26], but is influenced by warm environmental conditions. Therefore, in lieu of absolute T_{ty}, changes in T_{ty} were quantified (ΔT_{ty}) to reflect changes in core temperature. Each probe was used for one trial and then disposed.

Participants were seated in a custom-built wheelchair (Fig. 1B), the seating of which has two, 4 cm diameter holes (Fig. 1C), to allow for measurement of skin blood flow and sweating rate from the underside of the leg and were plugged with the appropriate cushion and cover material until sampling for set time periods. Skin blood flux was recorded using laser speckle contrast imaging (moorFLPI-2, Wilmington, DE, USA) from the underside of the right leg. Skin blood flux data were normalized for mean arterial pressure and are presented as cutaneous vascular conductance (CVC). Local sweating rate was measured from the underside of the left leg, using sweat collection patches that are applied directly to the skin area of interest. Absorbent patches, consisting of 4.7 × 3.1 cm filter paper, were affixed to the skin for 15 min periods with Tegaderm (3M Medical Technologies, Minneapolis, MN). Subsequently, they were placed in a sealed plastic bag and weighed within 90 min of collection (XSR105 Analytical balance, 0.01 mg readability).

Thermal comfort (TC) (4 point scale, Comfortable to Very uncomfortable) and thermal sensation (TS) (7 point scale from Cold to Hot) were obtained to gauge participant perception of the thermal environment [27]. Blood pressure was measured by manual auscultation in duplicate by the same investigator.

All procedures were performed with the participants resting in a seated position for 2 h of data collection. Participants were able to read, watch a movie, or use cell phones/tablets. The six experimental sessions were identical in protocol, with different environmental conditions. In the four Neutral trials (all four seating types), ambient temperature (T_{amb}) and relative humidity were 22.4±0.1°C and 40.4±6.5%. In the two Hot trials (seats 1 and 2) T_{amb} and relative humidity were 34.9±0.3°C and 36.6±6.2%. The order of the Neutral and Hot trials were counterbalanced among participants and all sessions were performed at the same time of day for each participant. Seating types were performed in order. Experimental trials for each participant were performed on different days and separated by at least 48 h to ensure no potential confounding effects of the HOT trial on thermophysiological measurements. We hypothesized that all three custom seats would provide enhanced physiological and perceptual responses over SEAT1. It was apparent that during the Hot condition, there was no added benefit of SEAT2 over SEAT1 (see results). Therefore, SEAT3 and SEAT4 were not tested in the Hot condition.

Data collection

The ECG recordings were collected continuously at 1 KHz (LabChart Pro v.8, PowerLab, ADInstruments). Temperature data (T_{tym}, $\overline{T}_{sk}$, T_{legT}, T_{legB}) were collected continuously at 4 Hz (LabChart Pro v.8, PowerLab, ADInstruments) using T-type thermocouples and thermocouple meter (TC-200, Sable systems, Las Vegas, NV, USA). Temperature Δ values were calculated from a 5 min resting period of data at the start of the trial and each data point presented is 1 min of data from the corresponding time point e.g. 5 min, 10 min, etc. Skin blood flux data were collected continuously at 0.1 Hz (moorFLPI-2, Wilmington, DE, USA). Local sweating rate was determined by patch weight increase (to 0.0001 g) from the dry weight and expressed per minute. Four patches were placed at the 10, 35, 70, and 100 min time points and left in place for 15 min. Blood pressure and perceptual measures (TC and TS) were collected at 10, 20 min, and every 20 min thereafter.

Statistical analysis

Data were normally distributed as assessed by Q-Q plots, and skewness and kurtosis measures. Normality was defined as a skewness value less than ± 3 and a kurtosis value less than ± 9. A repeated measures 2-way ANOVA was used to examine outcome variables or changes in outcome variables (from baseline) with each seat over time (within subjects), for Neutral and Hot trials (separately), with a Bonferroni *post-hoc* correction for multiple comparisons. Anthropometric data are presented as mean ± SD and, all other data are presented as mean ± SE. Data were analysed using SAS (SAS institute, Toronto, Canada) and GraphPad Prism 6 (GraphPad Software Inc., La Jolla, CA, USA) and statistical significance was defined as $p<0.05$.

Results

Temperature measurements

$\Delta\overline{T}_{sk}$ presented with no main effects (all p>0.3) in the Neutral condition, while in the Hot condition there was a main effect for time (p<0.001), but not for seat, and no interaction (p>0.5).

During the Neutral condition, there were no main effects (seat p>0.8, time p>0.9, or interaction p>0.9) in ΔT_{ty} among 3 seating combinations (Fig. 3A). In the Hot condition, there was a main effect for time (p=0.007) reflecting an increase in ΔT_{ty}, but not for seat, and no interaction (both p>0.9) (Fig. 3B).

In the Neutral condition, there were main effects for seat (p<0.001) and time (p<0.001) for ΔT_{legB}, but no interaction (p>0.9) (Fig 4A). Temperatures were significantly lower with SEAT3 compared to all other seating types. There were no differences in ΔT_{legT} during the Neutral condition (all main effects p>0.1) (Fig. 4C). For both ΔT_{legB} and ΔT_{legT} in the Hot condition, there were main effects for time (both p<0.001), but not for seat, and no interaction (all p>0.8) (Figs. 4B and 4D).

Thermoregulatory responses

For SR on the bottom of the leg, during the Neutral conditions, there were main effects for seat (p=0.012), but not for time or interaction (both p>0.45) (Fig. 5C) with SR being higher with SEAT 3 compared with the other seating types. There were no effects for the SR on the top of the leg in the Neutral trial, nor were there any main effects for SRs during the Hot conditions (Fig. 5B).

For skin blood flow in the Neutral condition, there were main effects for seat, time, and interaction (all p<0.001) (Fig. 6A). Compared with SEAT1, skin blood flow was lower in SEAT2 and SEAT4, and lowest with SEAT3. In the Hot condition, there was a main effect for time (p<0.001), but not for seat (p=0.18) or interaction (p>0.9) (Fig. 6B).

There were no main effects (all $p>0.4$) for systolic blood pressure, diastolic, or heart rate during the neutral condition (Fig. 7A, C, E). There were also no main effects (all ≥0.09) for heart rate (Fig. 7B) and systolic blood pressure (Fig. 7D) in the Hot condition. However, for diastolic blood pressure there was a main effect for time ($p=0.04$), but not for seat or interaction (both $p>0.2$) (Fig. 7F).

Perceptual responses

During both the Neutral and Hot trials there were no differences in TC or TS among the seating types ($p>0.9$) (Table 4).

Discussion

This study aimed to examine the effects of different wheelchair seatings (cushion and cover) on physiological and perceptual measures of thermoregulation in children. We found that the cushion had little effect on thermoregulatory measures; however, the newly designed cushion-and-cover combination (SEAT3 with new cushion and breathable cotton cover) had the greatest positive effect, as reflected by the skin temperature, local sweating rate and skin blood flow response. The physiological and perceptual responses in SEAT2 (new cushion) and SEAT4 (new cushion and incontinence cover) were not different from the standard cushion and seat covering currently available on the market (SEAT1).

Skin moisture increases pressure injury risk by increasing friction, which results in more tissue shear, and by causing moisture-associated skin damage, making the tissue more susceptible to pressure injury. We observed an increase in SR with SEAT3; while this might seem counter-intuitive (i.e. more sweating would lead to more wettedness) the breathable properties of the cotton cover likely facilitated higher evaporative cooling, which in turn led to increased sweating rate and better heat loss. This is reflected in the lower SkBF and T_{legB} for SEAT3 compared with all other seating combinations. Thus, positive effects achieved through simple modification of the seating type are likely to reduce the risk of pressure injury development. While we examined healthy children, our finding may be important for those with spinal cord injury, as it is well established that those with spinal cord injury have reduced sweat gland activity and response to increased temperature [28], and thus would allow for better heat loss despite reduced gland activity.

We also noted in SEAT3 that there was a lower skin temperature on the underside of the leg (i.e. side in contact with the seat). These data suggest that the new seating reduces the local heat storage, likely due to enhanced airflow and heat dissipation. It appears that the incontinence seat covers impair heat dissipation to a greater extent than the cushion. While SEAT3 was the most desirable from a thermophysiological standpoint, user feedback reported that the lack of an incontinence (fluid resistant) cover was a major drawback. This is despite the new cushion being made from nylon woven open cell foam, which is washable both by hand and in standard household washing machines.

We observed no differences in whole body skin temperature, core temperature, blood pressure, and heart rate. Whilst we did observe local changes in temperature, blood flow, and sweating in the areas in contact with the new seating, we did not see differences between seats in those regions not in contact with the seat (including top of the leg). Thus, the effects of the seat cover and cushion were limited to the interface of the person and the technology. This is likely the reason we observed no differences in perceptual measures between conditions. These data indicate that while the type of seating improved thermophysiological responses (SR, SkBF, and T_{LegB}), these did not alter the thermal perception of the children. This is likely related to the fact that we observed no differences between seats in the systemic/whole body responses (T_{sk}, T_{ty}, HR). Indeed, the scales are gross indices of thermal comfort and are not focused on the local response (seated area). It should be noted that the current study was only two hours in duration. It is possible that, if the participants were in SEAT3 (the seating that demonstrated the greatest benefit in terms of heat dissipation) for a longer time, as is typical for children who use a wheelchair (i.e. most of the day), perceptual responses to the new seating may be more noticeable.

Surprisingly, we found no differences between SEAT1 and SEAT2 in the Hot conditions for any of the measures. This could be that the magnitude of the heat stress in the Hot conditions was so great that any beneficial effects of the newly designed cushion were masked under such strong environmental stress (e.g. see figures on SkBF and T_{legB}). Indeed, there were clear, positive differences under Neutral conditions for T_{legB}, and SkBF.

A limitation of this study is that we tested healthy children who do not use wheelchairs. Future studies should aim to examine children who use a wheelchair. Potentially, there are numerous reasons for wheelchair use and the consequential effects of this on physiological responses may vary. For instance, it is known that in adults with spinal cord injury, sweating rate below the level of the lesion is often greatly reduced, if not, abolished [29–31]. This has a marked effect on the individual's ability to adequately thermoregulate [28,32,33], and the data from the present study clearly demonstrate a significant effect of seating materials on sweating rate and skin temperature.

Perspectives

These data indicate seat covers play a significant role in skin temperature and moisture, both risk factors for pressure injury development. This is due to the need for seat covers to prevent potential damage to seat cushions during a bout of incontinence. The SEAT3 in this study which had a cotton, non-incontinent cover had the best results from a thermophysiological standpoint.

In summary, we observed that the newly designed cover and cushion improved thermoregulatory responses during Neutral conditions, but not during Hot conditions. However, the incontinent covers, both standard and our new option, negated any benefits of the new cushion design. A hot environment negated any benefits from cushion design. These data suggest that seat cover is more important than seat cushion in terms of the physiological response during typical ambient room conditions.

Acknowledgements

We thank the participants and their families for volunteering for the study.

Author contributions

[redacted] conceived the idea. [redacted] designed the experiments. [redacted] completed data collection. [redacted] reduced and analysed the data. [redacted] interpreted the data. [redacted] drafted the manuscript. [redacted] edited the manuscript critically for intellectual content. All authors approved the final version.

Disclosures

[redacted] is the Co-Owner of [redacted]. All other authors have no disclosures.

Funding

This study was supported by a [redacted] and the [redacted].

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Figures and Tables

Table 1. Study participation

	SEAT1		SEAT2		SEAT3	SEAT4
Participant	Neutral	Hot	Neutral	Hot	Neutral	Neutral
1	x	x	x	x	x	x
2	x	x	x	x	x	x
3	x	x				
4	x	x	x	x	x	x
5	x	x				
6	x	x				
7	x	x				
8	x	x	x	x		
9	x	x	x	x		
10	x	x	x	x	x	x
11	x	x	x	x	x	x
12			x	x		
13			x	x		
14			x	x	x	
15			x	x	x	
16					x	x
17					x	x
18						x
19					x	x
20					x	x
21						x

Table 2. Participant characteristics. Data are mean±SD.

	Total (N=21)	Seat 1	Seat 2	Seat 3	Seat 4
Male / Female	12 / 9	6 / 5	6 / 5	7 / 4	7 / 4
Age (years)	9.5 ± 1.3	9.3 ± 1.6	9.4 ± 1.2	9.4 ± 1.2	9.6 ± 1.1
Mass (kg)	40.7 ± 8.3	40.2 ± 9.3	41.1 ± 11.3	38.9 ± 8.2	40.2 ± 6.4
Statue (m)	1.47 ± 0.98	1.48 ± 0.92	1.49 ± 0.9	1.45 ± 0.88	1.49 ± 0.74
BMI	18.8 ± 3.4	18.4 ± 3.7	18.5 ± 4.1	18.5 ± 4.7	18.1 ± 4.9
Pubertal stage	1(*n*=17), 2(*n*=3)	1(n=8), 2(n=3)	1(n=8), 2(n=3)	1(n=8), 2(n=3)	1(n=8), 2(n=3)
BF%	17.7 ± 4.1	18.4 ± 4.5	17.9 ± 3.9	18.7 ± 4.3	17.9 ± 4.7
Blood pressure (mm Hg)					
Systolic	85 ± 4	86 ± 4	85 ± 4	85 ± 4	85 ± 5
Diastolic	47 ± 4	48 ± 4	47 ± 4	46 ± 5	46 ± 4

BMI = body mass index; BF% = body fat percentage.

Table 3. Seating cushion and cover permutations used in this study.

	SEAT1	SEAT2	SEAT3	SEAT4
Cushion	Standard foam	New nylon	New nylon	New nylon
Cover	Standard incontinent	Standard incontinent	New cotton	New incontinence

Table 4. Perceptual measurements

TIME (min)	10	20	40	60	80	100	120
	Neutral						
Thermal Comfort							
SEAT1	1±0	1±0	1±0	1±0	1±0	1±0	1±0
SEAT2	1±0	1±0	1±0	1±0	1±0	1±0	1±0
SEAT3	1±0	1±0	1±0	1±0	1±0	1±0	1±0
SEAT4	1±0	1±0	1±0	1±0	1±0	1±0	1±0
Thermal Sensation							
SEAT1	4±0	4±0	4±1	4±1	4±0	4±1	4±1
SEAT2	3±1	4±0	4±1	4±0	4±1	4±0	4±1
SEAT3	4±0	4±0	4±0	4±1	4±0	4±0	4±0
SEAT4	4±0	4±0	4±0	4±0	4±1	4±1	4±1
	Hot						
Thermal Comfort							
SEAT1	2±1	2±1	2±1	3±1	3±1	3±1	3±1
SEAT2	2±1	2±1	2±1	3±1	3±1	3±1	3±1
Thermal Sensation							
SEAT1	6±1	6±1	6±1	6±1	7±1	6±1	7±1
SEAT2	6±1	6±1	6±1	6±1	6±1	6±1	7±1

Figure Legends

Figure 1. Photographs of new cushion and wheelchair set up. Panel A shows the structure of the new seat cushion. Panel B shows the wheel chair with the laser speckle contrast image attached. Note that supports for participant's legs were removed for clarity. Panel C shows the 4 cm diameter holes for the measurement of skin blood flow and the placement of sweat rate patches.

Figure 2. Mean whole body skin temperature. Panel A presents the data for the 4 Neutral conditions. Panel B shows the data from the 2 Hot conditions. Error bars are omitted from panel A for clarity.

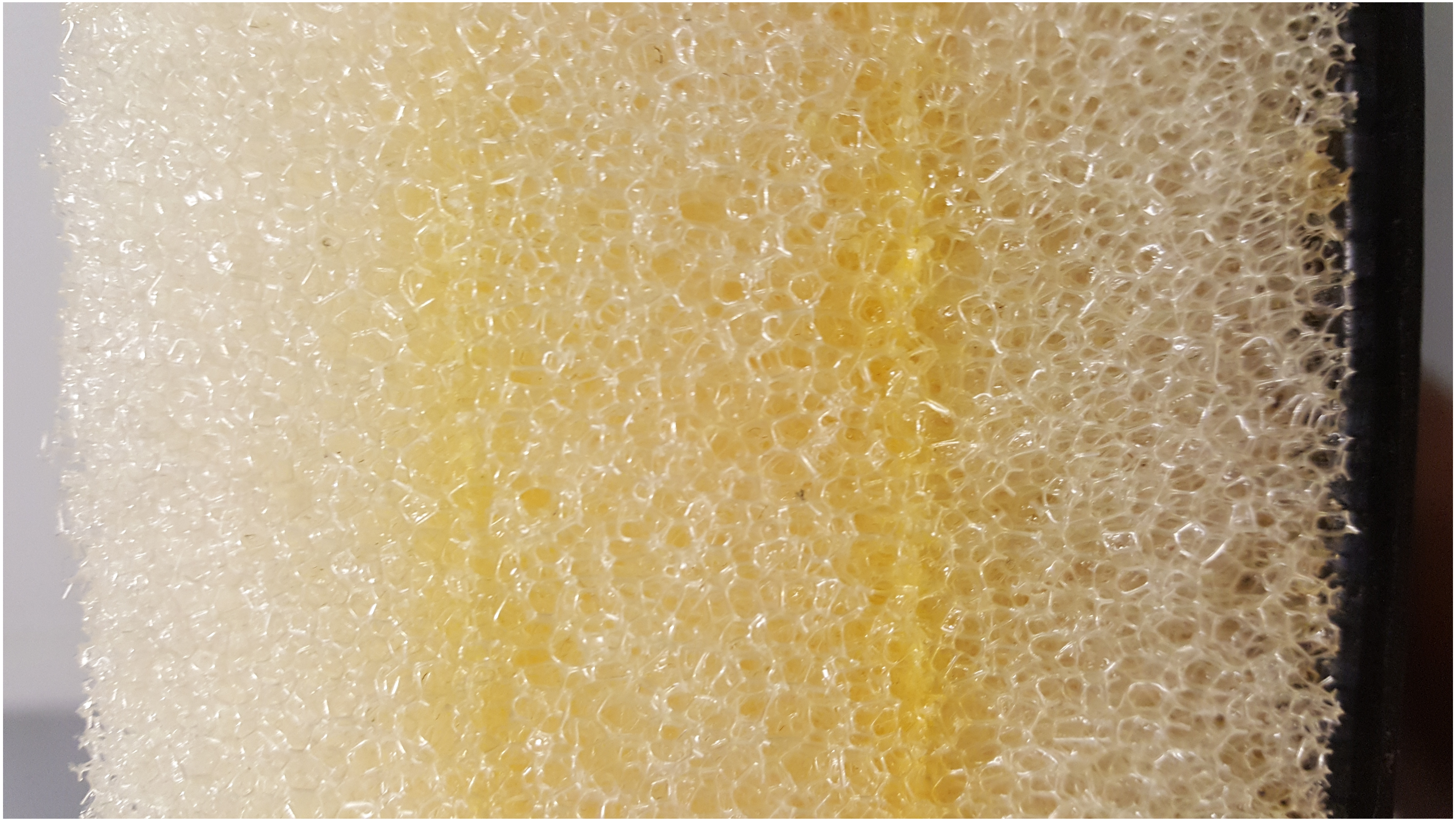
Figure 3. Change in tympanic temperature for the Neutral (A) and the Hot (B) condition. There were no differences among the seat types for either condition. Error bars are omitted for clarity.

Figure 4. Change in top and bottom of leg temperatures. Panels A and B present the data for the top of the leg from the Neutral and Hot conditions, respectively. There were no differences between the seating types for either condition. Error bars are omitted from panel A for clarity. Panels C and D are for the bottom of the leg from the Neutral and Hot conditions, respectively. Temperature was significantly lower with SEAT3 compared to the other seating types. There were no differences in bottom of leg temperature between the seating types in the Hot condition.

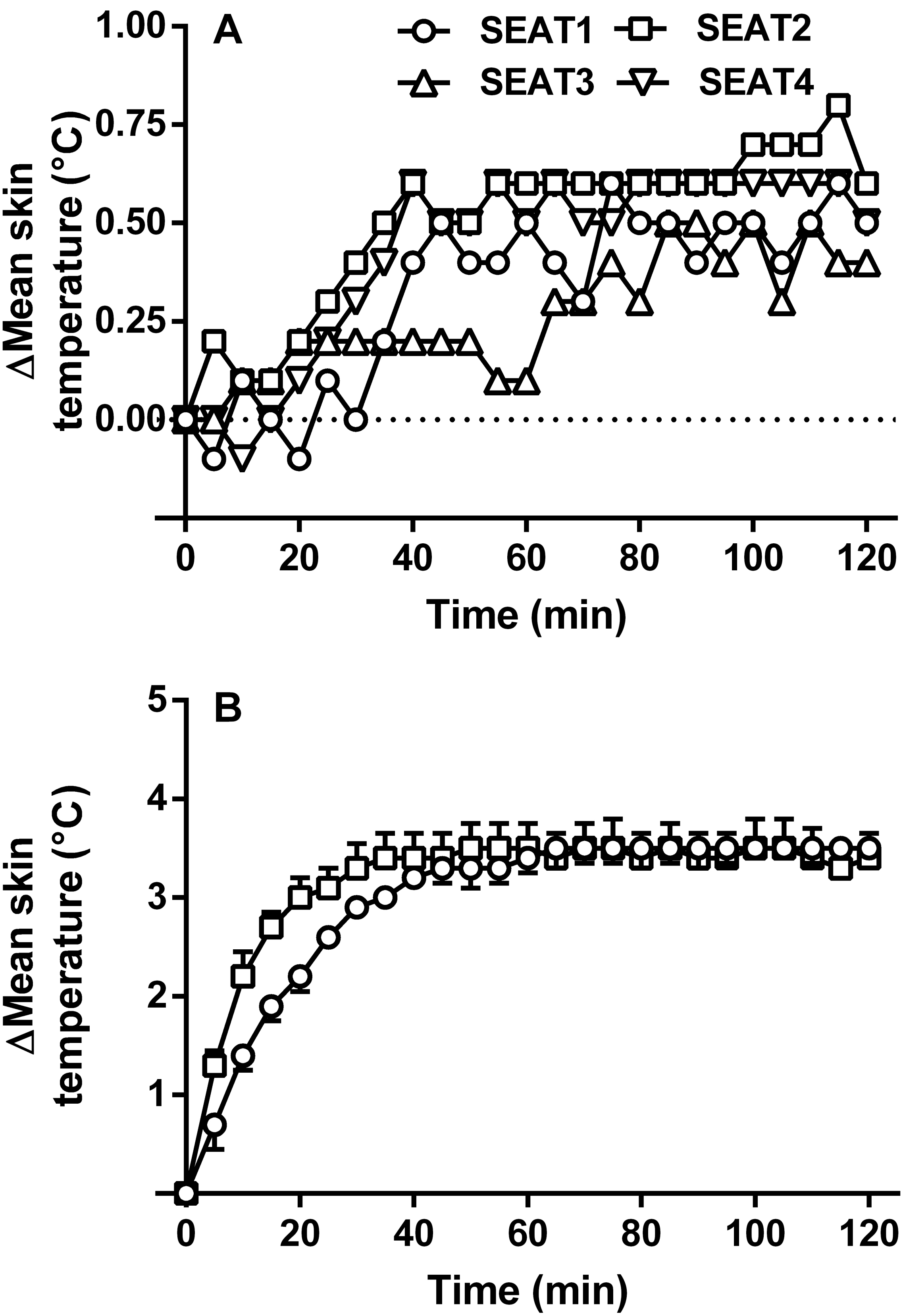
Figure 5. Sweating rate data from the top of the leg in the Neutral (A) and Hot (B) conditions, and bottom of the leg in the Neutral (C) and Hot (D) conditions. There were no statistical differences in sweating rate on the top of the leg in either the Neutral of Hot conditions. Sweating rate on the bottom of the leg was higher with SEAT3 compared to the other seating types (C). There were no differences in sweating rate between the seating types in the Hot condition.

Figure 6. Cutaneous vascular conductance data for the Neutral (A) and the Hot (B) conditions. In the Neutral condition, cutaneous vascular conductance was lower in SEATs 2 and 4 compared to SEAT1; SEAT3 was lower than all other seating types. There were no differences between the seating types in the Hot condition. Error bars are omitted for clarity.

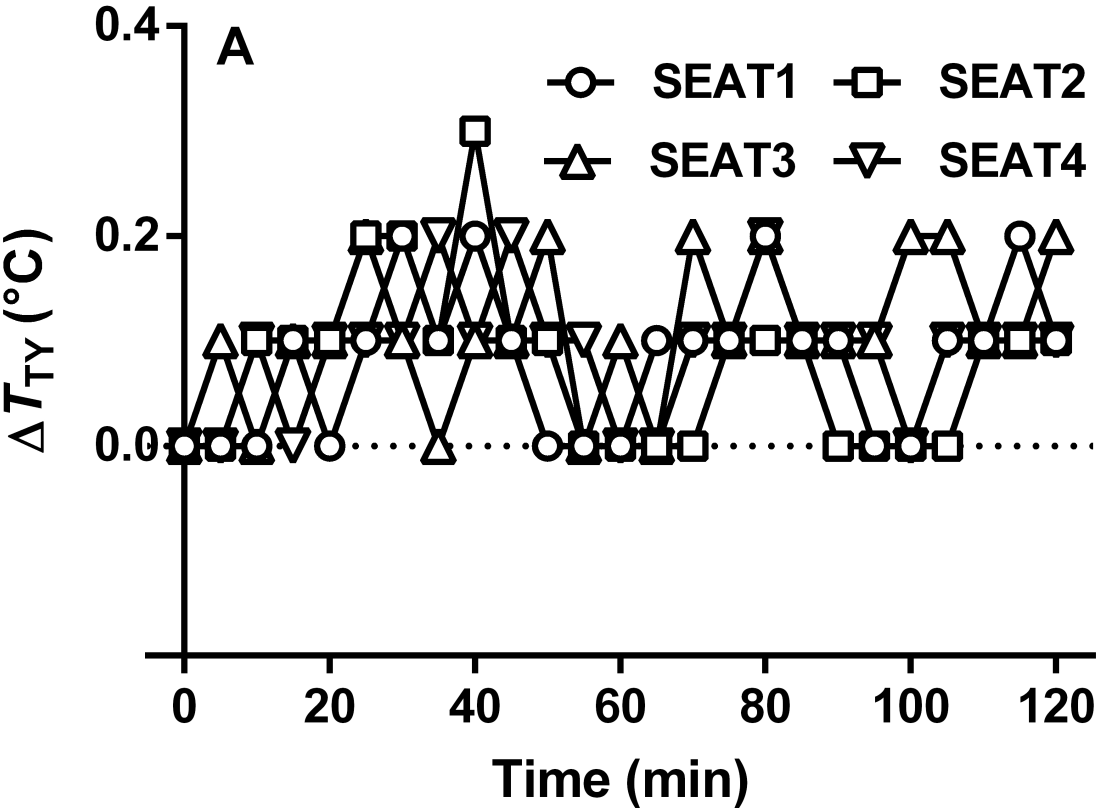
Figure 7. Heart rate (A and B), systolic blood pressure (C and D), and diastolic blood pressure (E and F) for the Neutral and Hot conditions. There were no differences among the seating types for any of the measures. Error bars are omitted from panel A for clarity.

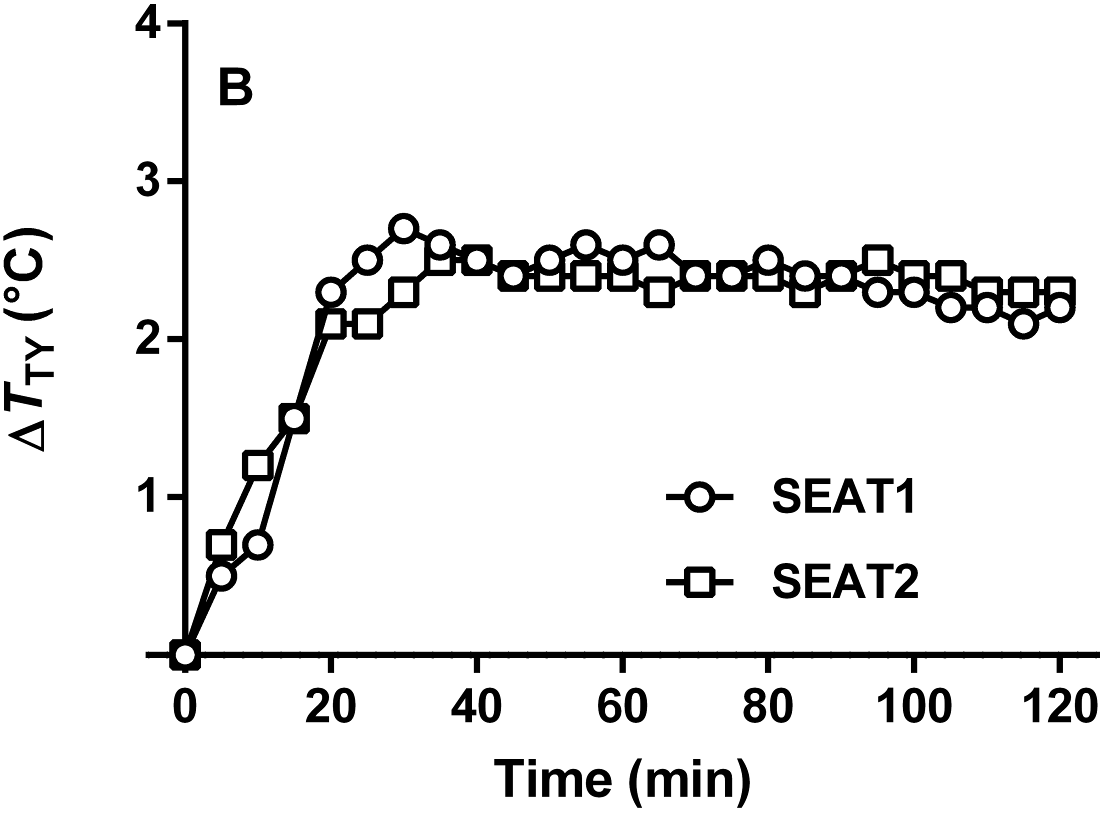


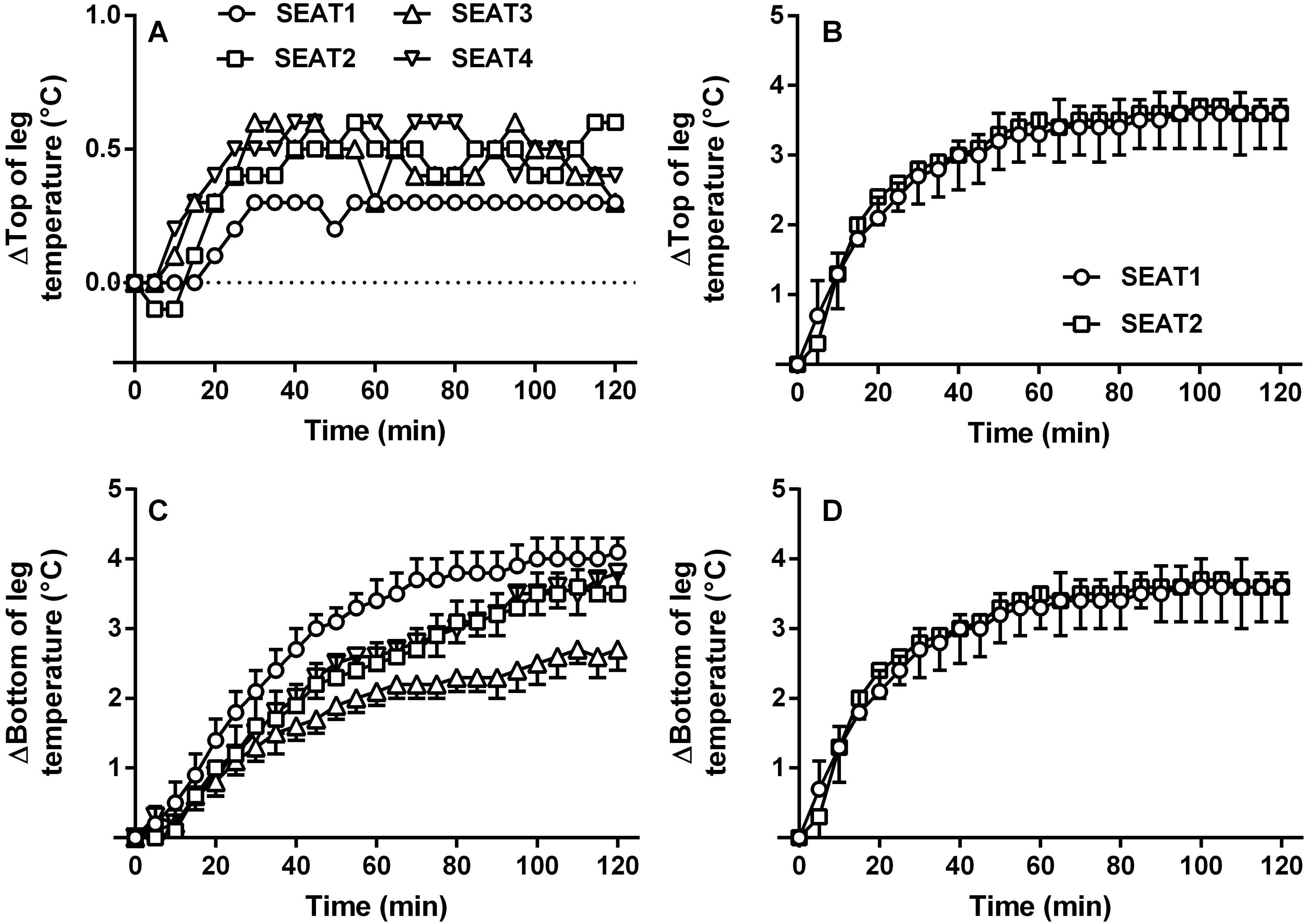

moor FLPI-2

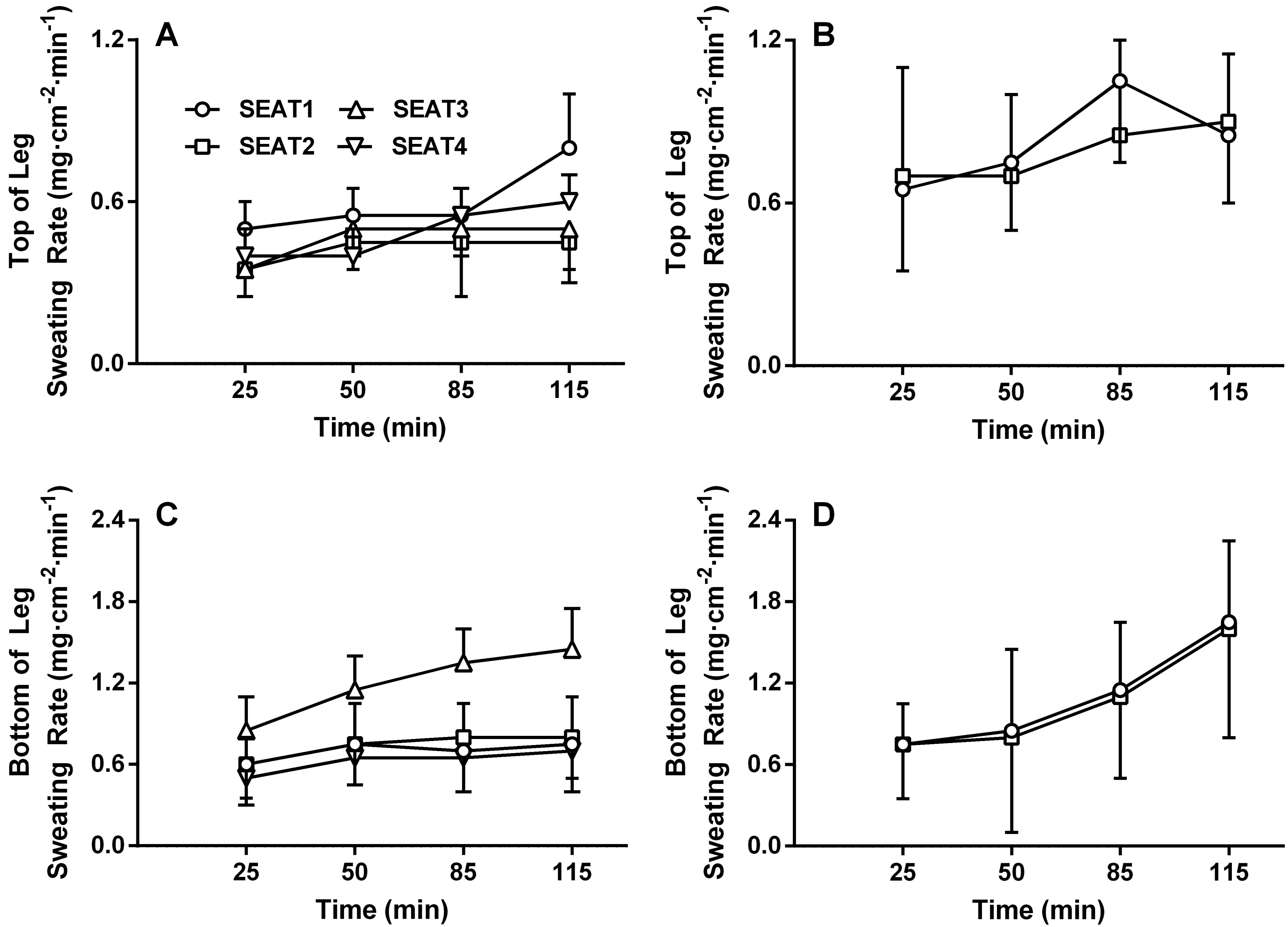


A
B
SEAT1
SEAT2
SEAT3
SEAT4
ΔMean skin temperature (°C)
Time (min)
1.00
0.75
0.50
0.25
0.00
0
1
2
3
4
5
0
20
40
60
80
100
120

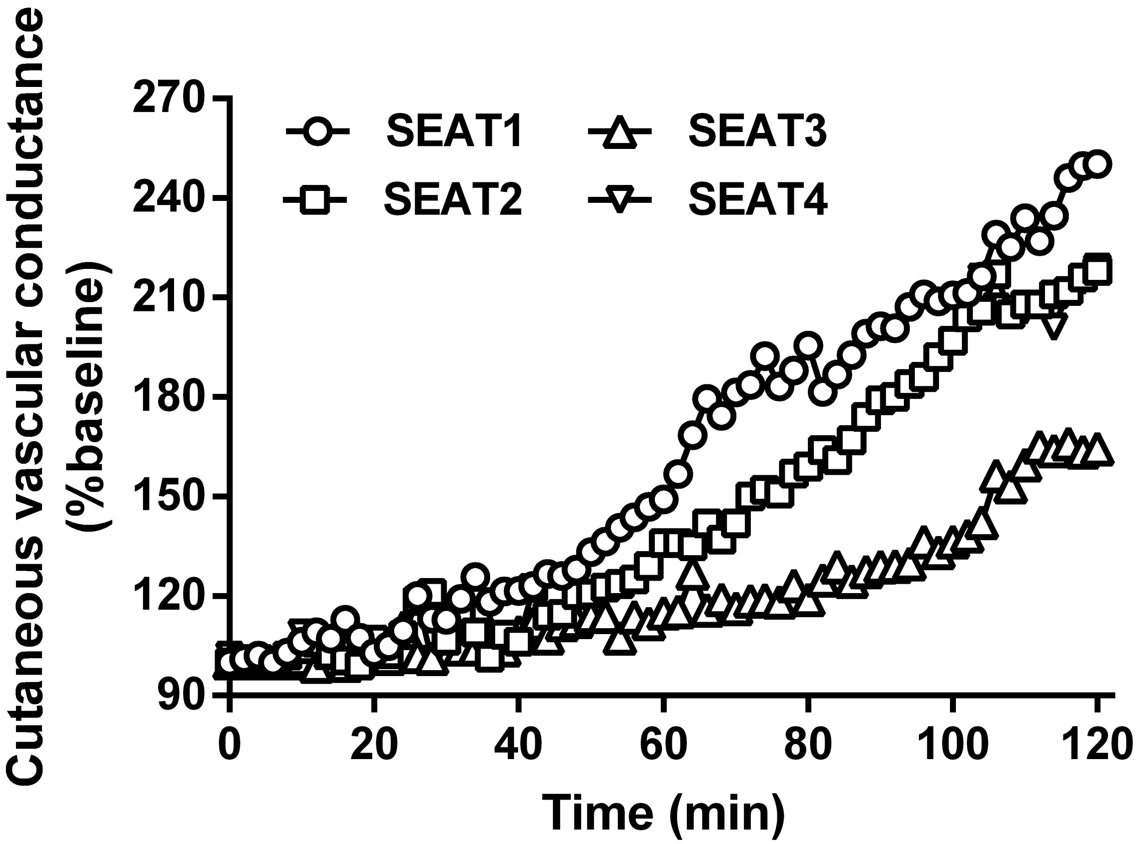

A
SEAT1
SEAT2
SEAT3
SEAT4
0.4
0.2
0.0
ΔT_{TY} (°C)
0
20
40
60
80
100
120
Time (min)

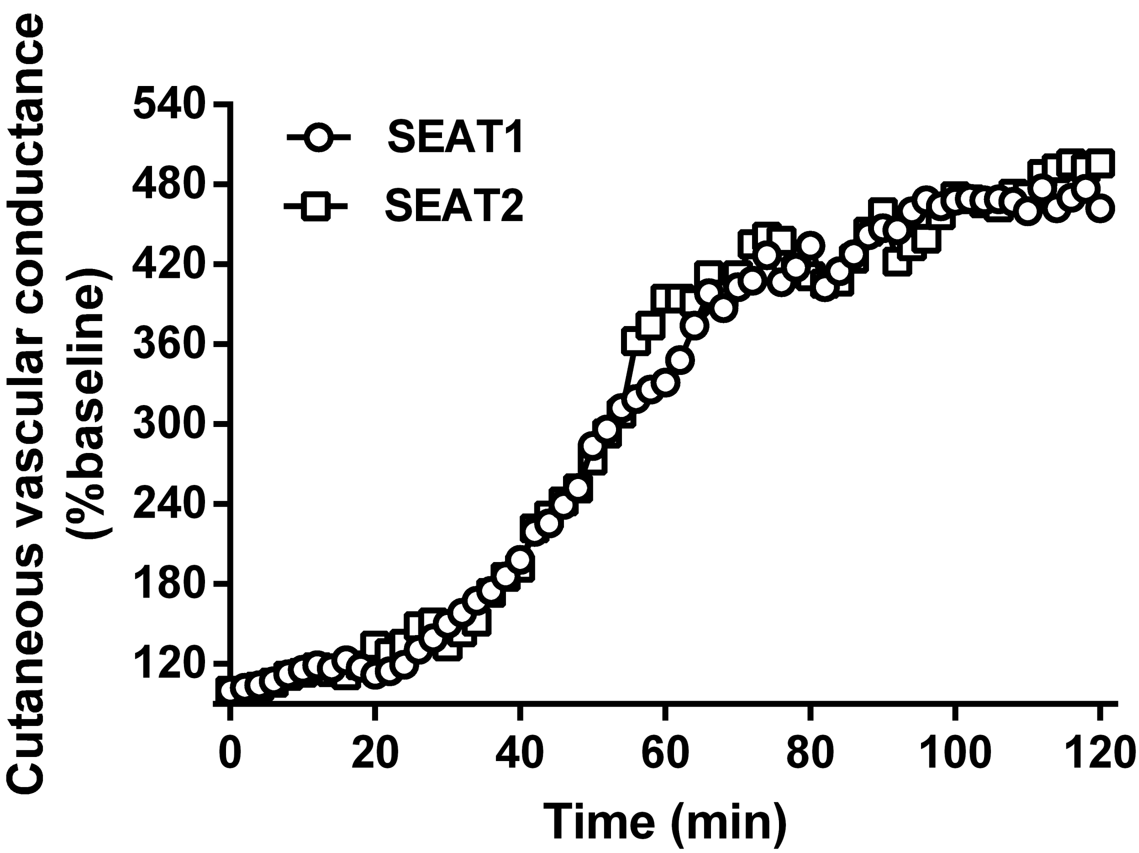

B
SEAT1
SEAT2
4
3
2
1
ΔT_{TY} (°C)
0
20
40
60
80
100
120
Time (min)

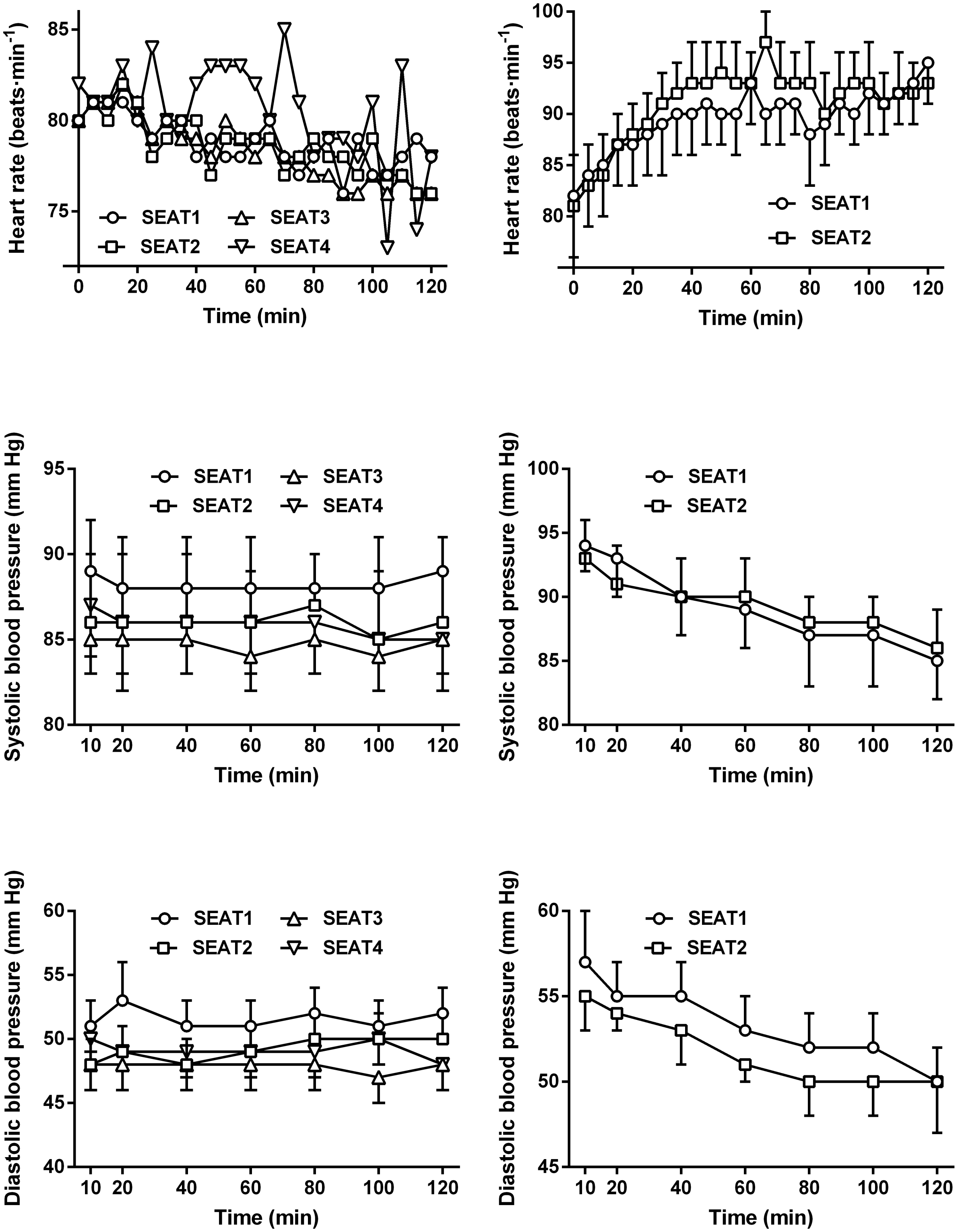

A
B
C
D
SEAT1
SEAT2
SEAT3
SEAT4
ΔTop of leg temperature (°C)
ΔBottom of leg temperature (°C)
Time (min)
0
20
40
60
80
100
120
1.0
0.5
0.0
1
2
3
4
5



A
B
C
D
SEAT1
SEAT2
SEAT3
SEAT4
Top of Leg
Sweating Rate (mg·cm-2·min-1)
Bottom of Leg
Sweating Rate (mg·cm-2·min-1)
Time (min)
0.0
0.6
1.2
1.8
2.4
25
50
85
115


Cutaneous vascular conductance (%baseline)
Time (min)
SEAT1
SEAT2
SEAT3
SEAT4


Cutaneous vascular conductance (%baseline)
Time (min)
SEAT1
SEAT2


Heart rate (beats·min-1)
Time (min)
SEAT1
SEAT2
SEAT3
SEAT4
Heart rate (beats·min-1)
Time (min)
SEAT1
SEAT2
Systolic blood pressure (mm Hg)
Time (min)
SEAT1
SEAT2
SEAT3
SEAT4
Systolic blood pressure (mm Hg)
Time (min)
SEAT1
SEAT2
Diastolic blood pressure (mm Hg)
Time (min)
SEAT1
SEAT2
SEAT3
SEAT4
Diastolic blood pressure (mm Hg)
Time (min)
SEAT1
SEAT2

Conflict of Interest:

Effect of different wheelchair seating technologies on physiological and perceptual measurements of thermal strain during normothermia and hyperthermia

Gary J. Hodges[1], Matthew M. Mallette[1], Alan Rigby[2], Panagiota Klentrou[1,3], Stephen S. Cheung[1], Bareket Falk[1,3]

The authors have no financial or other sources of conflict of interest relating to our submission of this manuscript