A high-intensity warm-up increases thermal strain but does not affect repeated sprint performance in athletes with a cervical spinal cord injury

PLEASE CITE THE PUBLISHED VERSION

https://doi.org/10.1123/ijspp.2021-0073

PUBLISHER

Human Kinetics

VERSION

AM (Accepted Manuscript)

Title

A high-intensity warm-up increases thermal strain but does not affect repeated sprint performance in athletes with a cervical spinal cord injury.

Original Investigation

Authors

Thomas J. O'Brien[1], Simon J. Briley[1], Barry S. Mason[1], Christof A. Leicht[1], Keith Tolfrey[1], Victoria L. Goosey-Tolfrey[1]

Author Affiliations

[1]Peter Harrison Centre for Disability Sport; School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, UK

Corresponding Author

Prof. Victoria L. Goosey-Tolfrey
Peter Harrison Centre for Disability Sport,
School of Sport, Exercise and Health Sciences,
Loughborough University
LE11 3TU
Telephone: 01509 226386
Email: v.l.tolfrey@lboro.ac.uk

Preferred running head: High intensity warm-up in wheelchair rugby

Abstract word count: 250

Text only word count: 3925

Number of figures: 3 **Number of tables:** 3

Abstract

Purpose: To compare the effects of typical competition versus high-intensity intermittent warm-up (WU) on thermoregulatory responses and repeated sprint performance during wheelchair rugby (WR) gameplay. **Methods**: An intermittent sprint protocol (ISP) simulating the demands of WR was performed by male WR players (7 with cervical spinal cord injury (SCI) and 8 without SCI (NON-SCI)) following two WU protocols. These included a typical competition WU (CON) and a WU consisting of high-intensity efforts (INT). Core temperature (T_{core}), thermal sensation and thermal comfort were recorded. Wheelchair performance variables associated to power, speed, and fatigue were also calculated. **Results**: During the WU, T_{core} was similar between conditions for both groups. During the ISP, a higher T_{core} was found for SCI compared with NON-SCI (38.1±0.3 vs 37.7±0.3°C: p=0.036, d=0.75), and the SCI group experienced a higher peak T_{core} for INT compared with CON (39.0±0.4 vs 38.6±0.6; p=0.004). Peak T_{core} occurred later in the ISP for players with SCI (96±5.8 vs 48±2.7 min; p<0.001). All players reported a higher thermal sensation and thermal comfort following INT (p<0.001), with no differences between conditions throughout the ISP. No significant differences were found in wheelchair performance variables during the ISP between conditions (p≥0.143). **Conclusions**: The high-intensity WU increased thermal strain in the SCI group during the ISP, potentially due to increased metabolic heat production and impaired thermoregulation, whilst not impacting on repeated sprint performance. It may be advisable to limit high-intensity bouts during a WU in players with SCI to mitigate issues related to hyperthermia in subsequent performance.

Key Words: Wheelchair Sport, Thermoregulation, Spinal Cord Injury, Intermittent-sprint exercise, Paralympic Sport.

Introduction

Wheelchair rugby (WR) is a Paralympic team sport played by individuals with a wide variety of physical impairments.[1] Because of this, it implements a classification system to minimise the impact of impairment on the outcome of competition.[2] WR has been described as an intermittent sport characterised by prolonged periods of low-speed activity interspersed by frequent, short bouts of high-speed activity, which differs according to classification.[3] Differences in type and severity of impairment also affect physiological responses such as oxygen consumption, heart rate, and blood lactate concentration during exercise and competition.[4,5] It has been established that WR players with a cervical spinal cord injury (SCI) experience a loss of temperature regulation making them susceptible to a heightened thermoregulatory strain, with body core temperatures (T_{core}) reaching >39°C during repeated sprint performance and competition.[6] This is due to reduced afferent input to the thermoregulatory centre and loss of both sweating capacity and vasomotor control below the level of lesion.[7] Therefore, WR players with a SCI are at greater risk of thermal strain and thermally induced fatigue than their NON-SCI counterparts, which, if not monitored, may have serious consequences on both performance and health.[6,8]

Active warm-up (WU) strategies are common practice by athletes as a pre-conditioning routine to improve performance,[9] with many benefits attributed to temperature-related mechanisms, e.g., increases in muscle temperature.[10] To date, the benefits of WU strategies in relation to performance have mainly been investigated in able-bodied athletes.[10] Peak speed and the ability to sustain intermittent high-intensity sprint performance are essential features of WR performance.[11] From the extensive able-bodied literature, increases in mean and peak power outputs during kayak ergometry have been reported following a high-intensity WU strategy in trained paddlers.[12] Whilst a comparable study to consider, it is unknown whether these findings would be seen in sports solely reliant on the upper-body musculature such as WR since the legs and torso also contribute to the power achieved during paddling.[13] Moreover, the above findings[12] were related to 500m with performances lasting 2 mins, WR is a game that comprises of four quarters, with each quarter comprising of ~16 minutes of active playing time (with stoppages).[11]

It is well documented that following high-intensity WUs body temperature can significantly increase,[14] which may place athletes with impaired thermoregulatory capacity at increased thermoregulatory risk.[15] Further, increases in muscle lactate concentration and subsequent decreases in muscle pH have been associated with fatigue during high-intensity activity.[16] The role of a WU on subsequent thermal strain or identifying an optimal WU to improve subsequent performance have not yet been investigated with appropriate rigour in WR players. Both Webborn et al.[17] and Griggs et al.[18] included a WU in their experimental designs, with a focus on intermittent sprint protocol (ISP) in athletes with tetraplegia. However, the warm-up design was self-selected and thus not standardised, precluding the isolation of WU effects *per se* on thermal strain and performance. The current study aimed to address these shortcomings by manipulating the WU to induce a level of hyperthermia. Hence, the purpose of this study was to compare the effects of a typical competition versus a high-intensity WU on thermoregulatory responses and repeated sprint performance variables during subsequent simulated WR gameplay in players with and without cervical SCI.

Methods

Participants

Fifteen male WR players (age: 30.3 ± 5.5 yrs; body mass: 65.3 ± 14.5 kg) volunteered to participate in the main experimental protocol. They were divided into two groups according to SCI status, seven players with SCI (C5-C7 complete, *n*=5, C6-C7 incomplete, *n*=2; IWRF classification range of 0.5-2.0) and eight players without SCI (NON-SCI) (multiple limb amputation, n=3, cerebral palsy, n=1, Roberts syndrome, n=1, critical illness polyneuropathy, n=1, and osteogenesis imperfecta, n=1, Arthrogryposis, n = 1; IWRF classification range of 1.5-3.5). Prior to participation all players provided written informed consent. The study was approved by the local ethical advisory committee and conducted in accordance with the Declaration of Helsinki.

Experimental Design

To establish the speed profiles of a typical pre-competition WU strategy adopted by a National WR team, 12 individual players representing IWRF classes 0.5-3.5 were monitored twice across a 2-day camp using an Indoor Tracking System sampling at 8 Hz (Ubisense, Cambridge, UK) as previously described.[19] The relative time spent in five pre-defined speed zones (Very low = ≤ 20% maximum speed; Low = 21-50% ; Moderate = 51-80%; High = 81-95%; Very high = >95%) based on the percentage of peak speed from competition were obtained.[3] Figure 1A and 1B illustrate the WU speed profile of one player, and the grouped mean WU speed profiles during the training camp respectively.

Insert Figure 1 here

The activity profile data were used to inform two laboratory-based WU protocols that were developed for implementation on a wheelchair ergometer (WERG: Lode B.V., Groningen, The Netherlands). The control condition was based on the duration players spent in different speed zones, replicating current WU practices (CON, Figure 2A). A modified WU with a high-intensity element replacing the final 5 minutes of CON was also developed (INT; Figure 2B). This closely replicated an upper body WU in able-bodied athletes which involved five 10s sprints separated by 50s of submaximal effort at the speed at 50% maximal oxygen consumption ($\dot{V}O_{2peak}$).[12] The submaximal propulsion speed in the current study was based on the $\dot{V}O_2$ – propulsion speed relationship which was taken from a previous visit to the laboratory as part of players' regular physiological screening.

Measurements

Prior to arrival at the laboratory (~8 hours), participants ingested a telemetry pill (HQ Inc,. Palmetto, Florida), for continual measurement of T_{core}, in accordance with previous recommendations.[20] Upon arrival to the laboratory, participants were asked to void their bladder, and were weighed to the nearest 0.1 kg (Marsden Weighing Group Ltd, Henley- on-Thames, UK) and fitted with four iButton thermistors (DS1922T, Maxim Integrated Products, Inc., Sunnyvale, CA, USA), placed on the chest, bicep, thigh and calf on the right side of the body for the measurement of skin temperature (T_{sk}) using the Ramanathan formula.[21] During all trials participants wore their typical training attire which included lightweight tracksuit bottoms and a short sleeve top.

After instrumentation, players transferred to their own sports wheelchair which was secured to a dual-roller WERG. An automatic calibration to account for body mass, chair mass and tyre pressure was performed. Resistance was based on previously recorded coast down trials to closely replicate wheelchair propulsion on an indoor court.[22] Familiarisation with the WERG (30 minutes before the start of the WU), consisted of 5 minutes of submaximal propulsion and two maximal 10s sprints. Peak speeds during the sprints were used to identify propulsion speeds based on pre-existing speed zone calculations,[3] for both WUs on an individual basis. To enable inferences regarding practical significance, data from these familiarisation sprints were used to derive the within-day reliability coefficients which was used to calculate the smallest worthwhile change (SWC) in power output, specific to performance.[23] Within-day CV for peak power, PP_{avg}, and PP_{avg5} was 7.6%, 5.2%, and 6% respectively. The corresponding ICC and SWC values were 0.97, 0.99, 0.97, and 8.7%, 5.9% and 6.9% respectively.

Each WU was conducted on separate days in a counter-balanced, randomised order and were scheduled at the same time of day to account for circadian variation.[24] Following each WU, an ISP (Figure 2C) was completed by all players for analysis of thermoregulatory and repeated sprint performance. Based on previous descriptions of WR activity profiles during competition,[3,11] the ISP consisted of four ~16-minute quarters.[25] Each quarter consisted of wheelchair propulsion at different percentages of maximum speed, based on speed zones previously described for the prescription of the WUs. Players performed bouts of 35-seconds, 30-seconds, and 20-seconds in the very-low, low, and moderate speed zones, respectively. Eleven blocks of each speed zone were distributed across each quarter to replicate the interval nature of an on-court game.[3] Throughout the ISP, exercise at these speed zones was separated by 5 s and 10 s sprints representing high- and very high-speed activity. Two 10-second sprints were analysed for performance measures as described below. Testing was conducted in a temperature-controlled laboratory (20.5 ± 0.2˚C, 52 ± 8% RH) with at least 24 h between visits. Players were asked to refrain from alcohol, caffeine, and strenuous exercise 24 h prior to each condition.

Insert Figure 2 here

Heart rate (HR) (Polar Team[2], Polar Electro Oy, Kempele, Finland) was recorded throughout both protocols and was reported as a mean of the WU and subsequent quarters of the ISP. Capillary blood samples were taken pre and post WU, pre Q1, post Q2 and at the end of the ISP for the measurement of blood lactate concentration (Biosen C-line, EKF Diagnostics, Barleben, Germany). *Ad libitum* fluid intake (water only) was measured and noted between players' arrival to the lab and finishing the exercise on visit 1 and replicated for visit 2. Thermal sensation, thermal comfort, and rating of perceived exertion (RPE) were recorded at the beginning and end of both WUs, the beginning of the ISP, and the end of each quarter. The thermal sensation scale comprised of categories from 0 "unbearably cold" to 8 "unbearably hot".[26] The thermal comfort scale ranged from 1 "comfortable" to 4 "very uncomfortable".[27] MATLAB (Matlab R2017a, The Mathworks Inc, Natickm MA, USA) was used for performance data processing[22] including calculation of peak power, peak speed, push frequency, average peak power per push throughout the 10 s sprint (PP_{avg}), average peak power per push for the first five pushes (PP_{avg5}) and fatigue index expressed as a percentage (using the highest peak power per push and the lowest subsequent peak power per push ([peak – minimum power]/peak power) x 100).

Statistical analyses

All data were analysed using the Statistical Package for Social Sciences (version 24; SPSS Chicago, IL), where significance was accepted at $p \leq 0.05$. Normality of data was assessed using the Shapiro-Wilk test. Where assumptions of sphericity were violated, a Greenhouse-Geisser correction was applied. A 2 x 2 x 10 mixed measures ANOVA was used to compare HR, blood lactate concentration, RPE, and repeated sprint performance measures across time, where the between subject factor was impairment group with two levels, with two within factors (time and condition). Linear mixed models (LMM) were used to compare T_{core} and T_{sk} between the groups across CON and INT and over the duration of the WU and ISP. The LMM included dependent fixed factors for condition and time; group was the independent fixed factor and baseline temperature at pre-WU was included as a covariate. Statistical outcomes were supplemented with absolute standardised paired effect sizes (Cohen d), with the magnitude of effect size classed as small (0.20), moderate (0.50) and large (0.80).[28] Within-day reliability of the wheelchair ergometer power measures was assessed using coefficient of variation (CV) and intraclass correlation coefficient (ICC). One participant with SCI was withdrawn at the end of Q3 during the ISP due to reaching the ethical cut off limit of T_{core} (39.5°C) in both CON and INT. All data are presented as mean ± SD.

Results

Warm-Up

Significantly higher values for HR ($p = 0.001$), RPE ($p < 0.001$) and blood lactate concentration ($p < 0.001$) were found following INT compared to CON (Table 1). A lower HR in both CON ($p = 0.004$) and INT ($p = 0.017$) WU conditions and a smaller change in blood lactate concentration following INT ($p = 0.024$) were identified in SCI compared to NON-SCI. All players reported a higher thermal sensation and thermal comfort following INT ($p < 0.001$), with no between group differences ($p = 0.507$; Table 1). Immediately post WU, T_{core} was not significantly different between groups ($p = 0.274$) or across conditions ($p = 0.322$).

Insert Table 1 here

Intermittent Sprint Protocol

No significant differences in HR ($p \geq 0.131$) were found between conditions, although HR remained lower for SCI than NON-SCI throughout ($p = 0.04$). There were no differences between conditions in blood lactate concentration throughout the ISP ($p = 0.998$), although blood lactate concentration was higher in the NON-SCI group between Q1-Q3 (Table 2; $p \leq 0.036$). No significant differences were found between conditions for RPE, thermal sensation or thermal comfort throughout the ISP (Table 2). Group differences were found during Q3 and Q4, with SCI players reporting higher RPE ($p = 0.009$), thermal sensation ($p = 0.042$) and thermal comfort ($p < 0.001$) (Table 2).

Insert Table 2 here

A significant group by condition interaction of T_{core} highlighted groups responding differently to the WU conditions ($p < 0.001$) with a progressive increase in T_{core} in both conditions across the ISP in the SCI group, and a levelling off in NON-SCI. A significant three-way interaction for group by condition by time was also reported ($p = 0.042$: Figure 3A).

The SCI group experienced a higher peak T_{core} for INT compared with CON (39.0 ± 0.4 vs 38.6 ± 0.6; $p = 0.004$; d = 0.78), whereas peak T_{core} was similar across the conditions in NON-SCI ($p = 0.770$). Furthermore, peak T_{core} was higher in SCI (38.8 ± 0.5 vs 37.9 ± 0.4°C; $p = 0.001$, d = 1.99: Figure 3B) and was reached at a significantly later stage of the ISP (96 ± 5.8 vs 48 ± 27 min; $p < 0.001$: Figure 3C) when compared with NON-SCI. In the NON-SCI group, INT induced a more rapid increase to peak T_{core} compared with CON (37 ± 34 vs 60 ± 12 min) with no differences in time to peak T_{core} in the SCI group. A large, significant between group difference in peak T_{sk} ($p = 0.004$; $d = 1.2$) was found, with NON-SCI exhibiting higher values than SCI (33.5 ± 1.4 vs 32.0 ± 0.6ºC, respectively). All interactions for T_{sk} were non-significant ($p \geq 0.266$).

Insert Figure 3 here

Analysis of performance sprints for each quarter revealed a significantly lower peak power, PP_{avg}, PP_{avg5}, and peak speed in SCI compared with NON-SCI during both ISPs (Table 3; $p \leq 0.026$). However, these variables were not significantly influenced by WU ($p \geq 0.143$). The fatigue index was significantly higher in Q2, Q3 and Q4 following the INT compared to CON in both groups ($p \leq 0.024$). The coefficient of variation for PP_{avg} was 5.2%; therefore the SWC was 5.9%.[23] The changes in PP_{avg} for sprint one between CON and INT for Q1 and Q2 did not differ statistically between conditions ($p = 0.33$), yet six players exceeded the SWC following INT during the first sprint of Q1 (five out of eight NON-SCI, and one out of seven SCI).

Insert Table 3 here

Discussion

This is the first study to address whether a high-intensity WU enhanced repeated sprint performance at the expense of increased thermal strain in WR players with and without SCI. Our findings revealed that a WU involving high-intensity propulsion significantly elevated T_{core} during subsequent performance in SCI players, however it had no significant bearing on repeated sprint performance, a finding that was independent of players' SCI status. Players with an SCI experienced a greater peak T_{core} and time to reach peak T_{core} compared to NON-SCI players. That said, during the first quarter following a high-intensity WU, positive performance benefits were evident, with five NON-SCI players improving their PP_{avg} to a greater extent than the SWC, with no change in thermoregulatory responses.

It was evident that the current WU strategy (CON) resulted in relatively low overall physiological demands. Players spent 77% of their time in very low to low intensity speed zones, reported an RPE of 11 (light), and no change in blood lactate concentration was observed. That said, these WU characteristics are representative of typical WR game play[3] and are similar to the physiological responses reported elsewhere following a WU in WR players.[5] Conversely, the high-intensity intervention WU that was investigated in the current study induced a significant increase in HR, blood lactate concentration and RPE (16 – hard/very hard), suggesting that, as intended, the WU was more challenging physiologically. Moreover, physiological differences during both WU strategies in the SCI group compared to NON-SCI were noted and are consistent with previous literature.[4,18,25]

To the authors' knowledge, no previous study has looked at the thermoregulatory effects of the WU within an experimental design of wheelchair athletes. In the present study, albeit a small increase, both WU strategies increased T_{core} at a group level (~0.4°C) but did not differ between conditions prior to the ISP. Interestingly, the WU elicited a slightly lower T_{core} change than reported elsewhere following an on-court WU in SCI and NON-SCI WR players,[20] yet descriptions of this WU were not provided, making comparisons difficult. Following the high-intensity WU, players reported a higher thermal sensation and reductions in thermal comfort in both SCI and NON-SCI groups prior to the start of the ISP. Further differences were found during Q3 and Q4 of the ISP, where SCI players reported a greater thermal sensation than NON-SCI. Whilst this is contrasting previous literature,[20] it may be partly explained by their higher T_{core} values at these time points. It has previously been shown that changes in thermophysiological variables and the associated thermal perceptions influence the voluntary selection of exercise intensity,[29] and are significantly associated to changes in cognitive performance.[30] However, we found no changes in repeated sprint performance, and despite one athlete within the SCI group being withdrawn due to reaching the ethical cut off limit of 39.5°C, no adverse events were reported. This contrasts with the findings of Griggs et al.[18] who commented that one player displayed difficulties with decision making when they reached a T_{core} ≥39.5°C. When T_{core} >39°C, hyperthermia induced fatigue has the potential to decrease repeated sprint performance in able-bodied individuals.[8,31] Contrasting to this, the lack of change in repeated sprint performance reported in the present study may suggest substantial fatigue was not present during the ISP. This is consistent with previous indoor tracking data that has found activity profiles do not deviate across the duration of a full match,[3] such that match play is likely not significantly influenced by fatigue and therefore may explain the reason we did not find any significant reductions in repeated sprint performance.

Our findings are comparable to previous literature reporting a greater T_{core} at the end of WR gameplay in players with a SCI,[20] with a continual rise in T_{core} throughout both conditions (Figure 3A). A lower metabolic heat production compared to NON-SCI has been reported in WR players with SCI during gameplay.[20] However, players with a SCI are unable to dissipate most of the heat produced by exercise through evaporative heat loss mechanisms.[7] This is primarily due to loss of sweating capacity below the lesion level,[7] leading to a progressive rise in T_{core}.[18] Further, a loss of vasomotor control in persons with a SCI may lead to limited peripheral heat storage and impaired convective heat flow, which is suggested in the little change in thigh and calf T_{sk}..[15] , Our findings suggest a WU *per se* may increase thermal strain in SCI during a subsequent ISP, as T_{core} was found to be slightly elevated following both warm-up strategies. This is supported by a lower T_{sk} in the SCI group, and a significantly greater peak T_{core} following INT (~0.5°C).

It has previously been suggested that measurement of T_{core} using an ingestible telemetric capsule may be less sensitive to changes in T_{core} in the early onset of exercise (~15 minutes).[33] This may partly explain why the increase in T_{core} following the warm-ups was fairly modest. Despite this, as T_{core} continually increased throughout INT, it may be advisable to apply cooling strategies following warm-ups to delay T_{core} rises to critical levels during subsequent performance in SCI. Given the value and practicality of performing a warm-up as a whole team, this approach may be preferrable to instructing players with SCI to limit high-intensity activities during the warm-up to avoid excessive metabolic heat production. This is particularly important as high intensity bouts may help with sprinting ability during subsequent performance.[12] Indeed, five of eight NON-SCI players, and one of seven SCI players experienced a meaningful increase in PP_{avg} during the first sprint of Q1 following INT. Such warm-ups need to be carefully balanced, as increases in muscle lactate concentration and subsequent decreases in muscle pH have been associated with fatigue during high-intensity activity.[16] Further, reductions in repeated sprinting ability have been noted from a simultaneous increase in core- and muscle temperature.[14] With regards to our own data, the observed increase in blood lactate concentration following INT in both groups suggests a greater anaerobic contribution, and a further *potential* source for peripheral muscle fatigue, even though INT did not have a negative impact on sprinting ability in the present study.

It should be recognised that no cooling strategies were administered throughout the protocol. Indeed, alternative strategies such as pre-cooling have also been investigated in this population.[25] A combination of ice vests used throughout a WU, and water sprays throughout simulated match play have been shown as an effective way of reducing thermal strain throughout a subsequent ISP in WR players with SCI (reductions of ~0.6°C T_{core}).[25] The current results highlight the need to consider pre-cooling as part of a pre-game routine due to the influence of WU intensity on thermal strain, especially when the WU intensity is high. It is likely that pre-cooling would offset time to reach peak T_{core} experienced by SCI players following a WU of higher intensity, with future research needed investigating the combination of pre-cooling and WU strategies in WR players. It must also be noted that participants were not exposed to any airflow during this study, as all exercise was performed stationary on a WERG. During on-court activities, players would be exposed to a degree of airflow, which may impact thermoregulatory parameters and thermal perceptions, presenting a limitation to the present study. Nevertheless, the lower mean speeds attributed to SCI players and thus lower

airflow on court, would have caused significantly lower dissipation of heat through convective and evaporative heat loss mechanisms for SCI compared to NON-SCI,[20] and would only have pronounced the group differences found in the current study.
[1614]

Future research could benefit from exploring the subjective perceptions of different WU strategies and how they may relate to readiness to perform prior to training and competition. As a final remark, the intensity of INT was based on the rationale that a high-intensity WU improves performance in AB athletes.[12] This finding was only partly replicated in the studied cohort of wheelchair rugby players. In addition to impaired thermoregulation, the reduced active muscle mass[4] and the associated increase in muscle fatigability in SCI[34] may further contribute.

Practical Applications

- Performing a high intensity WU increases thermal strain in SCI players during subsequent simulated gameplay. Therefore, careful consideration is needed when selecting WU intensities for players across the IWRF classes.
- A high-intensity WU provides no additional repeated sprint performance benefit for SCI players. However, for some NON-SCI players an increase in power output may be observed during the first quarter.
- In practice, it may be advisable to consider the use of cooling strategies during or after a warm-up to mitigate issues related to hyperthermia in subsequent performance in SCI.

Conclusions

A high-intensity WU increased thermal strain in WR players with SCI during subsequent performance, specifically peak T_{core}, with this peak occurring at the same time following both CON and INT. Further, a high-intensity WU may heighten thermal perceptions in players with a SCI during the second half of subsequent game play. Despite differences in T_{core} during the ISP, no changes in repeated sprint performance were found. Finally, a high-intensity WU may be more appropriate for NON-SCI players since five out of eight players in this group exceeded the SWC in PP_{avg} during Q1.

Acknowledgements

The Authors would like to thank the participants for their time and support during the study, and Dr Sven Hoekstra for proofreading the manuscript.

References

1. International Wheelchair Rugby Federation (IWRF). Published 2019. Accessed September 1, 2019. http://www.iwrf.com
2. Tweedy SM, Vanlandewijck YC. International Paralympic Committee position stand-background and scientific principles of classification in Paralympic sport. *Br J Sports Med*. 2011;45(4):259-269. doi:10.1136/bjsm.2009.065060
3. Rhodes JM, Mason BS, Perrat B, Smith MJ, Malone LA, Goosey-Tolfrey VL. Activity profiles of elite wheelchair rugby players during competition. *Int J Sports Physiol Perform*. 2015;10(3):318-324. doi:10.1123/ijspp.2014-0203
4. Leicht CA, Bishop NC, Goosey-Tolfrey VL. Submaximal exercise responses in tetraplegic, paraplegic and non spinal cord injured elite wheelchair athletes. *Scand J Med Sci Sport*. 2012;22(6):729-736. doi:10.1111/j.1600-0838.2011.01328.x
5. Gee CM, Lacroix MA, West CR. A 20×20m repeated sprint field test replicates the demands of wheelchair rugby. *J Sci Med Sport*. 2018;21(7):753-757. doi:10.1016/j.jsams.2017.12.006
6. Griggs KE, Stephenson BT, Price MJ, Goosey-Tolfrey VL. Heat-related issues and practical applications for Paralympic athletes at Tokyo 2020. *Temperature*. 2020;7(1):37-57. doi:10.1080/23328940.2019.1617030
7. Freund PR, Brengelmann GL, Rowell LB, Halar E. Attenuated skin blood flow response to hyperthermia in paraplegic men. *J Appl Physiol Respir Environ Exerc Physiol*. 1984;56(4):1104-1109. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0021333757&partnerID=40&md5=8da5b05d674c868834026788333550e1
8. Aldous JWF, Chrismas BCR, Akubat I, Dascombe B, Abt G, Taylor L. Hot and hypoxic environments inhibit simulated soccer performance and exacerbate performance decrements when combined. *Front Physiol*. 2016;6(JAN):1-14. doi:10.3389/fphys.2015.00421
9. Mohr M, Krustrup P, Nybo L, Nielsen JJ, Bangsbo J. Muscle temperature and sprint performance during soccer matches - Beneficial effect of re-warm-up at half-time. *Scand J Med Sci Sport*. 2004;14(3):156-162. http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=mekentosj&SrcApp=Papers&DestLinkType=FullRecord&DestApp=WOS&KeyUT=000221451700005
10. Bishop D. Warm up I: Potential mechanisms and the effects of passive warm up on exercise performance. *Sport Med*. 2003;33(6):439-454. doi:10.2165/00007256-200333060-00005
11. Rhodes JM, Mason BS, Malone LA, Goosey-Tolfrey VL. Effect of team rank and player classification on activity profiles of elite wheelchair rugby players. *J Sports Sci*. 2015;33(19):2070-2078. doi:10.1080/02640414.2015.1028087
12. Bishop D, Bonetti D, Spencer M. The effect of an intermittent, high-intensity warm-up on supramaximal kayak ergometer performance. *J Sports Sci*. 2003;21(1):13-20. doi:10.1080/0264041031000070912
13. Nilsson JE, Rosdahl HG. Contribution of Leg-Muscle Forces to Paddle Force and Kayak Speed During Maximal-Effort Flat-Water Paddling. *Int J Sports Physiol Perform*. 2016;11(1):22-27. doi:10.1123/ijspp.2014-0030
14. Drust B, Rasmussen P, Mohr M, Nielsen B, Nybo L. Elevations in core and muscle temperature impairs repeated sprint performance. *Acta Physiol Scand*. 2005;183(2):181-190.
15. Price MJ. Thermoregulation during Exercise in Individuals with Spinal Cord Injuries. *Sport Med*. 2006;36(10):863-879. doi:10.2165/00007256-200636100-00005
16. Westerblad H, Lee JA, Lannergren J, Allen DG. Cellular mechanisms of fatigue in

skeletal muscle. *Am J Physiol Physiol*. 1991;261(2):C195-C209. doi:10.1152/ajpcell.1991.261.2.C195
17. Webborn N, Price MJJ, Castle PCC, Goosey-Tolfrey VLL. Effects of two cooling strategies on thermoregulatory responses of tetraplegic athletes during repeated intermittent exercise in the heat. *J Appl Physiol*. 2005;98(6):2101-2107. doi:10.1152/japplphysiol.00784.2004
18. Griggs KE, Leicht CA, Price MJ, Goosey-Tolfrey VL. Thermoregulation during intermittent exercise in athletes with a spinal cord injury. *Int J Sports Physiol Perform*. 2015;10:469-475. doi:10.1123/ijspp.2014-0361
19. Rhodes J, Mason B, Perrat B, Smith M, Goosey-Tolfrey V. The validity and reliability of a novel indoor player tracking system for use within wheelchair court sports. *J Sports Sci*. 2014;32:1639-1647. doi:10.1080/02640414.2014.910608
20. Griggs KE, Havenith G, Price MJ, Mason BS, Goosey-Tolfrey VL. Thermoregulatory responses during competitive wheelchair rugby match play. *Int J Sports Med*. 2017;38:177-183. doi:10.1055/s-0042-121263
21. Ramanathan NL. A new weighting system for mean surface temperature of the human body. *J Appl Physiol*. 1964;19(3):531-533. doi:10.1152/jappl.1964.19.3.531
22. de Klerk R, Velhorst V, Veeger D (H EJ)., van der Woude LHV, Vegter RJK. Physiological and biomechanical comparison of overground, treadmill, and ergometer handrim wheelchair propulsion in able-bodied subjects under standardized conditions. *J Neuroeng Rehabil*. 2020;17(1):1-11. doi:10.1186/s12984-020-00767-2
23. Malcata RM, Hopkins WG. Variability of Competitive Performance of Elite Athletes: A Systematic Review. *Sport Med*. 2014;44(12):1763-1774. doi:10.1007/s40279-014-0239-x
24. Winget CM, DeRoshia CW, Holley DC. Circadian rhythms and athletic performance. *Med Sci Sports Exerc*. 1985;17(5):498-516. doi:10.1249/00005768-198510000-00002
25. Griggs KE, Havenith G, Paulson TA, Price MJ, Goosey-Tolfrey VL. Effects of cooling before and during simulated match play on thermoregulatory responses of athletes with tetraplegia. *J Sci Med Sport*. 2017;20(9):819-824. doi:10.1016/j.jsams.2017.03.010
26. Toner MM, Drolet LL, Pandolf KB. Perceptual and Physiological Responses during Exercise in Cool and Cold Water. *Percept Mot Skills*. 1986;62(1):211-220. doi:10.2466/pms.1986.62.1.211
27. Gagge AP, Stolwijk JAJ, Saltin B. Comfort and thermal sensations and associated physiological responses during exercise at various ambient temperatures. *Environ Res*. 1969;2(3):209-229. doi:10.1016/0013-9351(69)90037-1
28. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. Second Edi. Lawrence Erlbaum Associates; 1988. doi:10.1007/BF00544941
29. Schlader ZJ, Simmons SE, Stannard SR, Mündel T. Skin temperature as a thermal controller of exercise intensity. *Eur J Appl Physiol*. 2011;111(8):1631-1639. doi:10.1007/s00421-010-1791-1
30. Kingma BRM, Roijendijk LMM, Van Maanen L, Van Rijn H, Van Beurden MHPH. Time perception and timed decision task performance during passive heat stress. *Temperature*. 2021;8(1):53-63. doi:10.1080/23328940.2020.1776925
31. Nybo L, Rasmussen P, Sawka MN. Performance in the heat-physiological factors of importance for hyperthermia-induced fatigue. *Compr Physiol*. 2014;4(2):657-689. doi:10.1002/cphy.c130012
32. Normell LA. Distribution of impaired cutaneous vasomotor and sudomotor function in paraplegic man. *Scand J Clin Lab Invest Suppl*. 1974;138:25-41.
33. Au JS, Kamijo Y ichiro, Goosey-Tolfrey VL, et al. Comparison between esophageal and intestinal temperature responses to upper-limb exercise in individuals with spinal

cord injury. *Spinal Cord*. Published online 2019. doi:10.1038/s41393-019-0257-5
34. Burnham R, Martin T, Stein R, Bell G, MacLean I, Steadward R. Skeletal muscle fibre type transformation following spinal cord injury. *Spinal Cord*. 1997;35(2):86-91. doi:10.1038/sj.sc.3100364

Figure Captions

Figure 1. A) example speed trace obtained from tracking of one player during a training camp warm-up that simulated a competition warm-up; **B)** percentage time spent in relevant speed zones and mean speed profiles from grouped warm-up data collected over a two-day national training camp (n = 12).

Figure 2. A) generated trace of CON warm-up including intensity speed zones based on Figure 1A; **B)** the trace of INT warm-up including intensity speed zones; **C)** the timeline including familiarisation, warm-up, and subsequent intermittent sprint protocol. NOTE: BLa = Capillary blood sample; TS = thermal sensation; TC = thermal comfort.

Figure 3. A) core temperature from the start of the warm-up to the end of the protocol for SCI and NON-SCI players; **B)** peak core temperature for SCI and NON-SCI; **C)** time to peak core temperature for SCI and NON-SCI. Data are presented as mean ± SD. $^{\#}$denotes significant difference between groups, *denotes significant difference between conditions ($p < 0.05$). For SCI, all time points (n = 7), apart from final two time points (n = 6).

Table 1. Physiological and perceptual responses to each warm-up condition.

	All		SCI		NON-SCI	
	CON	INT	CON	INT	CON	INT
Average Heart rate ($b \cdot min^{-1}$)	94 ± 15	107 ± 19*	83 ± 13$^{\#}$	95 ± 12*$^{\#}$	103 ± 9	118 ± 18*
Blood lactate ($mmol \cdot l^{-1}$)						
Start	1.5 ± 0.7	1.4 ± 0.5	1.2 ± 0.4$^{\#}$	1.1 ± 0.3	1.9 ± 0.8$^{\#}$	1.6 ± 0.6
End	1.9 ± 1.0	5.5 ± 2.9*†	1.4 ± 0.3$^{\#}$	3.8 ± 1.1*$^{\#\dagger}$	2.3 ± 1.1$^{\#\dagger}$	7.0 ± 1.3*$^{\#\dagger}$
Change	0.3 ± 0.6	4.1 ± 2.5*	0.2 ± 0.3	2.6 ± 1.0*	0.4 ± 0.9	5.4 ± 2.7*$^{\#}$
RPE	11 ± 2	16 ± 2*	12 ± 2	16 ± 1*	11 ± 1	16 ± 2*
Thermal sensation	4.5 ± 0.8	5.7 ± 1.2*	4.3 ± 0.9	5.6 ± 1.2*	4.6 ± 0.7	5.8 ± 1.2*
Thermal comfort	1.1 ± 0.4	2.0 ± 0.8*	1.0 ± 0.0	1.6 ± 0.8*	1.3 ± 0.5	2.4 ± 0.7*

Data are presented as mean ± SD.

CON, control; INT, high intensity warm-up; RPE, rating of perceived exertion; SCI, spinal cord injury.

*significantly different to CON ($p < 0.05$). $^{\#}$significant difference between SCI and NON-SCI group ($p < 0.05$).

†significantly different to WU start ($p < 0.05$).

Table 2. Physiological and perceptual data from the intermittent sprint protocol (ISP).

		Q1		Q2		Q3		Q4	
		SCI	NON-SCI	SCI	NON-SCI	SCI	NON-SCI	SCI	NON-SCI
Average Heart Rate ($b \cdot min^{-1}$)									
	CON	95 ± 12#	120 ± 12	103 ± 17#	126 ± 13	104 ± 17#	126 ± 14	105 ± 18#	128 ± 14
	INT	101 ± 18	133 ± 16	107 ± 18	134 ± 13	119 ± 33	134 ± 15	122 ± 26	134 ± 13
Blood lactate ($mmol \cdot l^{-1}$)*									
	CON	2.7 ± 0.8#	4.9 ± 2.5	2.6 ± 1.1#	5.0 ± 3.1	2.6 ± 0.9#	5.2 ± 3.1	2.6 ± 1.0	4.8 ± 2.6
	INT	2.4 ± 0.8	6.0 ± 3.9	2.4 ± 1.0	5.2 ± 3.4	2.6 ± 0.9	4.7 ± 2.7	2.8 ± 1.0	4.1 ± 2.3
RPE*									
	CON	14 ± 2	14 ± 1	16 ± 2	15 ± 1	17 ± 2#	16 ± 1	18 ± 1#	16 ± 1
	INT	15 ± 2	15 ± 2	16 ± 2	15 ± 2	17 ± 1	16 ± 2	17 ± 1	16 ± 2
Thermal Sensation*									
	CON	5.3 ± 1.0	5.4 ± 0.8	6.0 ± 0.8	5.5 ± 0.8	6.4 ± 1.0#	5.9 ± 0.6	6.7 ± 0.9#	5.8 ± 0.8
	INT	5.8 ± 1.0	5.9 ± 0.9	6.1 ± 1.4	5.9 ± 0.7	6.6 ± 1.2	5.7 ± 0.8	6.8 ± 1.1	6.1 ± 0.7
Thermal Comfort*									
	CON	1.7 ± 0.5	1.6 ± 0.5	2.6 ± 0.5	1.8 ± 0.7	2.9 ± 0.7#	1.8 ± 0.7	3.1 ± 0.9#	1.9 ± 0.8
	INT	2.1 ± 0.9	2.1 ± 0.6	2.6 ± 1.0	2.1 ± 0.4	3.0 ± 0.8	2.0 ± 0.8	3.1 ± 1.1	2.1 ± 0.8

Data are presented as mean ± SD.
CON, control; INT, high intensity warm-up; RPE, rating of perceived exertion; SCI, Spinal Cord Injury; Q, quarter.
#significant difference between SCI and NON-SCI; $p < 0.05$.
*significant group x time interaction effect; $p < 0.05$

Table 3. Performance data measured during the intermittent sprint protocol (ISP).

		Q1		Q2		Q3		Q4	
		SCI	NON-SCI	SCI	NON-SCI	SCI	NON-SCI	SCI	NON-SCI
Peak speed ($m \cdot s^{-1}$)									
	CON	3.5 ± 0.6#	4.1 ± 0.5	3.6 ± 0.6#	4.1 ± 0.5	3.6 ± 0.6#	4.1 ± 0.5	3.6 ± 0.6#	4.2 ± 0.6
	INT	3.2 ± 0.7	4.0 ± 0.5	3.3 ± 0.6	4.0 ± 0.5	3.3 ± 0.7	4.1 ± 0.6	3.4 ± 0.7	4.1 ± 0.5
Peak power (W)									
	CON	323 ± 162#	524 ± 235	325 ± 159#	511 ± 216	311 ± 138#	523 ± 203	337 ± 144#	543 ± 253
	INT	304 ± 166	512 ± 186	311 ± 159	513 ± 192	321 ± 163	531 ± 227	320 ± 161	533 ± 219
PP_{avg} (W)									
	CON	276 ± 128#	408 ± 158	281 ± 126#	403 ± 156	273 ± 116#	411 ± 153	286 ± 118#	421 ± 177
	INT	268 ± 133	396 ± 135	280 ± 131	403 ± 144	282 ± 134	413 ± 158	283 ± 132	416 ± 160
PP_{avg5} (W)									
	CON	249 ± 114#	367 ± 144	258 ± 126#	376 ± 157	252 ± 108#	380 ± 143	263 ± 119#	394 ± 158
	INT	191 ± 62	344 ± 113	198 ± 58	350 ± 124	198 ± 65	391 ± 135	195 ± 59	384 ± 134
Fatigue index (%)									
	CON	29 ± 8	37 ± 13	29 ± 11#	37 ± 12	25 ± 10	36 ± 13	32 ± 6#	38 ± 10
	INT	28 ± 9	34 ± 15	23 ± 10	36 ± 10	31 ± 16	38 ± 11	19 ± 9	41 ± 10

Data are presented as mean ± SD.

CON, control; INT, high intensity warm-up; SCI, Spinal Cord Injury; Q, quarter; PP_{avg}, average peak power per push throughout 10 s sprint; PP_{avg5}, average peak power per push for the first five pushes.

*significantly different to CON ($p < 0.05$). #significant difference between SCI and NON-SCI ($p < 0.05$).

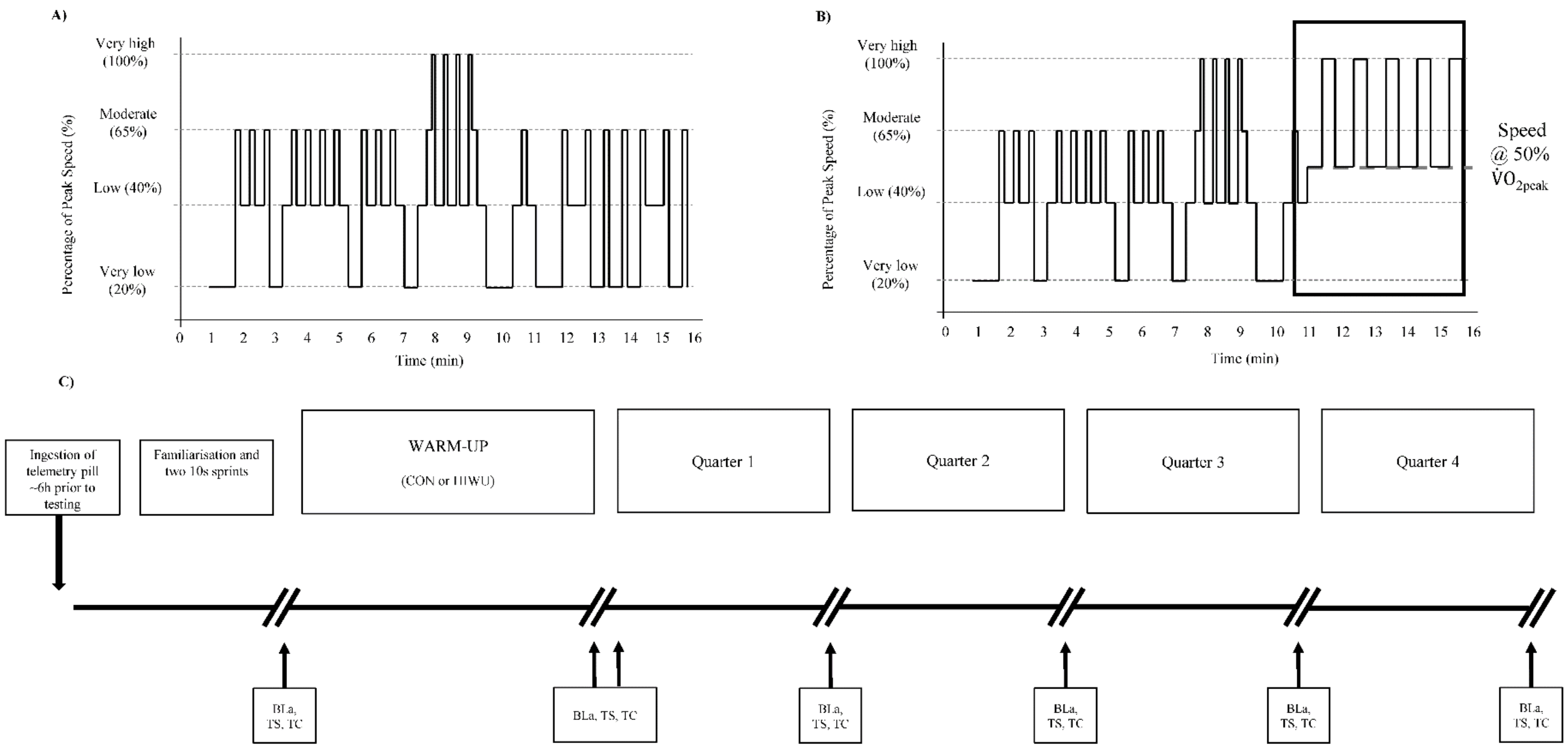
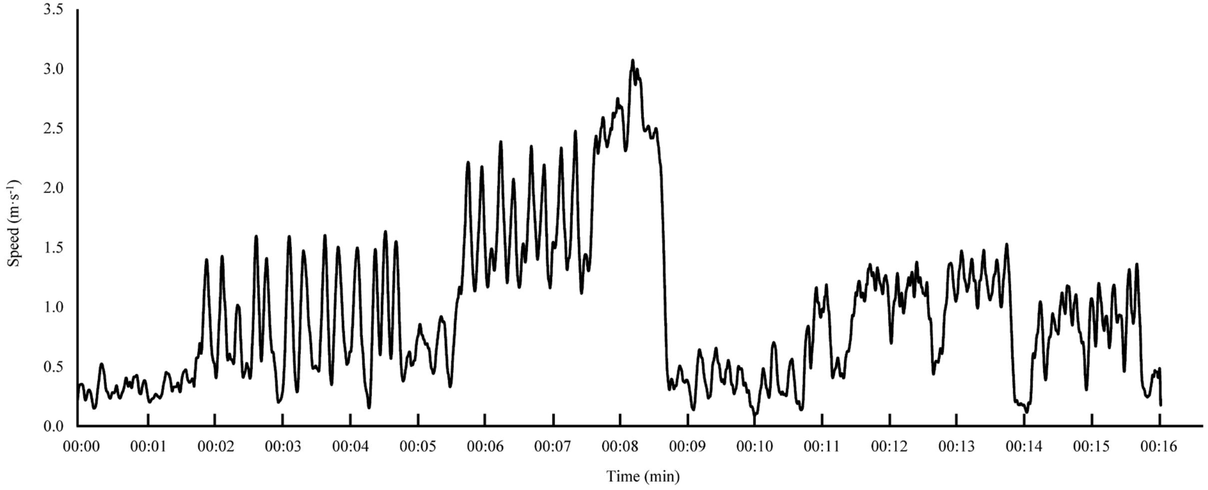


Figure 1. A) example speed trace obtained from tracking of one player during a training camp warm-up that simulated a competition warm-up; **B)** percentage time spent in relevant speed zones and mean speed profiles from grouped warm-up data collected over a two-day national training camp (n = 12).

A)



B)

Activity			Time spent in speed zones				
Active time (min)	Mean speed (m·s^{-1})	Peak speed (m·s^{-1})	Very low (%)	Low (%)	Moderate (%)	High (%)	Very high (%)
16:24 ± 01:43	1.10 ± 0.12	3.80 ± 0.28	45.7 ± 9.2	32.7 ± 7.1	17.6 ± 4.2	3.3 ± 1.4	0.6 ± 0.6

Figure 2. A) generated trace of CON warm-up including intensity speed zones based on Figure 1A; **B)** the trace of INT warm-up including intensity speed zones; **C)** the timeline including familiarisation, warm-up, and subsequent intermittent sprint protocol. NOTE: BLa = Capillary blood sample; TS = thermal sensation; TC = thermal comfort.

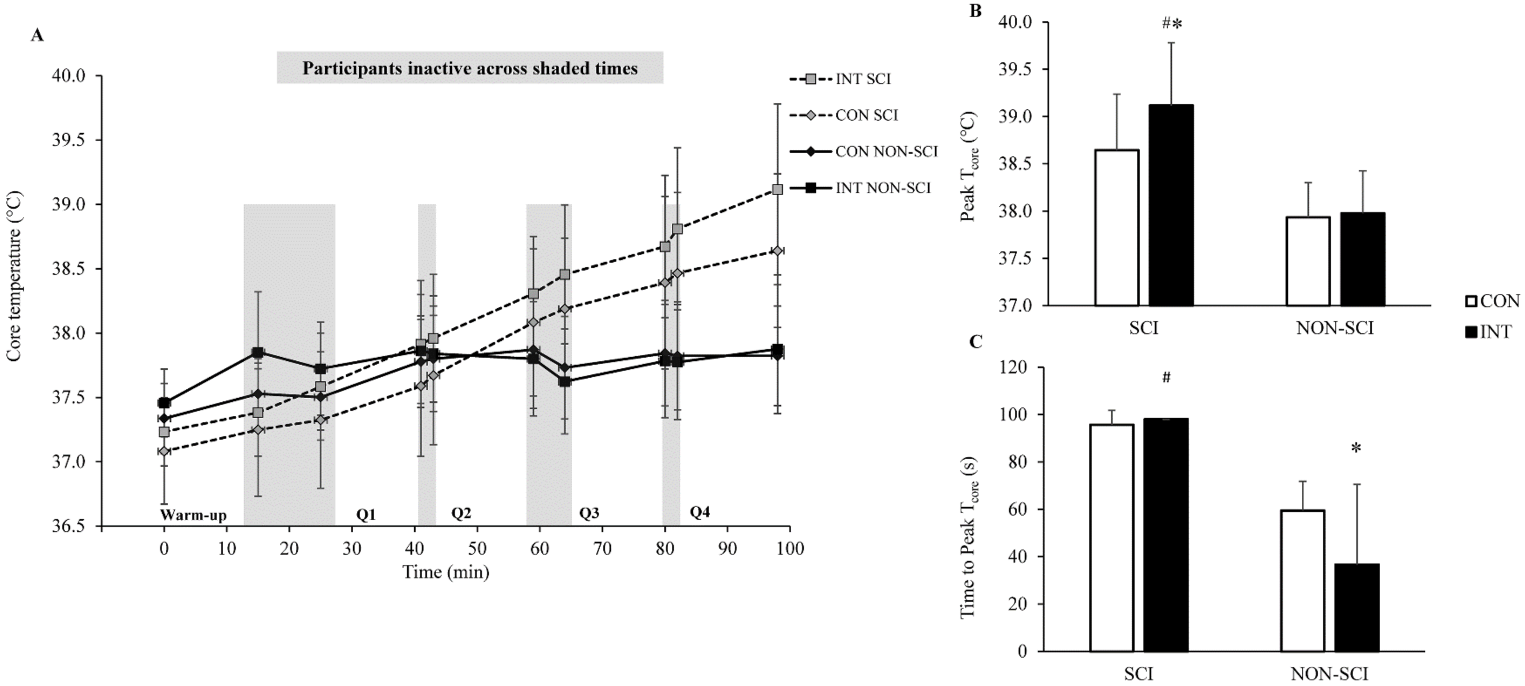


Figure 3. A) core temperature from the start of the warm-up to the end of the protocol for SCI and NON-SCI players; **B)** peak core temperature for SCI and NON-SCI; **C)** time to peak core temperature for SCI and NON-SCI. Data are presented as mean ± SD. #denotes significant difference between groups, *denotes significant difference between conditions ($p < 0.05$). For SCI, all time points (n = 7), apart from final two time points (n = 6).