Effect of lower limb compression on blood flow and performance in elite wheelchair rugby athletes

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Objective: To investigate the effects of compression socks worn during exercise on performance and physiological responses in elite wheelchair rugby athletes.

Design: In a non-blinded randomized crossover design, participants completed two exercise trials (4 × 8 min bouts of submaximal exercise, each finishing with a timed maximal sprint) separated by 24 hr, with or without compression socks.

Setting: National Sports Training Centre, Queensland, Australia.

Participants: Ten national representative male wheelchair rugby athletes with cervical spinal cord injuries volunteered to participate.

Interventions: Participants wore medical grade compression socks on both legs during the exercise task (COMP), and during the control trial no compression was worn (CON).

Outcome Measures: The efficacy of the compression socks was determined by assessments of limb blood flow, core body temperature, heart rate, and ratings of perceived exertion, perceived thermal strain, and physical performance.

Results: While no significant differences between conditions were observed for maximal sprint time, average lap time was better maintained in COMP compared to CON ($P < 0.05$). Lower limb blood flow increased from pre- to post-exercise by the same magnitude in both conditions (COMP: 2.51 ± 2.34 ; CON: 2.20 ± 1.85 ml. 100 ml.⁻¹min⁻¹), whereas there was a greater increase in upper limb blood flow pre- to post-exercise in COMP (10.77 ± 8.24 ml. 100 ml.⁻¹min⁻¹) compared to CON (6.21 ± 5.73 ml. 100 ml.⁻¹min⁻¹; $P < 0.05$).

Conclusion: These findings indicate that compression socks worn during exercise is an effective intervention for maintaining submaximal performance during wheelchair exercise, and this performance benefit may be associated with an augmentation of upper limb blood flow.

Keywords: Tetraplegia, Spinal cord injury, Plethysmography, Compression

Introduction

Wheelchair rugby is a popular sport for individuals with tetraplegia; and has been a Paralympic sport since the 2000 Paralympic Games. While the majority of wheelchair rugby players have suffered a cervical spinal cord injury (SCI); those with multiple limb amputations or neurological disorders, such as cerebral palsy that result in the loss of functional ability to three or more limbs, also participate.¹

Individuals with a high-level SCI have reduced inspiratory and expiratory capacities due to the

denervation of intercostal muscles² and an impaired thermoregulatory capacity due to dysfunction of the nervous systems governing skin blood flow and sweating below the lesion level.³ In addition, vascular atrophy occurs below the level of injury resulting in a reduction in femoral artery diameter, venous capacity, and resting and maximal blood flow.^{4,5} Excessive lower limb venous pooling is likely to occur in individuals with tetraplegia due to the culmination of peripheral vascular insufficiency and poor muscle pump function.^{6,7} This response may be exacerbated during upper-body exercise such as wheelchair rugby. These physiological changes that occur as a result of SCI tetraplegia are likely to limit overall athletic capacity.^{8,9}

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In recent years, the reported ergogenic benefits of compression garments have resulted in the increased popularity and routine use of such garments among many athletic groups.¹⁰ Previous research has found circulatory benefits associated with the use of compression garments including improved venous return, and an increase in stroke volume and cardiac output.^{4,10} The use of graduated compression garments and anti-gravity suits have been investigated in individuals with a SCI and found to improve the cardiovascular and metabolic responses to exercise.⁶ There is a reduction in venous pooling^{6,11,12} and a decrease in venous capacitance below the lesion level,¹¹ which potentially contributes to an improved hemodynamic state and enhanced sympathetic activity.⁵

Whether the physiological effects of lower limb compression garments are associated with alterations in wheelchair performance in individuals with a high-level SCI is not clear. Therefore, the purpose of the present study was to examine the effect of compression socks worn during exercise on upper and lower limb blood flow and wheelchair performance in elite wheelchair rugby athletes. It was hypothesised that compression socks would result in an improvement in arm blood flow and a better maintenance of maximum wheelchair sprint performance.

Methods

Participants

Ten male, national representative wheelchair rugby athletes with cervical SCI volunteered to participate in the study (Table 1). Prior to commencement, participants were informed of the potential risks and requirements of the study and provided informed written consent. All procedures were approved by the Australian Institute of Sport Research Ethics Committee.

Study overview and exercise protocol

Participants were familiarised with the study procedures and fastest lap time was determined as the best of three separate wheelchair time trials around a standard court (86 m circuit) in order to determine the submaximal target intensity used for the exercise trials. Following a non-training day, each participant completed two experimental trials, separated by 24 hours, and in a random order wore either below-knee medical grade compression socks (Venosan, Class II) on both legs (COMP), or no compression (CON). Neither the participants nor researchers were blinded to the experimental intervention.

The experimental trials consisted of a standardised 10 minute warm-up followed by 4 × 8 minute exercise bouts (quarters) consisting of fixed-intensity laps around the

court to replicate the duration of a typical wheelchair rugby game. Intensity of the trials was set at 85% of each individual's fastest lap time, and verbal feedback was provided during each lap to ensure the correct pace/intensity was maintained. Two minutes of passive rest separated the quarters, with five minutes passive rest at "half-time." In order to control diet, participants were required to document dietary intake for 24 hours prior to the first trial and the same meal and snack options were provided in an attempt to replicate the diet as closely as possible prior to the second trial. Participants refrained from caffeine (24 hours) and alcohol (48 hours) prior to each testing session, and were tested to ensure adequate hydration. Both trials were performed at the same time of day to minimise diurnal variation, and tests were performed on the same training court in similar environmental conditions (32.1 ± 0.3 °C, $73 \pm 1.2\%$ relative humidity).

Outcome measures

Performance

Individual lap times were manually recorded using a hand held stopwatch for each participant throughout each trial, from which an average lap time for each quarter was calculated. In addition, participants were required to perform one sprint lap of the court at the completion of each quarter. Performance was measured as the maximal sprint time and the ability to maintain the submaximal exercise task (average lap time) each quarter.

Limb blood flow

Before and immediately (three minutes) after each of the experimental exercise trials, lower limb (calf) and upper limb (forearm) blood flow was measured using strain gauge plethysmography while participants rested in a supine position. All assessments were made using the right limbs, except in two participants where measurements were made on the left side to avoid interference with catheter leg bags. A mercury-in-rubber strain gauge (Hokanson, EC-6 plethysmograph, Bellevue, WA, USA) was placed around the limb at the point with the largest girth, and the limb volume signal, as well as a single-lead ECG signal, was continuously monitored and recorded at 1 KHz (Powerlab; ADInstruments, NSW, Australia). The strain gauge was placed directly on the skin during the control trial and outside the garment during the compression trial, which is consistent with the approach taken during clinical investigations of compression garment therapy.¹³ Using a rapid cuff inflator (Hokanson, EC-20, Bellevue, WA, USA), a collection cuff around the

Table 1 Participant demographics

Participant	Age (years)	Height (m)	Body Mass (kg)	Injury Level	Complete / Incomplete	Years Since Injury
1	26	1.79	56.6	C6	Complete	10
2	29	1.88	77.4	C5–C6	Complete	13
3	41	1.81	74.4	C6	Complete	21
4	22	1.89	81.4	C5–C6	Incomplete	3
5	23	1.65	60.2	C6	Incomplete	21
6	24	1.90	87.1	C6–C7	Incomplete	7
7	25	1.84	70.2	C6–C7	Incomplete	6
8	34	1.82	74.2	C5	Incomplete	11
9	34	1.87	83.8	C6	Incomplete	15
10	44	1.83	75.0	C6–C7	Incomplete	24
Mean ($\pm$ SD)	30.2 ($\pm$ 7.7)	1.83 ($\pm$ 0.1)	74.0 ($\pm$ 9.7)			13 ($\pm$ 7)

thigh (for leg measures) or upper arm (for arm measures) was inflated to 55 mmHg to prevent venous outflow for a 10-second period. Blood flow relative to tissue volume ($\text{ml} \cdot 100 \text{ ml}^{-1} \cdot \text{min}^{-1}$) was then measured as the change in limb volume over a period of two cardiac cycles. On each occasion, measures were made in triplicate, separated by 20 seconds, and the average of all three was taken as the measure of blood flow. In our lab the test-retest variance of resting blood flow is 12–13%CV (coefficient of variation) and 4–5% for post-exercise blood flow.

Heart rate and core body temperature

Heart rate was monitored using a Suunto® Team system and each measurement was taken as the average of recorded values over a 60-second period. Baseline and post-exercise heart rate was measured while participants rested in the supine position. Exercise heart rates were calculated as the average over the final minute of the warm-up and each of the eight-minute quarters. Core body temperature was measured to establish thermal load using an ingestible temperature sensor (CorTemp™, HQ Inc, FL, USA), ingested six hours prior to testing.

Perceived thermal comfort and exertion

Prior to exercise (baseline), upon cessation of the warm-up, and following the completion of each quarter, participants rated their perceived thermal comfort on a scale of zero (unbearably cold) to eight (unbearably hot).¹⁴ In

addition, perceived exertion was rated on a scale of six (no exertion at all) to 20 (maximal exertion).¹⁵

Data analysis

Two-factor repeated measures analysis of variance was performed on all variables, including limb blood flow, to test for interactions between condition (COMP vs. CON) and time. Main effects are only reported where a significant interaction did not exist. Where there was a significant interaction or main effect, differences were located using Tukey's test. In addition, the change in blood flow with exercise (post-exercise blood flow minus pre-exercise blood flow), which accounts for variance in resting blood flow, was compared between conditions using a paired *t*-test. The strength of association between variables was determined using Pearson's correlation coefficient. Significance was set at $P < 0.05$ and data are expressed as Mean $\pm$ SD.

Results

For maximal sprint time there was no condition $\times$ time interaction ($F(1,3) = 0.400$, $P = 0.754$). There was a main time effect ($P < 0.001$) whereby maximal sprint time at the end of each quarter increased from the first quarter to the fourth quarter, however there was no difference between conditions (Table 2). For average lap time there was a significant condition $\times$ time interaction ($F(1,3) = 3.526$, $P = 0.028$) where lap time was maintained throughout the COMP trial, whereas it

Table 2 Maximal and average lap times completed during each quarter (seconds)

	Condition	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Max sprint time (s)	COMP	21.38 (2.84)	21.87 (2.87)	22.16 (3.08)	22.63 (3.07)
	CON	21.17 (2.71)	21.78 (2.73)	22.38 (2.52)	22.66 (2.61)
Avg lap time (s)	COMP	24.65 (2.04)	24.82 (2.03)	24.93 (2.38)	24.77 (2.81)
	CON	24.93 (2.21)	25.29 (2.42)	25.53 (1.77)	26.64 (3.70)*

*Significantly different from Quarter 1 and significantly different from compression trial at same time point ($P < 0.05$). Values are Mean (SD).

declined during the CON trial to be lower than in the COMP trial in the fourth quarter (Table 2).

Leg and arm blood flow were not different between conditions at rest prior to exercise, and both significantly increased with exercise to be elevated post-exercise (Fig. 1). Leg blood flow increased with exercise by the same magnitude during both conditions (COMP: 2.51 ± 2.34 ; CON: 2.20 ± 1.85 ml.100 ml.⁻¹min.⁻¹; $t(9) = 0.444$, $P = 0.667$), whereas the increase in arm blood flow was greater during the COMP (10.77 ± 8.24 ml.100 ml.⁻¹min.⁻¹ than the CON trial (6.21 ± 5.73 ml.100 ml.⁻¹min.⁻¹; $t(9) = 2.716$, $P = 0.024$), meaning that arm blood flow was significantly higher following exercise in the COMP trial compared with CON (Fig. 1). The difference in post-exercise arm blood flow between the COMP and CON conditions was significantly correlated with the difference in the fourth-quarter average lap time between the conditions ($r = 0.45$, $P < 0.05$). No such relationship was found for the change in leg blood flow or any other variables.

Heart rate, core body temperature and perceptual responses to the compression and control trials are shown in Table 3. There was a significant time effect for all variables whereby values increased from baseline during the exercise trials. For RPE there was a significant condition x time interaction ($F(4,1) = 3.957$, $P = 0.009$) which resulted in a small but significant elevation in RPE during COMP at the completion of the final exercise bout.

Figure 1 Arm and leg blood flow pre and post-exercise. There was a significant condition x time interaction for arm blood flow ($F(1,1) = 7.375$, $P = 0.024$), but not for leg blood flow ($F(1,1) = 0.179$, $P = 0.667$) *Significant difference between conditions ($P < 0.05$); Values are Mean (SD); **Significant difference from pre to post.

Discussion

Exercise capacity is believed to be reduced with SCI due to diminished venous return and stroke volume, limiting peak cardiac output and oxygen uptake.^{6,8,16} Lower limb compression garments have been used to alter blood volume distribution, improve venous return and create more favourable central and upper limb haemodynamics in SCI individuals. To date, it has not been clear whether these cardiovascular alterations are associated with changes in upper body exercise capacity and physical performance, however, there is evidence that compression garments have a positive effect on physical performance in able-bodied athlete populations.^{17–19} The present study established that wearing compression socks resulted in an improved maintenance of upper body submaximal exercise performance during wheelchair exercise. This finding was accompanied by an increase in arm blood flow suggesting that the improved maintenance of exercise capacity may have been mediated by a more efficient distribution of blood flow to the working muscles during exercise.

While average lap time gradually fell, and was significantly reduced relative to the target exercise intensity in the fourth quarter during the CON trial, lap time was maintained at the target intensity throughout the entire COMP trial. Therefore, wearing compression socks during exercise resulted in an improved maintenance of sub-maximal exercise performance. This is a novel and important finding, particularly as most previous studies of compression garments have investigated individuals with paraplegia,^{6,20,21} rather than individuals with a high level SCI resulting in tetraplegia. Furthermore, most previous studies have assessed the performance effects of compression garments during maximal exercise. Rimaud *et al.*⁶ found no effect on $\dot{V}O_{2peak}$ and maximal power output (W_{max}) in paraplegic athletes when lower limb compression (15–21 mmHg) was worn compared with control. Similarly, the application of compression with an anti-gravity suit²⁰ or an abdominal binder²¹ had a negligible effect on maximal exercise performance. It should be noted that maximal exercise performance in the present study, measured as maximal sprint time at the end of each quarter, was not different between the compression and control trials. Therefore, findings of the present study suggest the performance benefits associated with wearing compression may be limited to submaximal exercise and future research should conduct performance tests specific to “event pace.” This is supported by the finding that the use of an abdominal binder during exercise led to an improvement in performance during a

Table 3 Heart rate, core body temperature, perceived exertion and thermal comfort throughout the compression and control trials

	Condition	Baseline	Warm-up	Qtr 1	Qtr 2	Qtr 3	Qtr 4	Post-ex
Heart rate (bpm)**	COMP	56 (8)	85 (10)	122 (10)	123 (10)	122 (11)	123 (11)	113 (11)
	CON	59 (9)	85 (11)	122 (14)	125 (15)	125 (15)	128 (14)	120 (14)
Core body temp. (°C)**	COMP	37.4 (0.5)	38.3 (0.7)	39.1 (0.6)	39.4 (0.5)	40.0 (0.6)	40.2 (0.8)	40.1 (0.8)
	CON	37.3 (0.5)	38.1 (0.4)	39.0 (0.4)	39.6 (0.4)	39.9 (0.5)	40.1 (0.7)	40.1 (0.7)
Perceived exertion (6–20)**	COMP		11 (2)	13 (2)	15 (3)	17 (3)	18 (2)	
	CON		12 (2)	14 (3)	15 (3)	15 (3)	17 (3)	
Thermal comfort (0–8)**	COMP*	5 (0)	6 (0)	7 (0)	7 (1)	7 (1)	8 (1)	7 (1)
	CON	5 (0)	6 (1)	6 (0)	7 (1)	7 (1)	7 (0)	7 (0)

*Significant main effect for condition ($P < 0.05$).**Significant main effect for time for all variables ($P < 0.05$).

^Significantly higher than CON at same time point. Values are Mean (SD).

wheelchair acceleration/deceleration test and during a four minute push test.²² In addition, abdominal binding was found to reduce minute ventilation and blood lactate accumulation during submaximal exercise.²² Whether the benefits observed in the group of athletes with tetraplegia in this study also apply to athletes with paraplegia during submaximal exercise remains to be determined.

In the present study, it was hypothesised that lower limb compression would result in a greater distribution of blood flow to the working muscles of the arms during wheelchair exercise. Indeed, immediately following exercise, blood flow to the arms was elevated in the COMP trial compared with CON, while there was no difference in leg blood flow between conditions. It has previously been demonstrated that the use of an anti-gravity suit at a pressure of 52 mmHg led to a reduction in venous capacitance in individuals with paraplegia.²³ Compared with healthy control participants, this effect on central haemodynamics is augmented in those with SCI, which highlights the limiting effects of lower limb venous pooling in these individuals.¹¹ On the basis that compression garments had failed to improve performance in paraplegic athletes, it had previously been suggested that such garments fail to induce a significant haemodynamic effect.⁶ In contrast, the present study has demonstrated that compression socks that exert a pressure of ~21 mmHg (as stated by the manufacturer) may in fact be sufficient to initiate central haemodynamic changes, resulting in improved blood flow to the arms during submaximal wheelchair exercise. Furthermore, the increase in arm blood flow observed in the present study was correlated with an enhanced maintenance of performance (average lap time) in the fourth-quarter, suggesting that the improvement in blood flow potentially contributed to an increase in oxygen delivery and improved fatigue resistance. This is consistent with previous observations whereby blood lactate concentration, a marker of anaerobic

metabolism, was reduced in low-level paraplegic individuals following maximal exercise when wearing lower limb compression.⁶

Wearing lower limb compression has been suggested to reduce venous distension¹¹ and enhance sympathetic activity⁵ in paraplegic individuals, regardless of lesion level, leading to the prevention of orthostatic hypotension and post-exercise hypotension.⁵ The positive effect of lower limb compression on arm blood flow is likely to be achieved through an enhancement of venous return and, in turn, a positive effect on stroke volume and cardiac efficiency. While the present study did not aim to investigate these central cardiovascular dynamics, a tendency for heart rate to be reduced during the COMP trial (not significant), despite the higher volume of work that was achieved during this trial, was observed. Similar reductions in heart rate have been described in paraplegic participants during submaximal (40 and 60% W_{max}) arm-crank exercise while wearing an anti-gravity suit.²³ It is also possible that the observed increase in arm blood flow was the result of the additional work completed during the COMP trial. However, this seems unlikely given that the overall cardiovascular strain, as indicated by heart rate, tended to be lower during the final stage of this trial compared with CON.

The present study was conducted during the peak of Summer, creating challenging environmental conditions (32.1 ± 0.3 °C; $73.0 \pm 1.2\%$ relative humidity). Despite the conditions, there were no significant differences in core body temperature responses or thermal comfort between conditions (Table 3). Interestingly, performance was maintained at the target level during the COMP trial, with no associated increase in heart rate, core body temperature or perceived exertion compared with the CON condition. This suggests that there were no apparent negative physiological or perceptual responses to wearing lower limb compression during exercise. It should be noted, however, that perceived thermal

discomfort was higher during the final period of the exercise task during the COMP trial. This small difference may be the result of the additional work and associated energy expenditure during the COMP trial, and further studies are needed to determine whether lower limb compression adversely affects perception of effort during exercise in SCI individuals. It is possible that venous pooling and the associated disturbances in cardiovascular dynamics are exacerbated in SCI athletes in warm environmental conditions; and that the observed positive effects of compression are limited to such conditions. Therefore, further research is required to elucidate the effect of lower limb compression on performance, physiological and perceptual responses to exercise in cool and dry environmental conditions.

Conclusion

The present study is one of the first to investigate the effect of compression socks, worn by elite wheelchair rugby athletes, on performance and related physiological and perceptual responses in warm environmental conditions. While there was no effect on maximal exercise performance, below-knee compression socks were found to improve the ability to maintain submaximal performance, and this was related to an increase in post-exercise arm blood flow. Therefore, compression socks may be a practical and user-friendly intervention to assist in the maintenance of sustained wheelchair exercise performance.

Disclaimer statements

Contributors All authors/co-authors have contributed for this research and preparation of manuscript.

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Conflicts of interest Authors/co-authors declare no conflict of interest.

Ethics approval Institute's ethics committee approval obtained.

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