

Upper limb ischaemic preconditioning for community dwelling adults with chronic spinal cord injury: a feasibility trial

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Abstract

Study Design

Randomised, single blind, sham-controlled parallel trial

Objectives

To determine the feasibility of delivering and acceptability of an upper-limb ischaemic preconditioning (IPC) protocol and to explore its acute effect on elbow extension strength and endurance in chronic spinal cord injury (SCI).

Setting

Outpatient spinal injuries centre, UK

Methods

Thirty-eight community-dwelling adults at least one-year post-SCI (m. *triceps brachii* Medical Research Council grade at least 4/5) were randomised (19 IPC, 19 sham) from 770 screened, of which 37 received the allocated intervention. Feasibility was assessed via adherence, adverse events and retention; acceptability via the Theoretical Framework of Acceptability questionnaire, McGill Pain Questionnaire and pain and discomfort ratings. Maximal isometric elbow extension force, intermittent isometric time to exhaustion and m. *triceps brachii* surface electromyography were assessed pre- and post- intervention.

Results

Adherence was 100% and retention rate was 97%. No adverse events were reported. IPC was rated more uncomfortable than sham ($p < 0.001$), but acceptability did not differ between the groups ($p \geq 0.257$). Post-intervention strength and TTE did not differ between groups after adjusting for baseline ($p = 0.292$, $p = 0.438$). A significant interaction ($p = 0.003$) reflected lower triceps brachii sEMG at task failure following IPC.

Conclusions

Upper-limb IPC is feasible and acceptable in community dwelling adults with chronic SCI, but a single session protocol produced no significant changes in maximal elbow extension strength or endurance. The neuromuscular findings warrant investigation in an adequately powered efficacy trial.

Introduction

Fatigue affects over half of the community-dwelling individuals with spinal cord injury (SCI) [1, 2]. Fatigue is characterised by a performance decrement during sustained or an overwhelming and persistent sense of exhaustion disproportionate to activity [3]. Regular exercise helps preserve function and reduce

fatigue, yet low energy remains a common barrier to participation [4], creating a self-perpetuating cycle of deconditioning that is a fundamental challenge in SCI rehabilitation.

Individuals with impaired lower limb function disproportionately rely on their upper limbs serving as the primary means of locomotion, weight bearing transfers, pressure relief and personal care [5, 6]. The *m. triceps brachii* provides the elbow extension force critical for push off during propulsion and transfers. Weakness and fatigue of these upper limb muscles therefore limit the performance of essential daily tasks, jeopardising independence and increasing reliance on caregivers [7], yet effective and practically deliverable adjunct interventions to enhance upper limb performance in this population remain limited [8, 9].

Ischaemic preconditioning (IPC) is a non-invasive priming strategy that involves the application of brief, repeated episodes of blood flow occlusion, followed by reperfusion, applied to a limb/limbs using a pressurised cuff. Ischaemic preconditioning (IPC) has emerged as an ergogenic and neuroadaptive technique that results in improved muscle strength [10, 11], endurance [12, 13] and neuromuscular activation [14–16]. Importantly, IPC can increase time to task failure during handgrip exercise [12] and improve arm-crank ergometry time to exhaustion (TTE) by ~ 16% compared to a sham intervention [17] in non-SCI populations.

Although underexplored in SCI, IPC has proved effective in increasing paretic *m. quadriceps femoris* strength and activation in individuals post stroke [18]. The upper motor neuron lesion in both stroke and SCI provides a partial mechanistic parallel that may justify the extrapolation of these findings into SCI. To date, the efficacy of IPC in SCI has been reported by a single published pilot study reporting statistically non-significant change in handgrip TTE during sustained and intermittent isometric handgrip tasks in para-athletes [19]. However, the questions regarding the broader application of IPC in a non-athlete population remain unanswered. In addition, the practicality of administration, participant adherence, tolerability of procedure and absence of adverse events are fundamental prerequisites that must be established before efficacy can be meaningfully evaluated [20].

The present study therefore aimed to (1) determine the feasibility and acceptability of delivering a standardised IPC protocol in individuals with chronic SCI, and (2) investigate the effect of IPC on maximal isometric elbow extension force and time to exhaustion (TTE) performance. Based on the limited and heterogeneous evidence available for upper limb IPC in healthy adults and the absence of data in non-athletic SCI, we hypothesised that IPC would be acceptable in individuals with SCI, and that it would improve elbow extension strength and endurance performance compared to a sham condition.

Methods

Study design

This acute, single-blind, parallel-group randomised controlled trial (NCT05954715, clinicaltrials.gov) allocated participants to receive IPC or a sham intervention. Ethical approval was granted by the East

Midlands - Nottingham 1 Research Ethics Committee, and the study followed the Declaration of Helsinki.

Participants

Patients attending outpatient clinics at the Princess Royal Spinal Injuries Centre, Northern General Hospital, Sheffield, UK, were recruited between October 2024 and November 2025. Inclusion criteria were age 18–65 years, at least one year post-SCI at any lesion level, sufficient m. *triceps brachii* strength for resistance exercise (Medical Research Council grade at least 4/5), and resting systolic BP under 170 mmHg; exclusions were American Spina Injuries Association Impairment Scale (AIS) E classification, relevant comorbidities (traumatic brain injury, brachial plexus injury, upper-limb fractures, progressive neurological conditions), active pressure sores precluding sitting in the testing chair, autonomic dysreflexia within the preceding two weeks, and inability to communicate in English.

Eligible individuals, identified by consultants and the research team, were approached in person or by telephone and given a patient information sheet and at least 24 hours to consider participation before written informed consent was obtained. Of 770 patients screened, 50 were enrolled and 38 randomised into IPC and sham groups after 12 withdrew before consenting (Fig. 1).

Insert Fig. 1 here

Experimental Protocol

The researcher allocated participants to IPC or sham using an online random number generator (random.org) in blocks of two, the second participant in each block receiving the group not allocated to the first. Participants wore a chest-strapped heart-rate monitor (H10, Polar Electro, Kempele, Finland). After 10 minutes of seated rest, resting BP and HR were recorded (M2 Basic, Omron, Kyoto, Japan). sEMG electrodes were positioned on the long and lateral heads of m. *triceps brachii* per Surface Electromyography for Non-Invasive Assessment of Muscle (SENIAM) guidelines, and participants transferred to a custom isometric elbow extension rig (see Supplementary Fig. 1), seated with the dominant elbow at 90° flexion and forearm neutral, wrist strapped to a vertical bar attached to a force transducer (TSD121C, Biopac Systems Inc., Goleta, CA, USA) linked to a data acquisition system (MP36, Biopac Systems Inc.) that also recorded sEMG.

Participants then performed isometric elbow extension MVCs (pre-intervention MVC1), followed after 10 minutes by the pre-intervention TTE test at 60% of MVC, with Borg's rating of perceived exertion (RPE) recorded at task end. After a further 20-minute rest, a second MVC set was obtained (pre-intervention MVC2) and the IPC/sham protocol administered 5 minutes later. MVC and TTE were repeated post-intervention (see Supplementary Fig. 2), with RPE again recorded at the end.

Intervention and testing procedures

Ischemic Preconditioning Protocol

IPC was administered to both upper arms using a 20 cm wide manual blood pressure cuff (Accoson aneroid sphygmomanometer) inflated to 200 mmHg or 60 mmHg above systolic BP, whichever was higher. The sham intervention was administered using the cuff inflated to a pressure 30 mmHg below diastolic BP. Both IPC and sham protocol comprised four cycles of 5-minute inflation followed by 5-minute deflation, alternating between arms, with pain and discomfort recorded after each inflation phase.

Participants then completed a modified version of the Theoretical Framework of Acceptability (TFA) questionnaire and selected McGill Pain Questionnaire items to assess their perception of and tolerance to the intervention.

Strength Assessment

Isometric elbow extension strength was assessed after a standardised warm-up of two contractions each at participant-estimated 50%, 70% and 90% of maximum. Maximal contractions were then repeated until the two highest values were within 10% of each other, with participants given force-time feedback and standardised verbal encouragement.

Time to exhaustion (TTE) test protocol

Following the MVCs, participants performed an isometric, intermittent TTE test at 60% of MVC, contracting to auditory cues on a 3:2 (3 s on/2 s off) duty cycle.

Scales and Questionnaires

At the end of each inflation phase, participants rated any pain or discomfort on an 11-point Numerical Rating Scale (NRS; 0 = no pain/discomfort, 10 = worst imaginable pain/discomfort). From the long form McGill Questionnaire [21], selected three categories of descriptors (constrictive pain, evaluative, sensory miscellaneous) that were considered relevant to the IPC intervention were used to assess the participants' pain perception with the IPC/sham intervention. Components of the TFA questionnaire by Sekhon et al. [22] were modified to be specific to this study.

Safety Monitoring and Follow-up

Participants were monitored throughout for adverse events, including pain and neurological change. Testing took place in an acute hospital setting equipped to manage adverse events. To account for social desirability [23] and retrospective bias [24], participants were telephoned the next day to repeat the TFA questionnaire and pain/discomfort ratings. Those who could not be reached were excluded from this repeat analysis.

Data Processing

Force and sEMG data were analysed in Python (Spyder IDE, version 6.0.3).

MVC

The highest instantaneous force value was recorded as the MVC. However, pre-intervention MVC 1 was considered invalid if post-intervention MVC was greater than 30% of pre-intervention MVC 1 and the participant was excluded from all exercise performance analysis.

TTE test

Contraction initiation was defined as the highest positive value of the first derivative of the force signal. A 0.3 s delay was added, and the subsequent 2.2 s window used for all TTE calculations. Work done per contraction was the force-signal area under curve (AUC) (capped at target force values), and task failure was defined as three consecutive contractions with AUC below 95% of target. TTE ran from initiation of the first contraction to the end of the last valid contraction. Tests lasting over 15 minutes without signs of fatigue were terminated and excluded, as were tests in which participants failed to reach target intensity or stopped themselves due to discomfort before showing signs of failure, which was classed as premature termination.

Surface EMG data extraction

sEMG was bandpass filtered (20–500 Hz, zero-lag fourth-order Butterworth). For MVC contractions, EMG was quantified as a moving RMS (0.5 s window) across the contraction, with the maximum extracted as sEMG(MVC). For each TTE contraction, RMS over the 2.2 s window was similarly calculated and normalised to sEMG(MVC), with values extracted at 0-100% (20% increments) of each participant's TTE (proportionate points).

Statistical analysis

All analyses were carried out using IBM SPSS statistics (version 29.0.1.0 (171), IBM Corp., Armonk, NY). Prior to inferential analysis, data was checked for parametric assumptions. Non-parametric data were log transformed prior to analysis. Body mass was compared between the groups using an independent samples T-test; age, years since injury, injury level and AIS grades between groups were compared using the Mann-Whitney U test. Categorical variables (sex, exercise participation and ambulation status) were compared using the Pearson's chi-square test, with Fisher's exact test was used in place of chi-square test where more than 20% cells had an expected count < 5. MVC and TTE were analysed by one-way ANCOVA (group as fixed factor, pre-intervention score as covariate); pre-intervention MVC1 was used as an additional covariate for TTE. Force AUC during the TTE test and sEMG from the lateral and long heads of *m. triceps brachii* were analysed by three-way mixed ANOVA (phase and time within-subject, group between-subjects), with Greenhouse-Geisser correction where sphericity was violated and Bonferroni-adjusted pairwise comparisons for significant interactions. NRS pain and discomfort used 2 × 2 mixed ANOVA (time, within; group, between); the TFA questionnaire subquestions, 2 × 2 ANOVA; McGill subscale scores, Mann Whitney U test; and RPE, 2 × 3 × 2 mixed ANOVA (time and category, within;

group, between). To control for multiple comparisons, p-values for TFA and McGill subscales were Bonferroni corrected by multiplying each observed p-value by the number of comparisons, with adjusted values exceeding 1 reported as 1.000. Effect sizes are reported as partial eta-squared (η^2p) for ANOVA and ANCOVA, interpreted as small (≥ 0.01), medium (≥ 0.06), and large (≥ 0.14) according to Cohen's [25] conventions. Significance was set at $p \leq 0.05$.

Results

Participants

Of the 38 randomised participants, one session was terminated before testing due to lower limb spasms. Hence, 37 participants completed the entire testing session and were included in the feasibility and acceptability analysis. Two participants per group were excluded from both MVC and TTE analysis (Reasons: IPC – antispasmodic medication taken midway during the session ($n = 1$) and invalid pre-intervention MVC1 ($n = 1$); sham – invalid pre-intervention MVC1 ($n = 1$) and invalid post-intervention TTE ($n = 1$)). One participant from the IPC group was excluded from TTE analysis due to premature termination by the participant during the post-intervention TTE. Therefore, the total number of participants included in the MVC analysis were: 17 IPC, 16 sham; and TTE analysis were: 16 IPC, 16 sham. Twenty-one participants (11 IPC, 10 sham) were included the pain, discomfort and TFA questionnaire analysis since the other participants were not contactable on the day after the testing session. Baseline characteristics did not differ between groups ($p \geq 0.269$; Table 1).

Table 1
Group-wise participant characteristics

Characteristic	IPC	Sham
	n = 19	n = 18
Age, yr	48.9 (11.2)	50.9 ± 10.9
Body mass, kg	84.0 (19.0)	85.8 ± 18.8
Years since injury	20.5 (14.8)	19.6 (16.1)
Sex		
Male (n)	16	15
Female (n)	3	3
Injury level		
Cervical	4	3
Thoracic	9	9
Lumbar	0	2
Cauda Equina Syndrome	3	2
Spina Bifida	2	2
Unknown	1	0
AIS		
A	5	5
B	0	3
C	3	1
D	2	4
Not applicable	5	4
Unknown	4	1
Ambulatory status		
Independent walkers (n)	2	6
Wheelchair users (n)	15	10
Assistive aid users (n)	2	2
All values are presented as no. (n) or mean (SD).		

Characteristic	IPC	Sham
	n = 19	n = 18
AIS - American Spinal Injuries Association Impairment Scale		
Not applicable refers to Cauda Equina Syndrome and Spina Bifida.		

Insert Table 1 here

Feasibility

There were no adverse events or serious adverse events reported during the study. Retention was 97% (37/38 randomised participants received the intervention) with 100% adherence.

Pain and discomfort ratings did not exceed 7/10 in any participant in either group.

The IPC group reported significantly higher pain ($F(1, 19) = 15.90, p < 0.001, \eta^2p = 0.456$) and discomfort ($F(1, 19) = 30.88, p < 0.001, \eta^2p = 0.619$) ratings overall than the sham group, but there was no significant time $\times$ group interaction (pain: $F(1, 19) = 0.04, p = 0.851, \eta^2p = 0.002$; discomfort: $F(1, 19) = 0.26, p = 0.619, \eta^2p = 0.013$) (Table 2).

Table 2

Numerical rating scale (NRS) pain and discomfort recorded immediately after the intervention and repeated post 24 hours.

Group	Pain		Discomfort	
	After intervention	24 h post intervention	After intervention	24 h post intervention
IPC	2 (4)	2 (3)	4 (1)	4 (2)
Sham	0 (2)	0 (2)	1 (1)	1 (1)
Values are presented as median (interquartile range). IPC (n) = 11; sham (n) = 10.				

Theoretical Framework of Acceptability (TFA)

Only 21 participants were included in the analysis due to missing responses from the day after the intervention. There were no significant main effects of group or time $\times$ group interactions for likeability (group: $F(1, 19) = 0.15, p = 1.000, \eta^2p = 0.01$; interaction: $F(1, 19) = 0.26, p = 1.000, \eta^2p = .01$), effort (group: $F(1, 19) = 0.61, p = 1.000, \eta^2p = 0.03$; interaction: $F(1, 19) = 0.28, p = 1.000, \eta^2p = 0.02$), acceptability (group: $F(1, 19) = 1.37, p = 1.000, \eta^2p = 0.07$; interaction: $F(1, 19) = 0.20, p = 1.000, \eta^2p = 0.01$) or willingness (group: $F(1, 19) = 0.11, p = 1.000, \eta^2p = 0.01$; interaction: $F(1, 19) < 0.01, p = 1.000, \eta^2p < 0.001$) (Fig. 2).

Mc Gill Pain questionnaire

Scores for the constrictive and evaluative subclasses were significantly higher in the IPC group than in the sham group (constrictive: $U = 99.0$, $z = -2.72$, $p = 0.018$, $r = 0.45$; evaluative: $U = 108.0$, $z = -2.81$, $p = 0.015$, $r = 0.46$). There was no difference in sensory miscellaneous subclass scores ($U = 166.5$, $z = -0.16$, $p = 1.000$, $r = 0.03$).

Insert Fig. 2 here

Insert Table 2 here

Maximal strength

Controlling for pre-intervention MVC1, post-intervention MVC did not differ between groups ($F(1, 30) = 1.152$, $p = 0.292$, $\eta^2p = 0.037$, Fig. 3a).

Time to exhaustion performance

Post-intervention TTE did not differ significantly between the IPC and sham groups after controlling for pre-intervention TTE and pre-intervention MVC1 ($F(1, 28) = 0.619$, $p = 0.438$, $\eta^2p = 0.022$, Fig. 3b).

Insert Fig. 3 here

Neuromuscular activity

Force AUC decreased significantly over time ($F(3.808, 114.243) = 21.012$, $p < 0.001$, $\eta^2p = 0.412$, Fig. 4). There was no significant main effect of group ($F(1, 30) = 0.012$, $p = 0.912$, $\eta^2p < 0.001$) and no significant phase $\times$ time $\times$ group interaction ($F(3.234, 97.007) = 1.115$, $p = 0.349$, $\eta^2p = 0.036$).

Lateral head of m. triceps brachii sEMG activity increased significantly over time ($F(3.519, 105.565) = 46.887$, $p < 0.001$, $\eta^2p = 0.610$) with no group difference ($F(1, 30) = 1.600$, $p = 0.216$, $\eta^2p = 0.051$). However, there was a significant phase $\times$ time $\times$ group interaction ($F(3.898, 116.948) = 4.020$, $p = 0.003$, $\eta^2p = 0.118$). Within the sham group, pre-intervention sEMG at the 0% timepoint of the test was significantly higher than post intervention ($p = 0.015$). Within the IPC group, the post intervention sEMG at the 100% timepoint was significantly lower than the 100% timepoint at pre intervention ($p = 0.001$).

Long head sEMG activity significantly increased over time ($F(3.708, 103.837) = 23.698$, $p < 0.001$, $\eta^2p = 0.458$). Main effect of phase ($F(1, 28) = 0.156$, $p = 0.696$, $\eta^2p = 0.006$), groups ($F(1, 28) = 0.057$, $p = 0.813$, $\eta^2p = 0.002$) and the phase $\times$ time $\times$ group interactions ($F(3.096, 86.685) = 1.217$, $p = 0.309$, $\eta^2p = 0.042$) was non-significant.

Insert Fig. 4 here

Rating of Perceived Exertion

There was no significant main effect of time ($F(1, 30) = 1.071$, $p = 0.309$, $\eta^2p = 0.034$), nor did the RPE differ between IPC and sham ($F(1, 30) = 1.657$, $p = 0.208$, $\eta^2p = 0.052$, Table 3). The three-way time $\times$

category $\times$ group interaction was also non-significant ($F(2, 60) = 0.196$, $p = 0.822$, $\eta^2p = 0.007$).

Table 3
Rating of perceived exertion after the time to exhaustion test, by group and session.

		RPE		
		Local	Central	Overall
IPC	Pre-intervention TTE	16.6 (2.4)	13.2 (1.6)	15.1 (2.7)
	Post-intervention TTE	16.9 (2.9)	13.7 (1.5)	15.4 (3.1)
Sham	Pre-intervention TTE	15.9 (3.1)	13.2 (2.0)	13.2 (3.0)
	Post-intervention TTE	16.1(3.1)	13.1 (3.1)	13.3 (3.1)
Values are presented as mean (SD). IPC (n) = 16; sham (n) = 16.				

Insert Table 3 here

Discussion

This study provides the first evidence on the feasibility and acceptability of an upper limb IPC protocol in community-dwelling individuals with chronic SCI, alongside its acute effects on isometric elbow extension strength, performance on an isometric intermittent TTE test and neuromuscular activity recorded from *m. triceps brachii*. Overall, IPC was well tolerated and acceptable, with no adverse events and complete adherence among participants who received the intervention. IPC did not significantly alter the maximal elbow extension strength or TTE performance. However, IPC produced a significantly different neuromuscular activation trajectory during the TTE test, characterised by a lower sEMG amplitude at task failure. Given that low energy is a frequently reported barrier to exercise in SCI [4], the delivery of a demanding occlusion protocol without adverse events establishes the feasibility prerequisite for a subsequent efficacy trial.

The discomfort reported with IPC was comparable to previous clinical studies [18, 26]. Combined pain and discomfort ratings indicate that IPC is perceived as uncomfortable but not painful. Pain and discomfort ratings were unchanged at next day follow up, suggesting the intervention was not retrospectively perceived as more aversive once completed, arguing against meaningful social desirability bias in the immediate scores and the ‘peak-end rule’. No previous study has reported the McGill Pain Questionnaire to report the character and intensity of the pain or the acceptability of IPC using a theoretical framework. The higher McGill pain scores with IPC are consistent with the higher occlusion pressure causing transient limb ischaemia. However, it does not translate into reduced acceptability of the intervention, and provides a basis for evaluating its efficacy as an ergogenic adjunct in this population.

Previous evidence highlights that IPC's ergogenic effect on maximal strength is dependent on the population examined and whether the target muscle exhibited a pre-existing strength or activation deficit [18], although the evidence for this population dependence remains mixed and limited. The most compelling evidence of IPC-induced strength enhancement in a neurological population comes from Hyngstrom et al. [18], who demonstrated that a single session of IPC significantly increased paretic knee extensor strength in chronic stroke survivors. Participants with the greatest strength asymmetry between the paretic and the non-paretic limb had the greatest increase in knee extensor MVC following IPC. A recent meta-analysis found no significant effect of upper limb IPC on maximal strength, suggesting a comparatively limited ceiling for improvement in individuals without a baseline strength or activation deficit [27].

The absence of a significant effect on maximal strength in the present study may be attributed to several other factors including the heterogeneity in the voluntary activation deficits across participants due to the heterogeneity of lesion level and completeness. Stroke typically produces focal hemispheric damage resulting in hemiparesis of the contralateral limbs [28], whilst SCI produces a lesion level-dependent loss of function. Individuals with lesion C8 or below in the present study would have intact corticospinal projections to the m. *triceps brachii*, likely rendering voluntary activation of the m. *triceps brachii* effectively normal. Conversely, participants with higher cervical lesions would be expected to show most pronounced voluntary activation deficits. Since the primary aim of the study was to evaluate the safety and feasibility of IPC, the lesion level and completeness were broad, therefore plausibly diluting any group level effect on MVC.

IPC did not significantly change post-intervention TTE relative to sham, consistent with the only IPC study in an SCI population, in isometric and intermittent handgrip performance in para-athletes with incomplete cervical lesions [19]. The difference in the upper limb aerobic capacity between an athletic population and a non-athletic community dwelling population limits the direct comparison with the current study. Similar null findings have been reported in healthy individuals as well. Behrens et al. [29] and Tanaka et al. [13] similarly found that IPC did not improve m. *quadriceps femoris* performance on a sustained TTE knee extensor test, contrasting with several studies in healthy adults that have reported increased TTE following IPC [12, 13, 16]. The absence of a significant effect of IPC on TTE in this study is unlikely due to inconsistent test conditions since the testing was standardised and RPE did not differ between conditions or over time. More plausibly, the single-session design precluded full recovery between assessments, and accumulated fatigue may have masked any ergogenic benefit, an important consideration for future multi-session protocols.

The significant increase in sEMG over time both heads of m. *triceps brachii* reflects the progressive recruitment of higher threshold motor units as task approaches exhaustion [30, 31]. The temporal specificity of the pre to post divergence across conditions in SCI is a novel finding of the current study. Pethick et al. [16] similarly reported that IPC significantly slowed the rate of sEMG amplitude increase during a fatiguing isometric knee extension protocol, but alongside a 43% increase in time to task failure. Without a comparable increase in time to task failure, those findings cannot be used to interpret the

sEMG findings in the current study. Additionally, in the absence of recordings from other synergists, the present data cannot distinguish a genuine reduction in net neural drive to the elbow extensors from a redistribution of contribution from synergistic muscles [32]. Furthermore, the lower sEMG amplitude at task failure cannot be taken as evidence that fewer high threshold motor units were recruited at point of exhaustion since point of task failure was based on a performance criterion rather than a physiological marker of peripheral or central fatigue. The overall length and the non-muscular demand of the testing session may have potentially contributed to earlier task disengagement independent of the physiological capacity of the elbow extensors [33]. Also, the greater pain and discomfort associated with IPC intervention relative to sham may have reduced the potential motivation for the subsequent TTE test [34]. Definitive interpretation of the sEMG response to IPC will require future protocols that combine synergist EMG recordings with objective markers of peripheral and central fatigue. High-density EMG would allow more direct verification of motor unit recruitment patterns underlying the observed amplitude changes.

This feasibility randomised trial has several limitations that should be considered when interpreting the findings. First, the parallel group design did not allow for within participant comparison of IPC and sham conditions. Given the considerable inter-individual variability in lesion level, completeness, voluntary activation and physical activity levels within the SCI population, a within participant crossover design would allow the within-person estimation of IPC induced effects in a future efficacy trial. The absence of direct measures of oxygen uptake, oxygen uptake kinetics, voluntary activation and sEMG from the synergistic muscles precludes definitive conclusions regarding the physiological mechanisms underlying the observed reduction in sEMG amplitude at task failure.

To conclude, this study demonstrates that upper limb IPC is feasible and acceptable in a non-athletic community-dwelling SCI population. The present findings suggest no meaningful change in elbow extension strength or endurance performance. Furthermore, whilst lower sEMG amplitude at task failure was demonstrated for the IPC condition, this cannot be interpreted as evidence of altered neuromuscular efficiency given potential synergistic compensation and motivation driven disengagement during the TTE test. Together, these findings establish the feasibility prerequisite for a subsequent, adequately powered efficacy trial of upper limb IPC in this population.

Declarations

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Competing interests

The authors report no conflict of interest.

Author contributions

NM, CL, JS and IT contributed to the study conception and design. NM conducted the experiments. NM processed and analysed the data. All authors were responsible for data interpretation and revising it critically. The first draft of the manuscript was written by NM, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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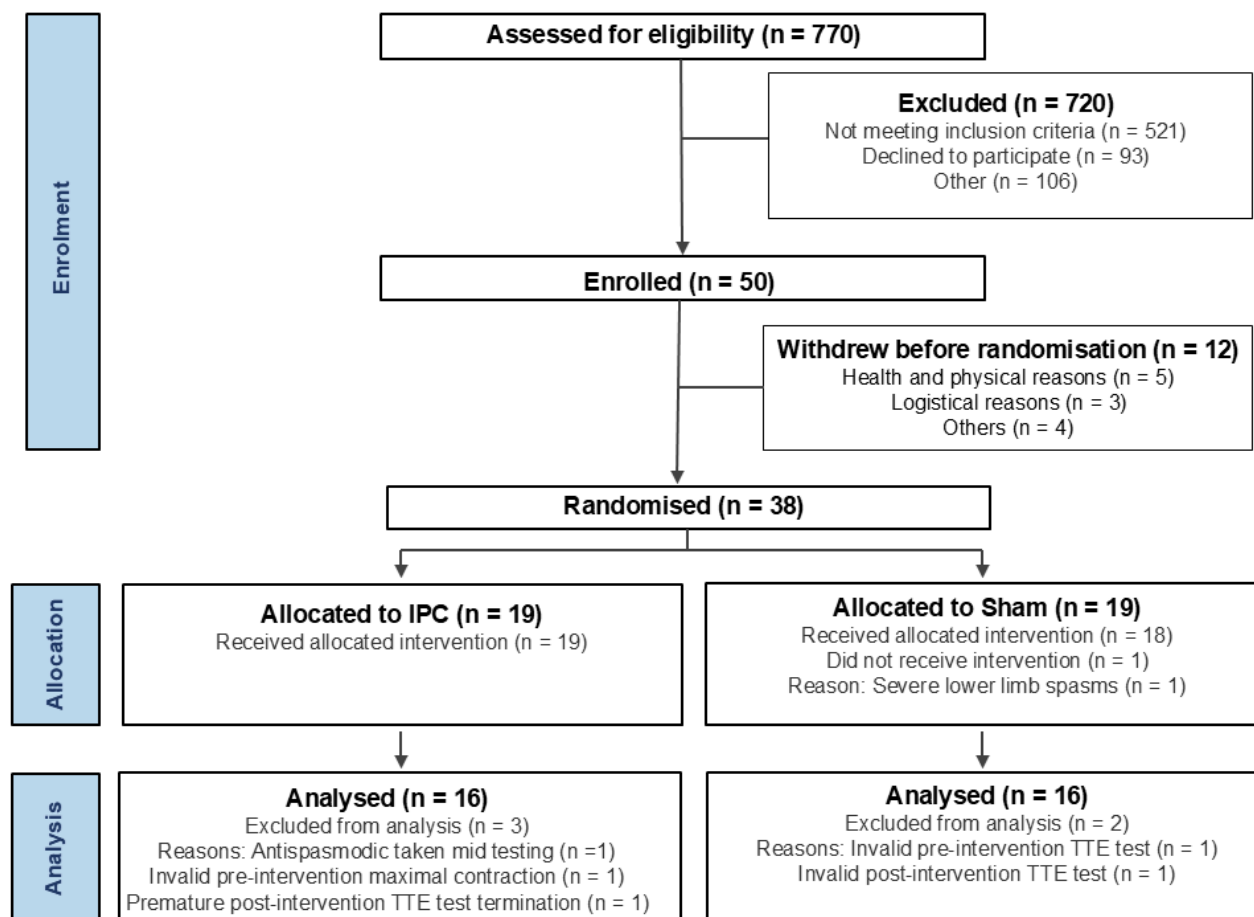
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Figures



IPC = ischaemic preconditioning; Sham = control condition; TTE = time to exhaustion

Figure 1

CONSORT flow diagram illustrating participant recruitment, allocation and analysis

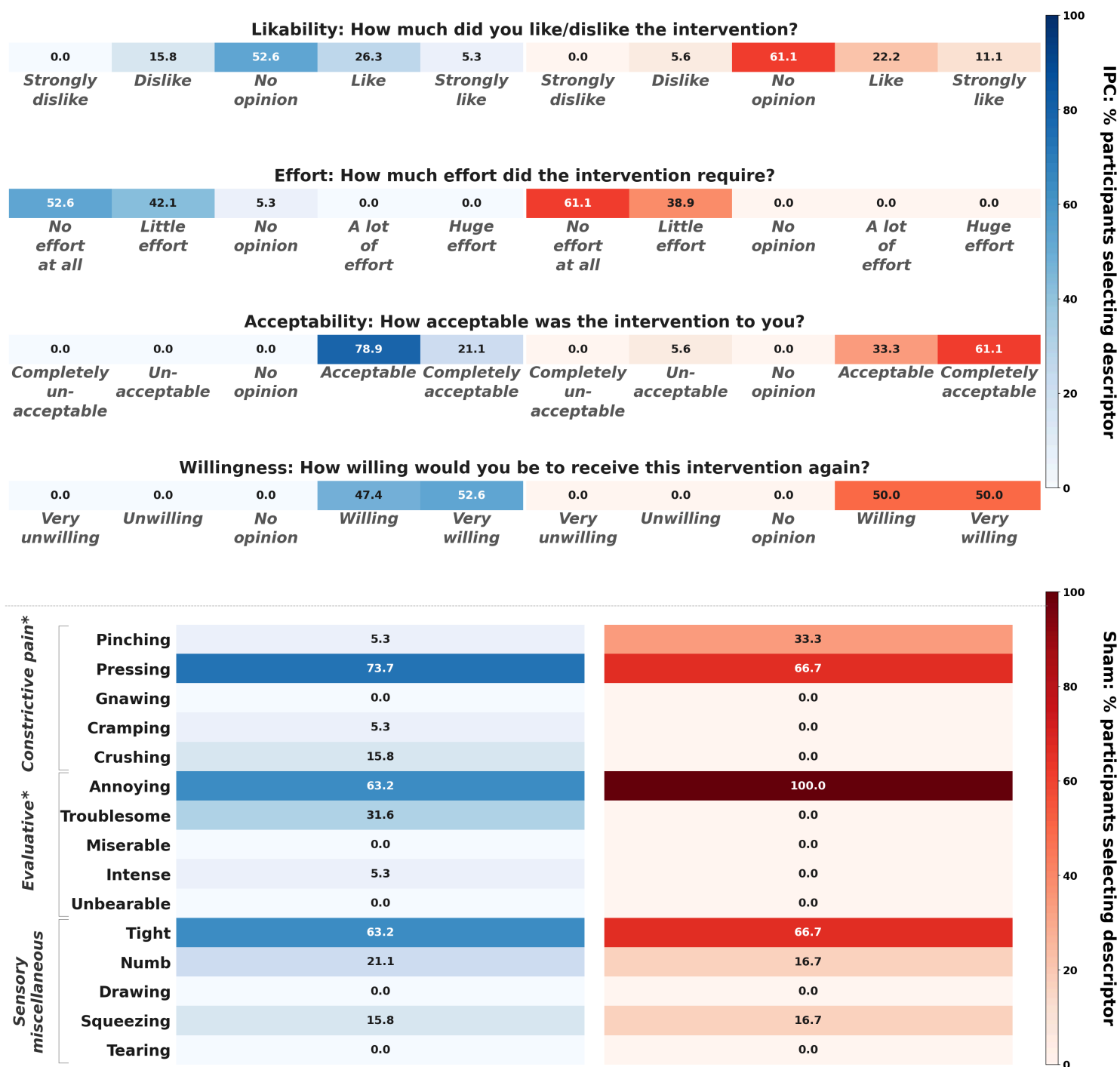


Figure 2

Participant responses to (a) the Theoretical Framework of Acceptability (TFA) questionnaire and (b) McGill Pain Questionnaire descriptors following IPC and Sham interventions recorded immediately after completing the IPC or sham intervention. (n) = 19; sham (n) = 18. * denotes overall statistical significance for 'Constrictive pain' and 'Evaluative' between IPC and sham groups.

Note: the group time TFA analysis reported in text used a reduced subset (IPC (n) = 11 and sham (n) = 10) with paired next day data available.

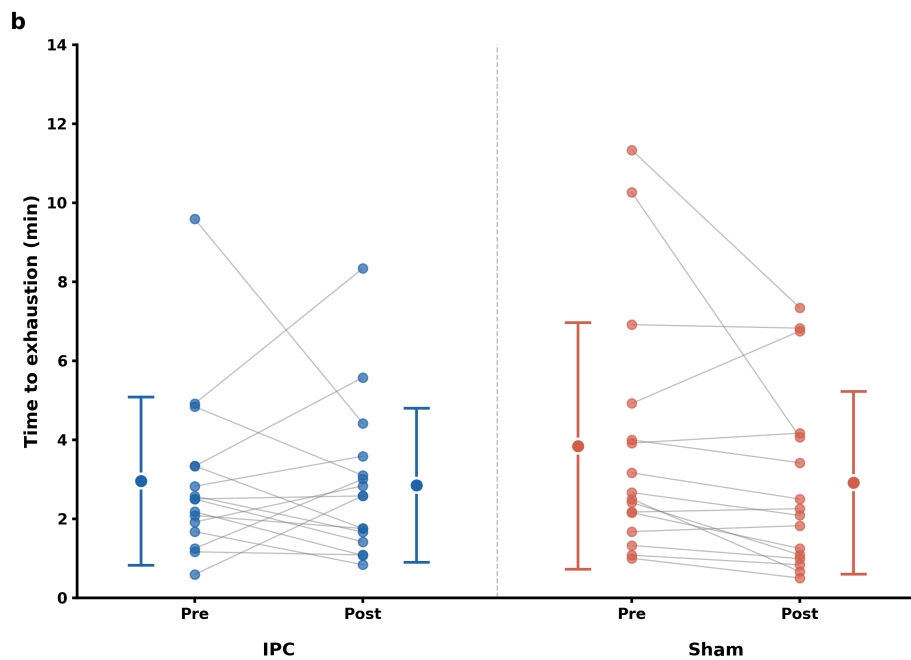
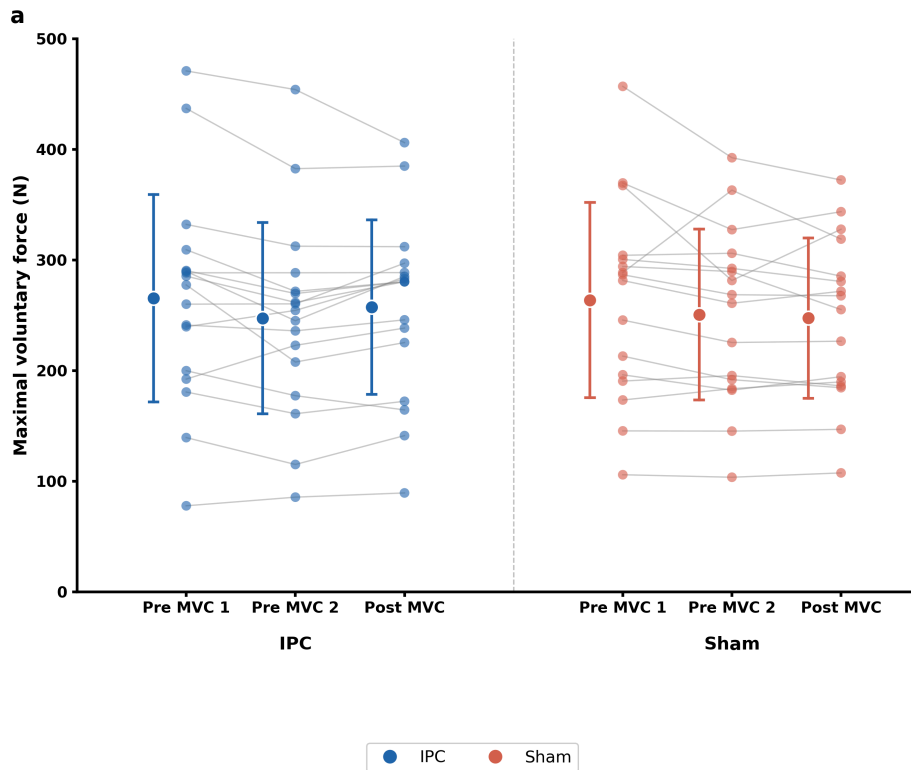


Figure 3

(a) – Individual and group means (IPC (n) = 17, sham (n) = 16)) with standard deviation of maximal voluntary contraction (MVC) force at each time point for IPC and sham groups. (b) – Individual and mean (IPC (n) = 16, sham (n) = 16) time to exhaustion (TTE) values pre- and post-intervention for the IPC and Sham groups. Lines connect individual participant data points between time points. Error bars represent standard deviation.

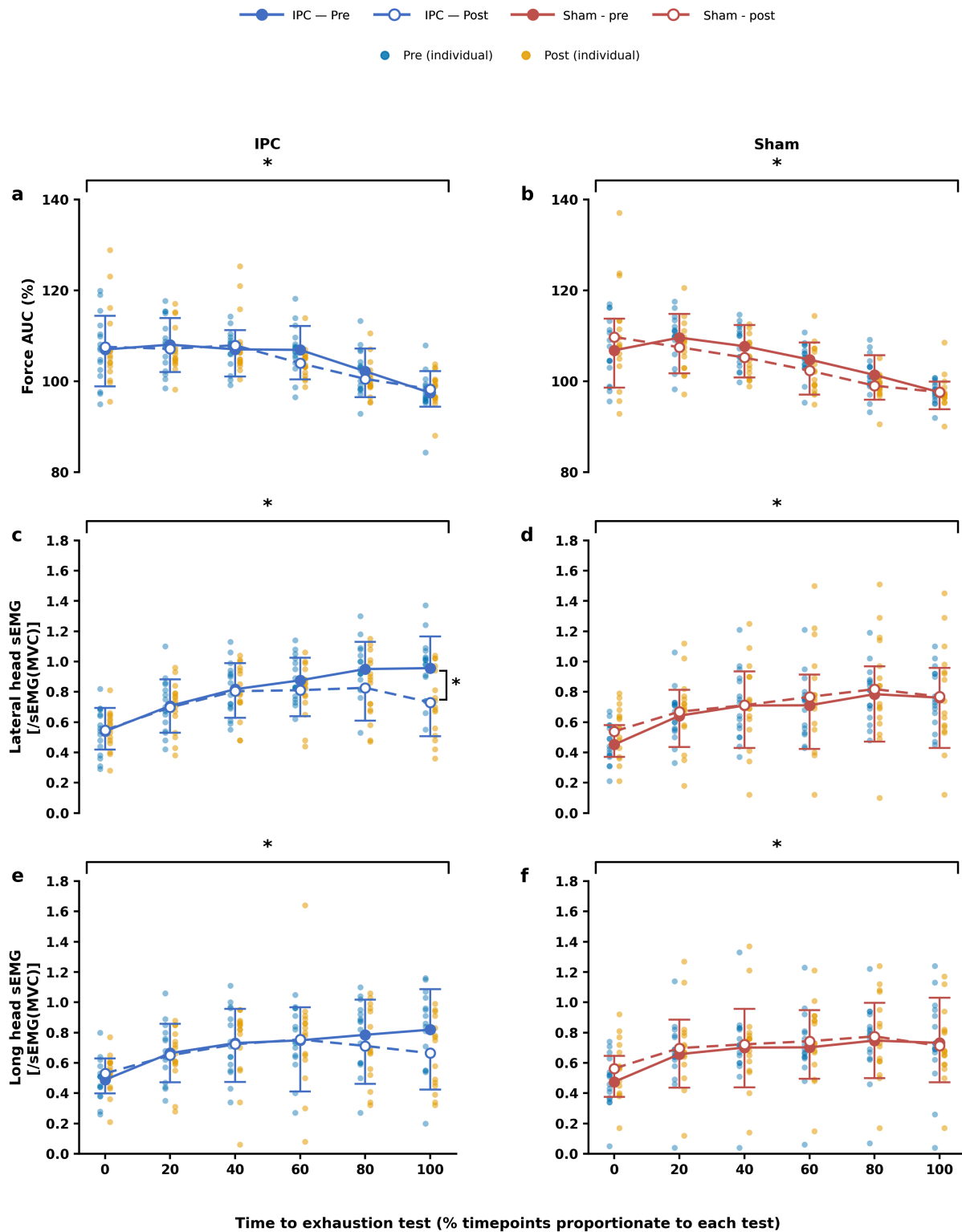


Figure 4

Force area under curve (AUC) and surface electromyography (sEMG) data across timepoints proportionate to each time to exhaustion (TTE) test. Graphs on the left and right side are from IPC and sham groups respectively. a, b - force AUC: IPC (n) = 16; sham (n) = 16; c, d – sEMG from the lateral head of *m. triceps brachii*: IPC (n) = 16; sham (n) = 16; e, f – sEMG from the long head of *m. triceps brachii*: IPC (n) = 16; sham (n) = 15. Error bars represent standard deviation.

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