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Systematic review

The effects of unimanual and bimanual massed practice on upper limb function in adults with cervical spinal cord injury: a systematic review

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Abstract

Background Individuals with cervical spinal cord injury (cSCI) have identified improving upper limb function as their most important rehabilitation goal. Unimanual massed practice (UMP) and bimanual massed practice (BMP) may help achieve this.
Objectives To evaluate and compare the effects of UMP and BMP on upper limb function in adults with cSCI.
Data sources Cochrane Central Register of Controlled Trials, PubMed, CINAHL, Web of Science and PEDro until April 2016.
Study selection Studies investigating the effects of UMP and/or BMP on upper limb function in adults with cSCI.
Data extraction and synthesis Data was extracted using a standardised form. Studies were appraised using a modified version of the Cochrane risk of bias tool. The findings were qualitatively synthesised.
Results Five randomised controlled trials and two case studies were included. Six studies included UMP, three included BMP, and two compared these approaches. Overall the studies reported that UMP and BMP improved upper limb function, particularly when combined with electrical stimulation, with no clear differences between UMP and BMP. These findings should be interpreted with caution however, as six studies presented a high or unclear risk of bias for all functional upper limb outcome measures included, and the remaining study was a small pilot study with no control group.
Conclusion Although the findings of the included studies support the use of UMP and BMP in adults with cSCI, only seven studies, all with significant limitations, were included; hence robust conclusions cannot be drawn and further research is warranted.
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Keywords: Systematic review; Unimanual; Bimanual; Massed practice; Cervical spinal cord injury; Upper limb function

Introduction

Almost 60% of spinal cord injuries are at the cervical level [1], resulting in catastrophic loss of arm and hand function, reducing societal participation and overall quality of life [2]. Given this, it is not surprising that individuals with cervical spinal cord injury (cSCI) cite recovery of arm and hand function as their most important goal during neurorehabilitation [3], thus identifying rehabilitation approaches which help improve upper limb function post-cSCI is of paramount importance. Unimanual massed practice (UMP) and bimanual massed practice (BMP) are two such rehabilitation approaches which deserve particular attention due to their recognised benefits in other neurological conditions such as stroke and cerebral palsy [4–6]. Both these approaches involve intense repetitive practice of task-orientated motor activities, typically for 2 hours per day,

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5 days per week, for 3 weeks, using either one upper limb (UMP) or both upper limbs (BMP) [7–10].

UMP may consist simply of intensive training of one limb or may be part of a more extensive training intervention such as constraint-induced movement therapy [11]. The intense use of one limb and resulting increased afferent input from that limb is thought to stimulate neuroplastic changes and help minimise "learned non-use" [11]. BMP is also believed to stimulate neuroplasticity, but is based on the principle of interlimb neural coupling and aims to optimise interhemispheric synchronisation and disinhibition [12,13]. BMP allows both upper limbs to be trained simultaneously; hence may be particularly helpful for individuals with cSCI as their impairments are typically bilateral [7]. It has however also been suggested that UMP may be more beneficial than BMP for individuals with cSCI, as focusing on one hand only allows more intense practice [7]. Achieving a sufficient intensity of practice may be important for optimising both strength and neuroplastic changes in individuals with cSCI [14,15]. Furthermore research conducted in individuals with stroke suggests the beneficial effects of neurorehabilitation are dose-dependent [16].

Although two recently published systematic reviews investigated spinal cord injury rehabilitation approaches, neither provided a detailed analysis of UMP or BMP [17,18]. This review therefore aimed to investigate whether UMP and BMP, delivered alone or with co-interventions, improve upper limb function in adults with cSCI, and to determine the comparative effectiveness of these rehabilitation approaches.

Methods

This review was conducted according to a protocol registered with PROSPERO (CRD42016037365) and reported based on the PRISMA guidelines [19].

Eligibility criteria

Studies were included if they met the following criteria:

- Published or unpublished completed study of any design.
- Reported in English.
- Include adults (aged 16 or over) with cSCI.
- Include UMP and/or BMP.
- Report the primary outcome (change in upper limb function from pre-intervention to post-intervention).

Based on cSCI-specific literature, UMP and BMP were defined as repetitive practice of task-orientated motor activities for a minimum of 2 hours per day, 5 days per week, for 3 weeks, using one upper limb or both upper limbs respectively [7–10]. A minimum training intensity was specified because there is moderate quality evidence that repetitive task training in individuals with stroke is intensity-dependent, with beneficial effects only occurring at high intensities [5].

Secondary outcomes were change in strength, sensation and corticomotor parameters from pre-intervention to post-intervention.

Search strategy

The following electronic databases were searched from inception until 14th April 2016: Cochrane Central Register of Controlled Trials (The Cochrane Library), PubMed, CINAHL, Web of Science, PEDro. Additionally, the reference lists of all relevant studies/reviews were hand searched, and OpenGrey was searched to assist identification of relevant unpublished literature.

The search strategy for PEDro employed the advanced search option based on the title/abstract, therapy, body part and method, while the search strategies for all the other electronic resources were based on MeSH terms and text words related to the study participants, interventions and outcomes (Table A, supplementary information).

Study selection

All studies identified by the searches were screened for eligibility by a single reviewer (AA) based on the title and abstract alone. To minimise the chance of omitting relevant articles the emphasis of this stage was on sensitivity rather than specificity. Full text copies of potentially relevant studies were then assessed for eligibility by two independent reviewers (AA, JA). All disagreements were resolved by discussion; with a third independent reviewer (SA) being available had this been required.

Data collection

Data about each included study's design, participants, interventions, outcomes and results was extracted using a standardised form, based on recommendations from the Cochrane Collaboration [20]. Data extraction was performed by two independent reviewers (AA, JA). All disagreements were resolved using the process described for study selection.

Study appraisal

The risk of bias of each included study was assessed using a modified version of the Cochrane risk of bias tool (Table B, supplementary information). The Cochrane risk of bias tool was designed for use in randomised controlled trials (RCTs) [21] and was therefore modified to enable the same tool to be used in studies with different designs. All modifications were based on suggestions provided by the Agency for Healthcare Research and Quality [22].

The modified risk of bias tool consists of six domains of bias, each comprising one or more items. All the domains and items included in the Cochrane risk of bias tool were included in the modified risk of bias tool; however the random sequence generation and allocation concealment items were only assessed for RCTs. Two additional items were included in the modified risk of bias tool- study design (selection bias domain) and concurrent intervention/unintended exposure (performance bias domain). Assessments for the participants/personnel blinding, outcome assessment blinding and incomplete outcome data items were made for the upper limb functional outcomes only. For each included study the reviewers rated the risk of bias for each applicable item as high, low or unclear.

Risk of bias summary assessments, specific to the upper limb functional outcomes, were made using the approach suggested by the Cochrane Collaboration [20]. Due to the inclusion of randomised and non-randomised studies, and the subjective nature of some upper limb functional outcome measures, selection bias (based on the study design), and detection bias (based on the outcome assessment blinding), were considered the key domains for the summary assessments. All aspects of the risk of bias assessments were performed by three independent reviewers (AA, JA, SA), with disagreements being resolved by discussion.

Study synthesis

The study findings were qualitatively synthesised by considering the following 3 categories: UMP, BMP and UMP versus BMP. Additionally the design, interventions, comparators and functional upper limb outcome measures of the studies were compared to determine if meta-analysis was appropriate.

Results

Study selection

Of the 159 records identified in the searches 44 were removed as duplicates, 93 were excluded based on the title and abstract alone and three were excluded due to being conference presentations with similar titles to published articles by the same authors. Full text eligibility assessments of the remaining 19 articles resulted in inclusion of 7 studies. Full details of the study selection process and the number of records identified from each database are shown Fig. 1 and Table A (supplementary information) respectively.

Study characteristics

Five of the included studies were RCTs [7–9,23,24] and two were case studies [25,26]. Tables 1–3 provide summaries of the participant characteristics, intervention characteristics and results of all the included RCTs. Table 4 provides a summary of the two case studies for reference. These case studies are not discussed further due to the high risk of selection bias of case studies.

The total number of participants across all the RCTs was 91. UMP was included in all five RCTs [7–9,23,24].

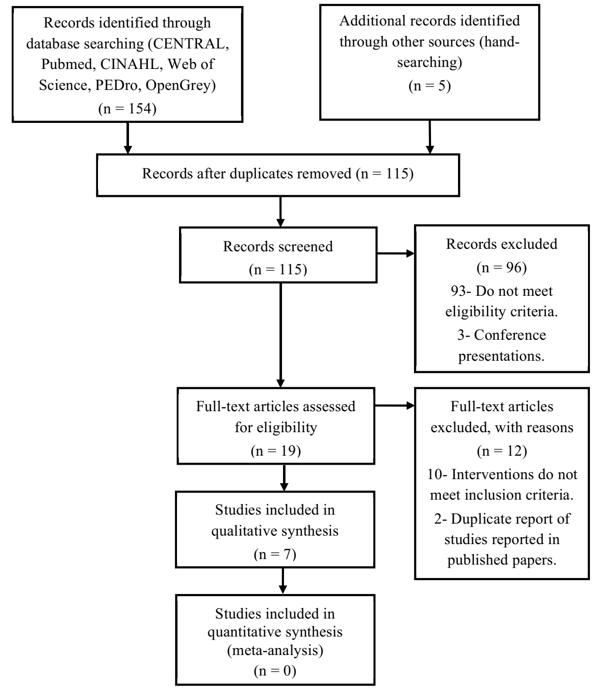

Fig. 1. Flowchart of study selection process.

BMP was included in two RCTs [7,9]. Electrical stimulation was the most commonly used co-intervention, delivered as somatosensory stimulation (SS) – continuous low intensity electrical stimulation which preferentially activates Ia afferent fibres [7–9,23,24], and/or functional electrical stimulation (FES) – higher intensity electrical stimulation which activates muscles, delivered only when muscle activation exceeds a threshold value [9].

Study synthesis

Two of the included studies were pilot studies [7,8] on which two of the other studies were based [9,23]. Furthermore, none of the studies involved the same design, interventions (including co-interventions and upper limb chosen for UMP/electrical stimulation), comparators and functional upper limb outcome measures; therefore a meta-analysis was not performed.

Study results

UMP

UMP was included in all five RCTs [7–9,23,24]. One RCT included UMP + SS, UMP + FES, BMP + SS and BMP + FES groups [9]. This RCT did not report the significance of within group changes in outcomes; however across all participants the Jebsen Taylor Hand Function Test, but not the Chedoke Arm and Hand Activity Inventory, scores improved significantly. The remaining four RCTs all included a UMP + SS group [7,8,23,24]. Three of these RCTs investigated the significance of post-intervention changes, all reporting that the

Table 1
Participant characteristics of all included randomised controlled trials.

Study	Intervention	Number of participants	% Males	Age—mean (SD)	Months post injury—mean (SD)	Neurological level	ASIA classification
Nasser *et al*.2014 [24]	UMP + conventional rehabilitation	10	80	33.2 (6.1)	21.8 (19.1)	50% C5, 40% C6, 10% C7	40% C, 60% D
	UMP + SS + conventional rehabilitation	10	80	38.7 (12.1)	24.1 (22.1)	50% C5, 40% C6, 10% C7	30% C, 70% D
	Conventional rehabilitation	5	60	33.4 (7.1)	18.0 (12.2)	40% C5, 40% C6, 20% C7	40% C, 60% D
Hoffman and Field-Fote 2013 [9]	UMP (SS-II, FES-II, SS-CDI, FES-CDI)	9 (2, 3, 2, 2)	78	31.8 (12.4)	41.3 (47.6)	11% C3, 22% C4, 22% C5, 22% C6, 22% C7	12% B, 56% C, 33% D
	BMP (SS-II, FES-II, SS-CDI, FES-CDI)	10 (4, 2,1,3)	60	48.2 (13.0)	79.2 (102.1)	30% C4, 40% C6, 30% C7	10% A, 20% B, 30% C, 40% D
Hoffman and Field-Fote 2010 [7]	UMP + SS	6	8	42.0 (16.9)	34.0 (14.0)	17% C3, 17% C4, 50% C5	14% B, 57% C, 14% D
	BMP + SS	7	71	34.7 (15.7)	51.96 (48.6)	42% C5, 57% C6	42% B, 57% C
Beekhuizen and Field-Fote 2008 [23]	UMP	6	100	34.7 (14.9)	47.5 (34.0)	17% C4, 33% C5, 33% C6, 17% C7	33% C, 67% D
	UMP + SS	6	83	47.8 (20.0)	66.8 (264.0)	50% C5, 33% C6, 17% C7	50% C, 50% D
	SS	6	100	34.5 (15.0)	72.12 (15.0)	66% C5, 17% C6, 17% C7	50% C, 50% D
	Control	6	83	33.3 (6.9)	82.6 (49.9)	66% C5, 17% C6, 17% C7	50% C, 50% D
Beekhuizen and Field-Fote 2005 [8]	UMP	5	100	45.0 (10.3)	58.6 (56.2)	20% C5, 80% C6	20% C, 80% D
	UMP + SS	5	80%	32.6 (8.0)	29.6 (12.1)	40% C5, 40% C6, 20% C7	60% C, 40% D

ASIA—American Spinal Cord Injury Association, BMP—bimanual massed practice, CDI—control/delayed intervention group, II—immediate intervention group, SS—somatosensory stimulation, UMP—unimanual massed practice.

Table 2
Intervention characteristics of all included randomised controlled trials.

Study	Intervention components	Intensity
Nasser *et al*. 2014 [24]	UMP, SS: standard formats. UMP/SS delivered to upper limb with lower ASIA motor score. Conventional rehabilitation—no details provided.	2 hours/day, 5 days/week for 3 weeks
Hoffman and Field-Fote 2013 [9]	UMP, BMP, SS: standard formats. FES—delivery of trains of electrical stimulation over median nerve at wrist at 120% of intensity required to cause observable twitch. Only delivered when muscle activation exceeded set threshold. UMP/SS/FES delivered to upper limb with lower ASIA motor score unless voluntary control of this limb's thenar muscles lacking or participant unable to perform any items on Jebsen Taylor Hand Function Test with this limb, in which case contralateral limb trained/stimulated[a]. Participants allocated to II started intervention immediately. Participants allocated to CDI had 3 week waiting period prior to commencing intervention. Regular activities only performed during waiting period.	2 hours/day, 5 days/week for 3 weeks.
Hoffman and Field-Fote 2010 [7]	UMP, BMP, SS: standard formats UMP/SS delivered to weaker upper limb unless voluntary control of this limb's thenar muscles lacking, in which case contralateral limb trained/stimulated.	2 hours/day, 5 days/week for 3 weeks
Beekhuizen and Field-Fote 2008 [23]	UMP, SS: standard formats. UMP/SS delivered to weaker upper limb unless voluntary control of this limb's thenar muscles lacking, in which case contralateral limb trained/stimulated. Participants in control group received no organised therapy and were instructed to continue their typical daily routines.	2 hours/day, 5 days/week for 3 weeks
Beekhuizen and Field-Fote 2005 [8]	UMP, SS—standard formats. UMP/SS delivered to upper limb with lower ASIA motor score.	2 hours/day, 5 days/week for 3 weeks

ASIA—American Spinal Cord Injury Association, BMP—bimanual massed practice, CDI—control/delayed intervention group, FES—functional electrical stimulation, II—immediate intervention group, SS—somatosensory stimulation, UMP—unimanual massed practice.
UMP standard format—repetitive practice of functional tasks from five different movement categories using one upper limb only.
BMP standard format—repetitive practice of functional tasks from five different movement categories using both upper limbs.
SS standard format—continuous delivery of trains of electrical stimulation over median nerve at wrist at intensity just below that required to cause observable twitch.
[a] Additional information for Hoffman and Field-Fote (2013) [9] obtained from Hoffman (2008) [35].

UMP + SS group showed significant improvements in all the functional upper limb outcomes assessed [7,8,24].

Three RCTs included an intervention group that received UMP without concurrent electrical stimulation [8,23,24], two of which reported within group changes in outcomes [8,24]. The UMP group showed significant improvements in Jebsen Taylor Hand Function Test scores in both these RCTs, but Wolf Motor Function Test scores in one RCT only [24]. Of the three RCTs which compared UMP and UMP + SS groups, one reported no significant differences in the improvements in Jebsen Taylor Hand Function Test and Wolf Motor Function Test scores between these two groups [24], while the other two RCTs reported that the UMP + SS group showed significantly greater improvements in Jebsen Taylor Hand Function Test and Wolf Motor Function Test scores than the UMP group [8,23].

The changes in secondary outcomes varied between RCTs. Two RCTs reported that the UMP + SS group showed significantly greater improvements in maximal pinch grip strength than the UMP group [8,24]; however one RCT found no significant difference in the change in maximal pinch grip strength between these two groups [23]. Neither of the two RCTs which compared the changes in sensory sensitivity of the UMP + SS and UMP groups found any significant differences for the comparison [23,24]. Two RCTs did however report significant improvements in sensory sensitivity in the UMP + SS group [7,24], and one RCT reported that the UMP + SS group showed a significantly greater improvement in sensory sensitivity than the control group [8]. Although one RCT reported that the thenar muscle motor threshold decreased significantly in the UMP + SS and UMP groups compared to the control group [23], another RCT reported no significant changes in this outcome for the UMP + SS and UMP groups [8].

BMP

BMP was included in two RCTs [7,9]. The BMP + SS group of one RCT showed significant improvements in Jebsen Taylor Hand Function Test and Chedoke Arm and Hand Activity Inventory scores and sensory sensitivity [7]. The remaining RCT did not report within group changes in

Table 3
Results of all included randomised controlled trials.

Study	Upper limb functional outcome measures (units)	Other outcome measures (units)	Results (statistically significant differences only)	
			Within group changes from pre- to post-intervention (mean (SD))	Between group difference in means
Nasser et al. 2014 [24][a]	Jebsen Taylor Hand Function Test (s) Wolf Motor Function Test timed task scores (s)	Maximal pinch grip strength (psi) ASIA motor scores ASIA sensory scores	*UMP group* Jebsen Taylor Hand Function Test: -68 (46) Wolf Motor Function Test: -68 (66) Maximal pinch grip strength: 0.2 (0.3) ASIA motor scores ($p < 0.001$): values not provided *UMP + SS group* Jebsen Taylor Hand Function Test: -80 (88) Wolf Motor Function Test: -90 (111) Maximal pinch grip strength ($p < 0.001$): 0.7 (0.3) ASIA motor scores ($p < 0.001$): values not provided ASIA light touch and pinprick sensory scores: 0.7 (0.5) *Control group* No significant changes	*UMP group versus control group* Greater increase in ASIA motor score in UMP group: values not provided *UMP + SS group versus control group* Greater increase in maximal pinch grip strength in UMP + SS group: 0.6 Greater increase in ASIA motor score in UMP + SS group ($p < 0.001$): values not provided *UMP group versus UMP + SS group* Greater increase in maximal pinch grip strength in UMP + SS group: 0.5
Hoffman and Field-Fote 2013 [9]	Jebsen Taylor Hand Function Test (s) Chedoke Arm and Hand Activity Inventory	Maximal pinch grip strength (lbs) Semmes-Weinstein Monofilament Test Thenar muscle corticomotor outcomes: map area (cm^2), map volume (cm^3), map centre of gravity[b] (longitudinal direction in cm), motor threshold[b] (% maximal stimulator output), maximum motor evoked potential[b] (% M-wave), maximum slope of recruitment curve[b]	*Significance of within group changes in outcomes not reported for UMP, BMP, SS or FES groups individually* *All participants* Jebsen Taylor Hand Function Test ($p < 0.001$) • UMP group: -70 (104) • BMP group: -45 (47) • SS group: -66 (98) • FES group: -48 (58) Corticomotor map area • UMP group: 11 (9) • BMP group: 7 (4) • SS group: 3 (4) • FES group: 12 (5)	*Significance of between group differences in corticomotor outcomes not reported from UMP versus BMP and SS versus FES groups (only fourteen participants completed testing for corticomotor outcomes)* *UMP group versus BMP group* Greater improvement in Chedoke Arm and Hand Activity Inventory in BMP group: 5 *SS group versus FES group* No significant between group differences for any clinical outcomes identified *Immediate intervention versus control/delayed intervention group* Greater improvement in Jebsen Taylor Hand Function Test in immediate intervention group: -81 Greater increase in corticomotor map area in immediate intervention group: 8

Table 3 (*Continued*)

Study	Upper limb functional outcome measures (units)	Other outcome measures (units)	Results (statistically significant differences only)	
			Within group changes from pre- to post-intervention (mean (SD))	Between group difference in means
Hoffman and Field-Fote 2010 [7]	Jebsen Taylor Hand Function Test (s) Chedoke Arm and Hand Activity Inventory	Maximal pinch grip strength (lbs) Semmes-Weinstein Monofilament Test Thenar muscle corticomotor outcomes: map area (cm^2), map centre of gravity (shift in cm), motor threshold (% maximal stimulator output), normalised map volume[b] (cm^3).	*UMP + SS group* Jebsen Taylor Hand Function Test: -92 (16) Chedoke Arm and Hand Activity Inventory: 2 (1) Semmes-Weinstein Monofilament Test: specific values not clear *BMP + SS group* Jebsen Taylor Hand Function Test: -47 (37) Chedoke Arm and Hand Activity Inventory: 4 (2) Semmes-Weinstein Monofilament Test: specific values not clear *Significance of within group changes in corticomotor outcomes not reported for UMP + SS or BMP + SS groups individually* *All participants who completed corticomotor testing* Map area bordered on significance ($p = 0.05$): 4 (SD not provided)	*Significance of between group differences in corticomotor outcomes not reported (only six individuals completed testing for corticomotor outcomes)* *UMP + SS group versus BMP + SS group* No significant between group differences for any clinical outcomes identified
Beekhuizen and Field-Fote 2008 [23]	Jebsen Taylor Hand Function Test (s) Wolf Motor Function Test timed task scores (s)	Maximal pinch grip strength (kg) Semmes-Weinstein Monofilament Test (%) Thenar muscle Corticomotor outcomes: motor threshold (% maximal stimulator output)	Significance of within group changes in outcomes not reported for individual groups or all participants	*One participant was excluded from testing for corticomotor outcomes* *UMP group versus control group* Greater improvement in Jebsen Taylor Hand Function Test in UMP group: -128 Greater improvement in motor threshold in UMP group ($p < 0.001$): -12 *SS group versus control group* Greater improvement in Jebsen Taylor Hand Function Test in SS group: -50 Greater improvement in Wolf Motor Function test in SS group: -13 Greater improvement in maximal pinch grip strength in SS group: 3 *UMP + SS group versus control group* Greater improvement in Jebsen Taylor Hand Function Test in UMP + SS group ($p < 0.001$): -89 Greater improvement in Wolf Motor Function test in UMP + SS group ($p < 0.001$): -27 Greater improvement in maximal pinch grip strength in UMP + SS group: 3 Greater improvement in Semmes-Weinstein Monofilament Test in UMP + SS group: 3 Greater improvement in motor threshold in UMP + SS group ($p < 0.001$): -14

				UMP group versus SS group No significant between group differences for any outcomes identified *UMP group versus UMP + SS group* Greater improvement in Jebsen Taylor Hand Function Test in UMP + SS group: 39[c] Greater improvement in Wolf Motor Function test in UMP + SS group: -13 *SS group versus UMP + SS group* Greater improvement in Jebsen Taylor Hand Function Test in UMP + SS group: -39 Greater improvement in Wolf Motor Function test in UMP + SS group: -15
Beekhuizen and Field-Fote 2005 [8]	Jebsen Taylor Hand Function Test (%) Wolf Motor Function Test (timed task scores only) (%)	Maximal pinch grip strength (%) Thenar muscle corticomotor outcomes: motor threshold (% maximal stimulator output), motor evoked potential amplitude at 1.2 × motor threshold (mV)	*UMP group* Jebsen Taylor Hand Function Test: 11 (14) *UMP + SS* Jebsen Taylor Hand Function Test: 33 (17) Wolf Motor Function Test: 52 (22) Maximal pinch grip strength: 190 (255)	*Two participants were excluded from testing for corticomotor outcomes* *UMP group versus UMP + SS group* Greater improvement in Jebsen Taylor Hand Function Test in UMP + SS group: 22 Greater improvement in Wolf Motor Function Test in UMP + SS group: 46 Greater improvement in maximal pinch grip strength in UMP + SS group: 173

ASIA- American Spinal Cord Injury Association, BMP- bimanual massed practice, FES- functional electrical stimulation, psi- pounds per square inch, S-seconds, SS- somatosensory stimulation, UMP- unimanual massed practice.

Negative values for changes in the Jebsen Taylor Hand Function Test and Wolf Motor Function Test timed task scores indicate improvements in upper limb function (unless reported as percentage change).

Unless otherwise stated, $p < 0.05$.

[a] Precaution should be taken when interpreting Nasser et al. (2014) [24] because the statistical analysis used to interpret mean differences within and between groups was not acceptable for their study design. Their results are thus a reflection of multiple comparisons which would likely have led to false positive findings.

[b] Additional information for Hoffman and Field-Fote (2013) [9] and Hoffman and Field-Fote (2010) [7] obtained from Hoffman (2008) [35]. No additional information from Beekhuizen (2004) [36] included in Beekhuizen and Field-Fote (2008) [23] due to different statistical tests being used and contradictory findings being reported.

[c] Based on additional information reported in Beekhuizen (2004) [36] the positive difference in means appears to be due to percentage change in Jebsen Taylor Hand Function Test, rather than actual values, being used for the between group comparison; however this is not stated in Beekhuizen and Field-Fote (2008) [23].

Table 4
Summary of all included case studies.

Study	Participant characteristics	Intervention	Results	Risk of bias judgements
Kim *et al.* 2015 [25]	35 year old	3 hours of modified constraint-induced movement therapy followed by 1 hour of functional bimanual task training per day, 5 days/week for 3 weeks.	Box & Block Test: 6	Type of study design[a]: high
	Gender and time post injury not stated	Modified constraint-induced movement therapy: practice of daily activity tasks with left (weaker) upper limb only whilst wearing mitten on right upper limb.	Left Manual Function Test: 2	Blinding of participants and personnel[b]: Box & Block Test high, Manual Function Test high
	Neurological level C4	Bimanual task training: practice of daily activity tasks using both upper limbs simultaneously.		Concurrent intervention/unintended exposure: unclear
	ASIA classification D			Blinding of outcome assessment[b]: Box & Block Test low, Manual Function Test unclear Incomplete outcome data[b]: Box & Block Test low, Manual Function Test low Selective reporting: high Previous interventions: unclear Within study summary assessment[b]: Box & Block Test high, Manual Function Test high
Hoffman and Field-Fote 2007 [26]	22 year old male	BMP and SS for 2 hours/day, 5 days/week for 3 weeks. SS only delivered to right (stronger) upper limb.	Jebsen Taylor Hand Function Test: right −57s, left 12s	Type of study design[a]: high
	12 months post-injury	BMP: repetitive practice of functional tasks from 5 different movement categories using both upper limbs.	Chedoke Arm and Hand Activity Inventory: 10	Blinding of participants and personnel[b]: Jebsen Taylor Hand Function Test high, Chedoke Arm and Hand Activity Inventory high
	Neurological level C6	SS: continuous delivery of trains of electrical stimulation over median nerve at wrist at intensity just below that required to cause observable twitch.	ASIA motor score: right triceps 1, left triceps 1	Concurrent intervention/unintended exposure: low
	ASIA classification B	Participant instructed to maintain current exercise programme and not participate in any new therapies/exercises during course of intervention.	ASIA light touch and pinprick sensory score: right C6-T1 dermatomes 1 or 2, left C5 dermatome 1	Blinding of outcome assessment[b]: Jebsen Taylor Hand Function Test low, Chedoke Arm and Hand Activity Inventory high
			Semmes-Weinstein Monofilament Test: right (median diameter): −0.8mm, left no change Corticomotor outcomes: map area 9 cm^2, map volume 8 cm^3, map centre of gravity 1.6 cm anteriorly, 0.3 cm medially, motor threshold no change.	Incomplete outcome data[b]: Jebsen Taylor Hand Function Test low, Chedoke Arm and Hand Activity Inventory low Selective reporting: high
				Previous interventions: low Within study summary assessment[b]: Jebsen Taylor Hand Function Test high, Chedoke Arm and Hand Activity Inventory high

ASIA—American Spinal Cord Injury Association, BMP—bimanual massed practice, S-seconds, SS—somatosensory stimulation, Negative values for changes in the Jebsen Taylor Hand Function Test and Semmes-Weinstein Monofilament Test indicate improvements in upper limb function and sensation respectively.

[a] Random sequence generation and allocation concealment items not included in risk of bias assessments due to case study design.

[b] Assessments made for upper limb functional outcome measures only.

outcomes (see preceding section for changes across all participants) [9].

UMP versus BMP

The effects of UMP and BMP were compared in two RCTs, one combining UMP/BMP with SS [7], the other combining UMP/BMP with SS or FES [9]. One RCT reported that the BMP + SS/FES group showed significantly greater improvements in Chedoke Arm and Hand Activity Inventory scores than the UMP + SS/FES group [9]; however the other RCT did not support this finding [7]. Both RCTs reported that the change in Jebsen Taylor Hand Function Test did not vary significantly between the UMP + SS/(FES) and BMP + SS/(FES) groups, although one of these RCTs was underpowered to detect between group differences in the Jebsen Taylor Hand Function Test, and trends in its data suggested that the UMP + SS group progressed more than the BMP + SS group in the Jebsen Taylor Hand Function Test [7].

Both RCTs assessed maximal pinch grip strength and sensory sensitivity; however neither RCT identified significant between group differences for these outcomes [7,9]. Between group differences in the corticomotor outcomes were not investigated in either RCT.

Study appraisal

The risk of bias judgements for all the included RCTs are displayed in Table 5. Justifications for the risk of bias judgements for all the included studies are available in Table C (supplementary information).

The overall risk of bias within three RCTs for all the functional upper limb outcomes reported [8,23,24], and within one RCT for the Jebsen Taylor Hand Function Test [9], was unclear, because these studies presented a low risk of bias for study design and outcome assessment blinding, but an unclear risk of bias for at least three additional items. The overall risk of bias for the Chedoke Arm and Hand Activity Inventory within one RCT was high, because this study presented a high risk of bias for four individual items, including outcome assessment blinding [9]. The overall risk of bias within the remaining RCT for the Jebsen Taylor Hand Function Test was low, because this study presented a low risk of bias for study design, outcome assessment blinding and four additional items [7]. This RCT's overall risk of bias for the Chedoke Arm and Hand Activity Inventory was however unclear, as it was not stated if the outcome assessors were blinded and the Chedoke Arm and Hand Activity Inventory involves subjective judgements.

Discussion

This review aimed to investigate the effects of UMP and BMP on upper limb function in adults with cSCI. Despite employing broad eligibility criteria only two case studies and five RCTs were included (Table 1) [7–9,23,26]. The overall risk of bias for all the functional upper limb outcomes in both case studies and four of the RCTs was high or unclear (Table 4) [8,9,23–26]. Although the remaining RCT presented a low risk of bias for the Jebsen Taylor Hand Function Test it was a small pilot study with no control group [7]. Robust conclusions based on the studies included in this review cannot therefore be drawn.

The findings of the latter pilot study suggested that both UMP and BMP, combined with SS, improve upper limb function in adults with chronic cSCI, and that these interventions are equally effective [7]. However, given that the study lacked a control group and the Jebsen Taylor Hand Function Test is influenced by learning [27], it is not known whether the changes made from baseline reflected true improvements or simply learning effects. Additionally the study was underpowered to detect significant between group differences, which is an important consideration given that trends in this study's data suggested the UMP + SS group improved more than the BMP + SS group in the Jebsen Taylor Hand Function Test (Table 3). The low power of this study also reduces the likelihood that the post-intervention improvements in Jebsen Taylor Hand Function Test scores were true positives [28].

Given the above pilot study's limitations [7], the same research group performed a follow-up RCT involving UMP + SS/FES or BMP + SS/FES groups [9]. This RCT employed a delayed intervention design to allow comparison of intervention and control groups. The change in Jebsen Taylor Hand Function Test scores did not differ significantly between the UMP + SS/FES and BMP + SS/FES groups; however the intervention group showed significantly greater improvements in Jebsen Taylor Hand Function Test scores than the control group (Table 3) [9]. Since the Jebsen Taylor Hand Function Test involves one upper limb only, this suggests UMP/BMP + SS/FES improves unimanual function.

In contrast the scores for the Chedoke Arm and Hand Activity Inventory, which involves both upper limbs, did not differ significantly between the intervention and control groups (Table 3) [9]. The authors suggested that, because the BMP + SS/FES group showed a significantly greater improvement in Chedoke Arm and Hand Activity Inventory scores than the UMP + SS/FES group, pooling of the training groups weakened the mean difference used in the comparison with the control group [9]. It could therefore be argued that BMP should be used if the focus is on improving bimanual function, and hence may be a more useful rehabilitation approach given that the majority of daily tasks involve both hands [13]. However, this RCT presented a high risk of bias for the Chedoke Arm and Hand Activity Inventory, involved multiple comparisons and its sample size was below that suggested by the power calculation (Table 1, Table 5) therefore firm recommendations cannot be made from this study.

Three RCTs included UMP and UMP + SS groups; however one of the studies lacked clarity about whether its methodology met the requirements of an RCT and employed inappropriate statistical analyses, with its use of multiple t-tests increasing the risk of type I errors (false positives) [24].

Table 5
Risk of bias judgments for all included randomised controlled trials.

	Nasser *et al*. 2014 [24]	Hoffman and Field-Fote 2013 [9]	Hoffman and Field-Fote 2010 [7]	Beekhuizen and Field-Fote 2008 [23]	Beekhuizen and Field-Fote 2005 [8]
Type of study design	Low	Low	Low	Low	Low
Random sequence generation	Unclear	Unclear	Low	Unclear	Low
Allocation concealment	Unclear	Unclear	Low[b]	Unclear	Unclear
Blinding of participants and personnel[a]	Jebsen Taylor Hand Function Test: high Wolf Motor Function Test: high	Jebsen Taylor Hand Function Test: high Chedoke Arm and Hand Activity Inventory: high	Jebsen Taylor Hand Function Test: high Chedoke Arm and Hand Activity Inventory: high	Jebsen Taylor Hand Function Test: high Wolf Motor Function Test: high	Jebsen Taylor Hand Function Test: high Wolf Motor Function Test: high
Concurrent intervention/unintended exposure	Low	Unclear	Low[b]	Unclear	Unclear
Blinding of outcome assessment[a]	Jebsen Taylor Hand Function Test: low Wolf Motor Function Test: low	Jebsen Taylor Hand Function Test: low Chedoke Arm and Hand Activity Inventory: high	Jebsen Taylor Hand Function Test: low Chedoke Arm and Hand Activity Inventory: unclear	Jebsen Taylor Hand Function Test: low Wolf Motor Function Test: low	Jebsen Taylor Hand Function Test: low Wolf Motor Function Test: low
Incomplete outcome data[a]	Jebsen Taylor Hand Function Test: low Wolf Motor Function Test: low	Jebsen Taylor Hand Function Test: high Chedoke Arm and Hand Activity Inventory: high	Jebsen Taylor Hand Function Test: low[b] Chedoke Arm and Hand Activity Inventory: low[b]	Jebsen Taylor Hand Function Test: low[c] Wolf Motor Function Test: low[c]	Jebsen Taylor Hand Function Test: unclear Wolf Motor Function Test: unclear
Selective reporting	High	High[b]	High[b]	High	High
Previous interventions	Unclear	Unclear	Unclear	Unclear	Unclear
Within study summary assessment[a]	Jebsen Taylor Hand Function Test: unclear Wolf Motor Function Test: unclear	Jebsen Taylor Hand Function Test: unclear Chedoke Arm and Hand Activity Inventory: high	Jebsen Taylor Hand Function Test: low Chedoke Arm and Hand Activity Inventory: unclear	Jebsen Taylor Hand Function Test: unclear Wolf Motor Function Test: unclear	Jebsen Taylor Hand Function Test: unclear Wolf Motor Function Test: unclear

[a] Assessments made for upper limb functional outcome measures only.
[b] Additional information for Hoffman and Field-Fote (2013) [9] and Hoffman and Field-Fote (2010) [7] obtained from Hoffman (2008) [35].
[c] Additional information for Beekhuizen and Field-Fote (2008) [23] obtained from Beekhuizen (2004) [36].

Additionally one of the RCTs was a pilot study with no control group [8]. A subsequent study performed by the same research group included UMP, SS, UMP + SS and control groups [23]. Although all three intervention groups showed significantly greater improvements in Jebsen Taylor Hand Function Test scores than the control group, only the SS and UMP + SS groups showed significantly greater improvements than the control group in Wolf Motor Function Test scores (Table 3), suggesting SS may be superior to UMP when either intervention is delivered in isolation. Furthermore the UMP + SS group showed significantly greater improvements in Jebsen Taylor Hand Function Test and Wolf Motor Function Test scores than the UMP and SS groups. The UMP + SS group also showed the greatest improvements in sensory sensitivity and strength (Table 3), corresponding with evidence that sensation and strength are key determinants of upper limb function [29]. However, given this study's unclear risk of bias for the Jebsen Taylor Hand Function Test and Wolf Motor Function Test and its small sample size, these findings should be interpreted cautiously.

Although no previous systematic reviews have specifically investigated the effects of UMP and BMP post-cSCI, these interventions have been included in systematic reviews investigating the broader topics of exercise therapy and physiotherapy interventions post-cSCI [17,18,30,31]. The results of the present review are largely consistent with these previous reviews, all of which reported that, although the current evidence suggests exercise therapy/physiotherapy interventions improve upper limb function post-cSCI, there are only a limited number of studies in this area, mostly with small sample sizes.

Limitations

This review has various limitations. Firstly, only seven studies, two of which were case studies, were included and no meta-analysis was performed. The search strategy was limited to English and no experts in the field were contacted to assist study selection; hence potentially relevant studies may have been missed. Furthermore, it could be argued that the UMP and BMP definitions used in this review were too restrictive due to the intensity of practice required. This may also have resulted in relevant studies being missed.

Due to the dearth of research in this area, and the fact that many SCI intervention studies do not include a control group [14], this review employed broad eligibility criteria. This resulted in inclusion of studies involving participants with heterogeneous clinical characteristics, especially regarding the level and completeness of cSCI, making it difficult to draw conclusions about the effectiveness of the interventions based on group data [32]. It also resulted in inclusion of case studies, which present a particularly high risk of bias [20]. To account for this a modified version of the Cochrane risk of bias tool was used. Arguably the case studies contribute little to this review and should have been excluded to allow use of the original risk of bias tool; however this was not performed to ensure adherence to the registered protocol.

The included studies employed generic functional upper limb outcome measures, all of which present significant limitations when used in individuals with cSCI. For example the Jebsen Taylor Hand Function Test is affected by learning, fails to detect changes in intrinsic muscles and includes tasks which are unrepresentative of those performed by individuals with cSCI [27,33]. Finally all the included studies were limited by a lack of long-term follow-up.

Future research

Given the encouraging findings of the studies included in this review the reasons for the paucity of research investigating UMP and BMP post-cSCI is not clear. Five of the seven included studies were from the same research group; therefore raising the profile of this research area is vital. Future studies should investigate UMP and BMP delivered in isolation, to help determine whether concurrent delivery of electrical stimulation is critical to their effectiveness. The UMP and BMP protocols employed in the included studies were largely similar in intensity and content (Table 2). Given evidence suggests repetitive task training in individuals with stroke is intensity-dependent [5], there is a need to investigate the effects of different UMP and BMP training intensities in individuals with cSCI. This would help determine the true effectiveness of these interventions and facilitate development of optimal training protocols.

All the RCTs only included participants who were at least 6 months post-injury (Table 1). Early initiation of SCI-specific rehabilitation is crucial to improving functional capability [14,34]; hence research investigating UMP and BMP at earlier stages post-cSCI is warranted.

Conclusion

The small number of studies included in this review and the considerable limitations of all the included studies mean that robust conclusions cannot be drawn. The limited evidence currently available does however suggest that UMP and BMP may help improve upper limb function in adults with cSCI, particularly when combined with electrical stimulation. Future high quality research is therefore warranted to investigate the effectiveness of UMP and BMP in individuals with cSCI in order to guide if, when and how these interventions should be applied in clinical practice.

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Key messages

- Improving upper limb function is considered to be an important rehabilitation goal among individuals with cervical spinal cord injury (cSCI). This paper reviews studies investigating two rehabilitation approaches, unimanual massed practice (UMP) and bimanual massed practice (BMP), which may help achieve this.
- This systematic review highlights that, although both UMP and BMP appear to be promising approaches for improving upper limb function in adults with cSCI, particularly when combined with electrical stimulation, research in this area is currently very limited.
- This demonstrates a clear need for further research investigating UMP and BMP post-cSCI, including consideration of how co-interventions, the intensity of practice and participants' clinical characteristics influence the effectiveness of these rehabilitation approaches.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.physio.2018.10.003.

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