JOURNAL OF MANUAL & MANIPULATIVE THERAPY
2020, VOL. 28, NO. 1, 4–14
https://doi.org/10.1080/10669817.2019.1569300

The effects of spinal manipulative therapy on lower limb neurodynamic test outcomes in adults: a systematic review

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ABSTRACT

Objective: Spinal Manipulative Therapy (SMT) is a routinely applied treatment modality for various musculoskeletal conditions, including low back pain. The precise mechanisms by which SMT elicits its effects are largely unknown, but recent research supports a multi-system explanation recognizing both biomechanical and neurophysiological mechanisms. Although the evaluation of changes in clinical presentation is complex, objective neurophysiological measures of sensitivity to movement (e.g. neurodynamic tests) can be a valuable clinical indicator in evaluating the effects of SMT. This review aimed to synthesize current literature investigating the effects of SMT on lower limb neurodynamics.

Method: Eight electronic databases were systematically searched for randomized controlled trials (RCT) that applied SMT (against any control) and evaluated lower limb neurodynamics (Passive Straight Leg Raise or Slump Test). Selection and data extraction were conducted by one researcher, reviewed by a second author. Risk of bias (RoB) was assessed using the Cochrane Back Review Group criteria.

Results: Eight RCTs were included, one with high RoB. SMT produced a clinically meaningful ($\geq 6^0$) difference in five of these studies compared with inert control, hamstring stretching, and as an adjunct to conventional physiotherapy, but not compared with standard care, as an adjunct to home exercise and advice, or when comparing different SMT techniques. Findings compared to sham were mixed. When reported, effects tentatively lasted up to 6 weeks post-intervention.

Conclusion: Limited evidence suggests SMT-improved range of motion and was more effective than some other interventions. Future research, using standardized Neurodynamic tests, should explore technique types and evaluate longer-term effects.

Level of Evidence: 1a

KEYWORDS

Low back pain; passive straight leg raise; randomized controlled trials; spinal mobilization; spinal manipulation

Introduction

Non-specific low back pain (NSLBP) is the most common musculoskeletal condition affecting the adult population, with a prevalence of up to 84%, costing the United Kingdom approximately £500 million annually [1,2]. While there appears to be a consensus within NSLBP clinical guidelines recommending treatment approaches such as exercise prescription, there continues to be inconsistent recommendations relating to the treatment efficacy of spinal manipulative therapy (SMT) [3]. SMT is a commonly applied treatment for NSLBP used by a variety of health professionals, including physiotherapists, osteopaths, and chiropractors [4]. It is a 'hands on' treatment applied to the spinal column, encompassing spinal manipulation and/or spinal mobilization [5]. The continued inconsistencies in guidelines and ongoing debate concerning the efficacy of SMT largely stems from the lack of understanding of perceived mechanisms involved in the application of SMT and how exactly they mediate the experience of pain [6].

Earlier research solely attributed the effects of SMT to be as a result of biomechanical mechanisms alone [7–10]. In the last decade, there has been a growing recognition of the multi-systems effect of SMT, also including neurophysiological and supraspinal-mediated mechanisms [11]. The effects of SMT have been shown to reduce levels of inflammatory pain biomarkers [12], reduce spinal cord-mediated responses [13–20]), and reduce activation within brain regions associated with pain processing [21,22]. The beneficial effects of SMT have also been attributed to supraspinally mediated mechanisms such as placebo effects, patient expectations, and psychosocial factors (e.g. fear) [23–25]. Therefore, in order to provide further clarity to clinicians on the treatment efficacy of SMT, it is crucial that we evaluate the effects of SMT on NSLBP recognizing the multiple mechanisms involved.

To date, there have been numerous systematic reviews evaluating the effects of SMT, showing positive treatment effects in relation to improving pain and function in adults with acute and chronic NSLBP

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[5,26–28] as well as asymptomatic populations with experimentally induced LBP [29]. Research investigating the effects of SMT has increasingly included neurophysiological outcome measures, with studies demonstrating changes in skin conductance and temperature [30–33]. While these measures provide valuable information, it has been suggested that there is a need to include more clinically meaningful outcome measures, such as changes in neurophysiological sensitivity to movement (i.e. neurodynamics [31,34]).

Heightened sensitivity to movement is a common clinical finding within the NSLBP population [35,36]. It is considered that this heightened sensitivity (due to adverse neurodynamics) describes abnormal neural tissue mobility, involving both mechanical and physiological mechanisms, resulting from excessive mechanical stress, and/or non-mechanical inputs from a peripherally and centrally up-regulated nervous system [37–41]. Studies evaluating the effects of SMT have demonstrated improvements in upper limb neurodynamics following the application of cervical spine mobilizations in both symptomatic (neck pain) and asymptomatic individuals [42]. To date, there have been no reviews conducted evaluating the effects of SMT on lower limb neurodynamics. Given the higher proportion of individuals reporting symptoms in the distribution of the L5 or S1 dermatomes [43], tests evaluating 'posterior chain' neurodynamics (i.e. passive straight leg raise test (PSLR) or Slump tests) are of particular interest assessing the sciatic nerve and associated nerve root (L4–S3) sensitivity [44,45]. Such tests form a routine component of the neurological assessment of individuals with NSLBP and have been shown to have a good level of reliability and validity [44,46–48].

Therefore, this systematic review aims to investigate the limited literature available evaluating the effect SMT on lower limb neurodynamics. Both symptomatic and asymptomatic populations were included to determine if a similar magnitude of change was evident between those with NSLBP and healthy population (as found in relation to upper limb neurodynamics [42]). The findings of this review will provide further insight into the effects of SMT providing additional evidence to inform clinical guidelines for the treatment of NSLBP.

Methods

The content and structure of the review were guided by the updated Cochrane Handbook for Systematic Reviews of Interventions, PRISMA 2009 and PRISMA-P checklists [49–51]. All screening, data extraction, and assessment of risk of bias (RoB) were performed by a single researcher (CM), and reviewed by a second researcher (DL), with consensus achieved through discussion. Eight electronic databases were searched (until 3 February 2018) for combinations of intervention and outcome measure (see Appendix A: SupplementalMaterial Table 1) and reference lists were hand-searched. The protocol of this review was not registered a priori.

Randomized controlled trials (RCTs), that recruited adult participants (≥18 years, asymptomatic or symptomatic) from any setting, applied SMT (mobilization and/or manipulation) and assessed posterior chain lower limb neurodynamics (PSLR test; Slump test) were included in the review. The SMT intervention could be combined with an alternative intervention provided the specific treatment effects of SMT on

Table 1. Comparison Groups used in included studies.

Types of Comparators	Study	Details of comparator groups
Inert intervention	Ganesh et al., 2015 [58] (2 arms)	Inert intervention: Prone lying for 3 min
Sham SMT	Vieira-Pellenz et al., 2014 [62] (2 arms)	Sham: Side lying position with hips and knees flexed for same time as intervention
	Wood and Moran, 2011 [63] (3 arms)	Sham: Prone lying with the application of low amplitude oscillation to lower lumbar (L4/5) skin and soft-tissue in lateral direction. Control: Supine lying for 3 min and 40 s
Other interventions	Szlezak et al., 2011 [61] (3 arms)	Other intervention: Static Hamstring stretching as per the PSLR protocol (ipsilateral side to tested leg) for 3 min at R1 Control group: Supine lying for 3 min
	Andersson et al., 1999 [56] (2 arm)	Other intervention: 8 Visits of 'Standard Care' involving a combination of analgesics, anti-inflammatories, Active Physiotherapy, Ultrasound, Diathermy, Hot/cold packs, back corset, TENS, 10 min educational lower back pain video.
Adjunct intervention alone	Bronfort et al., 2014 [57] (2 arms)	Adjunct Intervention: Home Exercise and Advice – four visits (1 h each) involving positioning, stabilization exercises with printed instructions, postural advice, pain management techniques, Modified back in action book.
	Kumar & Cherian, 2011 [59] (2 arms)	Adjunct Intervention: Conventional Physiotherapy – 5 min of intermittent lumbar traction, 15 min of heat, home exercise program handouts.
Different SMT techniques to one another and to a control	Pollard & Ward, 1998 [60] (3 arms)	Other interventions: (1) Upper Cervical Spine Manipulation involving a rotatory double index contact style to C1 with the side of application chosen at random, (2) Sacroiliac Joint Manipulation involving a lumbar pisiform contact to the sacroiliac joint with the side of application chosen at random. Control: Digital pressure on mastoid process bilaterally for 30 s x 3

neurodynamics could be determined. The control group could involve no treatment, sham, placebo, or an alternative conventional treatment. Articles not available with full text in English were excluded.

Articles were screened for inclusion by title, abstract, and full text. Study authors were contacted via e-mail if missing data were identified or if the article was inaccessible in full text.

The Cochrane Data Extraction Template for systematic reviews [52] was adapted following pilot-testing on a randomly selected study [49] to include items in relation to SMT dosage and implementation of the outcome measure(s). RoB was determined using the Updated Method Guidelines for Systematic Reviews produced by the Cochrane Back Review Group [53], presented across studies in a table. Studies were rated as low RoB with a score of ≥6/12, provided no serious flaws were detected. Outcomes were reported as the mean difference and 95% confidence intervals of the difference between groups of the change in ROM from baseline to follow-up assessment. When 95% confidence intervals were not reported in the original study, these were calculated from reported mean, standard deviation, and group size. When the original source only reported variability of group means for baseline and follow-up separately (i.e. did not report on variability of the change), pooled standard deviation was estimated assuming equal variance between groups. Between-group differences were interpreted as meaningful if the 95% confidence interval did not include zero, and clinically meaningful if the difference in ROM was ≥6° [54,55].

Results

Results of search

The search identified 1039 articles (Figure 1), and 8 RCTs were included in the review [56–63]. One author provided additional detail from their thesis [64]. Due to the clinical heterogeneity in the included studies, a meta-analysis was not possible, and the results are presented as a narrative synthesis. The included studies (Appendix B: Supplemental Material Table 2) compared SMT with a range of different comparison groups (Table 1).

Participants

Participants (aged 22–57 years) were mostly (n = 7) recruited from private settings (universities, private practices, research clinics), except one, that recruited from a secondary care setting [59]. Two of the studies only recruited male participants, attempting to limit variation due to gender [62,63]. Half of the studies recruited asymptomatic participants [58,60,61,63]. The other studies recruited participants with back-related leg pain (90% chronic [57]), degenerative lumbar disc disease at L5/S1 ± above-knee radiating leg pain (unknown duration [62]), intervertebral disc prolapse (L4/5 or L5/S1) with radiculopathy (average >3 years, i.e. chronic [59]), or low back pain (3 weeks to 6 months, i.e. acute to chronic) without signs of nerve root compression [56]. One study identified baseline significant differences in PSLR ROM (SMT group higher than Sham SMT group [62]), potentially overestimating treatment effects [65].

SMT interventions

SMT was applied mostly by physiotherapists (n = 5) [58,59,61–63] but also by chiropractors (n = 2) [57,60] and osteopaths (n = 1) [56]. The type of SMT applied varied, including spinal mobilizations (n = 4) [58,59,61,63], spinal manipulation (n = 2) [60,62], and a pragmatic approach (technique and dosage chosen by practitioners, n = 2 [56,57]).

Of those studies applying spinal mobilizations, two applied multilevel grade 3 posterior–anterior mobilizations to the L1–S1 facet joints [58,61], one applied a grade 3 posterior–anterior mobilization to L4 or L5 spinous process [63], and one applied grades 1–4 rotational mobilizations to L4/5 or L5/S1 [59]. When reported, oscillation rate ranged from 0.43 Hz [63] (below normal application rates of 1–2 Hz [66]) to 2 Hz [58,61]. Two studies applied spinal manipulation, one involving a grade 5 pull-move technique applied to L5/S1 in a side lying position [62], and the other involving either rotatory double-index contact-style manipulation to C1 or lumbar roll position pisiform contact-style manipulation to the sacroiliac joint with the side of application chosen at random [60]. In the two studies adopting a pragmatic approach, spinal manipulation was primarily applied. One changed to mobilizations for individuals with severe LBP pain [57]. The other also applied various manual therapy techniques including muscle energy, counterstrain, articulation, and myofascial release [56].

Assessment of neurodynamics

All studies used the PSLR test to assess neurodynamics [67], but with variable protocols. Only two studies [59,63] successfully met all three criteria required to determine a 'positive' neurodynamic test [39,68,69]. There was variation in symptom reproduction (criterion 1) in terms of end point of measurement (onset of pain or resistance) and whether patient or assessor determined these points. Structural differentiation, to distinguish between neural and non-neural tissue dysfunction (criterion 2), was not attempted in four studies [56,57,60,62], and was adequately met in only two studies [59,63]. Unless this criterion has been met, it is impossible to specifically attribute the reproduction of symptoms to neural tissue dysfunction, making this is

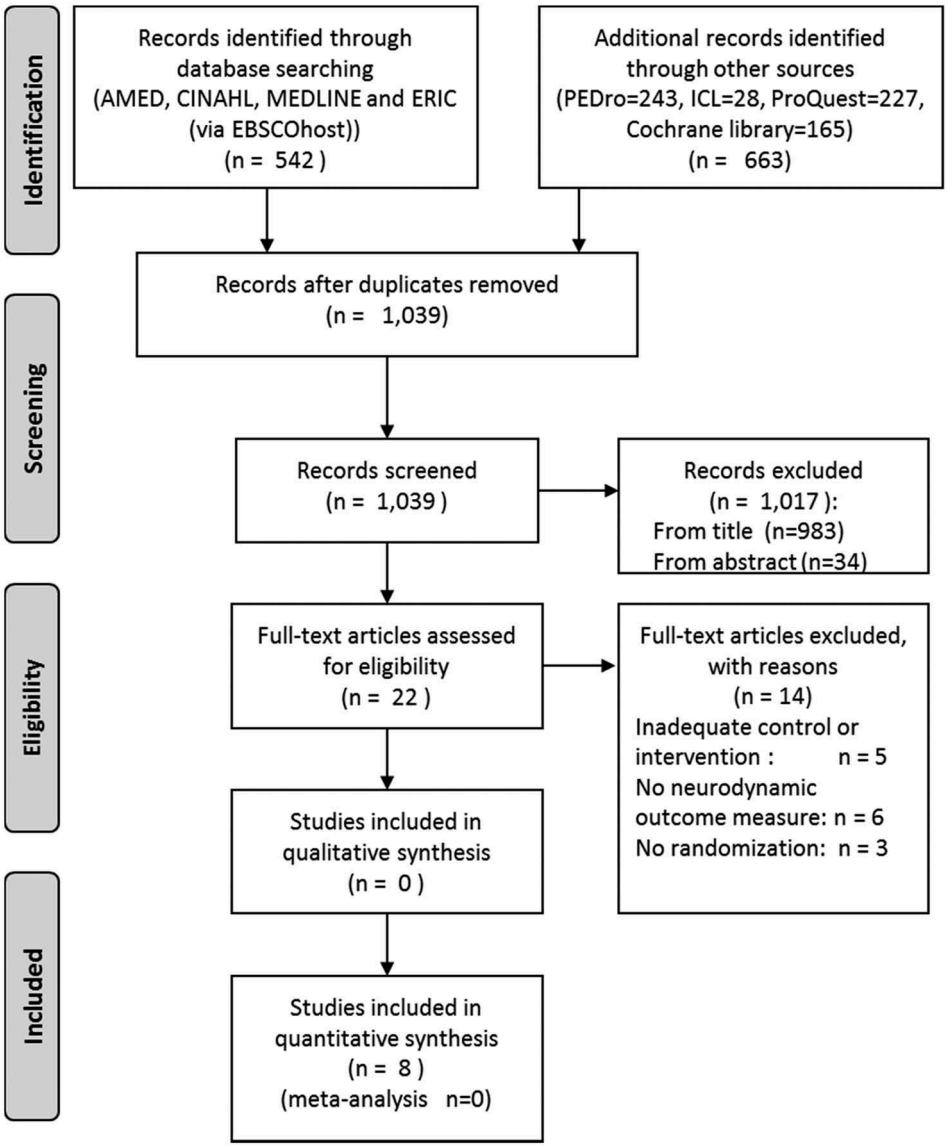

Figure 1. Study selection flow chart (PRISMA, 2009).

the 'key criterion' to determine the validity of the diagnostic test [68]. Lastly, inter-limb asymmetry (criterion 3) was reported as being assessed in two studies [59,63], but its value was only reported in one of these [63]. It was not reported on, but could be calculated from, data provided in a third study (baseline between 1° and 2.4° [57]), but below that considered normal (i.e. <11° [70]).

Risk of bias

All the included studies scored above 6/12 (range 6/12–11/12; Table 2), suggesting an overall low RoB. The main methodological weaknesses were lack of participant (n = 7) and care provider (n = 8) blinding. However, one study was downgraded from low RoB to high RoB due to a large (41.5%) and poorly reported (no explanation, no separation by group) dropout rate within the study (considered a serious flaw [59]), suggesting a strong likelihood of attrition bias in this study.

Effects of SMT on neurodynamics

Between-group differences (mean [95% confidence intervals]) in change in PSLR ROM from baseline to follow-up assessment are presented in Table 3 (see Appendix C: Supplemental Material Table 3 for within group changes).

SMT *versus* inert interventions

All of the four studies that compared SMT at a location in the lower thoracic and lumbosacral region with an inert intervention (control) [58,60,61,63] indicated that change in PSLR ROM from baseline to immediately post-test was higher in the SMT group than the control group. Although the mean difference between groups was clinically relevant in two of those studies [61,63], the lower bounds of the 95% confidence intervals were generally less than 6°, indicating that a clinically relevant difference might not always be expected. In both studies with a longer term follow-up, the

Table 2. Assessment of risk of bias of included studies.

Potential risk of bias sources			Pollard & Ward (1998) [60]	Andersson et al. (1999) [56]	Kumar & Cherian (2011) [59][a]	Wood & Moran (2011) [63][b]	Szlezak et al. (2011) [61]	Vieira-Pellenz et al. (2014) [62]	Bronfort et al. (2014) [57]	Ganesh et al. (2015) [58]
Selection bias	1) Random sequence generation		?	+	+	+	+	+	+	+
	2) Allocation concealment		–	+	+	+	+	–	+	–
Performance bias	3) Blinding of participants		?	–	–	+	–	+	–	?
	4) Blinding of personnel		?	–	–	–	–	–	–	–
Detection bias	5) Blinding of outcome assessment		?	+	?	+	+	+	+	+
Attrition bias	Incomplete outcome data	6) Dropout rate described and acceptable	+	+	–	+	+	+	+	+
		7) Participants analyzed in allocated groups	+	+	?	+	+	+	+	+
Reporting bias	8) Selective outcome reporting		–	+	+	+	+	+	+	+
Other bias	Other bias	9) Similarity of groups at baseline	+	+	+	+	+	+	+	+
		10) Co-interventions avoided or similar between groups	+	+	+	+	+	+	+	+
		11) Acceptable compliance in all groups	+	+	+	+	+	+	+	+
		12) Similar timing of outcome assessment in all groups	+	+	–	+	+	+	+	+
Overall score			7/12	10/12	6/12	11/12	10/12	10/12	10/12	9/12

[a]This study was downgraded to a high RoB due to a large and poorly reported dropout rate within the study despite scoring ≥6/12 [59].
[b]Additional information obtained from masters dissertation, resulted in the study going from high (5/12) to low RoB (11/12) [63].
Note: Each criterion is scored as either yes or +, denoting a low RoB; no or –, denoting a high RoB; and unclear or '?', denoting an unclear result due to insufficient information, with a total score of ≥6/12 indicating an overall low RoB [53].

between-group difference was marginally larger at follow-up than immediately post-test (at 24-h [58] and at 48 h [63]). The single study that compared SMT at the cervical spine to an inert control indicated no between group difference immediately post-intervention [60].

SMT *versus* sham SMT

Two studies compared SMT to sham, with mixed findings [62,63]. One study found a clinically relevant between-group improvement immediately post-test in favor of SMT [62]. In contrast, the other study [63] found no difference between groups immediately post-test, or at 48 h follow-up for the neurodynamic test when performed with a structural differentiation. There was a difference between groups at 48 h follow-up, when the PSRL test was performed without the structured differentiation.

SMT *versus* other interventions

There was a difference between groups in favor of SMT immediately post-intervention in one study comparing SMT to stretching [61]. The mean difference between groups was clinically relevant, but the lower bound of the 95% CI was only 3°. In contrast, in a study comparing SMT with standard care, there was no evidence of a difference between groups at 12 weeks post-intervention [56].

SMT as an adjunct to an intervention *versus* that intervention alone

In a study comparing Home Exercise and Advice (HEA) alone to HEA and SMT [57], there were no between-group differences at 12 weeks post-intervention. In contrast, a study with a high RoB [59] reported a clinically relevant between-group difference in favor of adding SMT to conventional physiotherapy compared with CP alone immediately post-intervention and at 6-weeks post-intervention.

SMT *versus* another SMT technique

Immediately post-intervention, there was a small difference in lower limb (PSLR) ROM between groups receiving SMT at different locations in favor of the inferior location (sacroiliac joint compared to the cervical spine), however this difference was small, and not clinically meaningful [60].

Discussion

Compared with other groups, SMT was never found to be less effective at increasing PSLR ROM, although it was not always demonstrated to be more effective. SMT was more effective than inert interventions (e.g. prone lying [58,60,61,63]), static hamstring stretching [61], and when used as an adjunct to conventional physiotherapy [59]. There were no meaningful between-group

Table 3. Between group differences: comparing mean change in PSLR ROM at each time interval relative to baseline.

				Assessment time period				
Study	Intervention	Comparator	Test variation	Post test	24 h	48 h	6 weeks	12 weeks
Ganesh et al. (2015) [58][a]	SMT	Inert control		4.4° [0.1 to 8.7]	**6.1°** [1.8 to 10.4]			
Wood & Moran (2011) [63][b]	SMT	Inert control	PSLR	**15°** [7.2 to 22.8]		**18.5°** [13.1 to 23.8]		
Wood & Moran (2011) [63][b]	SMT	Inert control	PSLR+NF	**12.9°** [3.7 to 22.2]		**15.6°** [10.3 to 20.8]		
Szlezak et al. (2011) [61][a]	SMT	Inert control		**8.4°** [4.4 to 12.3]				
Pollard & Ward (1998) [60][c,d]	SIJ SMT	Inert control		3.4° [1.5 to 5.4]				
Pollard & Ward (1998) [60][c,d]	Csp SMT	Inert control		1.5° [−0.7 to 3.6]				
Vieira-Pellenz et al. (2014) [62][b]	SMT	Sham		**14.1°** [11.4 to 16.8]				
Wood & Moran (2011) [63][b]	SMT	Sham	PSLR	3.0° [−5.0 to 11.0]		**9.4°** [3.4 to 15.4]		
Wood & Moran (2011) [63][b]	SMT	Sham	PSLR+NF	1.7° [−7.7 to 11.2]		4.6° [−2.2 to 11.4]		
Szlezak et al. (2011) [61][a]	SMT	Stretching		**7.0°** [2.9 to 11.0]				
Andersson et al. (1999) [56]	SMT	SC	supine					1.5° [−1.5 to 4.5]
Andersson et al. (1999) [56]	SMT	SC	sitting					1.4° [−2.4 to 5.1]
Bronfort et al. (2014) [57]	SMT+HEA	HEA alone	left leg					3.4° [−0.1 to 6.8]
Bronfort et al. (2014) [57]	SMT+HEA	HEA alone	right leg					3.6° [−0.02 to 7.2]
Kumar & Cherian (2011) [59][e]	SMT+CP	CP alone		**12.5°** [10.2 to 14.8]			**17.5°** [15.2 to 19.8]	
Pollard & Ward (1998) [60][c,d]	SIJ SMT	Csp SMT		2.0° [0.1 to 3.9]				

Data reported as mean difference [95% confidence intervals (CI)] between groups of change from baseline. [a]Mean difference and 95% CIs calculated from reported group means and standard deviation at each time point. [b]Mean difference and 95% CIs calculated from reported group mean and standard deviation of change pre to post. [c]95% CIs calculated from standard deviation of between group differences of change pre to post. [d]Values originally reported as relative to vertical, direction of difference inverted so that a positive difference is an increase in range of motion. When conducted, pooled standard deviation was calculated assuming equal variance of groups. [e]Mean differences between groups that are greater than clinical significance (6°) are marked bold. 95% CIs of the difference between groups are only positive, indicating potential improvement in favor of SMT, and are shaded in gray.

CP: Conventional Physiotherapy, Csp: Cervical spine, HEA: Home Exercise and Advice, SC: Standard Care, SMT: Spinal manipulative Therapy, SIJ: Sacroiliac Joint.

differences when SMT was compared to standard care [56] or when used as an adjunct to home exercise and advice, both of which were assessed only at 12 weeks post-intervention [57]. Comparisons of SMT to sham interventions were mixed, with one study reporting no difference [63] and one reporting SMT to be more effective [62].

Most of the six studies that evaluated ROM immediately post-SMT demonstrated that SMT performed better than each comparator group, although differences could be small (1.5–15°). However, it is the potential maintenance of meaningful therapeutic effects over a longer period (≥24 h) that is of greater clinical relevance. In the three studies that assessed changes at two time-intervals (immediately post-test and up to 6 weeks) [58,59,63], the difference between groups was larger at the longer-term follow-up. In contrast, both of the studies that assessed effect at 12 weeks showed no difference between groups [56,57]. As neither of these studies assessed effect immediately post-intervention, it is impossible to identify whether there was a trajectory of improvement that had subsided by 12 weeks post-intervention, or whether there was never a difference between groups. The hypoalgesic effects of SMT have previously been shown to typically last 5 min or less, with limited evidence showing effects lasting up to 24 h [31,32]. From this review, it can be suggested that the positive effects of SMT on PSLR ROM could be sustained in the longer term (tentatively up to 6 weeks [59]). However, such inferences are limited by the small number of studies at each follow-up time point, with further research required to explore how long after the application of SMT meaningful improvements in PSLR ROM last.

Half of the studies included in the review recruited asymptomatic participants [58,60,61,63]. A review investigating the effects of SMT on upper limb neurodynamics observed a similar magnitude of improvement between symptomatic and asymptomatic

populations [42]. In the current review, a clear trend could not be observed, due to how studies with asymptomatic and symptomatic populations were grouped. All the studies comparing SMT to inert interventions [58,60,61,63], and the study comparing types of SMT intervention [60], only included asymptomatic populations. Whereas, all the studies comparing SMT as an adjunct [57,59] only included symptomatic participants. Two studies compared SMT to a sham intervention, with the study including symptomatic participants [62] demonstrating a larger magnitude of change compared to that including asymptomatic participants [63]. However, these treatment effects could be overestimated given significant baseline between-group differences in PSLR ROM [62]. In contrast, the two studies comparing SMT to alternative interventions demonstrated a larger magnitude of change in the study including asymptomatic participants [61] compared with the study including symptomatic participants [56]. Therefore, due to the heterogeneity of comparator groups, it is not possible to make meaningful inferences about symptomatic and asymptomatic individuals.

There is mounting evidence advocating the need to classify patients into clinically relevant subgroups using prediction rules (i.e. criteria that may predict a more successful outcome) [71,72]. Within this review, symptomatic participants were widely heterogeneous in diagnosis and considered mechanism for pain. Given the lack of consensus and standardization in the methodologies used, it is impossible to conclude to what extent, criteria such as symptom duration or location of symptoms impact on the magnitude and duration of changes noted in PSLR ROM following SMT. Future exploration of SMT should recruit more clinically relevant subgroups of participants to develop understanding of what criteria may optimize the therapeutic effects of SMT.

Previous research studies have demonstrated that mobilization technique [73] and oscillation rates [74] have little impact on treatment efficacy, and that a non-specific level mobilization is preferable in the lumbar spine [75]. Within the current review, there was considerable variability in technique and location of spinal mobilization applied and comparator groups included. Consequently, it is impossible to make any specific recommendations on the superiority of any particular spinal mobilization approach [58,59,61,63]. Further investigation is clearly required to determine whether optimal parameters exist in relation to the application of this style of technique, location of application, and dosage (i.e. grade, speed etc.) of spinal mobilizations and what impact this has, if any, on the magnitude and/or duration of treatment effects. In relation to spinal manipulation, research studies have documented superior treatment effects associated with side-specific treatment responses in the lumbar spine [76]. In contrast, both side-specific [77] and bilateral responses [78,79] have been identified following cervical spine manipulation. Only two of the included studies provided information on the spinal manipulation applied, and as these were compared to different comparator groups it was impossible to draw any meaningful conclusions from this to contribute to the current knowledge base.

None of the selected studies used the Slump test, despite it being shown to have a higher sensitivity than the PSLR test [48]. PSLR protocols varied between studies with only two of the included studies adhering to all three PSLR test criteria [59,63]. Consequently, one cannot confidently attribute the improvements in ROM observed within this review specifically to neurodynamics. These findings highlight a definite need for consensus on the implementation and interpretation of such tests for application in future research.

Of the studies included in a recent review evaluating the effects of SMT on upper limb neurodynamics [42], statistically significant superiority was observed when SMT was compared to sham, placebo, and control [42]. In contrast, within the current review, although a superior magnitude of change was observed when SMT was compared to all comparator groups, only three studies demonstrated 95% confidence intervals with a lower boundary that exceeded the minimum threshold for clinical significance (i.e. 6°) [59,62,63], questioning whether positive trends such as these could be reproduced or generalized to the wider population. The review by Chu and colleagues [42] shares some of the current review's limitations, including lack of application of positive test criteria (i.e. none applied structural differentiation) and variability in SMT application (i.e. different location, duration, side of application).

Although the overall quality of studies was high, given the methodological limitations and diversity of the included literature, a meta-analysis could not be conducted [80]. Small sample sizes and unreported measures of variance increased the likelihood of sampling bias in non-random/convenience samples [58,60,63]. Standard care comparator groups [56,59] did not reflect current best practice [81]. Adverse events of treatment were only documented in one study [57]. However, small sample sizes and lack of follow-up make adverse events difficult to estimate accurately [82]. Without an evaluation of associated benefits and adverse effects, it is difficult to draw balanced conclusions about the clinical utility of SMT. Recruitment of participants from mostly private settings, and studies including only male participants [62,63], limit the generalizability of the review to the wider health care context. Although thorough, it is possible that relevant literature was not identified during the search. Three studies were excluded as they were unavailable in English that may have led to bias [83–85].

It is recommended that future studies provide full and transparent documentation of results, especially with regard to within- and between-group statistical calculations, calculations of data variance, and also reporting of adverse events. A full description of the SMT technique should be provided, including type, technique, and dosage, allowing replication and appropriate comparison between studies. Furthermore, neurodynamic testing procedures need to be standardized, with the key test criteria routinely and accurately applied. Furthermore, the longer term effects of SMT need to be routinely evaluated, given that the potential for such therapeutic effects to be sustained longer term is of particular interest.

Conclusion

SMT was more effective at increasing PSLR ROM when compared to all comparator groups, however these were only clinically meaningful in five of the eight included studies [58,59,61–63]. The beneficial effects of SMT persisted at a clinically significant level up to 6 weeks [59], suggesting that SMT could have the potential to produce lasting changes in terms of sensitivity to movement. The experience of NSLBP is complex and multifactorial. Research evaluating treatment for back pain needs to reflect it's multidimensional nature by incorporating a variety of subjective and objective outcome measures. Neurodynamic tests provide valuable objective and subjective information that can be used as a clinical indicator to monitor treatment response and subsequently make adaptions as required. It is important to note that due to the methodological weaknesses of the included studies, the improvements observed in ROM cannot be solely attributed to changes in neurodynamics. Although the conclusions drawn from this review are neither robust nor definitive, they highlight a real need to improve transparency and accountability within the research community in terms of reporting interventions such as SMT more thoroughly and applying outcome measures such as neurodynamic tests in a more standardized and criteria-focused format.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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