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Intervertebral kinematics of the cervical spine before, during, and after high-velocity low-amplitude manipulation

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Abstract

BACKGROUND CONTEXT: Neck pain is one of the most commonly reported symptoms in primary care settings, and a major contributor to health-care costs. Cervical manipulation is a common and clinically effective intervention for neck pain. However, the in vivo biomechanics of manipulation are unknown due to previous challenges with accurately measuring intervertebral kinematics in vivo during the manipulation.

PURPOSE: The objectives were to characterize manual forces and facet joint gapping during cervical spine manipulation and to assess changes in clinical and functional outcomes after manipulation. It was hypothesized that patient-reported pain would decrease and intervertebral range of motion (ROM) would increase after manipulation.

STUDY DESIGN/SETTING: Laboratory-based prospective observational study. Patient sample: 12 patients with acute mechanical neck pain (4 men and 8 women; average age 40 ± 15 years).

OUTCOME MEASURES: Amount and rate of cervical facet joint gapping during manipulation, amount and rate of force applied during manipulation, change in active intervertebral ROM from before to after manipulation, and numeric pain rating scale (NPRS) to measure change in pain after manipulation.

METHODS: Initially, all participants completed a NPRS (0−10). Participants then performed full ROM flexion-extension, rotation, and lateral bending while seated within a custom biplane radiography system. Synchronized biplane radiographs were collected at 30 images/s for 3 seconds during each movement trial. Next, synchronized, 2.0-milliseconds duration pulsed biplane radiographs were collected at 160 images/s for 0.8 seconds during the manipulation. The manipulation was performed by a licensed chiropractor using an articular pillar push technique. For the final five participants, two pressure sensors placed on the thumb of the chiropractor (Novel pliance system) recorded pressure at 160 Hz. After manipulation, all participants repeated the full ROM movement testing and once again completed the NPRS. A validated volumetric model-based tracking process that matched subject-specific bone models (from computed tomography) to the biplane radiographs was used to track bone motion with submillimeter accuracy. Facet joint gapping was calculated as the average distance between adjacent articular facet surfaces. Pre- to postmanipulation changes were assessed using the Wilcoxon signed-rank test.

RESULTS: The facet gap increased 0.9 ± 0.40 mm during manipulation. The average rate of facet gapping was 6.2 ± 3.9 mm/s. The peak force and rate of force application during manipulation were 65 ± 4 N and 440 ± 58 N/s. Pain score improved from 3.7 ± 1.2 before manipulation to 2.0 ± 1.4 after manipulation ($p <. 001$). Intervertebral ROM increased after manipulation by $1.\bar{2}$ ($p = .006$), $2.\bar{1}$ ($p = .01$), and $3.\bar{9}$ ($p = .003$) at the C4/C5, C5/C6, and C6/C7 motion segments, respectively, during flexion-extension; by $1.\bar{5}$ ($p = .028$), $1.\bar{9}$ ($p = .005$), and $1.\bar{3}$ ($p = .050$) at the C3/C4, C4/C5, and C5/C6 motion segments, respectively, during rotation; and by $1.\bar{3}$ ($p = .034$) and $1.\bar{1}$ ($p = .050$) at the C4/C5 and C5/C6 motion

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segments, respectively, during lateral bending. Global head ROM relative to the torso increased after manipulation by 8° (p = .023), 10° (p = .002), and 13° (p = .019) during lateral bending, axial rotation and flexion-extension, respectively, after manipulation.

CONCLUSIONS: This study is the first to measure facet gapping during cervical manipulation on live humans. The results demonstrate that target and adjacent motion segments undergo facet joint gapping during manipulation and that intervertebral ROM is increased in all three planes of motion after manipulation. The results suggest that clinical and functional improvement after manipulation may occur as a result of small increases in intervertebral ROM across multiple motion segments. This study demonstrates the feasibility of characterizing in real time the manual inputs and biological responses that comprise cervical manipulation, including clinician-applied force, facet gapping, and increased intervertebral ROM. This provides a basis for future clinical trials to identify the mechanisms behind manipulation and to optimize the mechanical factors that reliably and sufficiently impact the key mechanisms behind manipulation.

Keywords: Cervical spine; Manipulation; HVLA; Facet gapping; Intervertebral kinematics; Range of Motion.

Introduction

Neck pain is highly prevalent in the general population and a major contributor to increased health-care costs. The 12-month prevalence of neck pain ranges between 30% and 50% [1]. Lifetime prevalence rates are even higher, with up to 70% of all people experiencing neck pain at some point [2]. This makes neck pain one of the most frequently reported symptoms in primary care settings [1,3], and a major contributor to overall health-care costs due to the millions of health-care visits each year.

High-velocity low-amplitude (HVLA) cervical spine manipulation is a common treatment for neck pain, performed by physical therapists, chiropractors, and osteopaths [4,5]. HVLA manipulation involves a small-amplitude, high-velocity quick thrust applied to the cervical spine at the end range of movement [6]. Systematic reviews of the literature and clinical practice guidelines have concluded that cervical manipulation is a clinically effective and recommended intervention for treating neck pain [7−9]. Most trials found that manipulation provided greater short-term pain relief than the control intervention, with smaller improvements in neck disability and quality of life measures [10,11]. These systematic reviews also found that many clinical trials used a combination of manipulation and exercise, and therefore the optimal dosage of manipulation as an individual intervention is still unknown.

In addition, despite the widespread use and clinical efficacy of spinal manipulation, the biological mechanisms underlying this treatment remain unknown. This failure to understand the mechanisms behind spinal manipulation impedes the development of strategies for improving the effectiveness of the treatment [12] and for identifying patients most likely to respond favorably to manipulation. Several theories have been proposed as to the possible mechanisms by which spinal manipulation decreases pain and improves function, including biomechanical changes in segmental facet joint motion, psychological relaxation effect from personal interaction and/or manual contact by the provider, inhibition of ascending nociceptive (sensory) neural pathways, or reflex changes in muscle tone and motor neural pathways [12−17].

Previous research suggests that spinal manipulation may work through biomechanical and/or neurophysiologic mechanisms [12,13,17], whereby the mechanical force applied during the manipulation may initiate a series of neurophysiologic responses that lead to reduction in pain and increased range of motion (ROM). Although spinal manipulations are mechanical events that produce mechanical effects at the application site [18], little is known about the actual biomechanical effects of spinal manipulation on intersegmental vertebral motion [19]. Previous research has documented static pre- to postmanipulation changes in lumbar facet gapping [20−24], and the popping sound that is elicited during HVLA manipulation is believed to be cavitation of the spinal facet joints. This suggests that the facet joint kinematics during manipulation may be a key biomechanical mechanism of manipulation.

However, neither the relationship between clinician-applied forces and the in vivo biomechanics of the spine, nor the association between spine kinematics during manipulation and clinical or functional outcomes, are currently known. This lack of knowledge is due to the inability, up until now, to accurately measure the intervertebral kinematics of the spine during manipulation. Therefore, the objectives of this study were to characterize the manual forces and intervertebral kinematics (specifically facet joint gapping), during cervical spine manipulation and to assess changes in clinical and functional outcomes after manipulation. It was hypothesized that patient-reported pain would decrease and intervertebral ROM would increase after manipulation.

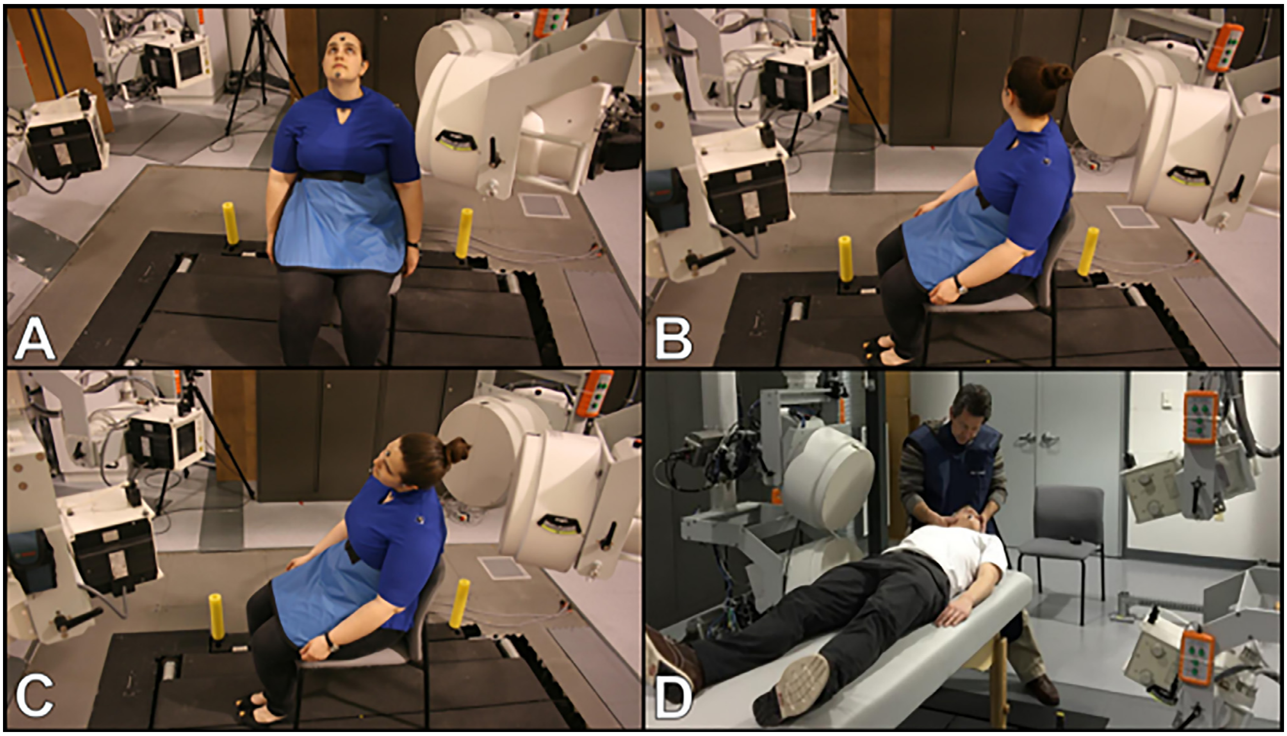

Fig. 1. Participants were seated within the biplane radiography system, which was configured with an angle of approximately 55° between X-ray tube-image intensifier pairs, and parallel with the ground for the dynamic flexion-extension (A), axial rotation (B), and lateral bending (C) trials. For the manipulation trials (D), the X-ray tube-image intensifier pairs were stacked directly on top of each other and angled at ±20° from the horizontal, whereas the patient laid supine on a radiolucent examination table.

Methods

Our study was designed to explore what biomechanical changes (if any) could be measured in the cervical facet joints of patients with neck pain before, during, and immediately after cervical manipulation. Therefore, we needed to recruit subjects that were actively experiencing neck pain (acute episode) but did not have any contraindications to manipulation. We were not concerned about any past history of previous episodes of neck pain unless the patient was experiencing ongoing chronic neck pain without any clear onset of a recent or new episode of neck pain.

This was a laboratory-based prospective observational study. Recruitment was performed by advertisement in a health-system employee newsletter. A total of 20 phone screenings were performed. After screening, two declined to participate, one did not appear for testing, one was excluded due to lack of previous manipulation, and one was excluded due to current breastfeeding.

Fifteen patients with acute mechanical neck pain provided informed consent before participating in this Institutional Review Board (IRB)-approved study (IRB protocol PRO15110304). We considered “acute mechanical neck pain” to be pain of <12 weeks in duration that was reproducible by neck movement and/or provocation tests, and did not radiate to the scapula or upper extremity. Inclusion criteria were the age between 18 and 70 years, pain reproducible by neck movement, and onset of pain <12 weeks in duration. Participants must have received spinal manipulation therapy for a previous episode of mechanical neck pain, which was required by our IRB as an indication that patients previously tolerated cervical manipulation without any adverse event. We were not concerned about patient bias in favor of manipulation, because our primary outcome was a measurement of segmental facet joint kinematics and not any clinical outcomes measured by patient self-report.

Exclusion criteria included pending litigation related to cervical spine injury, any history of cervical spine surgery, history of metastatic cancer, positive nerve root tension signs or radiculopathy, pregnancy, previous diagnosis of osteoporosis, or occupational exposure to radiation. Root tension and signs of radiculopathy were ruled out at a screening examination that consisted of performance of the upper limb tension test, upper extremity reflexes, sensory testing (pinprick), and manual muscle testing of the upper extremity muscles for motor weakness. We also excluded any patient who had a positive response to any of these nine cardinal warning signs or symptoms of transient ischemic attack or stroke: dysphagia, dysarthria, dizziness, diplopia, drop attacks, ataxia, nystagmus, nausea, or facial numbness.

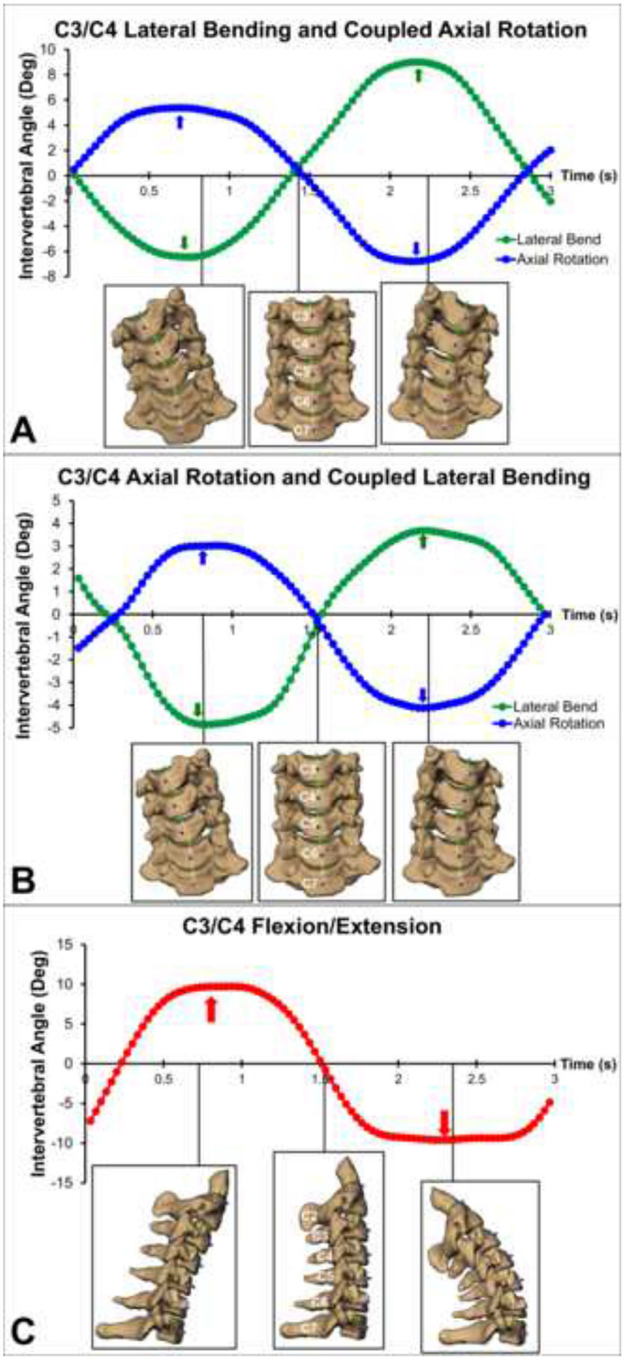

Fig. 2. Dynamic intervertebral kinematics over time during lateral bending (A), axial rotation (B), and flexion -extension (C). The maximum and minimum of each kinematic curve (indicated by arrows) were determined for each dynamic movement trial.

Initially, all participants completed a numeric pain rating scale before receiving manipulation, ranging from 0 (no pain) to 10 (maximum pain). Next, participants were seated within a custom biplane radiography system and synchronized static radiographs were collected as the subject looked forward with their head in the neutral position. Participants then performed continuous full ROM movements in the three primary planes of movement: flexion-extension, bilateral rotation, and bilateral side bending (Fig. 1A−C). These full ROM movements were performed to the beat of a metronome (40 beats/min) to ensure one full movement cycle was completed every 3 seconds. Skin-mounted reflective markers placed on the head and torso were tracked using conventional motion analysis to record global head motion for all ROM trials (12-camera Vicon Vantage). Synchronized biplane radiographs were collected at 30 images/s for 3 seconds during each of the three movement trials (radiographic imaging parameters: 70 kV, 160 mA, 2.5-milliseconds pulsed exposures). Next, cervical manipulation was performed with the participant laying supine on a radiolucent exam table (Fig. 1D). Synchronized biplane radiographs were collected at 160 images/second for 0.8 seconds during the manipulation (radiographic imaging parameters: 70 kV, 320 mA, 2.0-milliseconds pulsed exposures). The maximum radiation exposure during movement trials and manipulation within the biplane radiography system was estimated to be 1.50 mSv using PCXMC software (STUK, Helsinki, Finland).

The manipulation was performed by a licensed chiropractor who had been in clinical practice for over 20 years and routinely performed cervical HVLA manipulation on hundreds of patients with neck pain. The cervical manipulation was performed with the patient lying supine using an articular pillar push technique [25]. This manipulation technique comprises a thumb contact over the facet joints in the area of localized pain, with the patient's head positioned in slight extension, ipsilateral side bending, and contralateral rotation. The clinician targeted the manipulation to the level of the cervical spine that was most tender to manual palpation and perceived segmental ROM restriction, with manipulated level varying between patients.

For a subset of five participants, two pressure sensors (1.7 cm^2 each) were placed on the chiropractor's thumb (Novel pliance system, Novel GMBH, Munich, Germany) to record the force of the manual pressure applied during the manipulation at 160 Hz. Timing of the manipulation was initiated by a countdown timer visible to the chiropractor. When the timer reached zero, the motion capture, biplane radiography, and pressure sensing systems began recording data simultaneously, whereas the chiropractor performed the manipulation. Within a few minutes after the manipulation was performed, the participant returned to the seated upright position and movement testing was repeated in all ROMs using the biplane radiography system to take new measurements. Participants were then asked to once again complete the numeric pain rating scale postmanipulation.

High-resolution computed tomography (CT) scans ($0.29 \times 0.29 \times 1.25$ mm voxels) of the cervical spine were acquired on each participant (GE LightSpeed 16, GE Medical Systems, Wauskesha, WI). Bone tissue was segmented from the CT volume using a combination of commercial software (ScanIP, Synopsis, Exeter, UK) and manual segmentation [26]. A three-dimensional (3D) model of each

Table
Patient-specific manipulation data

Subject	Tracked levels	Targeted level(s)	Maximum gap	Maximum change in facet gap (mm)	NPRS change
1	C3−C6	N/A	C34	0.70	0
3	C4−C7	C4	C45	0.28	0.7
4	C2−C6	C4, C5	C56	1.34	1
5	C2−C6	C3	C45	1.27	3
6	C3−C6	C4, C5	C56	0.85	2
7	C2−C4	C3	C34	0.74	2
8	C2−C4	C3	C23	0.83	2
9	C2−C3	C4, C5	C23	0.51	2
12	C2−C3	C3, C4	C34	1.55	3
13	C2−C6	C4, C5	C34	0.64	1
14	C2−C3	C4	C23	0.61	3
15	C4−C5	C4, C5	C45	1.04	1.5

Cervical vertebrae were occluded by the chiropractor during manipulation of subjects 2, 10, and 11.

cervical vertebra was generated from the segmented bone tissue [27]. Markers were interactively placed on the 3D bone models to define bone-specific anatomic coordinate systems [28]. The average radiation exposure from the CT scan was estimated to be 3.0 mSv based upon our previous experience scanning the cervical spine and literature estimates for radiation dose associated with CT scans of the cervical spine [29,30]. For comparison, the annual effective dose due to background radiation in the United States is 3.0 mSv [31].

Intervertebral kinematics during the ROM trials and during the manipulation were determined with submillimeter accuracy (0.4 mm for translations and 1.1° for rotations; bone-to-bone distance precision of 0.4 mm or better) using a validated volumetric model-based tracking process that matched subject-specific bone models (from CT) to the nonuniformity and distortion corrected biplane radiographs [32]. The variability in joint kinematics associated with different personnel operating the software is very low (0.02 mm in translation and 0.06° in rotation) [32] because the matching of bone models to the biplane radiographs is optimized by a computer algorithm for each pair of synchronized biplane radiographs rather than relying on manual matching by the operator. Previous assessment of trial-to-trial variability in intervertebral kinematics using this system to assess full ROM flexion-extension, bending, and rotation of the cervical spine indicates rotational trial-to-trial variability of 0.9° or less for all three rotational degrees of freedom and 0.22 mm or less for all three translation degrees of freedom [33]. Full ROM kinematic data were filtered at 1.5 to 1.7 Hz, whereas bone kinematics during the manipulation trials were filtered at 1.0 to 2.0 Hz using a fourth-order, low-pass Butterworth filter with the filter frequency determined using residual analysis [34]. Six degrees-of-freedom kinematics between adjacent vertebrae were calculated for every frame in each trial in accordance with established standards for reporting spine kinematics [35] (Fig. 2). Facet joint surfaces were identified on each vertebra and the average distance between facet surfaces over the entire articulating surface region (ie, facet gapping) was calculated from every frame during the manipulation trial [36].

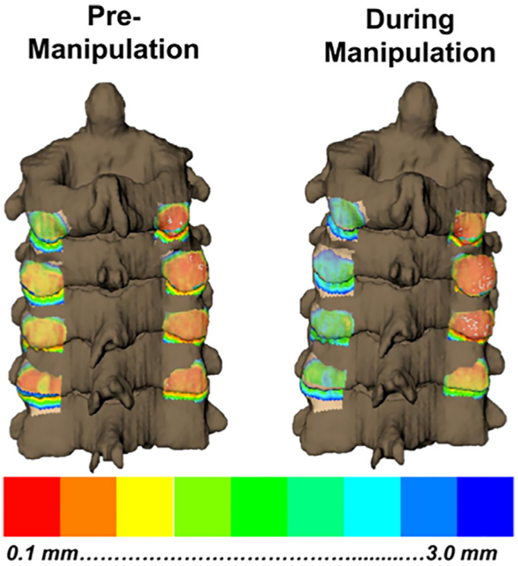

Fig. 3. A posterior view of the cervical spine premanipulation (left) and during manipulation (right). Gapping of the left facet joints is demonstrated by the color-coded facet joint surfaces.

Outcome measures included the amount and rate of cervical facet joint gapping during manipulation, the amount and rate of force applied during manipulation, the change in intervertebral ROM from before to after manipulation, and the change in pain score after manipulation. Pre- to postmanipulation changes were evaluated using the Wilcoxon signed-rank test. Significance was set at $p<.05$ for all tests. Power analysis indicated that 12 participants were required to detect facet gapping of 0.4 mm during the manipulation (ie, the precision of our bone-to-bone measurements and twice the size of the standard error of the measurement for facet gapping based upon our previous

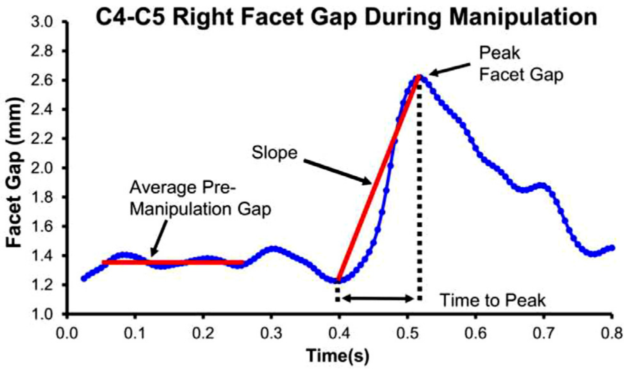

Fig. 4. Facet gapping during manipulation and measured outcome parameters for one representative subject. Each blue dot represents one frame of tracked motion during the manipulation.

research [37]), with a 0.5 mm standard deviation and 80% power [38].

Results

Three participants were excluded from analysis because portions of their upper cervical spine were occluded by the chiropractor's hands during the manipulation. Of the 12 remaining participants, 4 were men and 8 were women with an average age of 40.1 ± 15.0 years (range: 24−59 years). For 11 of the 12 participants, there was an audible cavitation (popping sound) associated with the manipulation. During the manipulation, motions of the target and at least one adjacent motion segment were tracked for all 12 participants and included in the final analysis (Table).

During manipulation, facet gapping occurred on the contralateral side of the target and adjacent motion segments (Fig. 3). The maximum increase in facet gap, from the premanipulation load to peak facet gap during manipulation, averaged 0.9 ± 0.4 mm, with a premanipulation gap average of 0.8 ± 0.5 mm. The average increase in facet gap over all tracked motion segments was 0.7 ± 0.4 mm, with a premanipulation gap average of 0.9 ± 0.5 mm. The average rate of facet gapping over all motion segments was 6.2 ± 3.9 mm/s, which occurred over an average of 136 ± 54 milliseconds (Fig. 4). For the segment that had the most facet gapping, the rate of gapping was 7.9 ± 4.2 mm/s over 124 ± 40 milliseconds. In 9 of the 12 manipulations, either the targeted motion segment or the inferior adjacent motion segment achieved the maximum facet gapping (n = 5 and n = 4, respectively).

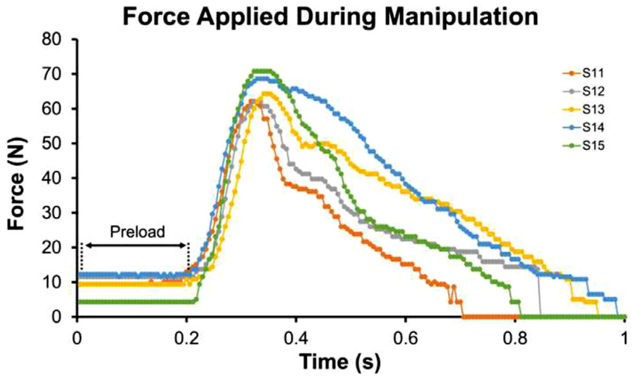

Fig. 5. Force applied by the clinician during the manipulation for all five subjects.

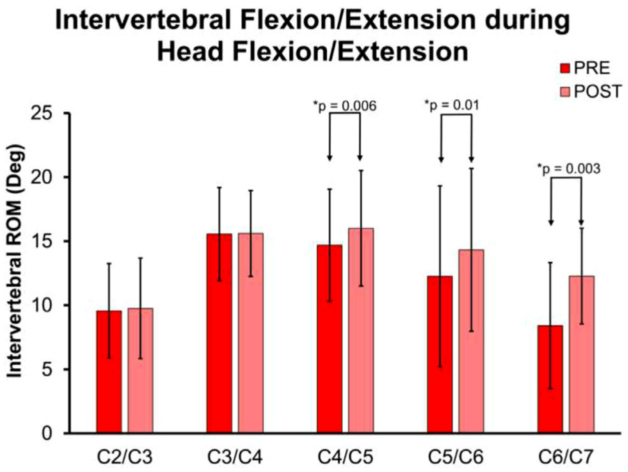

Fig. 6. Maximum flexion-extension range of motion for each cervical motion segment during head flexion-extension. Error bars represent ±1 standard deviation and * denotes significant change from pre- to postmanipulation.

Manipulation force-time characteristics were similar across the five manipulations that included force-sensing technology (Fig. 5). The average preload was 9.4 ± 3.1 N, and the average peak force applied during the manipulation was 65.6 ± 3.9 N. On average, the manipulation force was applied over 130 ± 10 milliseconds at a rate of 440.4 ± 57.6 N/s.

During the global cervical flexion-extension motion, intervertebral flexion-extension ROM increased significantly at the C4/C5, C5/C6, and C6/C7 motion segments pre- to postmanipulation (Fig. 6). The increase in segmental ROM was largest at C6/C7 (3.9 ± 1.8°; p = .003), followed by C5/C6 (2.1 ± 2.4°; p = .01), and C4/C5 (1.2 ± 1.3°; p = .006).

During head lateral bending, intervertebral lateral bending ROM increased after manipulation at the C4/C5 (0.6 ± 0.8°; p = .034) and C5/C6 (1.0 ± 1.4°; p = .050) motion segments. No changes in coupled axial rotation ROM were observed during head lateral bending (all $p \geq .084$) (Fig. 7).

During head axial rotation, increased segmental ROM was observed in all motion segments from C3/C4 through C6/C7 (Fig. 8). Axial rotation increased at the C3/C4 (1.3 ± 1.4°; p = .006), C4/C5 (1.1 ± 1.6°; p = .034), and C6/C7 (0.9 ± 0.8°; p = .01) motion segments. Lateral bending ROM increased at the C3/C4 (1.5 ± 2.1°; p = .028),

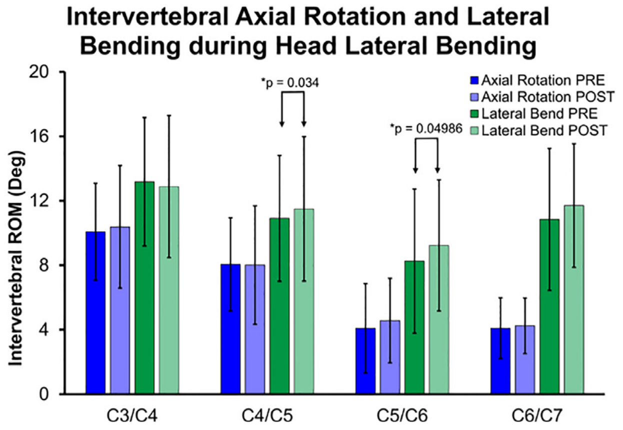

Fig. 7. Maximum lateral bending and coupled axial rotation range of motion for each cervical motion segment during head lateral bending. Error bars represent ±1 standard deviation and * denotes a change from pre- to postmanipulation.

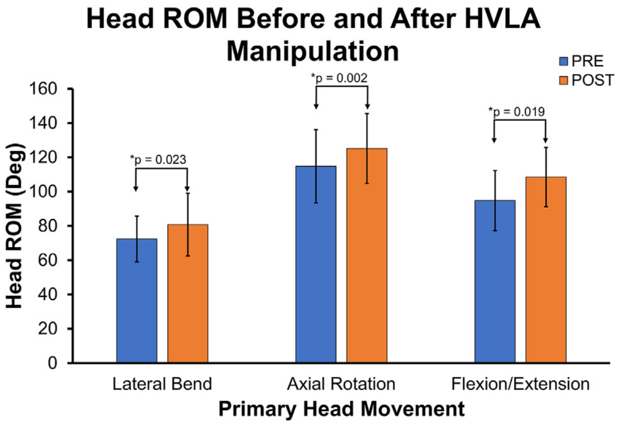

Fig. 9. Maximum head range of motion during lateral bending, axial rotation, and flexion-extension. Error bars represent ±1 standard deviation and * denotes a change from pre- to postmanipulation.

C4/C5 (1.9 ± 2.3°; p = .005), and C5/C6 (1.3 ± 1.9°; p = .050) motion segments.

Head ROM relative to the torso increased after manipulation for all head rotations (Fig. 9). Lateral bending ROM increased from 72.3 ± 13.3° to 80.7 ± 18.3° (p = .023), axial rotation ROM increased from 114.8 ± 21.3° to 125.1 ± 20.3° (p = .002), and flexion-extension ROM increased from 94.7 ± 17.5° to 108.0 ± 17.3° (p = .019).

Numeric pain rating scores improved from an average of 3.7 ± 1.2 points (0−10 scale) before manipulation, to an average of 2.0 ± 1.4 points after manipulation (p <. 001).

Discussion

This study is the first to characterize facet joint gapping during cervical spine manipulation in vivo and to quantify changes in dynamic intervertebral kinematics after manipulation. The novel and important findings of this study are that facet joint gapping occurs on the contralateral side of the targeted joint and adjacent motion segments during HVLA manipulation, and that intervertebral ROM significantly increases in all three planes of motion in the target and inferior adjacent motion segments after manipulation. The ancillary findings of increased head ROM after HVLA manipulation and reporting of the force-time characteristics of the manipulation are confirmatory and similar to previous studies.

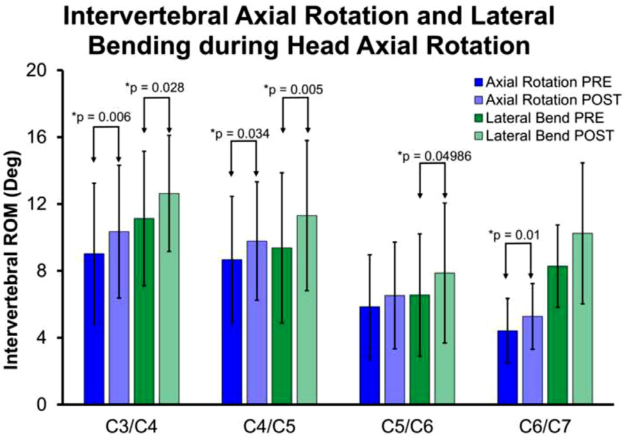

Fig. 8. Maximum axial rotation and coupled lateral bending range of motion for each cervical motion segment during head axial rotation. Error bars represent ±1 standard deviation and * denotes a change from pre- to postmanipulation.

The increase in facet gap during manipulation of 0.9 ± 0.4 mm is more than double the maximum facet joint distraction that occurs during full ROM flexion-extension in healthy individuals [37]. This suggests that cervical spine HVLA manipulation induces facet joint motion beyond the normal active physiologic range and provides support for the theory that HVLA manipulation takes the facet joint into the paraphysiological movement zone. No previous reports of in vivo cervical facet gapping are available in the literature; however, the change in lumbar facet gap from before to after lumbar manipulation has been reported to average 1.3 mm [22], which is approximately double the 0.7 ± 0.4 mm facet gap increase we found during cervical manipulation. When comparing these results, one must keep in mind that the data of Cramer et al. were acquired in the lumbar spine statically before and after manipulation, versus the present study, which measured cervical facet gapping dynamically during the manipulation. Furthermore, the present study defined gapping as the amount of increase in the facet joint space from preload to peak gapping; however, facet gapping is likely affected by patient positioning during preload.

This study clarifies some of the controversy related to what clinicians report that they feel during the HVLA thrust. It was previously not possible to determine in vivo if the manipulative thrust caused specific movement of only the target joint, or if other joints neighboring the target joint were also brought to the end ROM by the preload force application [19]. These results unequivocally demonstrate that the target joint and adjacent joints are gapped during the manipulation, casting doubt on the conceptual model of “specific level” manipulation.

It is not clear if the amount of force or the rate at which the force is applied during manipulation (or both) is critical factor in successful manipulation. Previous research indicates the preload force is between 0 N and 40 N, the peak force is between 41 N and 190 N, and the average time to peak force is between 47 and 175 milliseconds [39−42] during cervical HVLA manipulation. Although the force-time parameters collected in the present study fell within the bounds of these previous reports, the present results include a generally smaller preload (approximately 10 N), a somewhat smaller peak force (65 N), and a slightly longer time to peak force (130 milliseconds) than most previous reports. Differences in these force-time characteristics are likely due to a combination of different force-pressure measurement technology, different manipulation techniques, and chiropractor-specific factors. Further research is necessary to determine if there are relationships between applied force-time characteristics, facet gapping, and clinical and functional outcome after cervical manipulation.

Surprisingly, little data exist documenting the effects of cervical manipulation on global and intervertebral ROM in patients with neck pain. One previous study reported increases of 15°, 10°, and 19° in global head flexion-extension, lateral bending, and axial rotation, respectively, after a single application of HVLA manipulation [43]. Those changes in global head ROM are similar to the increased ROM found in the current study for flexion-extension (13°) and lateral bending (8°) but slightly larger than the increased axial rotation (11°) found in this study. We are aware of only one previous study that measured the change in intervertebral kinematics after cervical manipulation. In that study, no significant increase in intervertebral flexion-extension was found after a series (up to 12) of neck manipulations (in addition to other therapy) over 4 weeks [44]. In contrast, our study found increased intervertebral ROM during movements in all three planes of motion. These conflicting results could be due to different measurement techniques, the passage of time between treatment and evaluation, or possibly other psychological factors such as kinesiophobia or pain avoidance behavior. We did not obtain patient self-reported measures of these or other psychological factors.

There was a tendency for ROM to increase in the middle and lower cervical motion segments, rather than in the mid to upper motion segments, which were the targeted segments and where the maximum gapping occurred (Table). This may be due to the way in which intervertebral motion segments sequence their contributions to global head motion during these full ROM activities. As we have reported previously, the upper and midcervical motion segments make the greatest contribution to midrange motion, whereas lower cervical motion segments increase their contributions to motion near the ends of the ROM [45,46].

Pain scores from this study confirm that patients experienced more pain before manipulation, which likely contributed to their restricted global cervical ROM. This suggests that, due to pain before manipulation, patients restricted their ROM and did not reach the global ROM limits that require full contributions from the lower cervical motion segments. Future studies with increased number of participants will be required to conclusively determine if the increased intervertebral ROM is direction-dependent and correlates with symptoms and clinical exam findings.

There were several limitations associated with this study that are worthy of discussion. First, the intervertebral ROM analysis was carried out only for motion segments up to the C2/C3 level during flexion-extension and up to the C3/C4 level during rotation and lateral bending, so changes in upper cervical ROM after HVLA manipulation remain unknown. In the future, the upper cervical spine will be included in the ROM analysis by using techniques we have recently demonstrated to track upper cervical motion during dynamic flexion-extension and rotation [47]. Only one type of cervical manipulation technique was performed by a single chiropractor in this study. Additional studies are needed to determine if facet gapping and functional outcomes (ie, intervertebral ROM) are affected similarly by other types of manipulation and mobilization techniques. Also, the variability in these manual force parameters among different clinicians needs to be established. Correlational analyses were not performed due to the relatively small sample size. Increased sample size in future studies will enable testing for relationships between clinician-applied forces, facet gapping, increased ROM, and patient-reported outcomes. Another key point to note is that ROM data were collected immediately before and immediately after a single application of HVLA manipulation, so results from this study should not be extrapolated to longer term outcomes after manipulation. Also, these results are not necessarily representative of kinematic changes that occur after a series of manipulation treatments provided over the course of several weeks. Finally, the clinician-applied force is a 3D vector, with two components parallel and one component perpendicular to the clinician-patient contact surface. In this study, only the force component perpendicular to the contact surface was measured, whereas the other components of force may also be significant [42].

The present study provides novel information about the biomechanics of cervical spine HVLA manipulation. Specifically, this study demonstrates it is possible to measure clinician-applied force and facet gapping during manipulation, as well as changes in intervertebral motion from before to after the manipulation. These capabilities provide a foundation for future studies to investigate the biomechanical mechanisms of manipulation. In addition, it is now feasible to study the effects of force application (amount and rate) and manipulation technique on spine kinematics during manipulation, and to begin to investigate associations between these factors and clinical and functional outcomes after HVLA manipulation.

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