

## BIOMECHANICS

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# Spinal Tissue Loading Created by Different Methods of Spinal Manipulative Therapy Application

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**Study Design.** Comparative study using robotic replication of spinal manipulative therapy (SMT) vertebral kinematics together with serial dissection.

**Objective.** The aim of this study was to quantify loads created in cadaveric spinal tissues arising from three different forms of SMT application.

**Summary of Background Data.** There exist many distinct methods by which to apply SMT. It is not known presently whether different forms of SMT application have different effects on spinal tissues. Should the method of SMT application modulate spinal tissue loading, quantifying this relation may help explain the varied outcomes of SMT in terms of effect and safety.

**Methods.** SMT was applied to the third lumbar vertebra in 12 porcine cadavers using three SMT techniques: a clinical device that applies forces through a hand-held instrument (INST), a manual technique of applying SMT clinically (MAN) and a

research device that applies parameters of manual SMT through a servo-controlled linear actuator motor (SERVO). The resulting kinematics from each SMT application were tracked optically via indwelling bone pins. The L3/L4 segment was then removed, mounted in a parallel robot and the resulting kinematics from SMT replayed for each SMT application technique. Serial dissection of spinal structures was conducted to quantify loading characteristics of discrete spinal tissues.

**Results.** In terms of load magnitude, SMT application with MAN and SERVO created greater forces than INST in all conditions ( $P < 0.05$ ). Additionally, MAN and SERVO created comparable posterior forces in the intact specimen, but MAN created greater posterior forces on IVD structures compared to SERVO ( $P < 0.05$ ).

**Conclusion.** Specific methods of SMT application create unique vertebral loading characteristics, which may help explain the varied outcomes of SMT in terms of effect and safety.

**Key words:** lumbar spine, robotics, spinal loading, spinal manipulation, spine biomechanics, vertebral kinematics.

**Level of Evidence:** N/A

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The device(s)/drug(s) is/are FDA-approved or approved by corresponding national agency for this indication.

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Spinal manipulative therapy (SMT) is a common manual intervention for low back pain involving the application of a dynamic, high-velocity, low-amplitude thrust that results in a mechanical deformation of the spine and surrounding soft tissues.<sup>1–3</sup> As is the case with medication where a therapeutic effect may be influenced by parameters such as method of application, dosage, frequency etc, there are thought to be similar variables related to SMT application that modulate its efficacy. To date, a variety of studies have shown that specific parameters of SMT application can influence outcomes including the number of applied treatments in humans<sup>4,5</sup> and, in animal models, the applied force magnitude and location of application.<sup>6–13</sup>

In addition to these SMT application parameters, the method of SMT application is also a consideration. Indeed, several different forms of SMT application have been used

in different regions of the spine.<sup>14</sup> To date, these studies have investigated biomechanical variables at the clinician/subject interface (*i.e.*, force-time profiles).<sup>15</sup> Unfortunately, the effect of different SMT application methods on internal loading of spinal tissues remains unknown. By identifying how load distribution within spinal tissues change as a function of SMT application method, it may be possible to identify if one method of SMT application can preferentially load specific spinal structures. If it were to be shown that spinal tissue loading can be modified by SMT application method, then important indicators regarding SMT-specific health outcomes might be revealed in addition to the potential of tailoring clinical interventions to a patient's specific needs. Indirectly, understanding whether different SMT application methods change tissue loading may help to understand the known variability that occurs with SMT outcomes; different SMT application techniques may load different spinal tissues resulting in different clinical outcomes.

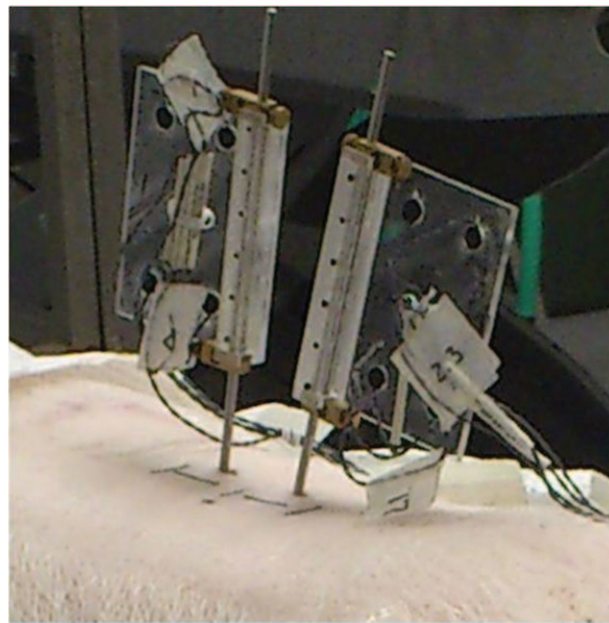
Therefore, the purpose of this study was to investigate the spinal tissues loading as a function of SMT application method. We hypothesized that SMT load distribution within spinal tissues will significantly differ as a function of the method of SMT application.

## MATERIALS AND METHODS

### Specimen Preparation

Fourteen fresh porcine cadavers (Duroc X [Large White X Landrace breeds]) of approximately 60 to 65 kg were used. In each intact porcine cadaver, ultrasound imaging and needle probing were used to identify vertebral levels and landmarks. Bone pins were drilled into the L3 and L4 vertebral bodies with each pin supporting a rectangular flag having four infrared light-emitting diodes (Figure 1). This study was approved by the Animal Care and Use Committee of the University of Alberta.

Each cadaveric pig was then positioned in a neutral, prone position and SMT from three different application methods was applied. Following the application of SMT on the intact porcine cadaver (below), the lumbar spine was removed *en bloc*.<sup>16</sup> The L3/L4 segment was then isolated, cleaned of nonligamentous tissues, and then refrigerated at

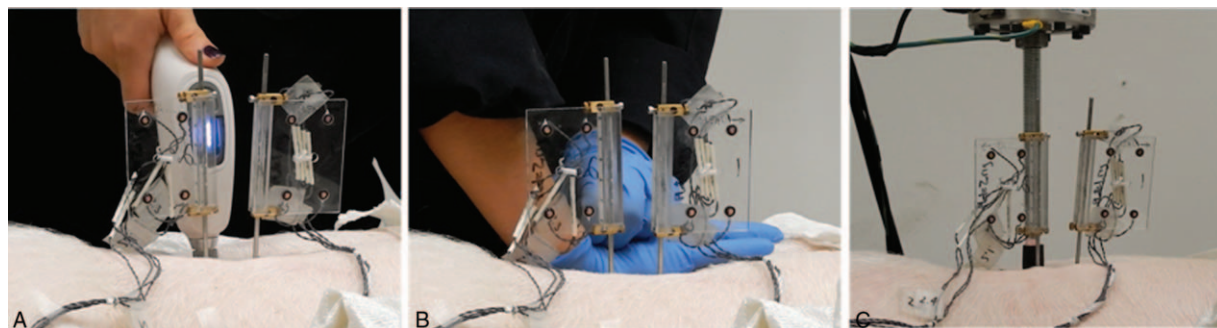


**Figure 1.** Rectangular flags with four infrared light-emitting diode markers attached to bone pins drilled into L3 and L4 vertebrae.

3°C for <5 hours until testing the following day.<sup>17</sup> The specimen was kept moist with physiologic saline throughout the experiment.<sup>18,19</sup> Owing to calibration complications, two specimens were excluded leaving 12 for analysis.

### Application of SMT

Three methods of SMT were used to apply a posteroanterior thrust to the skin overlying the L3/L4 left facet joint (FJ): a clinical instrument (Activator V-E, Activator Methods International, Phoenix, AZ) (INST), a trained clinician with 3 years of clinical experience (MAN), and the servo-controlled linear actuator motor (SERVO)<sup>20</sup> (Figure 2). For INST, the maximal force setting was used. For MAN, the clinician was instructed to apply SMT using the hypothenar push manipulation.<sup>14</sup> For SERVO, a peak force magnitude of 300 N was used with a preload force of 10% of the peak force and a loading rate of 2.6 N/ms with a time to peak of 112.5 ms. These SERVO parameters were derived from clinical application of manual SMT.<sup>15</sup>



**Figure 2.** Three methods used to apply spinal manipulative therapy: (A) mechanical force manually assisted instrument (Activator V-E); (B) manual spinal manipulative therapy application; (C) linear actuator motor.

To measure SMT force-time characteristics at the skin interface, a pressure array (Pressure Profile System Inc, Los Angeles, CA) was used with INST and MAN applications of SMT (SERVO parameters were already known by definition). The pressure array was composed of  $10 \times 10$  pressure sensors ( $1 \text{ cm}^2$  each sensor) with a pressure sensitivity of 0.15% and obtained data at 120 Hz.

### Segmental Motion Recording

During SMT application, L3 and L4 vertebral motion was recorded in three dimensions by an optical tracking system (Optotrack Certus, NDI, Waterloo, Canada) at a rate of 400 Hz with a 0.01-mm system resolution and a 0.15-mm rigid body resolution.

### Robotic Testing

After SMT application with the three methods, the L3/L4 motion segment was removed and the specimen potted in a vertical orientation using dental stone (Modern Materials, South Bend, IN) with the intervertebral disc aligned horizontally via a projected laser beam. The L4 end of the potted specimen was fixed to a six-axis load cell (AMTI MC3A-1000, Advanced Mechanical Technology Inc., Watertown, MA), which was mounted rigidly to a parallel robot platform (Parallel Robotics Systems Corp, Hampton, NH), with the following orientation:  $x$  = mediolateral,  $y$  = anteroposterior, and  $z$  = superoinferior.

The cranial end of the potted specimen was then fixed to a stationary cross beam and the segment positioned in its intact neutral pose (Figure 3). By following the procedures described by Goldsmith *et al*,<sup>21</sup> the system was calibrated to transform vertebral motion into robot trajectories. These three trajectories for three methods of SMT application were then applied robotically in the order they were applied to the porcine cadaver (INST, MAN, SERVO) using a 2-minute recovery time between trajectories and three preconditioning trials before testing and data collection.<sup>16</sup>

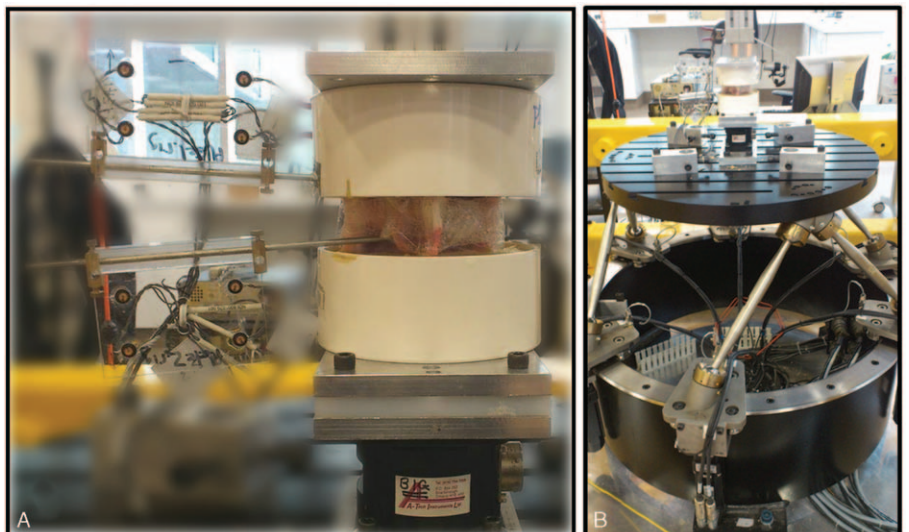
Following robotic replication of SMT kinematics in the intact specimen, spinal structures were removed and/or transected and the same robotic trajectories repeated. In this way, the load distribution within the spinal tissues was quantified. Based on previous findings,<sup>22</sup> the spinal structures were removed/transected in same order for all specimens: supra- and interspinous ligament (SL) bilateral facet capsules, facet joints (via rongeur), and ligamentum flavum (PJ); intervertebral disc and anterior and posterior longitudinal ligaments (IVD).

### Data Analysis

Peak and mean forces along each axis were identified by customized software as were rotations at peak loads (LabVIEW; National Instruments, Austin, TX). Peak force was considered to be the maximum measured force during the thrust phase of SMT. Mean force correspond to the average value of forces involving both the preload and thrust phases of SMT. For spinal structures loading analysis, relative peak and mean forces were normalized to the respective load experienced by the intact condition during the SMT application with each method.

Peak pressure and contact surface area during SMT thrust phase and time to peak were extracted by software and used for INST and MAN force-time characterization (Chameleon Visualization and Data Acquisition Software 2012, Version 1.7.0.6; Pressure Profile Systems Inc., Los Angeles, CA).

Given that all methods of SMT application were performed on each specimen, each observation of forces arising from SMT was considered a repeated measure. Therefore, for the intact specimen, a repeated-measure multivariate analysis of variance (MANOVA) followed by a Bonferroni post-hoc analysis for pairwise comparisons was conducted. For the analysis of change in loads following the removal of each spinal structures, a MANOVA for the regression coefficients was conducted followed by a Tukey post-hoc



**Figure 3.** Robotic testing. (A) Potted specimen with L4 mounted to the six-axis load cell and L3 fixed to a stationary cross beam. (B) Parallel robot platform with load cell and specimen attached.

**TABLE 1. Contact Interface Characteristics of Each SMT Application Method (Average, SD)**

Method of SMT Application	Applied Peak Force (N)	Peak Surface Area, cm <sup>2</sup>	Time to Peak Force, ms	Loading Rate, N/ms	Peak Applied Pressure, N/cm <sup>2</sup>
INST	120 (±12.7)*, †	0.95*, †	99 (±31)*	1.21	126.31
MAN	524 (±41)†	16.63†	220 (±15)†	2.38	31.51
SERVO	300	0.8	112.5	2.6	375

INST indicates mechanical force manually assisted instrument (Activator V-E); MAN, Manual SMT; SD, standard deviation; SERVO, linear actuator motor; SMT, spinal manipulative therapy.

\*Statistically significant difference ( $P < 0.05$ ) in comparison with MAN.

†Statistically significant difference ( $P < 0.05$ ) in comparison with SERVO.

test for the multiple pairwise comparisons of the removed spinal structures (SPSS v22.0 [IBM Corp, Armonk, NY]; R: [R Foundation for Statistical Computing, Vienna, Austria]).

**RESULTS**

**Contact Interface Characteristics**

Peak force magnitudes, surface area, time to peak force, and contact area are shown in Table 1. Figure 4 displays a representative example of contact surface area at peak force magnitude during INST and MAN application. Of note, SMT-applied peak force, contact surface area during peak force, and time to peak force applied during MAN were significantly greater than both INST and SERVO ( $P < 0.05$ ).

**Vertebral Rotations**

Relative rotations of L4 vertebra in relation to L3 are shown in Table 2. Vertebral rotations created by INST were significantly smaller compared to the ones created during MAN and SERVO ( $P < 0.05$ ). Additionally, MAN created flexion-extension and torsion rotations significantly greater than SERVO ( $P < 0.05$ ).

**Forces**

Table 3 shows the average peak and mean forces experienced by the intact specimen and the average of normalized peak and mean forces experienced by spinal structures during the SMT application with different methods with confidence intervals.

**Intact Specimen**

Figure 5 shows the average peak and mean forces experienced by the intact specimen. Peak lateral and anteroposterior forces were significantly smaller when SMT was applied with INST than when applied with MAN and SERVO.

**Supra- and interspinous ligaments (SL)**

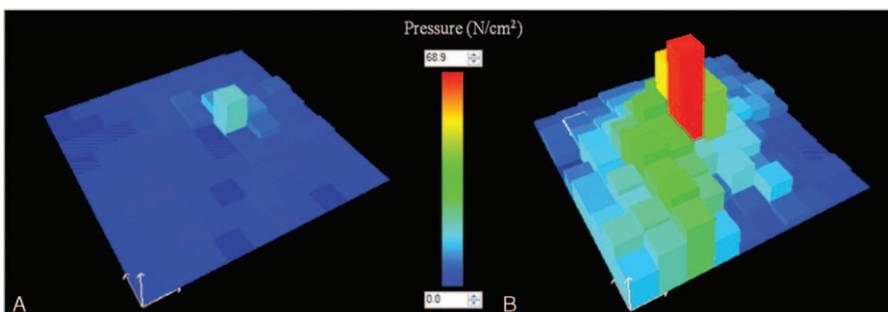
Figure 6 presents the average of normalized peak and mean forces experienced by SL structures. Although SL structures experienced significant changes in forces as a function of the method in which SMT was applied, they were substantially smaller than the forces experienced by PJ and IVD structures.

**Bilateral Facet Joints, Capsules and Ligamentum Flavum (PJ)**

Figure 7 shows the average of normalized peak and mean forces experienced by PJ structures. The change in peak superior-inferior force when SMT was applied with INST was significantly smaller and in the opposite direction than both MAN and SERVO. Additionally, the change in mean anteroposterior and superior-inferior forces during MAN was significantly greater and in opposite direction than INST and SERVO.

**Intervertebral Disc, Anterior and Posterior Longitudinal Ligaments (IVD)**

Figure 8 shows the average of normalized peak and mean forces experienced by IVD structures. SMT applied with SERVO created peak lateral force significantly greater than both INST and MAN. The change in peak anteroposterior



**Figure 4.** Representative example of contact surface area (1 cm<sup>2</sup> each sensor) at peak force magnitude during (A) mechanical force manually assisted instrument (Activator V-E) and (B) manual spinal manipulative therapy application.

**TABLE 2. L4 Rotation (°) (SD) in Relation to L3 Created in Intact Cadaveric Specimens at Peak Loads During the Three Methods of SMT Application**

Method of SMT Application	Rotation (°)		
	X (flx ext)	Y (lat bend)	Z (axial rot)
INST	0.65 (0.36)*,†	-0.28 (0.28)*,†	0.10 (0.30)*,†
MAN	3.06 (1.00)†	-0.65 (0.52)	-1.71 (1.20)†
SERVO	2.20 (1.09)	-0.86 (0.44)	-1.09 (0.74)

*INST indicates mechanical force manually assisted instrument (Activator V-E); MAN, manual SMT; SD, standard deviation; SERVO, linear actuator motor; SMT, spinal manipulative therapy.*

\*Statistically significant difference ( $P < 0.05$ ) in comparison with MAN.

†Statistically significant difference ( $P < 0.05$ ) in comparison with SERVO.

force experienced by IVD structures was significantly greater when SMT was applied with SERVO compared to INST. The change in peak superior-inferior forces during SERVO was significantly greater and in opposite direction than INST and MAN. Although change in mean antero-posterior forces experienced by IVD structures was significantly greater and in opposite direction during MAN, compared to INST and SERVO, the change in mean superior-inferior forces was significantly greater during SERVO and MAN.

In summary, although SMT application with MAN and SERVO created comparable forces in the intact specimen, IVD structures experienced greater posterior forces during MAN in comparison to SERVO (Figures 5 and 8). Additionally, SMT application with both MAN and SERVO generally created greater forces than INST in all conditions.

## DISCUSSION

This study aimed to quantify and compare the tissue loading characteristics of cadaveric porcine lumbar spine structures when SMT was provided with different methods of application (INST, MAN, SERVO). The results support our hypothesis that load distribution within spinal tissues differs significantly as a function of the SMT application method. Generally, although SMT application with INST created forces significantly smaller than MAN and SERVO, MAN and SERVO created greater forces in different directions. Sequential dissection of spinal structures revealed that IVD structures experienced greater forces during SMT application with SERVO. Although previous studies have investigated the biological outcomes elicited by SMT by using methods of application,<sup>8,16,23-25</sup> this is the first study to quantify forces experienced by internal spinal structures.

### Spinal Manipulative Therapy Characteristics Compared to Other Studies

In the current study, SMT application with INST provided an average peak force magnitude of 120N ( $\pm 12.7$ N) with a time to peak of 99 ms ( $\pm 31$  ms) and a loading rate of 1.21 N/ms. Previous studies have investigated the force-time

characteristics of SMT mechanical devices<sup>26,27</sup> and specifically the SMT characteristics of Activator V-E have been recently reported<sup>28</sup> and are comparable to the peak force magnitude measured in the current study.

Manual SMT was applied with an average peak force magnitude of 524N ( $\pm 41$ N) with an average time to peak of 220 ms and a loading rate of 2.38 N/ms. Despite the well-known variability in SMT force-time characteristics,<sup>2,29,30</sup> similar force-time characteristics to those in this trial have been described in previous investigations.<sup>15,31-33</sup> Given the above, we considered MAN to be representative of a clinical SMT application on humans, even though cadaveric porcine models were used.

### Vertebral Rotations

Despite differences in the magnitude of vertebral rotations between methods of SMT application observed in the current study, all three methods resulted in vertebral trajectories in which the greatest rotations occurred around flexion extension axis. Similar to these observations, previous studies have also reported substantial extension rotations during SMT applied manually<sup>16,34</sup> and with mechanical devices.<sup>35</sup> Specifically, Kawchuk *et al* (2010) applied manual SMT in a similar model to the one used in the current study and observed extension rotations of 1.96°. Additionally, Gal *et al* (1997) observed extension rotations of 0.2° to 1.8° during manual SMT application at the low thoracic region of human cadavers. Despite the similar axes of greatest rotations between previous and the current study, the magnitudes of rotations were considerably different between studies and are likely related to well-known force-time profile significant variability between clinicians<sup>1,29</sup> and SMT application site.

### Forces

Given that all SMTs were applied at the same location of the spine, differences in loading distribution are likely related to differences in SMT characteristics.<sup>26,36</sup> Indeed, each method of SMT application was unique in terms of its characteristics and the estimated total pressure applied (Table 1). Accordingly, it would be expected that if each SMT technique differs in terms of its application characteristics at the skin surface, then the internal loads would also differ. This expectation was indeed congruent with our results.

In addition to the above-mentioned SMT characteristics and given the viscoelastic behavior of involved soft tissues, SMT loading rate has also been described as a cause of differing spinal tissue responses.<sup>10</sup> Figure 9 presents a graph where loading rates from our data are represented by the slope of the plots. Given that SMT was provided with different loading rates by each method (INST: 1.21 N/ms; MAN: 2.38 N/ms; SERVO: 2.6 N/ms) (Figure 9), it is possible that particular loading characteristics of specific spinal structures would be more sensitive to high loading rates. Indeed, Figures 7 and 8 show that not only peak superior-inferior forces experienced by PJ structures, but also

**TABLE 3. Average and 95% Confidence Intervals of Peak and Mean Forces Experienced by the Intact Spinal Segment and Spinal Structures During Different Methods of SMT Application**

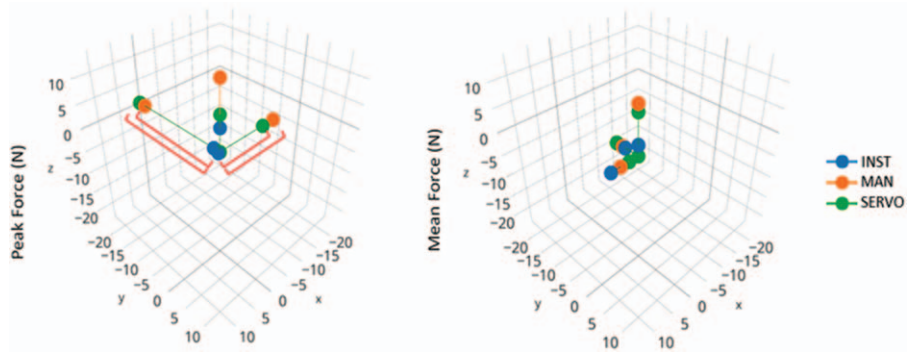
Method of SMT Application	Intact Specimen					
	Peak			Mean		
	X (lateral)	Y (ant post)	Z (sup inf)	X (lateral)	Y (ant post)	Z (sup inf)
INST	0.41 N;*† 95% CI: (-7.37, 8.20)	-1.64 N; *†95% CI: (-3.40, 0.11)	4.79 N; 95% CI: (-5.85, 15.45)	6.56 N; 95% CI: (-0.20, 13.32)	-3.38 N; 95% CI: (-5.12, -1.64)	2.20 N; 95% CI: (-8.63, 13.03)
MAN	-14.92 N; 95% CI: (-24.78, -5.06)	-22.23 N; 95% CI: (-29.45, -15.02)	13.84 N; 95% CI: (4.84, 22.85)	4.32 N; 95% CI: (-4.08, 12.73)	-4.06 N; 95% CI: (-6.95, -1.16)	10.01 N; 95% CI: (3.17, 16.85)
SERVO	-11.78 N; 95% CI: (-22.17, -1.40)	-24.00 N; 95% CI: (-29.09, -18.90)	7.33 N; 95% CI: (2.58, 12.09)	2.26 N; 95% CI: (-5.27, 9.79)	-5.66 N; 95% CI: (-7.72, -3.60)	8.50 N; 95% CI: (2.74, 14.25)
Supra- and interspinous ligaments						
	Peak			Mean		
	X (lateral)	Y (ant post)	Z (sup inf)	X (lateral)	Y (ant post)	Z (sup inf)
INST	-0.02 N; 95% CI: (-0.08, 0.02)	-0.08 N; 95% CI: (-0.31, 0.14)	-0.05 N; 95% CI: (-0.22, 0.11)	-0.03 N; 95% CI: (-0.06, -0.00)	-0.24 N; 95% CI: (-0.31, -0.17)	-0.08 N; *95% CI: (-0.22, 0.05)
MAN	0.08 N; 95% CI: (-0.13, 0.30)	-0.00 N; 95% CI: (-0.05, 0.03)	0.18 N; 95% CI: (-0.02, 0.39)	-0.05 N; 95% CI: (-0.10, -0.00)	-0.13 N; 95% CI: (-0.52, 0.26)	-1.04 N;† 95% CI: (-2.22, 0.15)
SERVO	-0.00 N; 95% CI: (-0.03, 0.03)	-0.03 N; 95% CI: (-0.06, -0.01)	-0.06 N; 95% CI: (-0.52, 0.39)	0.11 N; 95% CI: (-0.14, 0.37)	-0.15 N; 95% CI: (-0.31, 0.37)	-0.33 N; 95% CI: (-1.24, 0.56)
Facet Joints, Capsules and Ligamentum Flavum						
	Peak			Mean		
	X (lateral)	Y (ant post)	Z (sup inf)	X (lateral)	Y (ant post)	Z (sup inf)
INST	-0.18 N; 95% CI: (-0.42, 0.05)	0.23 N; 95% CI: (-0.42, 0.88)	-0.18 N;*† 95% CI: (-0.84, 0.47)	-0.12 N; 95% CI: (-0.23, -0.01)	0.39 N;* 95% CI: (0.00, 0.78)	-0.21 N; *95% CI: (-0.50, 0.06)
MAN	-0.24 N; 95% CI: (-1.10, 0.61)	0.04 N; 95% CI: (-0.43, 0.51)	0.31 N; 95% CI: (0.00, 0.62)	-0.37 N; 95% CI: (-0.61, -0.13)	-0.63 N;† 95% CI: (-2.51, 1.24)	-1.22 N;† 95% CI: (-3.13, 0.68)
SERVO	0.17 N; 95% CI: (-0.06, 0.40)	0.17 N; 95% CI: (0.06, 0.27)	0.54 N; 95% CI: (-0.20, 1.28)	-0.12 N; 95% CI: (-0.38, 0.14)	0.74 N; 95% CI: (-0.16, 1.66)	-0.68 N; 95% CI: (-2.06, 0.69)
Intervertebral disc, anterior and posterior longitudinal ligaments						
	Peak			Mean		
	X (lateral)	Y (ant post)	Z (sup inf)	X (lateral)	Y (ant post)	Z (sup inf)
INST	-0.82 N;† 95% CI: (-1.00, -0.64)	-0.65 N; *†95% CI: (-1.23, -0.07)	-0.42 N;† 95% CI: (-1.17, 0.32)	-0.73 N; 95% CI: (-0.87, -0.59)	-0.90 N;* 95% CI: (-1.21, -0.60)	-0.78 N; †95% CI: (-1.19, -0.37)
MAN	-0.82 N;† 95% CI: (-1.50, -0.14)	-1.01 N; 95% CI: (-1.26, -0.76)	-0.33 N;† 95% CI: (-0.97, 0.31)	-0.46 N; 95% CI: (-1.00, 0.08)	0.85 N;† 95% CI: (-0.98, 2.68)	-0.64 N;† 95% CI: (-3.05, 1.76)
SERVO	-1.16 N; 95% CI: (-1.49, -0.84)	-0.95 N; 95% CI: (-1.03, -0.87)	0.68 N; 95% CI: (-0.66, 2.03)	-0.38 N; 95% CI: (-1.93, 1.16)	-0.48 N; 95% CI: (-1.15, 0.17)	-3.37 N; 95% CI: (-5.51, -1.23)

CI indicates confidence interval; INST, mechanical force manually assisted instrument (Activator V-E); MAN, manual spinal manipulative therapy application; SERVO, linear actuator motor; SMT, spinal manipulative therapy. Negative forces correspond to the opposite direction of the force observed in relation to the direction of the axis of movement.

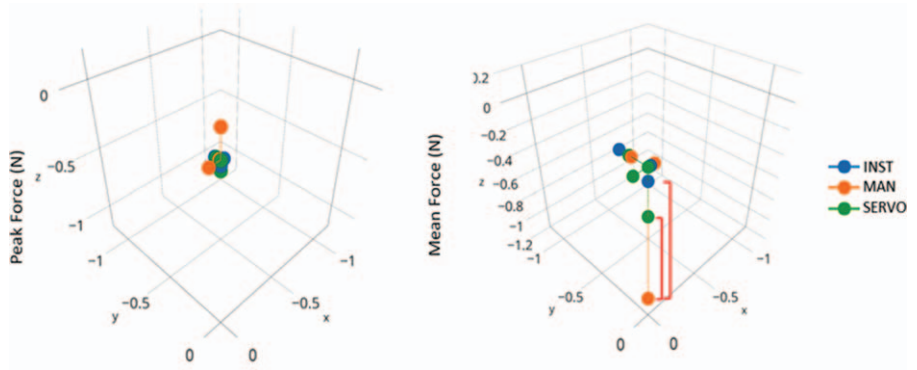
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†Significant difference ( $P < 0.05$ ) in comparison with SERVO.

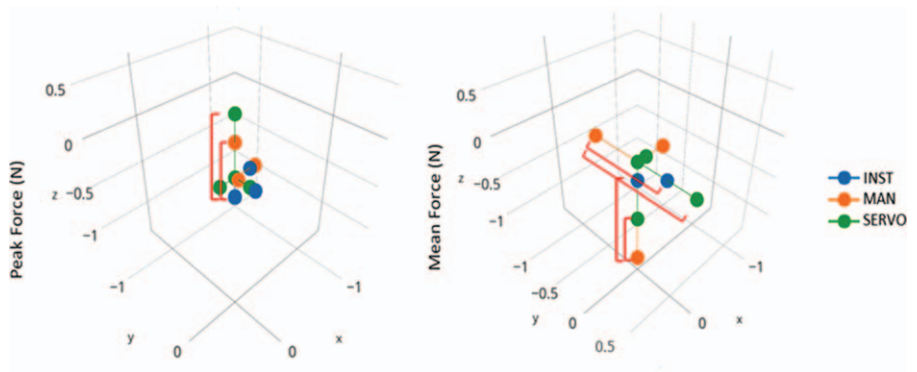
**Figure 5.** Average peak and mean forces experienced by the intact specimen during the application of spinal manipulative therapy with different methods. Red bars indicate significant comparisons ( $P < 0.05$ ).



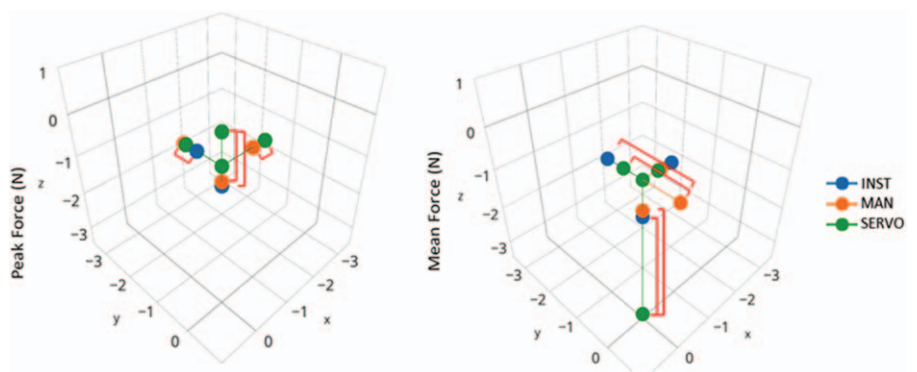
**Figure 6.** Average of normalized peak and mean forces experienced by supra- and interspinous ligaments during the application of spinal manipulative therapy with different methods. Red bars indicate significant comparisons ( $P < 0.05$ ).

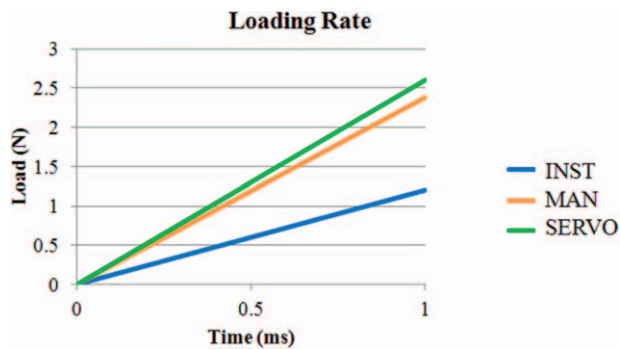


**Figure 7.** Average of normalized peak and mean forces experienced by bilateral facet joints, capsules and ligamentum flavum during the application of spinal manipulative therapy with different methods. Red bars indicate significant comparisons ( $P < 0.05$ ).



**Figure 8.** Average of normalized peak and mean forces experienced by intervertebral disc, anterior and posterior longitudinal ligaments during the application of spinal manipulative therapy with different methods. Red bars indicate significant comparisons ( $P < 0.05$ ).





**Figure 9.** Loading rate representation of different methods of spinal manipulative therapy application. INST indicates mechanical force manually assisted (Activator V-E); MAN, manual SMT; SERVO, linear actuator motor.

peak lateral force experienced by IVD structures may be associated with the SMT loading rate of each method. This suggests that higher loading rates may elicit different responses of PJ and IVD structures.

Interestingly, the results of this study also showed significant differences in mean forces along specific axes that were not observed in peak forces along the same axes. Similarly, differences in peak forces along the specific axes were not observed in mean forces along the same axes. This suggests there are unique aspects of SMT preload phase that also affect the SMT load distribution within spinal tissues. In support of this speculation, recent investigations have reported the influence of preload phase characteristics on electromyographic (EMG) and muscle spindles responses related to changes in SMT loading rate as a consequence of altered preload phase characteristics.<sup>8,37</sup>

### Limitations

Although porcine models have been described to be suitable for the investigation of the human spine,<sup>38–40</sup> reported anatomical and biomechanical differences limit the direct application of these results in human subjects. Results from cadaveric models are also limited owing to differences between *in vivo* and *in vitro* conditions such as muscular effects, although most muscular effects would likely be passive effects given that the SMT application rate is potentially faster than the muscular reflex reaction.<sup>41</sup> Additionally, potential differences in repeated biomechanical loading testing are also a limitation. Given recently reported results regarding the order of tissue removal,<sup>22</sup> the loads observed here are specific to the order in which spinal structures were removed from the specimen. Similar to what is done in clinical practice, this study did not control for the resultant direction of the applied thrust during SMT application with INST and MAN. Finally, it was not the intent of this study to evaluate all different types of SMT techniques. Rather, this was the first study to investigate the internal forces created by different types of SMT application to understand if in general, different SMT application methods influence spinal tissues differently. Therefore, different SMT techniques resulting in different force-time profiles and/or surface

pressure profiles appear to result in different loading within spinal structures.

In conclusion, this is the first study to show that SMT application method influences loads created in spinal tissues. Given our previous work showing that SMT creates forces that are unique from passive movements, it is possible that different SMT application techniques could be capable of eliciting unique outcomes in terms of effect and safety. These results may partially explain the variation in SMT outcomes observed in clinical trials.

### Key Points

- ❑ Specific methods of SMT application create unique vertebral loading characteristics.
- ❑ Generally, SMT application with a servo-controlled linear actuator motor and a manual SMT created greater forces than the SMT application with a mechanical force manually assisted device.
- ❑ These results may partially explain the variation in SMT outcomes observed in clinical trials.

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