NCMIC Lou Sportelli Research — New Investigator Award

Influence of Spinal Manipulative Therapy Force Magnitude and Application Site on Spinal Tissue Loading: A Biomechanical Robotic Serial Dissection Study in Porcine Motion Segments

Martha Funabashi, MSc, PhD,[a] François Nougarou, MSc, PhD,[b] Martin Descarreaux, DC, MSc, PhD,[c] Narasimha Prasad, MSc, PhD,[d] and Greg Kawchuk, DC, MSc, PhD[a]

Abstract

Objective: In order to define the relation between spinal manipulative therapy (SMT) input parameters and the distribution of load within spinal tissues, the aim of this study was to determine the influence of force magnitude and application site when SMT is applied to cadaveric spines.

Methods: In 10 porcine cadavers, a servo-controlled linear actuator motor provided a standardized SMT simulation using 3 different force magnitudes (100N, 300N, and 500N) to 2 different cutaneous locations: L3/L4 facet joint (FJ), and L4 transverse processes (TVP). Vertebral kinematics were tracked optically using indwelling bone pins, the motion segment removed and mounted in a parallel robot equipped with a 6-axis load cell. The kinematics of each SMT application were replicated robotically. Serial dissection of spinal structures was conducted to quantify loading characteristics of discrete spinal tissues. Forces experienced by the L3/L4 segment and spinal structures during SMT replication were recorded and analyzed.

Results: Spinal manipulative therapy force magnitude and application site parameters influenced spinal tissues loading. A significant main effect ($P < .05$) of force magnitude was observed on the loads experienced by the intact specimen and supra- and interspinous ligaments. The main effect of application site was also significant ($P < .05$), influencing the loading of the intact specimen and facet joints, capsules, and ligamentum flavum ($P < .05$).

Conclusion: Spinal manipulative therapy input parameters of force magnitude and application site significantly influence the distribution of forces within spinal tissues. By controlling these SMT parameters, clinical outcomes may potentially be manipulated. (J Manipulative Physiol Ther 2017;40:387-396)

Key Indexing Terms: *Spinal Manipulation; Robotics; Lumbar Vertebrae*

[a] Department of Physical Therapy, University of Alberta, Edmonton, Alberta, Canada.
[b] Département de Génie Électrique et Informatique, Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada.
[c] Département des Sciences de l'Activité Physique, Université du Québec à Trois-Rivières, Trois-Rivières, QC, Canada.
[d] Department of Mathematical and Statistical Sciences, University of Alberta, Edmonton, AB, Canada.
Corresponding author: Greg Kawchuk, DC, MSc, PhD, Department of Physical Therapy, University of Alberta, 3-48 Corbett Hall, Edmonton, Alberta, Canada, T6G 2G4. (e-mail: *Greg.kawchuk@ualberta.ca*).
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Introduction

Spinal manipulative therapy (SMT) is defined as a high-velocity, low-amplitude dynamic force applied to a specific location of the spine for therapeutic reasons resulting in a mechanical deformation of the spine and surrounding tissues.[1-3] Spinal manipulative therapy is a common intervention to treat low back pain, and its usage has increased over the last decade as a result of the public's interest in complementary and alternative therapies.[4,5] Despite the increase in SMT usage, the underlying mechanisms of SMT remain largely unknown.

To date, investigations of SMT mechanisms have focused on 2 domains: physiological outcomes, both biomechanical and neurophysiological,[3,6,7] and SMT input parameters (eg, thrust duration, loading rate).[8-10] With respect to SMT input parameters, peak force magnitudes and application site have been described as important parameters as they influence both neurophysiological and biomechanical outcomes elicited by SMT.[8,11-16] While the applied SMT force magnitude has been described to change vertebral displacements and accelerations as well as electromyographic responses and muscle spindles neural responsiveness,[9,16-18] SMT application site has been demonstrated to influence spinal stiffness and muscle spindle sensory input magnitude.[15,19]

Unfortunately, few studies have succeeded in linking these domains together (ie, SMT input parameters and physiological outcomes) by investigating how altering SMT input parameters can change the response of spinal tissues. If it can be shown that spinal tissue response is modified by SMT input parameters, then important indicators related to SMT-specific health outcomes may be revealed.

Toward understanding SMT's underlying mechanisms, a previous study from our research team[20] identified the loads experienced by spinal tissues during a general clinical application of SMT. This study reported that within the boundaries of a specific SMT application in a cadaveric preparation, the intervertebral disc is the spinal structure that experiences the greatest load.[20] Despite these findings, it remains unknown if changes in SMT application parameters can modify the load distribution within spinal tissues. Specifically, the investigation of loading distribution within spinal tissues when SMT is applied with different peak force magnitudes and at different application sites has not been conducted to elucidate the relation between SMT input parameters and spinal tissue response.

Given the above, exploratory studies are needed to define the relation between SMT input parameters and the distribution of load within spinal tissues. Therefore, the objective of this study was to evaluate the relation between SMT input parameters and their effect on spinal tissue loading.

Methods

Sample Size Calculation

The sample size calculation was conducted based on the data previously reported by Kawchuk et al[20] using the General Power Analysis Program (G*Power 2) (University of Trier, Germany). With a statistical power set to 0.80 (80%), 2-tailed tests with level of significance set at $\alpha = .05$ (5%) and an effect size of 0.99 to 1.2, a sample size of 9 porcine cadavers was required. Five additional porcine models were included to mitigate any loss of data for a total of 14 cadaveric porcine specimens. All experimental protocols of this study were approved by the Animal Care and Use Committee of the University of Alberta (AUP00000866).

Specimen Preparation

Fourteen fresh porcine cadavers (Duroc X [Large White X Landrace breeds]) of approximately 60 to 65 kg were included in this study. In each intact cadaver, ultrasound imaging and needle probing were used to identify the L3 and L4 vertebrae, the L3/L4 left facet joint (FJ), and the left L4 transverse process (TVP). Bone pins were drilled into the L3 and L4 vertebral bodies and a rectangular flag having 4 infrared light-emitting diode markers was attached to the upper end of each bone pin (Fig 1).

After the application of SMT on the intact porcine cadaver (detailed in the following sections), the lumbar spine was removed en bloc.[20] The L3/L4 spinal segment was cleaned of nonligamentous tissues, sealed in a plastic bag, and kept refrigerated at 3°C for less than 5 hours until potting and testing on the following day.[21] The specimen was kept moist with physiological saline throughout preparation, embedding, and testing.[22,23] As a result of complications during data collection, 4 specimens were excluded: 2 due to problems in robotic calibration for attaining neutral position alignment, and 2 due to delays resulting in cadaveric rigor mortis. Therefore, data from 10 specimens were analyzed. Given the fragile nature of the intertransverse ligaments and their frequent damage during en bloc spinal removal, all specimens had their intertransverse ligaments removed before testing.

Spinal Manipulation and Kinematic Recording

To minimize significant SMT force-time profile variance known to exist between clinicians,[2] SMT was delivered by a servo-controlled linear actuator motor.[24] A posteroanterior SMT thrust was delivered using 3 different peak force magnitudes (100 N, 300 N, and 500 N) at 2 different application sites: L4 left TVP and L3-L4 left FJ. For all SMTs, the preload set at 10% of the peak force and the slope of the force curve from preload to peak load (loading rate) was kept constant at 2.6 N/ms. Therefore, time to peak was 37.5 ms, 112.5 ms, and 187.5 ms for SMT applications having 100 N, 300 N, and 500 N peak force, respectively.

Kinematic Recording

During the application of each SMT, the resulting motion of each bone pin and sensor flag was recorded in 3 dimensions by an optical tracking system at a rate of 400 Hz (0.01 mm system resolution with 0.15 mm rigid body resolution; NDI, Waterloo, Canada).

Robotic Testing

After application of SMTs with all peak force magnitudes at both locations, the L3/L4 motion segment was removed as described previously and the specimen potted in a vertical orientation using dental stone (Modern Materials, South Bend, IN) with the intervertebral disc aligned in the horizontal plane by a projected laser beam. The caudal end (L4) of the potted spinal segment was fixed to a 6-axis load cell (AMTI MC3A-1000, Advanced Mechanical Technology, Inc., Watertown, MA), which was mounted rigidly to a parallel robot platform

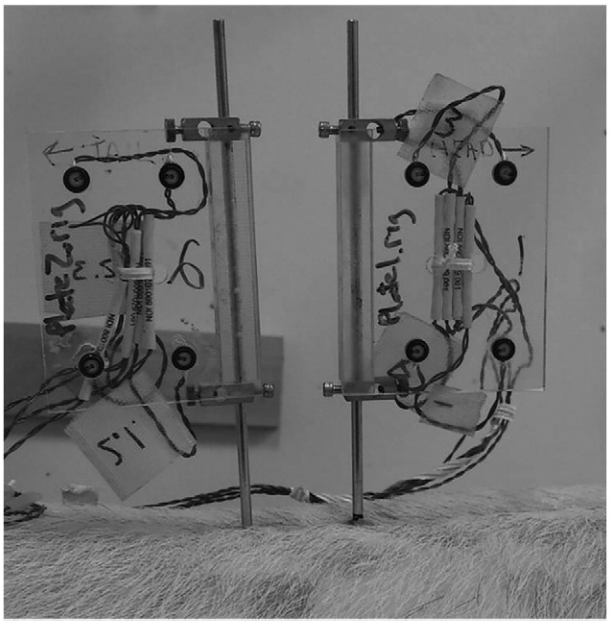

Fig 1. *Rectangular flags with 4 infrared light-emitting diode markers attached to bone pins drilled into L3 and L4 vertebrae.*

(Parallel Robotics Systems Corp., Hampton, NH), such that the anatomic axes of the specimen aligned with both the load cell axes and the robot axes as follows: x = mediolateral, y = anteroposterior, and z = superoinferior.

To calibrate the system, a series of known translations and rotations were provided to the robot and the resulting change in position of the optical markers on L4 recorded. This calibration provided the position and orientation of the L4 marker set with respect to the robotic platform.[25]

The cranial end of the potted specimen was then fixed to a stationary cross beam and the segment positioned in the same position and orientation recorded previously from the cadaver's intact neutral pose (Fig 2). By following the procedures described by Goldsmith et al,[25] the marker movements caused by SMT with each force magnitude at each application site were then transformed into robot trajectories that replicated the relative motions between L3 and L4 vertebrae recorded by the optical tracking system. These 6 trajectories were then applied by the robot in the order that the corresponding procedures were applied to the porcine cadaver, and forces experienced by the spinal segment were recorded by the load cell. Starting from the initial neutral position as obtained from the intact cadaver, SMTs were reproduced in the following sequence: 100 N at L4 FJ and L4 TVP; 300 N at L4 FJ and L4 TVP; and 500 N at L4 FJ and L4 TVP. Each applied trajectory was separated by a 2-minute recovery time with 3 preconditioning trials executed before testing and data collection.[20]

Serial Dissection

After application of all robotic trajectories in the intact specimen, spinal structures were then removed or transected

Fig 2. *Potted spinal segment with L4 mounted to the 6-axis load cell and L3 fixed to a stationary cross beam.*

and the same robotic trajectories repeated. In this way the loading distribution within specific spinal tissues was quantified. Based on the findings reported by Funabashi et al,[26] the following spinal structures were removed or transected (via scalpel unless otherwise noted) in the same order for all specimens: (1) supraspinous and interspinous ligaments (SL); (2) bilateral facet capsules, posterior facet joints (via rongeur), and ligamentum flavum (posterior joints, PJ); (3) intervertebral disc and anterior and posterior longitudinal ligaments (IVD).

Data Analysis

The resulting forces of each specimen were plotted against time. Peak and mean forces along each axis were identified using customized software (LabVIEW, National Instruments, Austin, TX). Peak force was the maximum measured force during the entirety of each applied trajectory. Mean force corresponded to the average value of forces involving both the preload and thrust phases of SMT. Using the same axis definitions as for the forces (see Robotic Testing), the values of L4 rotations relative to L3 where peak loads occurred were taken from the rotations of the robotic platform for each of the 6 trajectories.

Given our objective of describing the relation between SMT input parameters of force magnitude and application site and spinal tissues loading characteristics, each spinal structure removal condition was analyzed independently. Therefore, a split-plot analysis of variance was performed using R: a language and environment for statistical computing (R Foundation for Statistical Computing, Vienna, Austria) with 2 factors: force magnitude (main-plot factor) and SMT application site (subplot factor). A

Table 1. *Maximal Rotation (°) (SD) Created in the Cadaveric Specimens With the Application of SMT (With Different Force Magnitudes at Different Application Sites) Trajectories for All Conditions*

SMT Parameters		Rotation (°)		
Location	Force Magnitude (N)	X (flx ext)	Y (lat bending)	Z (axial rot)
L4 FJ	*100*	1.34 (0.78)[a,b]	–0.72 (0.45)	–0.78 (0.66)[a,b,c]
L4 FJ	*300*	1.36 (0.84)[a,b]	–0.10 (0.17)	–1.47 (1.08)[b]
L4 FJ	*500*	1.58 (1.02)[b]	–0.70 (0.40)	–1.91 (1.12)[b]
L4 TVP	*100*	1.90 (0.67)	–0.67 (0.57)	–1.54 (0.71)[b]
L4 TVP	*300*	2.14 (0.85)	–0.47 (0.46)	–2.17 (1.32)[b]
L4 TVP	*500*	2.32 (1.04)	–0.49 (0.21)	–3.22 (1.70)

FJ, facet joint; *flx ext,* flexion extension; *lat bending,* lateral bending; *N,* Newtons; *SMT,* spinal manipulative therapy; *SD,* standard deviation; *TVP,* transverse process.
[a] Significantly difference with 300 N at L4 TVP.
[b] Significantly difference with 500 N at L4 TVP.
[c] Significant difference with 500 N at L4 FJ.

post-hoc multiple comparison based on Tukey test was performed for pairwise analysis of significant interaction between factors. Force magnitude and application site main effects were analyzed on the conditions (intact condition or after spinal structure removal) and variables that did not reveal a significant interaction. For all statistical tests an α level of .05 was considered.

Results

Vertebral Rotations

Vertebral rotations of L4 vertebra in relation to L3 arising from SMT parameters of force magnitude and application site are displayed by axis of movement in Table 1.

Forces

Intact Specimen. Figure 3 shows the average peak and mean forces experienced by the intact specimen while changing SMT parameters of applied force magnitude and application site.

In the intact specimen, significant main effects were identified, and generally, the intact specimen experienced significantly greater loads with the application of a SMT with greater force magnitudes. Specifically, a significant SMT force magnitude main effect was identified in all peak forces and mean lateral and anteroposterior forces (Fig 3). A significant application site main effect was also noted in peak and mean superoinferior forces (Fig 3), and greater superoinferior forces were observed when SMT was applied at FJ than when applied at TVP. There was no significant interaction between force magnitude and SMT application site for any of the comparisons. Details of this statistical analysis are reported in Table 2.

Loading Distribution

Supra- and Interspinous Ligaments (SL). Figure 4 shows the average of normalized relative peak and mean forces experienced by the SL structures during the SMT application with each force magnitude at each application site.

A statistically significant main effect of force magnitude was observed for the mean lateral force (Table 3). Paradoxically, lateral loads borne by SL when SMT was applied using a 100-N force magnitude (average mean force along x-axis: –0.18 N ± 0.21) were significantly greater than with 500 N (average mean force along x-axis: –0.04 N ± 0.12; Fig 4). The application site main effect was not significant and no significant interaction between SMT force magnitude and application site was noted for the SL structures.

Bilateral Facet Joints, Capsules, and Ligamentum Flavum (PJ). Figure 5 shows the average of normalized relative peak and mean forces experienced by the PJ structures during the SMT application with each force magnitude at each application site.

Although the force magnitude main effect did not reveal a statistically significant difference, the application site main effect was statistically significant for peak lateral force: Loads experienced by PJ structures were significantly greater when SMT was applied at L4 FJ (average peak lateral force: –0.58 N ± 2.00) than at L4 TVP (average peak lateral force: 0.28 ± 0.48) (Table 4). The PJ structures did not reveal a statistically significant interaction between force magnitude and SMT application site.

Intervertebral Disc and Anterior and Posterior Longitudinal Ligaments. Figure 6 shows the average of normalized peak and mean forces experienced by IVD structures during the SMT application with each force magnitude at each application site.

For the IVD structures, no significant force magnitude and application site main effects were identified (Table 5). The interaction effect between force magnitude and application site also did not reveal a statistically significant difference.

Discussion

This study aimed to describe the loading characteristics of cadaveric spinal tissues experiencing SMT of different application parameters. The results indicate that SMT force

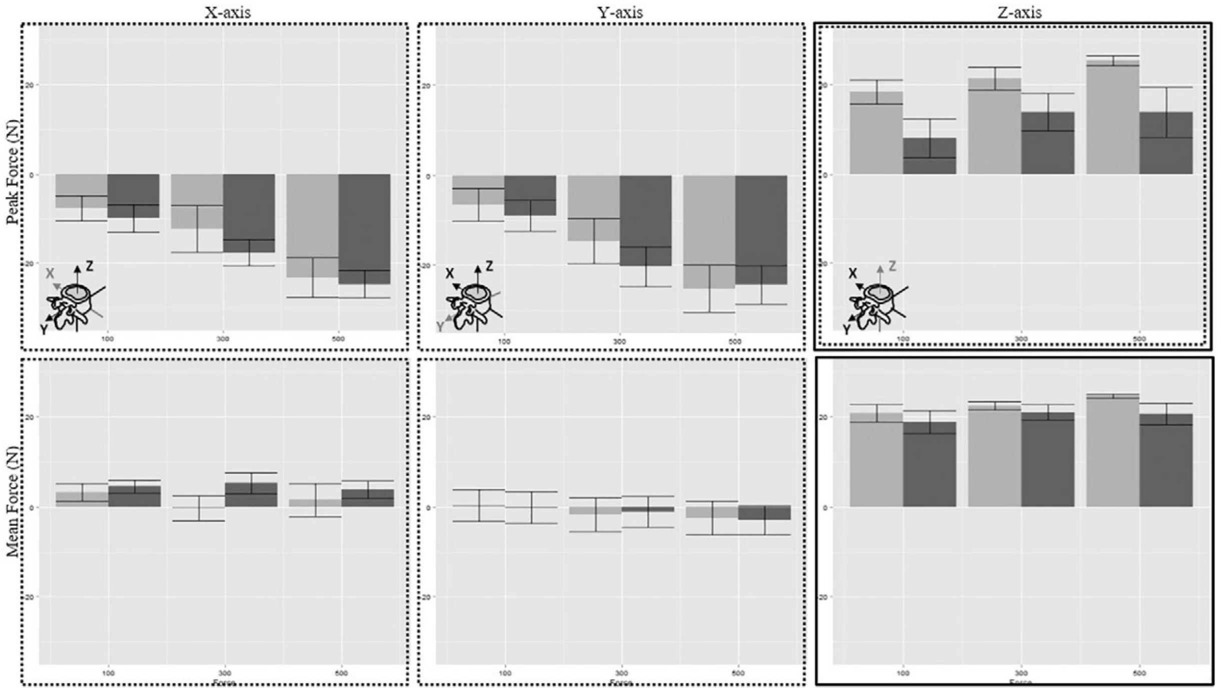

Fig 3. *Average peak and mean forces experienced by the intact specimen during the spinal manipulative therapy (SMT) application with each force magnitude (bottom of each graph) at each application site (grayscale bars). Dotted boxes indicate significant force magnitude main effect. Full boxes indicate significant application site main effect.*

Table 2. *Split-Plot ANOVA Table for the Intact Condition*

Factor	DF	Sum Sq	Mean Sq	*F*	*P*	DF	Sum Sq	Mean Sq	*F*	*P*
		Peak Force Along x-Axis					**Mean Force Along x-Axis**			
Force	2	1214.2	1157.09	15.09	**.001**	2	22.45	11.225	0.2968	.74
Error	18	1380.2	76.68			18	680.87	37.826		
Location	1	140.6	140.58	3.2233	.08	1	138.71	137.712	4.9646	**.03**
Force:Location	2	41.2	20.59	0.4720	.62	2	50.62	25.311	0.9059	.41
Error	27	1177.6	43.61			27	754.38	27.940		
		Peak Force Along y-Axis					**Mean Force Along y-Axis**			
Force	2	2891.0	1445.49	32.0610	**<.001**	2	78.9	39.46	9.5985	**.001**
Error	18	811.5	45.09			18	74.0	4.11		
Location	1	86.3	86.28	2.9814	.09	1	0.3	0.28	0.0552	.81
Force:Location	2	106.7	53.33	1.8428	.17	2	4.3	2.16	0.4289	.65
Error	27	781.4	28.94			27	136.2	5.04		
		Peak Force Along z-Axis					**Mean Force Along z-Axis**			
Force	2	426.7	213.37	4.0065	**.03**	2	86.29	43.144	2.5240	.10
Error	18	958.6	53.26			18	307.68	17.094		
Location	1	1431.5	1431.52	12.0459	**.001**	1	91.71	91.712	4.6859	**.03**
Force:Location	2	42.7	21.35	0.1796	.83	2	17.95	8.974	0.4585	.63
Error	27	3208.7	118.84			27	528.44	19.572		

Statistical significance (P <0.05) are shown in bold. *ANOVA,* analysis of variance.

magnitude and application site parameters influenced spinal tissues loading. Although an interaction effect was not identified in any condition, significant differences in loads as a result of force magnitude were noted in the intact specimen and for SL structures. Similarly, application site significantly influenced the intact specimen and PJ structures loading. Overall, the results of this study suggest that SMT input parameters of force magnitude and application site significantly change SMT load distribution within spinal tissues and consequently the forces experienced by the intact specimen and by spinal structures. Although several prior studies have investigated the effects of various SMT parameters on biomechanical and neurophysiological responses,[8,9,15,16,27,28] this is the first study to quantify the effect of changing SMT application parameters on spinal tissue response.

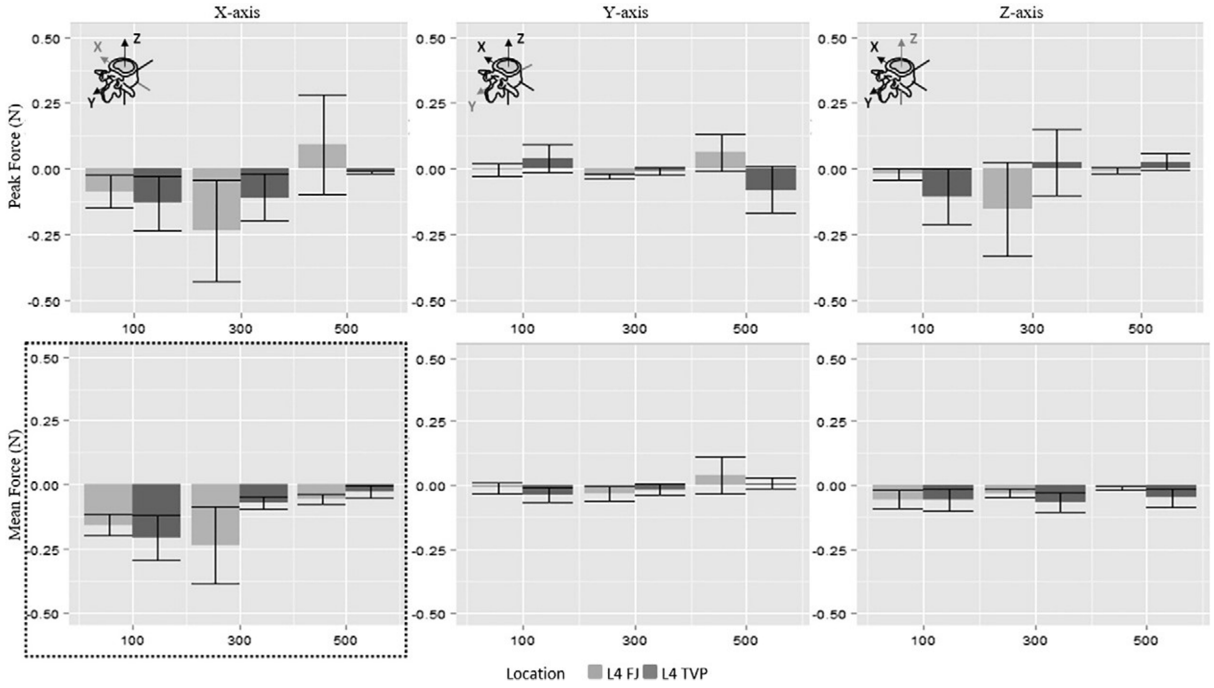

Fig 4. *Average of normalized relative peak and mean forces experienced by the supra- and interspinous ligaments during the spinal manipulative therapy (SMT) application with each force magnitude (bottom of each graph) at each application site (grayscale bars). Dotted box indicate significant force magnitude main effect. FJ, facet joint; TVP, transverse process.*

Table 3. *Split-Plot ANOVA Table for the Supra- and Interspinous Ligaments*

Factor	DF	Sum Sq	Mean Sq	*F*	*P*	DF	Sum Sq	Mean Sq	*F*	*P*
		Peak Force Along x-Axis					**Mean Force Along x-Axis**			
Force	2	0.4738	0.23689	1.3052	.29	2	0.19636	0.09818	4.3454	**.02**
Error	18	3.2670	0.18150			18	0.40669	0.02259		
Location	1	0.0011	0.00112	0.0108	.91	1	0.00159	0.00158	0.1136	.73
Force:Location	2	0.1482	0.07411	0.7127	.49	2	0.02840	0.014200	1.0160	.37
Error	27	2.8080	0.10400			27	0.37734	0.013976		
		Peak Force Along y-Axis					**Mean Force Along y-Axis**			
Force	2	0.01444	0.00721	0.2351	.79	2	0.02978	0.014889	1.6817	.21
Error	18	0.55272	0.03070			18	0.15936	0.00885		
Location	1	0.01102	0.01021	0.5754	.45	1	0.00258	0.002582	0.3455	.56
Force:Location	2	0.1021	0.05109	2.8776	.07	2	0.00747	0.003735	0.4999	.61
Error	27	0.4793	0.01775			27	0.20174	0.007472		
		Peak Force Along z-Axis					**Mean Force Along z-Axis**			
Force	2	0.06956	0.034778	0.4383	.65	2	0.00739	0.003696	0.7087	.50
Error	18	1.42837	0.079354			18	0.09388	0.00521		
Location	1	0.02752	0.02751	0.2406	.62	1	0.01002	0.010024	2.888	.10
Force:Location	2	0.17410	0.08705	0.7612	.47	2	0.00404	0.002022	0.5826	.56
Error	27	3.08763	0.114357			27	0.09369	0.003470		

Statistical significance (P <0.05) are shown in bold. *ANOVA,* analysis of variance.

In the intact specimen, although differences in spinal forces were identified when SMT was applied with 100 N, 300 N, and 500 N, this was only present in specific axes of movement and when a 100-N force magnitude was compared with 500 N. For these structures, the comparison between 100 N with 300 N and 300 N with 500 N force magnitudes did not reveal any significant difference in experienced loads. This indicates that a difference of applied forces greater than 200 N is required to influence the loads experienced by spinal structures, given the method of SMT application used here.

Despite the observation that greater loads were generally observed when greater vertebral displacements were also present, some exceptions could be noted. For example, even though the application of a 500-N SMT at L4 TVP caused the largest axial rotation (rotation about z-axis) (Table 1), the forces in the intact specimen along x-axis were not maximal (Fig 3). Likewise, Kawchuk et al[20] observed that

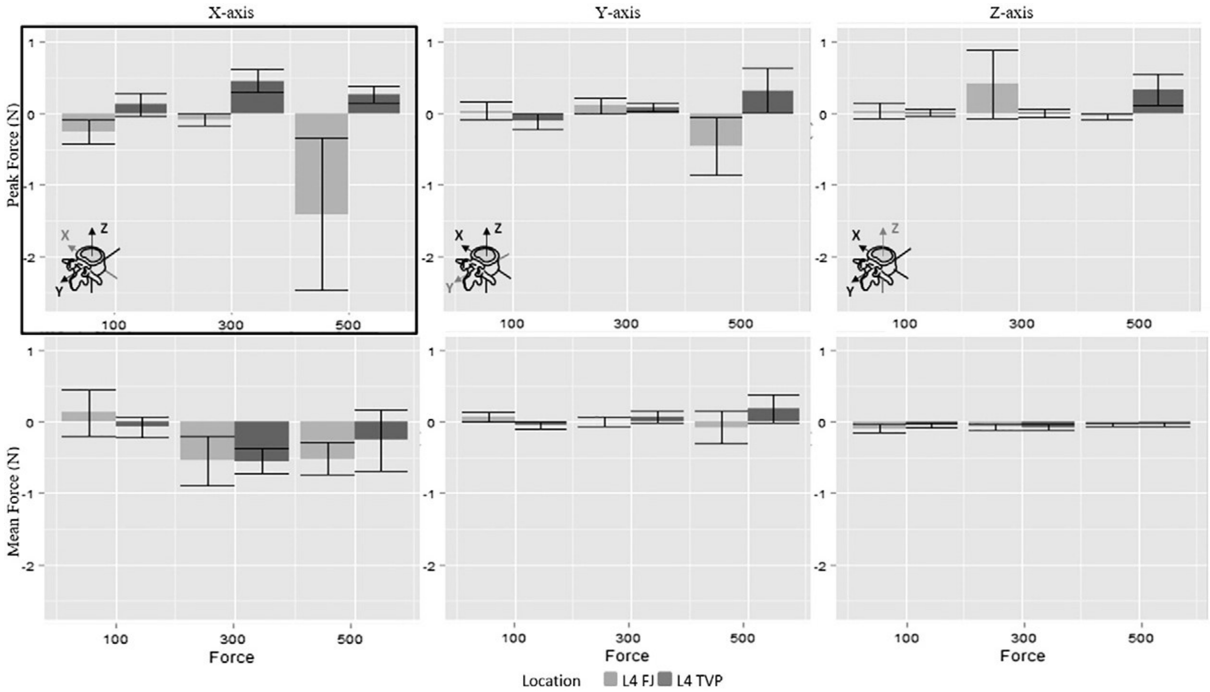

Fig 5. *Average of normalized relative peak and mean forces experienced by the bilateral facet joints, capsules, and ligamentum flavum during the spinal manipulative therapy (SMT) application with each force magnitude (bottom of each graph) at each application site (grayscale bars). Full box indicate significant application site main effect. FJ, facet joint; TVP, transverse process.*

Table 4. *Split-Plot ANOVA Table for the Bilateral Facet Joints, Capsules, and Ligamentum Flavum*

Factor	DF	Sum Sq	Mean Sq	*F*	*P*	DF	Sum Sq	Mean Sq	*F*	*P*
		Peak Force Along x-Axis					**Mean Force Along x-Axis**			
Force	2	2.939	2.9694	1.5459	.24	2	4.1084	2.05418	2.2088	.13
Error	18	34.574	1.9208			18	16.7399	0.9300		
Location	1	11.199	11.1986	5.8021	**.02**	1	0.0431	0.04311	0.0438	.83
Force:Location	2	4.960	2.4798	1.2848	.29	2	0.5451	0.27254	0.2768	.76
Error	27	52.112	1.9301			27	26.5833	0.98457		
		Peak Force Along y-Axis					**Mean Force Along y-Axis**			
Force	2	0.3195	0.1597	0.5116	.60	2	0.0205	0.01026	0.0643	.93
Error	18	5.6201	0.3122			18	2.8715	0.15953		
Location	1	0.6248	0.62483	1.2356	.27	1	0.0794	0.07941	0.9995	.32
Force:Location	2	2.5118	1.2559	2.4835	.10	2	0.3645	0.18227	2.2944	.12
Error	27	13.6541	0.50571			27	2.1450	0.07944		
		Peak Force Along z-Axis					**Mean Force Along z-Axis**			
Force	2	0.3476	0.1782	0.4433	.64	2	0.01303	0.006516	0.7452	.48
Error	18	7.0583	0.39213			18	0.15738	0.008743		
Location	1	0.0045	0.00445	0.0095	.92	1	0.00351	0.003509	0.8884	.35
Force:Location	2	1.5229	0.76143	1.6179	.21	2	0.00709	0.003546	0.8976	.41
Error	27	12.7070	0.47063			27	0.10666	0.003950		

Statistical significance ($P < 0.05$) are shown in bold. *ANOVA,* analysis of variance.

the axis presenting greater displacements were not the same axes experiencing the greater loads. This indicates that greatest vertebral motion is not always associated with greatest loading, a result most likely explained by different anatomic connections and boundaries between axes. This also suggests that some motions caused by SMT application occur within the neutral zone, where vertebral motion is produced with minimal resistance.[29] Because the neutral zone has been described to be a result of the nonlinear load-displacement curves presented by biological structures,[29] this indicates that the nonlinear, time-dependent behavior of spinal structures also play an important role on the SMT load distribution. Even when greater vertebral displacements are produced by SMT, if they exist within the neutral zone of the motion segment, small tissue loads will result.

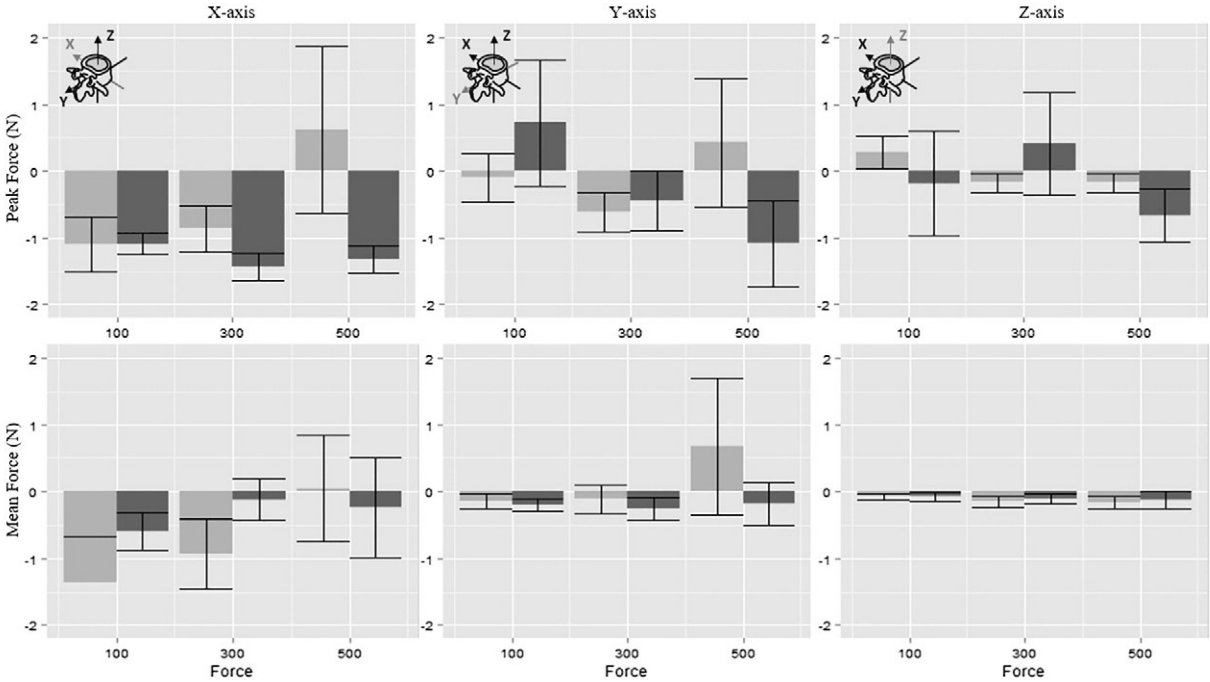

Fig 6. *Average of normalized peak and mean forces experienced by intervertebral disc and anterior and posterior longitudinal ligaments during the spinal manipulative therapy (SMT) application with different force magnitudes (bottom of each graph) at each application site (grayscale bars).*

Table 5. *Split-Plot ANOVA Table for the Intervertebral Disc and Anterior and Posterior Longitudinal Ligaments*

Factor	DF	Sum Sq	Mean Sq	*F*	*P*	DF	Sum Sq	Mean Sq	*F*	*P*
		Peak Force Along x-Axis					**Mean Force Along x-Axis**			
Force	2	7.925	3.9625	0.9616	.40	2	7.784	3.8922	1.7808	.19
Error	18	74.148	4.1193			18	39.342	2.1857		
Location	1	10.453	10.4526	3.5390	.07	1	2.835	2.8353	0.7488	.39
Force:Location	2	10.039	5.0195	1.6995	.20	2	3.838	1.9192	0.5069	.60
Error	27	79.746	2.9535			27	102.22	3.7863		
		Peak Force Along y-Axis					**Mean Force Along y-Axis**			
Force	2	7.680	3.8402	0.7902	.46	2	2.445	1.2223	0.6185	.54
Error	18	87.478	4.8599			18	35.751	1.9762		
Location	1	0.446	0.4464	0.1825	.67	1	1.872	1.8715	1.7852	.19
Force:Location	2	14.462	7.2312	2.9561	.06	2	1.954	0.9771	0.9320	.40
Error	27	66.047	2.4462			27	28.306	1.0484		
		Peak Force Along z-Axis					**Mean Force Along z-Axis**			
Force	2	3.317	1.6585	0.7519	.48	2	0.0556	0.02779	1.2155	.31
Error	18	39.702	2.2057			18	0.4115	0.02286		
Location	1	0.233	0.2335	0.1040	.74	1	0.0103	0.01026	0.9099	.34
Force:Location	2	3.714	1.8568	0.8271	.44	2	0.0042	0.00209	0.1852	.83
Error	27	60.612	2.2449			27	0.6044	0.0128		

ANOVA, analysis of variance.

Considerably different vertebral rotations were observed when SMT was applied with different input parameters of force magnitude and application site (Table 1). Specifically, although many of the great rotations observed were caused by greater force magnitudes, greater lateral rotation was caused by smaller SMT force magnitudes. Additionally, the SMT application at L4 TVP caused greater vertebral rotation only in specific axis (eg, rotation about x- and z-axis). This indicates that SMT input parameters of force magnitude and application site not only significantly influence SMT load distribution within spinal structures but also influence the coupled motion of the spinal segment. It is possible that SMT input parameters of force magnitude and application site affect spinal structure engagement as well as the length of moment arms created, influencing the resulting vertebral motion.

Given that this was the first study to investigate the differences in spinal structure loading characteristics caused by the different SMT input parameters of force magnitude and application site, comparisons to existing literature are limited. Results from the current study indicate that SMT force magnitude and application site parameters influence the resulting complex 3-dimensional vertebral motion as well as the loading distribution within spinal tissues and, consequently, the loads spinal structures experience during SMT.

Limitations

Although porcine lumbar spine models have been described to be suitable alternative to human spines,[30-32] anatomic and biomechanical differences can be identified. Therefore, the extrapolation of these results to human spines warrants caution. Secondly, by using cadaveric models, limitations associated with differences between in vivo and in vitro conditions, such as physiological and muscular effects, and potential differences in repeated loading testing are also present. Additionally, given the results reported by Funabashi et al,[26] the loads noted in this study are specific to the order in which spinal structures were removed from the specimen. Finally, this was an exploratory study initiating scientific investigations regarding the effect of SMT input parameters of force magnitude and application site on spinal tissues load distribution. More research is necessary to further explore these parameters and investigate additional outcomes (eg, moments) as well as other SMT input parameters, such as thrust duration and loading rate.

Future Studies

Based on the results of this study, future studies continuing to investigate the underlying mechanisms of SMT are planned. Specifically, the structural response of specific spinal structures (such as SL and PJ structures) to the specific SMT loads should be investigated to delineate the link among SMT application, SMT input parameters, and the physiological benefits elicited by SMT. Additionally, considering that unique spinal structure loads during SMT may be responsible for SMT's therapeutic effects, the investigation of these specific loads on pathologic spine models and the response of pathologic spine structures may provide important evidence regarding the differential therapeutic mechanisms of SMT. Finally, additional SMT characteristics, such as loading rate and force direction, are likely important contributors to modulating spinal structure loading and should be investigated.

Conclusion

Based on the findings of this study, SMT input parameters of force magnitude and application site significantly influence the distribution of forces within spinal tissues. Consequently, forces experienced by the intact L3/L4 spinal segment and SL and PJ structures were significantly influenced by force magnitudes and application site parameters of SMT.

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Contributorship Information

Concept development (provided idea for the research): M.F., G.K.
Design (planned the methods to generate the results): M.F., F.N., M.D., G.K.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): M.F., F.N., M.D., G.K., N.P.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): M.F.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): M.F., N.P.
Literature search (performed the literature search): M.F.
Writing (responsible for writing a substantive part of the manuscript): M.F.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): M.F., F.N., M.D., G.K., N.P.

Practical Applications

- Spinal manipulative therapy force magnitude significantly influences the forces experienced by the intact specimen and SL structures.
- Spinal manipulative therapy application site significantly influences the forces experienced by the intact specimen and PJ structures.
- Distinct load distribution within spinal tissues may influence SMT clinical outcomes.

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