3-11-2019

Biomechanical Characteristics of Lumbar Manipulation Performed by Expert, Resident, and Student Physical Therapists

Joseph M. Derian

Jo Armour Smith

Yue Wang

Wilson Lam

Kornelia Kulig

KEYWORDS

Education, Ground reaction force, Kinematics, Manual therapy/spine, Thrust

INTRODUCTION

Low back pain is one of the most common musculoskeletal pain syndromes in the United States. In 2015, the global point prevalence was estimated at 7.3%, meaning that 540 million people are affected by low back pain at any one time.[23] Thus, development of effective treatments for low back pain, and the proper delivery of these treatments, is of utmost importance. Spinal manipulation, defined as the application of rapid movement to vertebral segments, is an effective treatment for low back pain and is a first-line intervention in primary care/direct access settings.[5,11,14,15,19,20]

Despite its importance, the optimal technique for performing the motor skill of lumbar manipulation has not been identified. Researchers have investigated the forces applied to the patient during manipulative techniques.[2,4,6,7,8,9,21,22] The movements that the practitioner makes in order to generate these forces are less well understood. Therefore, current teaching of this manual skill to entry-level and post-professional clinicians is neither standardized nor based upon evidence. A recent Delphi study found that practitioners who teach side-lying lumbar manipulation believe that maintaining close contact with the patient, generating force through body and legs, dropping the body downwards, and providing a "short-amplitude high-velocity" thrust are important characteristics of clinician movement during manipulation.[18] This suggests that linear motion of the center of mass, pelvis kinematics, and ground reaction forces may be important biomechanical features of manipulation performance. Center of mass mechanics provide an estimation of total body motion during the thrust while measurement of angular and linear pelvis kinematics may help to demonstrate how forces are generated while contact with the patient is maintained. Vertical and horizontal ground reaction forces provide a measure of how the interaction with the ground through the feet is modulated by the clinician to generate motion.

The purpose of this study was to identify primary features of ground reaction forces, center of mass mechanics, and pelvic kinematics during lumbar manipulation and to determine which of these features distinguish experts from less experienced practitioners. We hypothesized that expert performance of side-lying lumbar manipulation is characterized by increased rate of ground reaction force modulation, faster pelvic movement, and greater center of mass momentum of the practitioner.

METHODS

Study Design

This was a cohort observational study. Approval for study procedures was provided by the Internal Review Board of XXX and participants signed an informed consent statement prior to inclusion in the study.

Participants

Practitioners

Four groups of practitioners were recruited via email through professional networks of the investigators and the student body of the XXX residency and entry-level physical therapy programs. Practitioners were grouped into four categories: experts, residents, entry-level Doctor of Physical Therapy (DPT) students in their final (third) year of training, and DPT students in their first year of training. Experts were eligible for inclusion if they had been practicing for a minimum of 10 years and were either frequently performing the side lying lumbar manipulation in clinical practice or teaching manipulation techniques, including side-lying lumbar manipulation, to post-graduate physical therapists. Residents were recruited from current Orthopedic and Sports Physical Therapy residency cohorts. All residents were licensed physical therapists who had recently graduated from an APTA credentialed entry-level DPT program. Students were recruited from current first year and third year DPT cohorts at the same institution. To help homogenize body type and size, only male participants were recruited.

Patient-Models

Patient-models had to be between the ages of 18 and 35 and have at least one hypomobile lumbar spine segment, assessed via prone posterior-to-anterior glide. Although this method has moderate to poor inter-tester reliability it is also a very widely used method of assessing spinal stiffness and is part of a clinical prediction rule for those likely to benefit from spinal manipulation. [5,16] Exclusion criteria for patient-models were life history of low back pain and contraindications/risk factors to manipulation (known presence of a disc herniation, known pars defect, Beighton score greater than 4, active infection, cancer history or rheumatoid arthritis). To help homogenize body type and size and reduce risk of side effects, all male patient-models were used.[1]

Data Collection Procedure

Models lay in the right lateral recumbent position on a high-low table in front of two force plates (AMTI OR-6, Watertown, MA) (Figure 1). Practitioners stood with one foot on each force plate facing the model. Vertical and horizontal ground reaction force (GRF) data were sampled at 1600Hz. The practitioners were instrumented with 14mm retro-reflective markers placed on the skin overlying the L5-S1 spinous process interspace and the iliac crests and on the greater trochanters. Motion capture data were collected using an 11-camera motion capture system (Qualisys Oqus System, Qualisys AB, Gothenburg, Sweden) sampling at 200Hz. First, a calibration trial was collected with the participant standing still to establish the dimensions of the pelvic segment. The greater trochanter markers were then removed and pelvic motion during the manipulation was tracked using the L5-S1 and iliac markers. Ground reaction force and motion capture data were digitally synched (Qualisys Track Manager, Qualisys AB, Gothenburg, Sweden). Practitioners completed two manipulations on one model, and two on another model for a total of four manipulations per practitioner. Each manipulation was separated by at least 30 minutes to allow for absorption of synovial joint gasses produced by potential cavitation.[3]

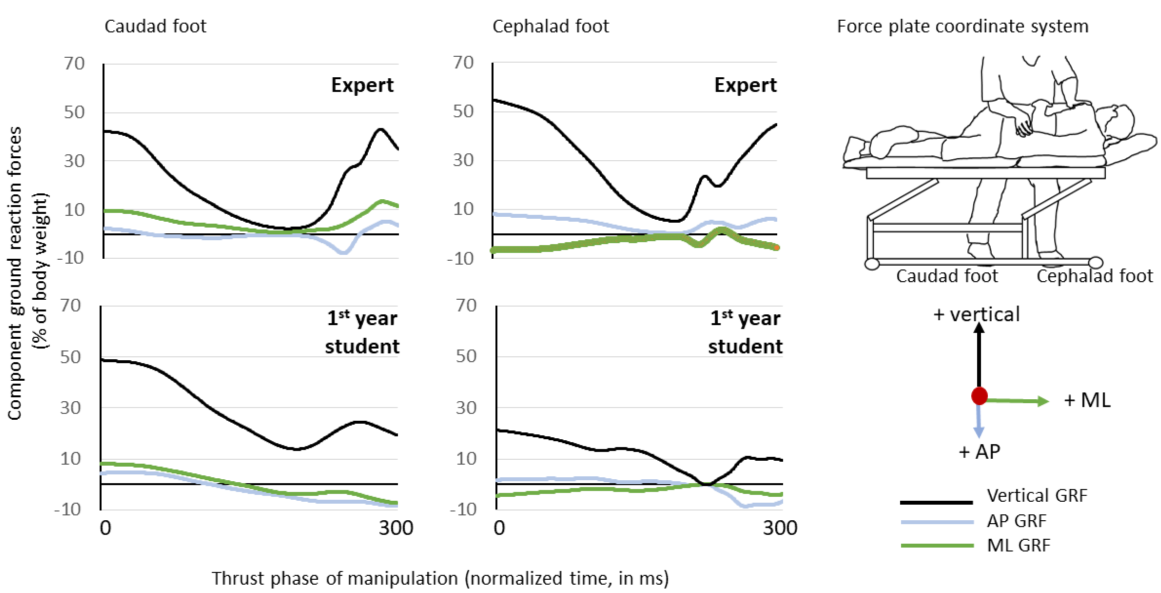

FIGURE 1. Exemplar vertical and horizontal ground reaction force data from one expert (top) and one first year student (bottom). The force plate coordinate system is shown, with the positive mediolateral (ML), anteroposterior (AP) and vertical directions indicated relative to the practitioner. The caudad and cephalad foot was defined in reference to the position of the patient-model. The thrust phase of the manipulation was defined as: the moment when vertical GRF under one or both feet peaked prior to rapidly decreasing until the lowest height of the L5-S1 marker.

Data Processing

Kinetic analysis

Ground reaction force (GRF) data were low-pass filtered at 50Hz. For each trial, onset of the thrust phase of the manipulation was defined as the moment when vertical GRF under one or both feet peaked prior to rapidly decreasing (Figure 2). This event indicates the start of the thrust as it is the beginning of a sharp drop in GRF associated with loading the patient and treatment table with the practitioner's body weight, and it immediately precedes the start of the downward movement of the practitioner's center of mass. The end of the thrust phase of the manipulation was defined as the moment when the L5-S1 marker (a proxy for the center of mass) reached its lowest point (Figure 2).The completion of the thrust was defined in this way as practicing clinicians agree that the side-lying lumbar manipulation is a primarily downward body movement.[18] Vertical and horizontal GRF data were normalized to body weight. This removed the potentially confounding influence of practitioner weight from the kinetic analyses. The following variables were calculated for the cephalad and caudad foot: vertical GRF (GRF_V), anteroposterior GRF (GRF_{AP}) and mediolateral GRF (GRF_{ML}) at the beginning of the thrust phase; minimum (lowest point) of the GRF_V during the thrust phase; rate of GRF_V decrease during the thrust phase (peak slope of the normalized GRF_V/time curve from start of thrust phase to minimum GRF_V). Cephalad and caudad were defined relative to the model's position (Figure 1).

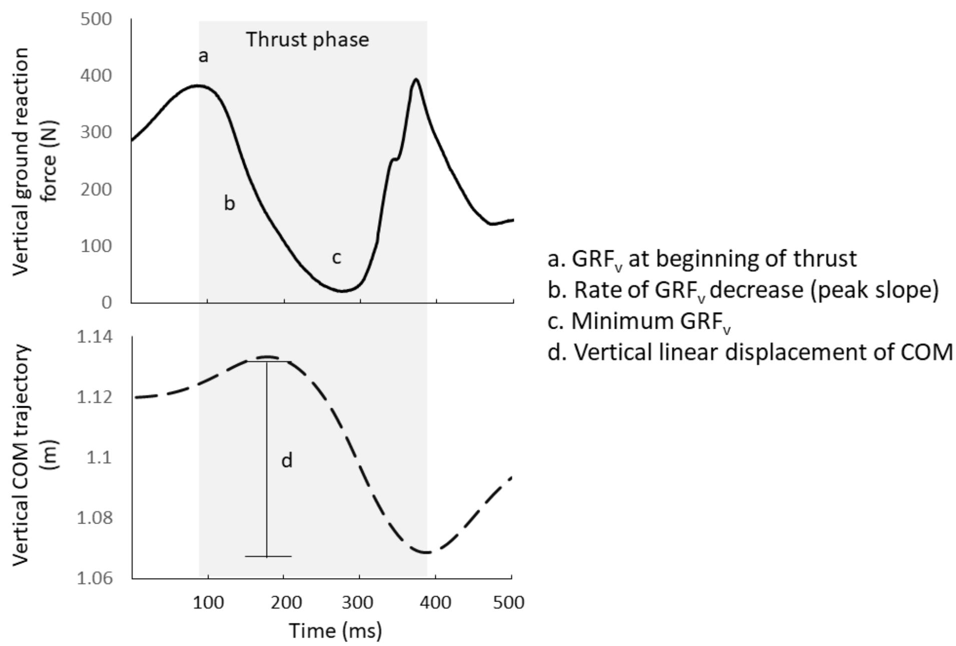

FIGURE 2. Exemplar vertical ground reaction force data (top) and center of mass vertical trajectory data (bottom) from a single expert participant. The thrust phase of the manipulation is defined as starting at the peak of the vertical ground reaction **(GRF_V)** under one or both feet prior to the thrust, ending at the lowest point of the center of mass trajectory after the thrust. Selected kinetic and kinematic variables are indicated.

Force-force analysis

Coordination of modulation of GRF_V between the two feet was calculated utilizing a modified vector coding method.[17] Vector coding is used to identify the relationship between the magnitude of two changing variables over time. In this case, it was the GRF_V of each foot. The vector coding method can be visualized using a force-force scatterplot with the x-axis representing the magnitude of the caudad foot GRF_V and the y-axis representing the magnitude of the cephalad foot GRF_V (Figure 3). Each point on the graph represents these values at one time point during the thrust. The angle (drawn from the right horizontal) from one time point to the next is defined as the “coupling angle. The coupling angle at each time point is used to define the pattern of coordination of GRF_v between the feet at that time point as shown in Figure 3. An *inphase decreasing* coordination pattern occurs when the cephalad and caudad foot GRF_V decrease synchronously at a similar rate, whereas a *cephalad foot decreasing* pattern occurs when the cephalad foot GRF_V is decreasing more rapidly than caudad foot GRF_V, and vice versa for *caudad foot decreasing* pattern. The time spent in each coordination pattern was expressed for each individual as a percentage of the total thrust time. Full details and equations for the vector coding methodology are provided in Appendix A.[17]

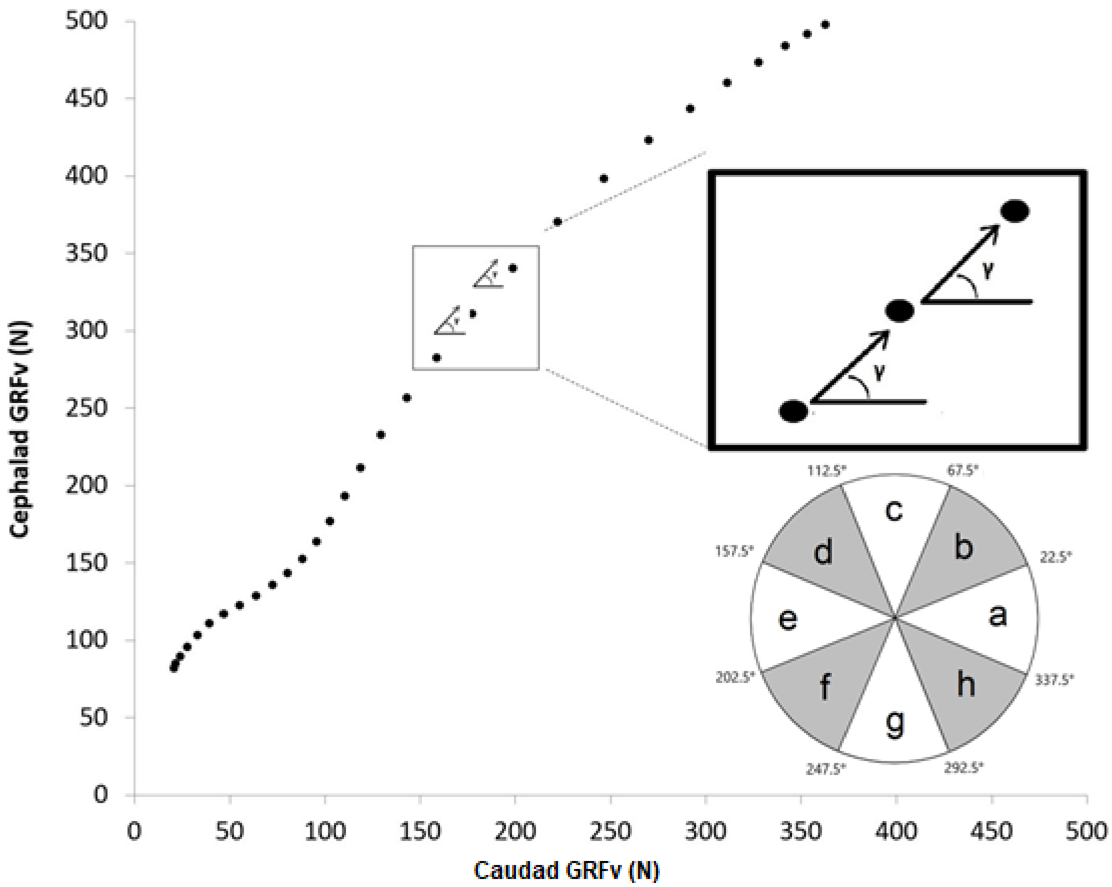

FIGURE 3. Example force-force scatterplot comparing change in GRFv in each foot through time. Top inset: coupling angle determined by vector orientation between two adjacent data points in time relative to the right horizontal. Bottom inset: Coupling angle chart. Key to patterns of GRFv coordination: a; Caudad GRFv increasing (coupling angle between 337.5 degrees and

22.5 degrees), b; Cephalad and caudad GRFv increasing (inphase increasing), c; Cephalad GRFv increasing, d; Cephalad GRFv increasing & caudad GRFv decreasing (antiphase), e; Caudad GRFv decreasing, f; Cephalad and caudad GRFv decreasing (inphase decreasing), g; Cephalad GRFv decreasing, h; Cephalad GRFv decreasing and caudad GRFv increasing (antiphase).

Kinematic analysis

A 3-dimensional model of the pelvis was constructed from the static calibration trial using the markers on the greater trochanters, iliac crests and L5-S1. A virtual coordinate system was calculated that translated and rotated the global laboratory coordinate system to the position of the practitioner's pelvis at the start of the thrust and all motion was referenced to this starting position. The following variables were calculated during the thrust (from the highest point of the L5-S1 marker to the lowest point of the marker): peak angular velocity of the pelvis in the sagittal, frontal and transverse planes and peak vertical linear velocity of the pelvis.

Vertical linear displacement and acceleration of the center of mass (COM) was approximated by tracking the linear motion of the marker placed on the L5-S1 marker.[13] COM variables were normalized to the height of the COM for each individual during the standing static calibration trial.

Statistical Analysis

All data were tested for normality of distribution. Variables that were not normally distributed were log-transformed.

Group comparisons

Participant age was compared between groups utilizing the Mann Whitney U test. All other group comparisons were made with one-way analysis of variance (ANOVA) (four levels; experts, residents, third year students, first year students). Pairwise post-hoc group comparisons were made for variables with a significant main effect of group. To account for unequal sample size and reduce family-wise Type 1 error rate, the conservative Dunnett's T3 test was utilized for post-hoc comparisons.[10] Estimates of effect sizes were calculated with an unbiased Cohen's *d*, with correction for small sample size (d_{unb}).[12] 0.8 indicates a large effect size, 0.5 a medium effect size and 0.3 a small effect size.

Regression

Multiple regression was performed to explore the variables that contributed to manipulation performance in addition to years of experience. The metric of manipulation performance was defined as the biomechanical variable that best discriminated between groups. First, bivariate correlation analyses were conducted to identify potential kinematic and kinetic predictor variables. For the regression model, years of experience was entered first. Then a forward stepwise approach was used to determine which other predictor variables significantly contributed to variance in manipulation performance (α_{enter} = .05 and α_{exit} = .10, IBM SPSS Statistics, Version 25).

	Experts*	**Residents†**	**Third year students‡**	**First year students§**	**p value**
Age (years)	66.30 (4.10)	26.63 (1.43)	28.77 (5.33)	23.93 (2.15)	<0.05
Height (m)	1.81 (0.06)	1.80 (0.07)	1.82 (0.07)	1.81 (0.08)	0.067
Mass (kg)	96.05 (9.81)	83.66 (11.78)	83.95 (15.25)	76.49 (7.00)	0.029
Manipulation experience (years)	44.50 (5.20)	3.22 (0.75)	2.15 (0.36)	0.33 (0.00)	<0.0001

*n = 4, †n = 11, ‡n = 13, §n = 15

P value indicates significance of Mann-Whitney U Tests (age) and ANOVA F tests for main effect of group (height, mass and manipulation experience)

TABLE 1. Participant demographics/morphometrics

RESULTS

Demographics

Demographic information for all participants is shown in Table 1. There was no difference in height between groups. There was a group difference in mass, with experts tending toward being significantly heavier than first year students (post-hoc p = .086). As expected, experts were significantly older than the other three groups (p < .005 for all post-hoc comparisons). Similarly, experts had significantly greater manipulation experience than all other groups (p < .001 for all post-hoc comparisons). Residents had greater experience than both student groups and the third-year students had more experience than the first-year students (p <.01 for both comparisons).

Kinematic analysis

See Appendix 2 for all between group omnibus (F-test) statistics and Table 2 for post-hoc group comparisons. Two participants in the first-year student group were excluded from the kinematic analyses due to occlusion of iliac crest markers during the manipulation.

Pelvis motion – angular

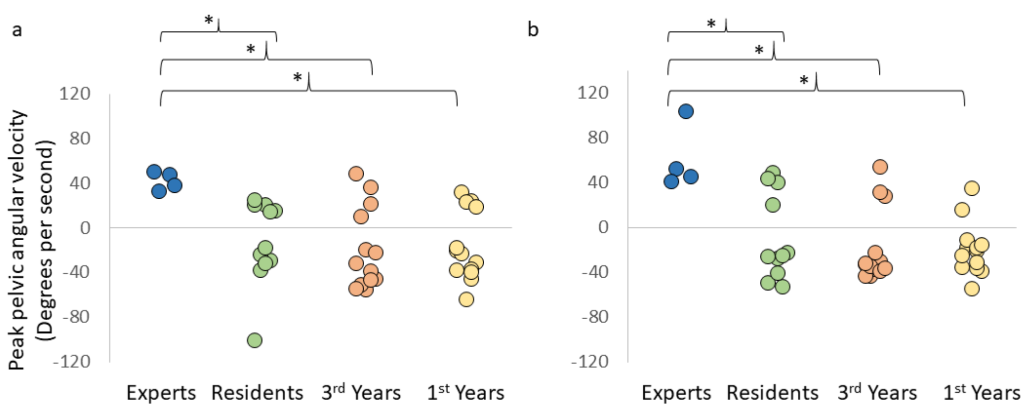

FIGURE 4. Peak pelvic angular velocity for each individual in all groups. a. Frontal plane. Positive angular velocity indicates caudad (right) side flexion b. Transverse plane. Positive angular velocity indicates cephalad (left) rotation. Asterisks indicates significant post-hoc comparison between groups.

Peak angular velocity of the pelvis in the sagittal plane did not differ between groups. However, there was a group difference in velocity of pelvis motion in the frontal plane.

Experts had greater peak angular velocity than all other groups and all of the experts demonstrated peak angular velocity in the direction of caudad side flexion (right side of the pelvis tilting downward) whereas on average all of the other groups demonstrated peak pelvic angular velocity in the direction of cephalad side flexion (Figure 4a. Table 2). There was also a difference between groups for peak angular velocity of the pelvis in the transverse plane. Experts had greater peak angular velocity than all other groups and experts all rotated the pelvis cephalad (toward the model's head) whereas on average the other groups rotated toward the caudad side (Figure 4b. Table 2).

Pelvis motion - linear

Peak downward velocity of the pelvis was significantly different between groups Experts had greater downward linear velocity than third year students and first year students. Residents had greater downward linear velocity than first year students (Figure 5, Table 2).

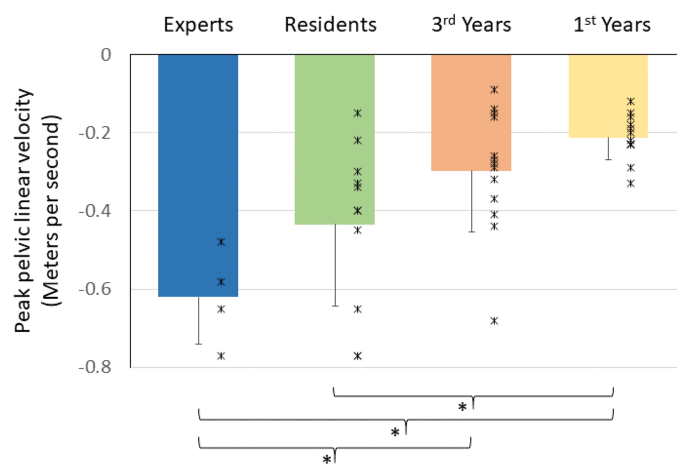

FIGURE 5. Peak downward linear velocity. Error bars represent group standard deviations. Crosses are individual data points for each group and asterisks indicate significant post-hoc comparisons between groups.

Center of mass motion

There was a significant difference between groups for the vertical displacement of the COM. Experts had greater displacement than first year students (Table 2). Vertical (downward) acceleration of the COM also differed significantly by experience. Experts and third year students had significantly greater downward COM acceleration than first year students (Table 2).

	Experts: Residents	Experts: third years	Experts: first years	Residents: third years	Residents: first years	third years: first years
Pelvis peak frontal AV	**0.004** ***1.411***	**0.000** ***1.601***	**0.000** ***1.568***	0.999 *0.087*	1.000 *0.009*	1.000 *0.058*
Pelvis peak transverse AV	**0.036** ***1.694***	**0.020** ***1.974***	**0.026** ***2.311***	0.982 *0.287*	0.946 *0.333*	1.000 *0.039*
Pelvis peak vertical LV	0.144 *0.847*	**0.002** ***1.527***	**0.000** ***1.95***	0.389 *0.718*	**0.013** ***1.15***	0.662 *0.436*
COM vertical LD	0.316 *0.977*	0.197 *1.167*	**0.043** ***1.751***	0.993 *0.202*	0.122 *0.825*	0.425 *0.633*
COM peak vertical LA	0.122 *1.529*	0.136 *1.487*	**0.025** ***2.463***	1.00 *0.058*	0.100 *0.926*	**0.043** ***0.987***
Cephalad foot peak GRF_V	0.291 *0.845*	**0.050** ***1.380***	**0.009** ***1.987***	0.655 *0.532*	**0.013** ***1.149***	0.400 *0.618*
Cephalad foot peak GRF_{AP}	0.762 *0.473*	**0.011** ***1.310***	**0.009** ***1.205***	0.128 *0.859*	0.125 *0.849*	1.000 *0.107*
Caudad foot min GRF_V	**0.000** ***1.973***	**0.000** ***1.692***	**0.000** ***1.618***	0.998 *0.170*	0.528 *0.484*	0.298 *0.590*
Cephalad foot peak GRF_V unloading rate	0.354 *1.108*	0.243 *1.288*	0.104 *1.770*	0.995 *0.205*	0.264 *0.680*	0.534 *0.492*
Caudad foot peak GRF_V unloading rate	**0.018** *1.687*	**0.039** *1.205*	**0.009** ***3.105***	0.997 *0.174*	0.791 *0.418*	0.462 *0.512*

Abbreviations: AV, angular velocity. LV, linear velocity. LD, linear displacement. LA, linear acceleration, GRFv, vertical ground reaction force, GRF_{AP}, anterior-posterior ground reaction force

TABLE 2. Post-hoc comparisons showing adjusted p-values and unbiased effect sizes (italicized). Bold font indicates significant group differences.

Kinetic analysis

See Appendix 2 for all between group omnibus (F-test) statistics and Table 2 for post-hoc group comparisons. Ground reaction force data from the caudad foot of one resident were excluded due to the participant’s heel landing outside the area of the force plate during the thrust.

Exemplar vertical (GRF_V) and horizontal GRF data from one expert and one student are shown in Figure 1.

Ground reaction forces at the beginning of the thrust

For GRF_V of the cephalad foot at the beginning of the thrust phase there was a significant difference between groups. Experts started the thrust with significantly higher GRF_V under the cephalad foot compared with third year and first year students, and residents had higher GRF_V under the cephalad foot than first year students (Table 2). There was no difference between groups for GRF_V of the back foot at the beginning of the manipulation.

At the beginning of the thrust there was a group difference in the magnitude of GRF_{AP} of the cephalad foot. Experts had larger, more positive GRF_{AP} than third year students and first year students (Table 2). There was no difference between groups for GRF_{AP} of the caudad foot and GRF_{ML} forces for either foot at the beginning of the thrust.

During the thrust

During the thrust, experts demonstrated lower minimum GRF_V and greater rate of unloading in the caudad foot compared with the other groups (Table 2). The minimum GRF_V under the cephalad foot did not differ between groups and although the rate of GRF_V unloading under the cephalad foot was significantly different across groups there were no significant pairwise comparisons (Table 2).

Force-force analyses

For the force-force analyses, an additional participant from the first year student group was excluded due to loss of force plate data. The force-force analyses demonstrated that there were three primary patterns of ground reaction force coordination between feet during the thrust: *inphase decreasing (*GRFv decreasing under both feet at the same rate*)*, *cephalad foot decreasing*, and *caudad foot decreasing*. Across the groups, thirty-four individuals utilized predominantly *inphase decreasing* coordination, six individuals demonstrated predominantly *cephalad foot decreasing* coordination and one individual demonstrated predominantly *caudad foot decreasing* coordination. There was no difference between groups for the percentage of time spent in any of the coordination patterns during the manipulation.

Within the subgroup of participants who primarily utilized the *inphase decreasing* coordination strategy however, there was a trend toward a group difference. Experts tended to spend a greater percentage of thrust time inphase than residents and third year students.

Regression analysis

Peak downward linear velocity of the pelvis was selected as the manipulation performance metric for the regression analysis. Variables that were significantly associated with downward pelvis velocity and were included in the regression model are shown in Appendix 3.: In addition to years of experience, peak downward velocity of the pelvis during the thrust was predicted best by a combination of COM displacement and GRF_v on the cephalad foot at the beginning of the thrust (full model with 3 variables $R^2 = 0.668$, $F_{3,36} = 24.107$, $p = .000$).

DISCUSSION

For the first time, this study demonstrates the kinematic and kinetic characteristics that delineate expert performance from more novice performance of lumbar manipulations.

The kinematic results demonstrated significant differences between expert and novice performance. The experts performed the manipulation with significantly greater downward COM acceleration. This finding is consistent with results from the Delphi study examining lumbar manipulation, with clinicians agreeing that “dropping the body downward” is an important aspect of manipulation.[18] Additionally, the experts displayed faster pelvic rotation in the transverse plane, and interestingly, in the opposite direction as the other groups. Though the total arc of motion of the pelvis in transverse plane rotation is not large (approximately 7 degrees), it was different in experts compared to all other groups. Cephalad rotation of the pelvis may help to improve the force application of the experts’ thrust. The close pelvis-to-pelvis contact between the therapist and the patient may allow the therapist’s pelvis to “push” the patient’s pelvis in a superior-anterior direction (in reference to the patient’s body), providing additional force to the patient into lumbar rotation. The extent of COM vertical displacement also differed between groups. Nearly all participants elevated the COM just prior to the thrust (see Figure 2, bottom). Contemporary instruction of lumbar manipulation advises against this because it is thought that novice therapists may “de-rotate” the patient as they raise up prior to thrusting, losing joint localization. More experienced therapists are likely able to move their own COM prior to the thrust without moving the patient and thus optimize their ability to generate quick downward motion without losing the segment localization and pre-positioning.

The kinetic results also demonstrated significant differences between experts and other groups. First, overall increased modulation of GRF_V was found in experts: they began the manipulation with greater weight on the front foot, demonstrated lower minimum GRF_V during the manipulation, and achieved the highest rate of unloading of the back foot during the manipulation. These results generally show that the experts utilize vertical ground reaction forces significantly more than other groups. Again, this result mirrors the results of O'Donnell et al., with clinicians agreeing that the thrust force "should be generated by the body and legs", not the force applicator (usually the arm or hand).[18] The differences in kinetics demonstrate that the experts and more experienced therapists indeed do this. The force-force results between force plates did not demonstrate any significant pattern differentiation between experience levels. Most participants were categorized into *"inphase decreasing"*. This is likely due to the fact that the overall movement dynamics of this technique are that the therapist is dropping his body weight, and GRF must decrease in both feet.

Many of the factors identified in the results were not only significantly greater in experts, but the means of each group formed a graduated spectrum in which, with each successive increase in group experience, the group mean became more "expert like". Both kinematic and kinetic results demonstrate this stepwise improvement. For example, peak downward linear pelvic velocity increased significantly from first years to residents, third years to experts, and first years to experts. These results are similar to those found by Descarreaux in which students and clinicians of increasing experience level displayed a stepwise improvement in unloading time and hand-body delay (factors which identify the quickness of the manipulation).[8] Similar differences in manipulation speed and force production between students and more experienced manipulators are demonstrated with this stepwise improvement in other chiropractic literature.[6,8,9] Although the kinetic measurement methods between this study and the other chiropractic studies are different, a single similarity is seen across all studies: more experienced manipulators apply force over a shorter period of time compared to novices.

Since there is no previous biomechanical analysis of performance of this manipulation, we must assume that the expert performance is the gold-standard. This assumption is a reality in many instances of sports and performance where kinetic and kinematic norms have not been established. In the data analysis, peak downward linear pelvic velocity was the variable that best distinguished amongst the groups, so this was chosen as the metric of manipulation performance for the regression analysis. The regression analysis found peak vertical velocity of the pelvis during the thrust was predicted best by three factors; normalized vertical displacement of the COM, initial GRF_v under the cephalad foot, and years of experience. This suggests that focusing on downward COM motion and loading on the cephalad foot may help to improve manipulation performance in novice therapists. These are simple verbal instructions that could be given in laboratory practice environments in both entry-level and continuing education curricula.

There were limitations to the study. The expert group had fewer participants than the resident and student groups. This was due to our efforts to recruit individuals for the expert group that are leaders in the field. All students enrolled in the study were from the same institution. This ensured that each group had learned the manipulation in the same way, however it is not known if students from a different institution would display the same results. Though we could not measure reaction forces through the table, we must assume that the downward force produced by dropping the COM is being transmitted through the therapists' arms, and perhaps pelvis as well. Different patient models were used during the study, whose anthropometrics were not all matched, and the argument may be made that two patients of different size may require different magnitude of force from the practitioner. This was controlled as much as possible by having each participant manipulate two different patient models and averaging the data for each participant across the four trials. Finally, we did not attempt to characterize if the expert-performed manipulation is a more effective/therapeutic manipulation than one performed by a student. There are a multitude of factors that affect the patient-therapist therapeutic relationship and will alter the likelihood of an intervention providing the intended result.

CONCLUSION

The kinetics and kinematics of side-lying lumbar manipulation change significantly with increasing practitioner experience. This study demonstrates important biomechanical factors for performance of lumbar manipulation and provides information for educators teaching this complex manual skill.

HIGHLIGHTS

- Operator mechanics of lumbar manipulation (SLM) are not well understood
- Experts rotate their pelvis in the opposite direction during SLM
- Experts perform SLM with greater downward pelvic velocity
- Pelvic velocity can be predicted though years of experience, among other factors

REFERENCES

1. Cagnie B, Vinck E, Beernaert A, Cambier D. How common are side effects of spinal manipulation and can these side effects be predicted? *Man Ther*. 2004;9(3):151-156. doi:10.1016/j.math.2004.03.001
2. Cambridge EDJ, Triano JJ, Ross JK, Abbott MS. Comparison of force development strategies of spinal manipulation used for thoracic pain. *Man Ther*. 2012;17(3):241-245. doi:10.1016/j.math.2012.02.003
3. Chandran Suja V, Barakat AI. A Mathematical Model for the Sounds Produced by Knuckle Cracking. *Sci Rep*. 2018;8(1):1-9. doi:10.1038/s41598-018-22664-4
4. Chang J-Y, Chang G-L, Chang Chien C-J, Chung K-C, Hsu A-T. Effectiveness of two forms of feedback on training of a joint mobilization skill by using a joint translation simulator. *Phys Ther*. 2007;87(4):418-430. doi:10.2522/ptj.20060154
5. Childs MJD, Fritz JM, Flynn TW, et al. A clinical prediction rule to identify patients with low back pain most likely to benefit from spinal manipulation: A validation study. *Ann Intern Med*. 2004;141(12):920-928. doi:141/12/920 [pii]
6. Cohen E, Triano JJ, McGregor M, Papakyriakou M. *Biomechanical Performance of Spinal Manipulation Therapy by Newly Trained vs. Practicing Providers: Does Experience Transfer to Unfamiliar Procedures?* Vol 18.; 1995.
7. Descarreaux M, Dugas C, Raymond J, Normand MC. Kinetic analysis of expertise in spinal manipulative therapy using an instrumented manikin. *J Chiropr Med*. 2005;4(2):53-60. doi:10.1016/S0899-3467(07)60114-1
8. Descarreaux M, Dugas C. Learning Spinal Manipulation Skills: Assessment of Biomechanical Parameters in a 5-Year Longitudinal Study. *J Manipulative Physiol Ther*. 2010;33(3):226-230. doi:10.1016/j.jmpt.2010.01.011
9. DeVocht JW, Owens EF, Gudavalli MR, Strazewski J, Bhogal R, Xia T. Force-time profile differences in the delivery of simulated toggle-recoil spinal manipulation by students, instructors, and field doctors of chiropractic. *J Manipulative Physiol Ther*. 2013;36(6):342-348. doi:10.1016/j.jmpt.2013.05.027
10. Dunnett CW, Dunnett CW. in the Unequal Pairwise Multiple Comparisons Variance Case. *J Am Stat Assoc*. 2012;75(372):796-800.
11. Flynn T, Fritz J, Whitman J, et al. A Clinical Prediction Rule for classifying patients with low back pain who demonstrate short-term improvement with spinal manipulation. *Spine (Phila Pa 1976)*. 2002;27(24):2835-2843. doi:10.1097/00007632-200212150-00021
12. Fritz CO, Morris PE, Richler JJ. Effect size estimates: Current use, calculations, and interpretation. *J Exp Psychol Gen*. 2012;141(1):2-18. doi:10.1037/a0024338

13. Gard SA, Miff SC, Kuo AD. Comparison of kinematic and kinetic methods for computing the vertical motion of the body center of mass during walking. *Hum Mov Sci*. 2004;22(6):597-610. doi:10.1016/j.humov.2003.11.002
14. Jull G, Moor A, Falla D, Lewis J, McCarthy CJ, Sterling M. *Grieve's Modern Musculoskeletal Physiotherapy*. 4th ed. Elsevier; 2015.
15. Koes BW, van Tulder M, Lin C-WC, Macedo LG, McAuley J, Maher C. An updated overview of clinical guidelines for the management of non-specific low back pain in primary care. *Eur Spine J*. 2010;19(12):2075-2094. doi:10.1007/s00586-010-1502-y
16. Koppenhaver SL, Hebert JJ, Kawchuk GN, et al. Criterion validity of manual assessment of spinal stiffness. *Man Ther*. 2014;19(6):589-594. doi:10.1016/j.math.2014.06.001
17. Needham R, Naemi R, Chockalingam N. Quantifying lumbar-pelvis coordination during gait using a modified vector coding technique. *J Biomech*. 2014;47(5):1020-1026. doi:10.1016/j.jbiomech.2013.12.032
18. O'Donnell M, Armour Smith J, Abzug A, et al. How Should We Teach Lumbar Manipulation? A Consensus Study. *Man Ther*. 2016;25:1-10. doi:10.1017/CBO9781107415324.004
19. Pillastrini P, Gardenghi I, Bonetti F, et al. An updated overview of clinical guidelines for chronic low back pain management in primary care. *Jt Bone Spine*. 2012;79(2):176-185. doi:10.1016/j.jbspin.2011.03.019
20. Rubinstein SM, Middelkoop M Van, Boer MR De, et al. Spinal Manipulative Therapy for Chronic Low-Back Pain. *Spine (Phila Pa 1976)*. 2011;36(2):2-5. doi:10.1097/BRS.0b013e3182197fe1
21. Triano JJ, Gissler T, Forgie M, Milwid D. Maturation in rate of high-velocity, low-amplitude force development. *J Manipulative Physiol Ther*. 2011;34(3):173-180. doi:10.1016/j.jmpt.2011.02.007
22. Van Geyt B, Dugailly PMA, De Page L, Feipel V. Relationship Between Subjective Experience of Individuals, Practitioner Seniority, Cavitation Occurrence, and 3-Dimensional Kinematics During Cervical Spine Manipulation. *J Manipulative Physiol Ther*. 2017;40(9):643-648. doi:10.1016/j.jmpt.2017.09.002
23. Vos T, Allen C, Arora M, et al. Global, regional, and national incidence, prevalence, and years lived with disability for 310 diseases and injuries, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet*. 2016;388(10053):1545-1602. doi:10.1016/S0140-6736(16)31678-6