ACCRAC Award Winning Paper

Development of a Linked Segment Model to Derive Patient Low Back Reaction Forces and Moments During High-Velocity Low-Amplitude Spinal Manipulation

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Abstract

Objective: The purpose of this paper is to present the experimental setup, the development, and implementation of a new scalable model capable of efficiently handling data required to determine low back kinetics during high-velocity low-amplitude spinal manipulation (HVLA-SM).
Methods: The model was implemented in Visual3D software. All contact forces and moments between the patient and the external environment (2 clinician hand contact forces, 1 contact force between the patient and the treatment table), the patient upper body kinematics, and inertial properties were used as input. Spine kinetics and kinematics were determined from a single HVLA-SM applied to one healthy participant in a right side-lying posture to demonstrate the model's utility. The net applied force was used to separate the spine kinetic and kinematic time-series data from the HVLA-SM into preload as well as early and late impulse phases.
Results: Time-series data obtained from the HVLA-SM procedure showed that the participant's spine underwent left axial rotation, combined with extension, and a reduction in left lateral bending during the procedure. All components of the reaction force, as well as the axial twist and flexion/extension reaction moments demonstrated a sinusoidal pattern during the early and late impulse phases. During the early impulse phase, the participant's spine experienced a leftward axial twisting moment of 37.0 Nm followed by a rightward moment of −45.8 Nm. The lateral bend reaction moment exhibited a bimodal pattern during the early and late impulse phases.
Conclusion: This model was the first attempt to directly measure all contact forces acting on the participant/patient's upper body, and integrate them with spine kinematic data to determine patient low back reaction forces and moments during HVLA-SM in a side-lying posture. Advantages of this model include the brevity of data collection (< 1 hour), and adaptability for different patient anthropometries and clinician-patient contacts. (J Manipulative Physiol Ther 2016;39:176-184)
Key Indexing Terms; *Chiropractic; Lumbar Region; Biomechanics; Low Back Pain*

Given that high-velocity low-amplitude (HVLA) spinal manipulation (SM) has an inherent biomechanical link, substantial chiropractic research efforts have recently focused on quantifying biomechanical parameters associated with the HVLA impulse that seek to optimize patient safety, clinician education, and patient outcomes.[1–6] While each of the aforementioned studies have advanced our scientific understanding of the biomechanical control parameters involved with HVLA-SM, only one[1] has attempted to quantify the reaction forces and moments experienced by the low back of patients during HVLA-SM. Despite the use of a simplified model and making assumptions regarding the relationship between transmitted forces and those acting at the patient's low back, the processing of data was computationally demanding and time consuming. Results, while of academic interest, pragmatically were not easily available to inform educational, clinical, or research protocols.

Linked-segment models (LSMs) have been routinely employed throughout the biomechanics literature to quantify reaction forces and moments acting at specific joints in the body.[7–9] As the name suggests, reaction loads in biomechanics represent the net forces and moments supplied by the body's passive and active structures that

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Paper submitted April 16, 2015; in revised form June 22, 2015; accepted October 26, 2015.
0161-4754

http://dx.doi.org/10.1016/j.jmpt.2016.02.009

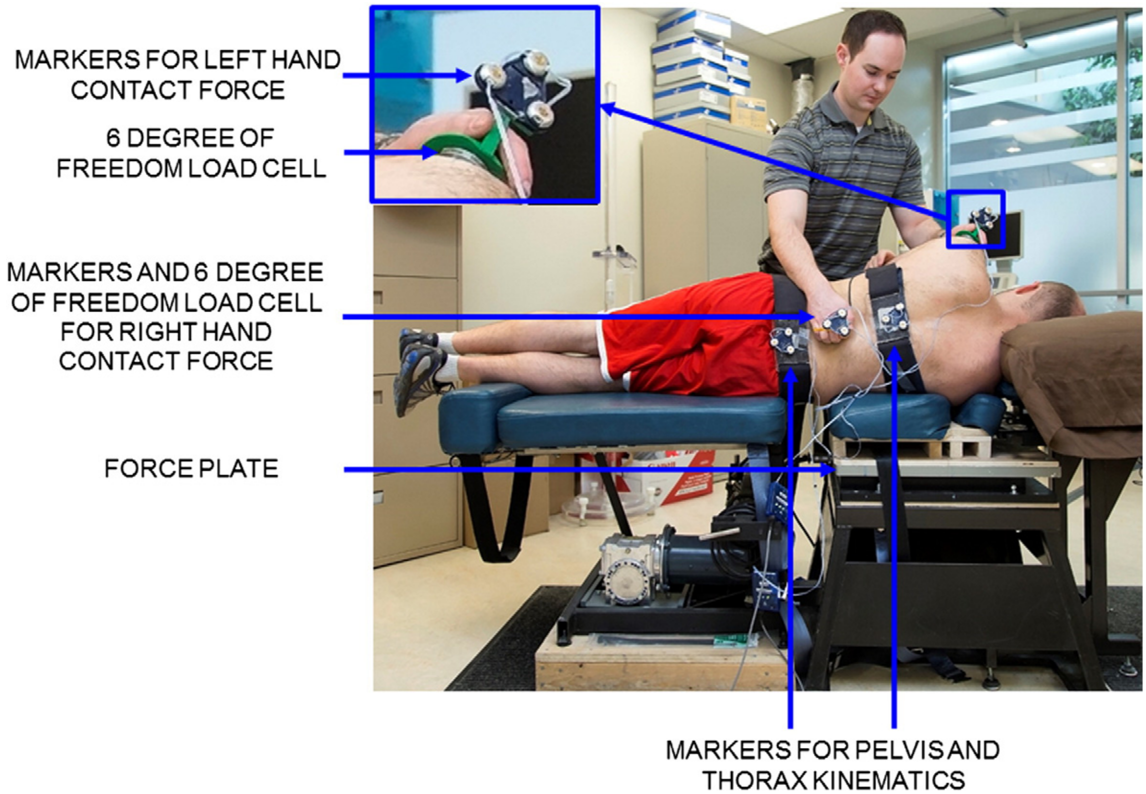

Fig 1. *An image demonstrating the kinematic and kinetic instrumentation, and experimental setup for collecting data to be entered into a linked segment model for determining low back loads during high-velocity low-amplitude spinal manipulation.*

counteract the action of external forces applied to a person's body and the inertial contributions produced by movement. To derive reaction loads at the lumbosacral joint (L5-S1) or the joint between the fourth and fifth lumbar vertebrae (L4-L5), these analyses can be performed using either a bottom-up (starting in the lower body and working up towards the pelvis) or top-down (starting in the upper body and working down towards the pelvis) approach.[7] For HVLA-SM a top-down approach is preferred primarily because of the greater ease in accounting for upper body segment orientations and geometry.

Recent technological advancements in instrumentation and biomechanical software have simplified the process for quantifying joint reaction forces and moments in biomechanics studies. The current report presents the experimental setup, as well as the development and implementation of a new LSM within a commercially available software package (Visual3D, C-Motion Inc., Germantown, MD, USA) that is capable of quickly deriving low back reaction forces and moments during HVLA-SM.

Methods

General Overview

The larger problem of performing a linked segment analysis during HVLA-SM can be broken into four smaller sub-problems:

1.) Determining the three-dimensional (3D) clinician hand contact forces, and the contact force between the patient and the treatment table. Included in this sub-problem is the task of locating the point of force application on the patient's thorax;
2.) Determining 3D rotational kinematics of the patient's thorax and pelvis;
3.) Scaling the model's anthropometry to reflect patient-specific anthropometry; and,
4.) Handling the relatively large time-series data to solve the equations of motion.

Participants

A single healthy male participant (27 years old, 1.83 m, 88.6 kg) without any current complaints of lower back pain was recruited since the primary goal of this work was to describe the model's development. Prior to data collection, the participant read and signed an informed consent document that outlined the instrumentation and experimental protocols that were approved by the Research Ethics Board at the Canadian Memorial Chiropractic College.

Instrumentation

An image of the entire experimental setup is presented in Figure 1.

Kinetics. The 3D contact force and moment between the participant's upper body and the treatment table was measured with a force plate (OR6-7, AMTI Inc, Watertown, MA), embedded within a chiropractic treatment table. The chiropractic treatment table had previously been designed to record forces and moments transmitted through the thorax during low back spinal manipulative procedures by using a break in the table at approximately the level of the target segment for treatment.[5] A pair of 6 degree of freedom (DOF) load cells (Mini45, ATI Industrial Automation Inc, Apex, NC) were used to measure applied forces and moments at the two contact locations between the clinician and participant's thorax.[10] One load cell was positioned over the participant's shoulder for the clinician's left hand contact, and the second was positioned over the L5 spinous process for the clinician's right hand/finger contact. Custom plastic objects were fabricated using a 3D printer (Airwolf3D HDL, Airwolf 3D, Costa Mesa, CA), and rigidly interfaced with each load cell to ensure that the clinician's hands only interacted with the participant through the load cells during the HVLA-SM. This mitigated the possibility for load sharing that can occur if either of the clinician's hands were to contact the participant's thorax in addition to the contact between the clinician's hands and the load cells. Analog voltages from the load cells and force plates were amplified (MiniAmp MSA-6, AMTI Inc., Watertown, MA, USA; FTIFPS1, ATI Industrial Automation Inc, Apex, NC) before being digitally converted using a ±10V range on a 16-bit analog to digital conversion board (Optotrak Data Acquisition Unit III, Northern Digital Inc., Waterloo, ON, Canada). All analog data were sampled at a rate of 1500 Hz.

Kinematics. Three-dimensional coordinates of active infrared light emitting diodes (IREDs) were recorded using 2 banks of optoelectronic cameras (Optotrak Certus, Northern Digital Inc., Waterloo, ON, Canada). Prior to data collection, the capture volumes of both cameras were registered and aligned to a common global coordinate system for the lab. Three IREDs were adhered to plastic flags that extended from each of the 6DOF load cells. Two additional sets of three IREDs were affixed to plastic plates that were held in place by belts strapped around the participant's thorax at the level of the spinous process for the ninth thoracic vertebra and pelvis. The fixed geometrical arrangements for each set of three markers defined local coordinate systems for separate rigid bodies, and the movement of each rigid body represented the 3D angular and linear kinematics of the segments/load cells to which they were attached.[11]

Prior to data collection, four points were digitized on each load cell. These points were used to identify the location and orientation of the load cells within the lab's global coordinate system. Anatomical landmarks representing the participant's greater trochanters, iliac crests, anterior superior iliac spines, L5 spinous process, acromion processes, suprasternal notch, xiphoid process, and T12 spinous process were also digitized prior to data collection using a calibrated probe. These landmarks served to construct anatomical frames of reference for the participant's pelvis and thorax. The 3D coordinates for the load cell and anatomical landmarks were virtually monitored throughout all experimental trials by assuming a fixed spatial relationship between the landmarks and the rigid bodies that measured the positions and orientations of their parent segment/load cell. The static 3D coordinates of the force plate's four corners were also digitized, along with the location of a reference point on the treatment table's surface. These coordinates were used to transform forces and moments from the force plate's local coordinate system into the lab's global coordinate system so that the force plate was located within the lab.

Kinematic data from the IREDs and digitized landmarks were continuously monitored throughout all trials. These data were also synchronized with the analog data obtained from the load cells and force plate, and sampled at a rate of 150 Hz. Previous work has demonstrated that sampling rates between 50 and 100 Hz are sufficient for measuring force-time profiles of high-velocity low-amplitude spinal manipulation.[12]

Protocol

After instrumentation, a 5-second recording of the participant's upright standing posture was obtained. Data from the upright standing trial defined the neutral orientations for the pelvis and thorax segments. Next, the participant was instructed to lie on the treatment table on their right side. The arms were bent at the elbow and crossed over the front of the body, and the subject was instructed to hold them in position without movement during the procedures. The participant was positioned so that the L5 vertebra was centered over the break in the table to actively affect the L4-L5 and L5-S1 joints during the HVLA-SM. This ensured that the force plate recorded the net interaction between the participant's thorax and the treatment table. The participant's left hip was also flexed by approximately 90 degrees, which was confirmed by a goniometer. A licensed chiropractor delivered an HVLA-SM to the participant using a diversified technique (lumbar spinous hook) on the L5 spinous process. During the HVLA-SM, the clinician's intended effort attempted to induce right twist and left bend of the patient's L5 vertebra. A single HVLA-SM was used, since the purpose of this investigation was to describe the development and implementation of a model that was capable of determining low back reaction forces and moments that occurred during the procedure. The clinician was instructed to only make contact with the participant at the locations of the two load cells during the HVLA-SM (ie, they were not allowed to use the long-lever by contacting the participant's left thigh).

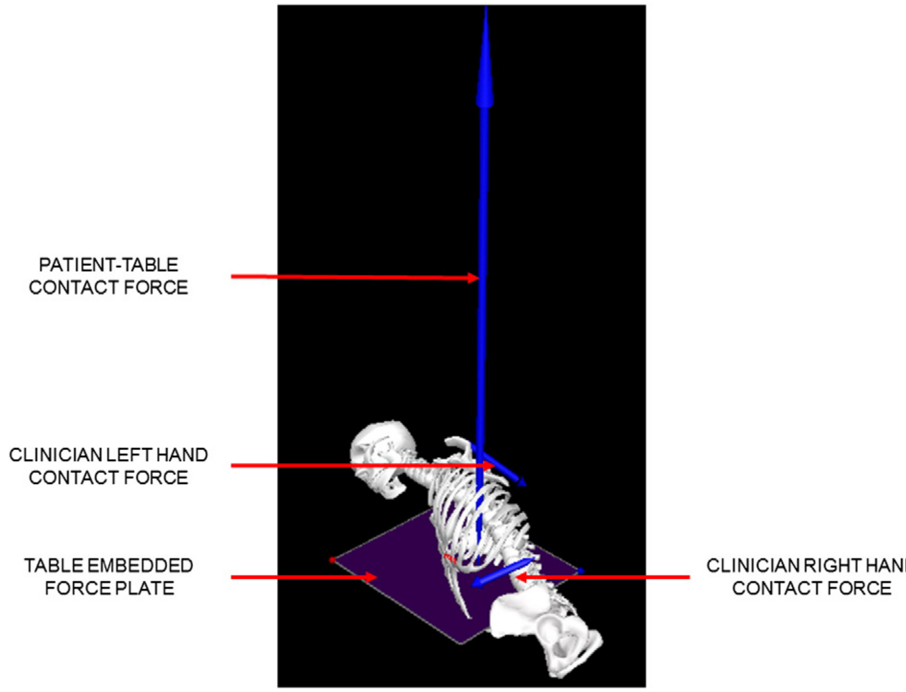

Fig 2. *A static frame visualizing the forces that were applied to the patient during the high-velocity low-amplitude spinal manipulation.*

Data Processing and Analysis

A top-down rigid LSM was implemented in Visual3D to determine low back reaction forces and moments during HVLA-SM (Fig 2). Participant anthropometric measures were used to scale the model inertial properties. A brief description of this process is provided below.

Low back reaction forces and moments were the net result of the three external forces and moments acting on all body segments cranial to the pelvis (2 clinician hand contact forces and 1 force acting between the patient and the treatment table), along with inertial components generated by segmental accelerations. We assumed that the contact force between the patient's head and the treatment table was negligible in comparison to the other external forces acting on the thorax.

The inverse dynamics calculations for a top-down analysis required the 3D components of the applied force vector, the center of pressure location, and the freemoment from each load cell and the force plate as input along with the inertial properties and kinematics of the body segments cranial to the pelvis. Proper implementation in Visual3D required that each of these quantities were reported with respect to the lab's global coordinate system.

First, digital voltage data obtained from the force plate and load cells were calibrated to units of force and moment using the manufacturer-provided calibration matrices. The force vector, center of pressure, and freemoment of the force plate were automatically determined within the lab's global coordinate system by using Visual3D's built-in processing commands. Deriving the force vector, center of pressure, and freemoment from the load cell data required additional steps.

Calibration of the digital voltage data obtained from each 6DOF load cell generated the three components of the force vector, and the three components of the moment vector that were expressed with respect to the load cell's local coordinate system. Methods outlined in Robertson et al[13] were used to derive the location for the center of pressure, and the 3D vector representing the freemoment that were local to each load cell. Components of the vectors representing the applied force, center of pressure, and freemoment were then transformed from each load cell's local coordinate system into the lab's global coordinate system by using the load cell's virtual landmarks that were previously digitized. The lab-based forces and freemoments were applied at the respective center of pressure for each load cell and the force plate, and were assigned to act on the thorax segment of the anatomical model constructed in Visual3D.

Inertial properties of the participant's upper body (e.g. mass, center of mass location, inertial tensor) were modeled as a single segment representing the head, arms, and thorax (HAT).[14] This assumed that the HAT moved as a single segment during the spinal manipulation. The HAT segment geometry was modeled as an elliptical cylinder where the major diameter was equivalent to the distance between the participant's acromion processes (i.e. thorax width), the minor diameter was equal to the horizontal distance between the digitized location for the T12 spinous process and the participant's xiphoid process (i.e. thorax depth), and the segment length was equal to the distance from the midpoint between the acromions and the midpoint between the greater trochanters.[14] Modeling the upper body in this manner allowed for participant specific anthropometries to be represented in the LSM.

Kinematic data from the HAT were used to define its angular/linear orientations/positions, velocities, and accelerations that along with the aforementioned inertial properties were used to determine the inertial contributions of the HAT to the low back reaction forces and moments. Time-series data representing the lumbar spine angular kinematics, reaction forces, and reaction moments were obtained from the HVLA-SM to demonstrate the model outputs. The net applied force (Eq. (1)) was used to define the preload and impulse regions of the HVLA-SM.

$$F_A = \sqrt{\sum_{i=1}^{3}\sum_{j=1}^{3} F_{i,j}^2} \quad (1)$$

In this equation F_A represented the net applied force, i = 1…3 represented the three contact forces that were measured, j = 1…3 represented the three components for each of these forces, and $F_{i,j}$ represented each component of the three contact forces acting on the participant. The impulse region was subdivided into two segments that were called early impulse and late impulse.

Results

Time-series data representing the net applied force, lumbar kinematics, and L5-S1 reaction forces and moments during the HVLA-SM are presented in Figures 3-5.

Kinematic data showed that the participant was flexed 7.7 degrees, bent 7.8 degrees to the left, and twisted 16.9 degrees to the left at the start of preload. During preload the clinician induced an additional 12.8 degrees of left twist, while extending the spine from its flexed posture into 1.1 degrees of extension (net angular displacement of 8.8 degrees), and increasing the spine's left lateral bend by 1.4 degrees. A sinusoidal pattern was observed for left lateral bend in the impulse region where an initial decrease was followed by an increase that reached a peak of 13.7 degrees. The impulse also induced an additional 6.3 degrees of left axial rotation, and 1.9 degrees of extension.

Low back reaction moments determined prior to the start of preload application were left lateral bend (−30.3 Nm), right axial rotation (−16.1 Nm), and flexion (−19.6 Nm). Lateral bend and axial rotation reaction moments respectively decreased in magnitude by 8.7 Nm and 8.1 Nm during preload while the flexion reaction moment increased by 11.0 Nm. During the impulse region, a sequence of changes occurred involving each plane centered on the targeted spinal region. The lateral bend reaction moment exhibited a bimodal pattern with two peaks of lateral bend directed to the right (62.0 Nm and 68.7 Nm). The axial rotation moment demonstrated a sinusoidal pattern of left axial rotation (peak = 37.0 Nm) followed by right axial rotation (peak = −45.8 Nm). Likewise, the flexion/extension reaction moment also demonstrated a sinusoidal pattern of extension (peak extension moment = 28.1 Nm) followed by flexion (peak = −18.3 Nm).

Low back reaction forces at the start of preload were directed in posterior shear (41.4 N), compression (54.0 N), and in right lateral shear (−254.8 N). Magnitudes of reaction forces in all three directions were reduced at the end of preload. Within the impulse region, all three components of the reaction forces demonstrated sinusoidal patterns. Reaction forces were developed in anterior shear (peak = −436.8 N), tension (peak = −320.8 N), and left lateral shear (peak = 337.5 N) within the first segment of the impulse. This was followed by peak reaction forces in posterior shear (252.2 N), compression (388.6 N), and right lateral shear (−375.8 N) within the second segment of the impulse.

Discussion

Our investigation presented a new experimental setup and LSM that is capable of deriving low back reaction forces and moments that are developed within a patient during HVLA-SM. The model takes advantage of recent technological advancements in force sensing transducers, and biomechanical software used to efficiently process the large amount of data required to derive low back reaction forces and moments from a dynamic three-dimensional task such as an HVLA-SM. The advantages of this model over prior attempts are the brevity of experimental time (less than 1-hour), facility to model differing patient postures and applied loads as well as the built-in scalability to accommodate different patient body characteristics.

The reaction moment at any joint represents the net moment produced internally by anatomical structures that cross the joint. Mathematically, a joint reaction moment is equal in magnitude, and acts in the opposite direction to the sum of moments imposed on the joint by externally applied forces and moments and gravito-inertial forces from the movement of body segments. Active forces generated by muscles that span a joint during voluntary movements are primarily responsible for producing internal moments. The moment-generating capacity of a muscle increases with its moment arm length for a given level of contraction. The involuntary and ballistic nature of the HVLA-SM procedure likely prevents muscles from actively generating large internal moments during the early impulse. Triano and Schultz,[1] in a sample of 66 procedures performed on participants in a similar side-posture HVLA-SM found that consistent myoelectric responses among the large trunk muscles (e.g. rectus abdominus, external oblique, lateral

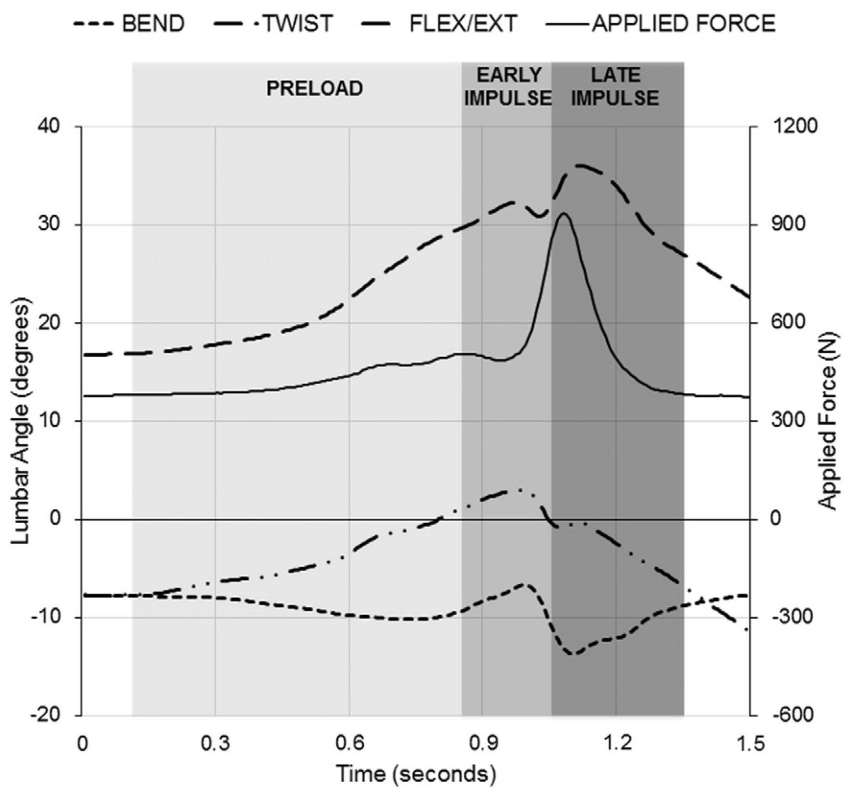

Fig 3. *Time-series data of lumbar spine angular kinematics during preload and impulse regions of the high-velocity low-amplitude spinal manipulation. The impulse region is sub-divided into early and late impulse regions. The net applied force is also shown.*

and medial erector spinae groups) were small and inconsistent. Herzog and colleagues,[15] however, found responses from muscles that might traverse the L4-S1 segments to occur in 50% to 80% of cases. When muscle did respond, it was within 50 to 200 milliseconds after the onset of the impulse loading. In context of the timing observed in the loads to the participant in the current report, any muscle action would be associated with the late impulse region. Intensity of contractions observed would be considered small in contrast, for example, to a maximum voluntary contraction.[15] Thus, internal moments during the HVLA-SM procedure are predominantly the result of forces developed within passive structures in the muscle, as well as ligaments, the intervertebral disc, and by interactions between bony structures of adjacent vertebrae (e.g. facets). For example, the peak extension moment that occurred within the impulse region of the HVLA-SM is likely generated by passive structures (e.g. ligaments, intervertebral disc) that contribute to supporting moments during spine forward flexion. It is important to reiterate that the reaction moment represents the net sum of moments generated by individual structures. By itself the net reaction moment cannot be parsed amongst individual tissues, and similarly do not account for effects of sufficiently strong co-contraction preceding or volitionally tensed muscles during the impulse.

Similar to reaction moments, reaction forces represent the interactive forces between adjacent body segments that are produced by external forces acting on the body, and gravito-inertial forces from the movement of body segments. These forces do not consider active force produced by muscles and other spinal structures. Thus, the reaction forces are not equal to the bone-on-bone contact forces. Interestingly, all three components of the reaction force derived from data obtained during the HVLA-SM demonstrated a similar sinusoidal pattern. In particular, the development of tensile force during the early segment of the impulse region is noteworthy since the spine does not experience force in this direction during activities of daily living.

Limitations

First, the participant's upper body was modeled as a single rigid segment with a cylindrical geometry to define its inertial parameters. Second, externally measured kinematics of the spinal column represent the overall angular deviations between the pelvis and thorax; however, these external kinematics may not be representative of intersegmental kinematics that occur internally. Third, the hand contacts adopted by the clinician in our investigation were similar, but not the same as those used by practicing clinicians. This was due to the fact that the clinician's

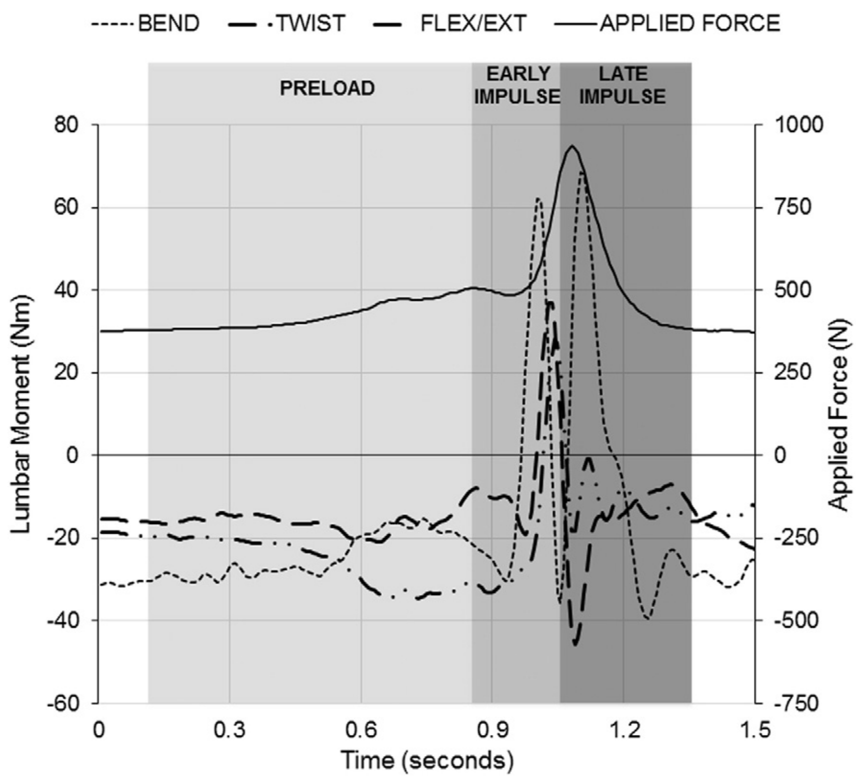

Fig 4. *Time-series data of derived low back reaction moments during preload and impulse regions of the high-velocity low-amplitude spinal manipulation. The impulse region is sub-divided into early and late impulse regions. The net applied force is also shown.*

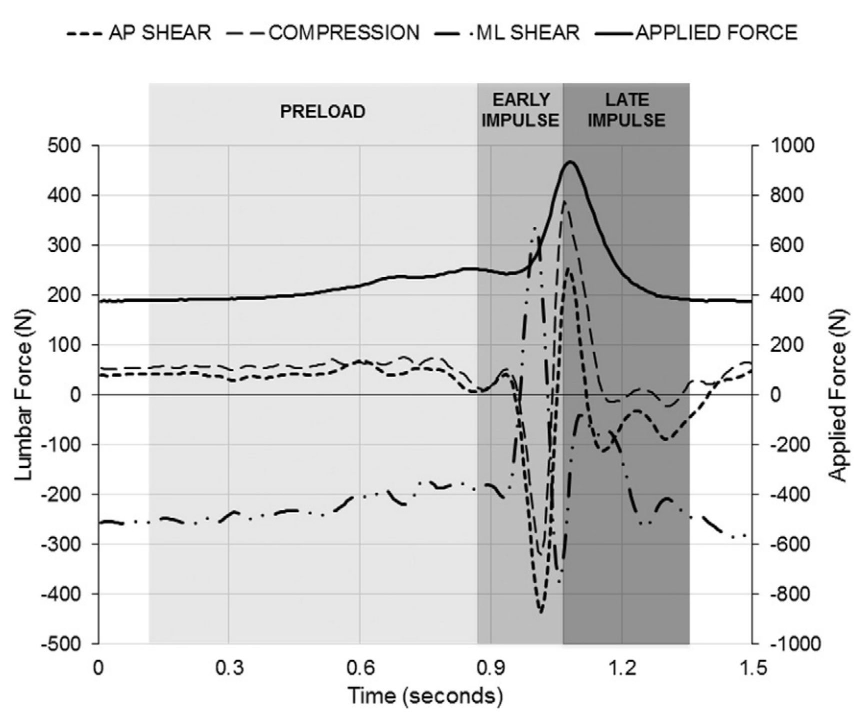

Fig 5. *Time-series data of derived low back reaction forces during preload and impulse regions of the high-velocity low-amplitude spinal manipulation. The impulse region is sub-divided into early and late impulse regions. The net applied force is also shown.*

hands were not allowed to directly contact the patient to ensure that all hand contact force passed directly through the load cell that was interfaced with the clinician's hand. Finally, the clinician was instructed to not invoke the long lever by having contact between their right thigh and the patient's left thigh. This restriction was placed on the clinician since the dataset presented here is part of a larger investigation into the relative effectiveness of different HVLA-SM procedures.

Future Studies

Future use of this model can include investigations into kinematic and kinetic differences experienced by the patient as a result of different HVLA-SM and other manual techniques. Additional metrics that can be obtained from the LSM time-series data include linear or angular impulse by integrating the force or moment time-series, rate of force or moment development, and peak-to-peak reaction forces or moments. The model can also be used to study the influence of different initial patient postures on the motions and loads occurring during manual techniques. Output from the LSM can be used as quantitative input to finite element models of the vertebral joint so that tissue-specific stresses and strains that arise from HVLA-SM can be determined. Finally, the LSM can be used to evaluate the effects of training, education, and/or experience on the development of low back forces and moments during HVLA-SM.

Conclusion

The LSM presented in this investigation represents the first attempt to integrate all contact forces acting on the participant/patient's upper body with kinematics of the pelvis and thorax to derive low back reaction force and moments during HVLA-SM in a side-lying posture. It further holds the advantage of being computationally rapid, with the ability to provide feedback within minutes of having performed the procedure.

Funding Sources and Potential Conflicts of Interest

This project was supported by funds from the SafetyNet CIHR grant #TIR112758. No conflicts of interest were reported for this study.

Contributorship Information

Concept development (provided idea for the research): S.H., K.D., J.T.

Design (planned the methods to generate the results): S.H., K.D., J.T.

Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): S.H., J.T.

Data collection/processing (responsible for experiments, patient management, organization, or reporting data): S.H., K.D.

Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): S.H., K.D., J.T.

Literature search (performed the literature search): S.H., K.D., J.T.

Writing (responsible for writing a substantive part of the manuscript): S.H.

Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): K.D., J.T.

Practical Applications

- The linked-segment model makes use of recent technological advancements in force-sensing instrumentation and biomechanical data processing software.
- This model can be used to provide quantitative evidence for relative effectiveness of different spinal manipulative procedures.
- Model outputs can be used as subsequent input to higher-order models to derive tissue-specific loads.

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