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Biomechanical studies of spinal manipulative therapy

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The purpose of this article is to present a review of our research related to spinal manipulative therapy (SMT). The first part of this review will concentrate on studies that were aimed at quantifying possible changes in the mechanics of locomotion associated with SMT. The second part will focus on studies that were aimed at measuring the forces exerted by chiropractors on patients during SMT. In the locomotion studies, we found that SMT was associated with changes in the mechanics of walking. In particular, sacroiliac joint patients were found to become more symmetrical in their ground reaction force patterns with increasing exposure to SMT. In the force studies we found that the force-time histories of SMT on the sacroiliac joint and thoracic spine were similar, however, the mean peak and preload forces recorded for SMT on the thoracic spine were about 60 N larger than those recorded on the sacroiliac joint. Treatments on the cervical spine were executed faster and with less force than treatments on the sacroiliac joint or the thoracic spine.
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KEY WORDS: chiropractic, locomotion, treatment forces, biomechanics, manipulation.

Le but de cet article est de présenter une révision de notre recherche relative à la thérapie manipulatoire spinale (TMS). La première partie de cette révision portera sur les études qui avaient pour but de quantifier les changements possibles dans les mécanismes de locomotion associés à la TMS. La deuxième partie aura pour objet les études visant à mesurer les forces exercées par les chiropraticiens sur leurs patients pendant la TMS. Dans les études de locomotion, nous avons trouvé que la TMS était associée aux changements dans les mécanismes de la marche. En particulier, les patients présentant des troubles sacro-iliaques sont devenus plus symétriques dans la façon dont ils distribuent leur force de réaction au sol à mesure qu'ils étaient davantage exposés à la TMS. Dans les études de force, nous avons trouvé que les histoires force-temps de la TMS l'articulation sacro-iliaque et la colonne dorsale étaient similaires; cependant, le maximum moyen et les forces de pré-charge enregistrées pour la TMS sur la colonne dorsale étaient à peu près 60N de plus que celles enregistrées sur l'articulation sacro-iliaque. Les traitements sur la colonne cervicale étaient executés plus rapidement et avec moins de force que les traitements sur l'articulation sacro-iliaque ou sur la colonne dorsale.
(JCCA 1991; 35(3):156–164)

MOTS-CLÉS : chiropratique, locomotion, forces de traitement, biomécanique, manipulation.

Introduction

The purpose of this review article is to present an overview of the research related to spinal manipulative therapy (SMT) performed at the University of Calgary, Human Performance Laboratory.

Our research approach is mechanical. That means, a SMT is viewed as a thrusting force applied to a specific area of a patient causing a change in mechanics of the area involved. For example, SMT on the sacroiliac joint may restore joint mobility. This may happen as a direct consequence of the forces exerted onto the joint, or may be caused indirectly, for example, through reflex pathways causing muscles to relax.

Our long-term objective in chiropractic research is to understand the precise mechanics of SMT and the mechanical and neurophysiological effects SMT has on patients. This long-term objective has been divided into several short-term objectives. First, we wanted to establish if SMT influences movement mechanics. This was done using a series of studies in which human locomotion was quantified before and after SMT for treatment periods ranging from one day to four weeks. This short-term objective was addressed between 1985–1989. Second, we wanted to develop and apply a method that allows the measurement of forces exerted by a chiropractor on a patient during SMT. Such a method was developed and has been applied for recording forces during SMT on the sacroiliac joint, the thoracic spine and the cervical spine. Work in this area

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started in 1989 and is continuing. Third, we would like to describe the effects of the forces exerted during SMT on the musculoskeletal and neuromuscular structures underlying the treatment area. The third short-term objective will be addressed within the next two years.

In the following, our research of quantifying changes in human locomotion as a function of SMT, and the work on measurements of the forces exerted during SMT will be presented. The methods are described briefly to give a general understanding of the research approach however, the reader will be referred to specific references for a complete and detailed account of all aspects of the procedures involved.

Results will focus on the major findings to allow for the discussion of general concepts. Additional specific results may be found in the original articles.

Locomotion studies

The purpose of the locomotion studies was to assess if (and how) human locomotion was changing as a function of SMT.

Methods

All locomotion studies were performed with symptomatic sacroiliac joint patients. The patients were referred to these studies by local chiropractors, or answered an advertisement placed in the University newsletter. All patients were screened by two chiropactors and were admitted to the study only if both chiropractors agreed that there was a sacroiliac joint problem. Patients were adults between 18–50 years; they were ambulatory and not extremely obese. Subjects who were admitted to the study gave free informed consent after all experimental procedures had been carefully explained to them.

Locomotion studies were performed using a force platform (Kistler, Inc., Winterthur, Switzerland) to measure ground reaction forces, and high speed film (Locam, Markham, Canada) or video (Motion Analysis, St. Rosa, USA) to quantify movements. Patients were typically required to walk at an average horizontal speed of 1.5 m/s ($\pm$ 0.15 m/s) along a 30 m long walkway, hitting the force platform with the left and right leg 3–5 times in one treatment session both before and after receiving SMT. Average walking speed was controlled using a set of light barriers placed approximately one meter in front and one meter behind the force platform. Trials in which patients did not hit the force platform properly, where walking did not appear normal, or where the average speed deviated more than $\pm$ 0.15 m/s from the required value were disregarded.

Measurements obtained from the force platform included the vertical, antero-posterior, and medio-lateral components of the ground reaction force as a function of time, as well as 34 specific parameters that were derived from the force-time histories of these components.[1] Furthermore, symmetry between force parameters of the left and right leg were calculated using equation (1):

$$\text{symmetry} = \frac{x\,(\text{right}) - x\,(\text{left})}{0.5\,[x(\text{right}) + x\,(\text{left})]} \times 100\% \qquad (1)$$

where x (right) and x (left) are the values of selected force parameters from the right and left legs, respectively.

Measurements obtained from the film or video records included displacement vs. time data of selected body landmarks on the lower limbs, and corresponding angular displacement vs. time data of ankle, knee and hip joints.

In all locomotion studies, a series of clinical evaluation tools were also used to identify the patient population and to record clinical progress of the patients while participating in the study. These clinical tools typically included a patient interview/questionnaire, Gillet motion palpation tests,[2] the Oswestry functional ability questionnaire,[3] a visual analog pain scale,[4] and sometimes radiographs.

Results

The results of all locomotion studies may be summarized with two statements: (1) SMT caused measurable and significant changes in the walking mechanics of most patients; and (2) these changes were typically not systematic for an entire patient group, with the exception of symmetry values which tended to become smaller (i.e. more symmetrical) throughout a treatment period. The first result will be illustrated in the following using

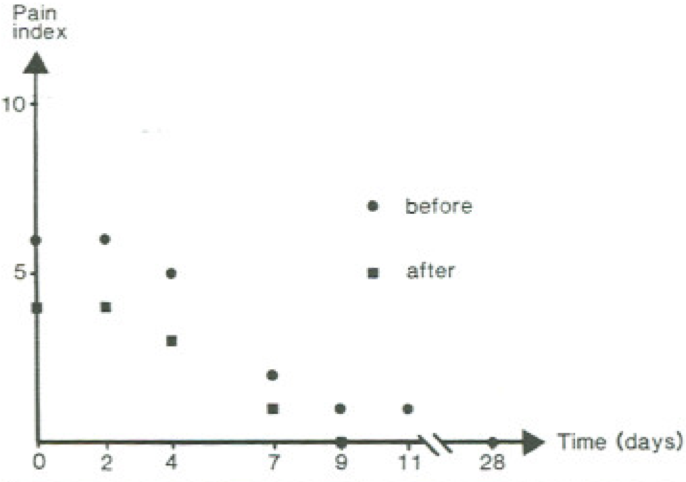

Figure 1 Pain scores from a representative sacroiliac joint patient obtained five minutes before and five minutes after spinal manipulative therapy. Treatments were given on days 0, 2, 4, 7, and 9. Days 11 and 28 were used for follow-up procedures not involving SMT. Post-treatment pain scores were always lower (i.e. less pain) than corresponding pre-treatment scores. Pain decreased nearly continuously throughout the treatment and follow-up periods.

Figures 1–8 reprinted with permission of JMPT.

findings from one representative patient;[5] the second result will be illustrated using a study where the effectiveness of SMT was compared to the effectiveness of a back school program using 29 symptomatic sacroiliac joint patients.[6]

First result: Figure 1 shows the pain measures of a 34-year-old male (1.79 m, 70 kg) attending six treatment sessions on days 0 (start of study), 2, 4, 7, 9, and 11, and a follow-up session on day 28. A "10" on this particular pain scale indicates unbearable pain, a "0" indicates no pain. Pain measures were taken before and after treatments, except for days 11 and 28 where the patient was not symptomatic anymore and thus, did not receive SMT. SMT in the five treatment sessions consisted of a manipulation of the upper right sacrum with the subject in a side lying position, left side up.

Figure 2 shows joint immobility scores as assessed by the treating chiropractor using two tests of the Gillet motion palpation procedure.[7] For a completely fixed sacroiliac joint, a score of "10" was given; for a normal joint, a score of "0" was given.

Figures 1 and 2 indicate that the patient had considerable pain and joint immobility when entering the study, however, these symptoms were virtually gone after five treatments, and recovery remained good for at least 17 days following the patient's last visit.

Figures 3 and 4 show quantitative changes of walking mechanics for the patient shown in Figures 1 and 2. The negative impulse of the antero-posterior component of the ground reaction force increased throughout the treatment period for both legs. Figure 3 shows the mean values of the left leg for each treatment session (n = 6 for days 0–9, n = 3 for day 11). The best fitting regression line has a slope significantly different from zero (α = 0.05), therefore indicating that part of the change in negative impulse of walking can be explained with the duration of the treatment period.

In concert with the increase in negative impulse, support times for walking also increased throughout the treatment period and for the follow-up session (Figure 4). These support times are means from the right and left legs from all walking trials in each session (n = 12 for days 0–9, n = 6 for days 11 and 28).

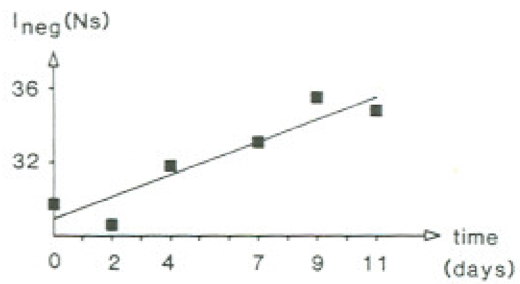

Figure 3 Negative impulse of the antero-posterior component of the ground reaction force during walking at a nominal speed of 1.5 m/s, left leg. The data points represent means of all trials (n = 6 for days 0–9, n = 3 for day 11) executed in one testing session. The straight line approximating the data is a best fitting regression line with a slope significantly (α = 0.05) different from zero, indicating that the increase in the impulse values can be explained to some extent with the increasing duration of the treatment period.

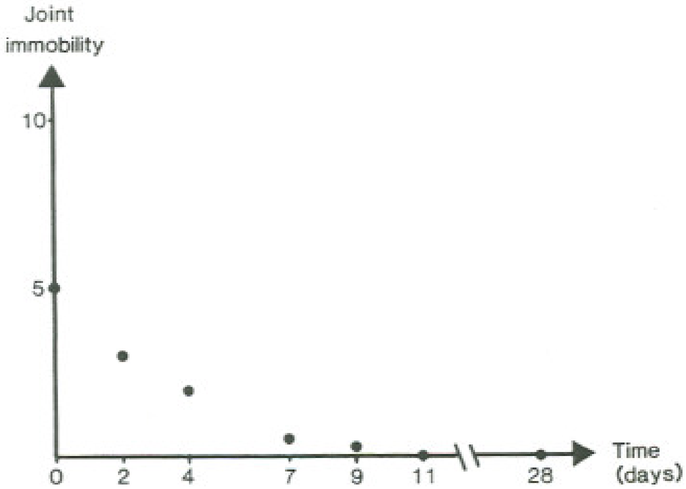

Figure 2 Joint immobility scores for the same patient as shown in Figure 1. The decreasing scores throughout the treatment (days 0–9) and follow-up periods (days 11–28) indicate that the sacroiliac joint became more mobile during that time. The score of zero on days 11 and 28 is associated with normal joint mobility.

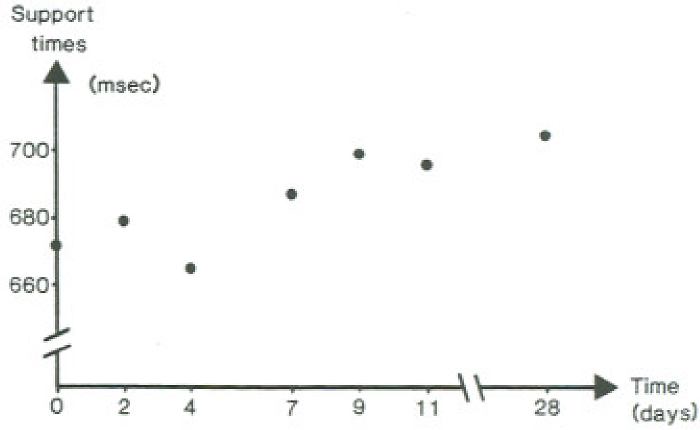

Figure 4 Mean support times for walking at a nominal speed of 1.5 m/s as a function of duration of the treatment period. The data were obtained from the left and right legs of the same patient as in Figures 1–3. Mean support times tend to increase throughout the treatment period (days 0–9, n = 12) and the follow-up period (days 11–28, n = 6).

The results shown in Figures 3 and 4 are examples of changes in walking mechanics during a period of time where a patient received SMT. Similar changes, however, not necessarily for the same variables, were observed for most patients in our studies.

In the following, we will present selected results from a study that yielded the only consistent finding for an entire group of patients receiving SMT, namely, a significant improvement in gait symmetry from the beginning to the end of a treatment protocol.

Second result: The aim of this study was to compare the effectiveness of SMT to the effectiveness of back school therapy (BST) in the treatment of symptomatic sacroiliac joint patients. The final analysis was done on 16 patients in the SMT group and 13 patients in the BST group. Each patient had received 9–10 treatments in a four week period. For further details of the methods, please be referred to Herzog et al. (1991).[6]

Figure 5 shows the mean pain scores obtained before and after treatment for the SMT and BST groups. For both treatment groups, the post-treatment values were always lower than the pre-treatment values indicating a decrease in pain that may be associated with the treatment received. For the first three sessions, there is no consistent trend differentiating between the two treatment groups. However, starting from session five, the pre- and post-treatment values for the BST group were always lower than the corresponding SMT values. Non-parametric statistics, testing for differences in the pain values of the SMT and BST group, showed no differences in the first treatment session, but significant differences ($\alpha = 0.05$) in the ninth session. This result indicates that the patients receiving BST had a larger reduction in subjectively-experienced pain than patients receiving SMT.

Figures 6 and 7 show a summary of the results for the gait symmetry analysis for patients receiving SMT and BST, respectively. The percentage values on the vertical axes indicate the number of times that symmetry values were found outside the limits representing a 95 percent confidence interval of symmetry for a normal reference population.[1] Therefore, a value of 5 percent is considered normal. For the SMT patients, the mean percentage of all variables of the vertical, antero-posterior and medio-lateral components of the ground reaction force are significantly larger than 5 percent in the first session but are (statistically) not different from 5 percent in the last session (Figure 6; note that the antero-posterior and medio-lateral components overlap). This means, that the SMT patients as a group were walking more asymmetrically compared to a normal reference population when entering the study, but could not be distinguished from the reference population at the end of the four week treatment period.

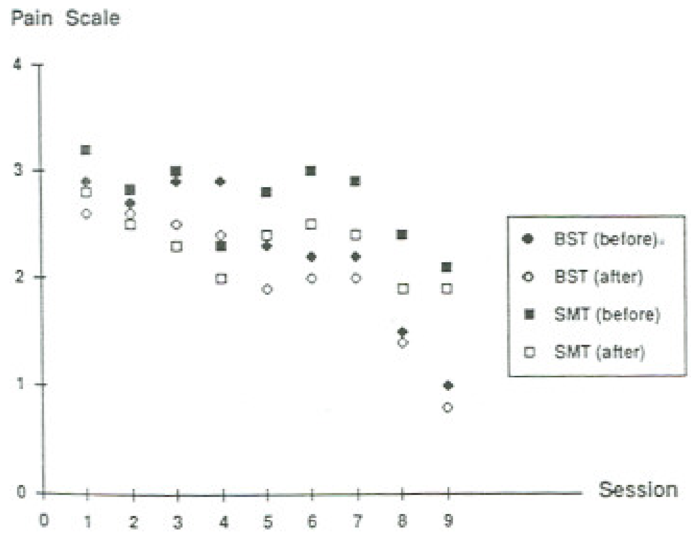

Figure 5 Mean pain scores obtained from patients receiving spinal manipulative therapy (SMT) and back school therapy (BST). Pain scores were recorded approximately five minutes before and after each treatment. In each case the post-treatment pain score was lower than the corresponding pre-treatment score. Initially, the scores of the SMT and BST patients were similar, however, towards the end of the four week treatment period, the scores became significantly smaller (i.e. less pain) for the patients receiving BST compared to those receiving SMT.

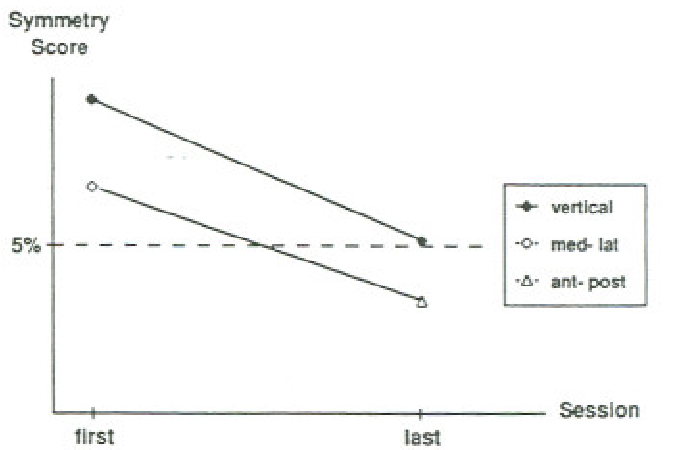

Figure 6 Mean symmetry scores for the vertical, antero-posterior and medio-lateral component of the ground reaction force for patients receiving spinal manipulative therapy. The scores are given in percentages representing the relative number of times where parameters were found to be outside those established for a 95 percent confidence interval of a normal reference population. Therefore, a value of 5 percent is considered normal. Values are given for the first and last treatment sessions. (Note: the values for the antero-posterior and medio-lateral components are identical, i.e. the lines overlap.)

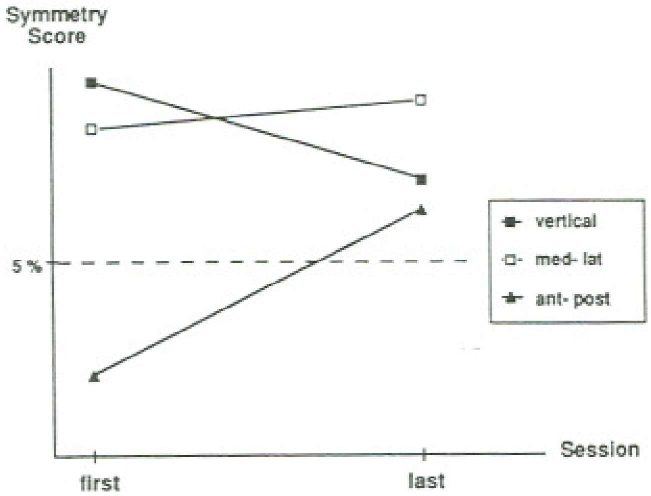

Figure 7 Mean symmetry scores for the vertical, antero-posterior and medio-lateral component of the ground reaction force for patients receiving back school therapy. The scores are given in percentages representing the relative number of times where parameters were found to be outside those established for a 95 percent confidence interval of a normal reference population. Therefore, a value of 5 percent is considered normal. Values are given for the first and last treatment sessions.

The symmetry scores for the BST group were different from those of the reference population at the beginning of the treatment period and remained different throughout the treatment period (Figure 7). If attaining normal symmetry of walking is considered an aim of sacroiliac joint treatments, then it may be speculated from this study that SMT was more effective in reaching this aim than BST. Thus, we are left with the interesting result that BST appeared to be more effective in reducing pain, but less effective in restoring normal walking symmetry compared to SMT.

Our locomotion studies showed that SMT causes changes in walking mechanics and improves gait symmetry for sacroiliac joint patients. In view of these results, it is feasible to speculate that SMT causes changes in the mechanics of the musculoskeletal area that has been treated. The following studies will describe our first attempts of quantifying these internal mechanical changes.

Forces exerted by chiropractors during SMT

The purpose of these studies was to assess how much force was exerted by chiropractors on patients during SMT. We have measured these forces in the past two years for sacroiliac joint, thoracic spine and cervical spine manipulative treatments.[8,9,10,11] Knowing the forces exerted during SMT, we hope to quantify the mechanical effects of these forces on the musculoskeletal and neuromuscular systems in the near future.

Methods

The forces exerted by chiropractors on patients during SMT were measured using a thin, flexible pressure pad (EMED Inc., Munich). This pressure pad is thin enough (about 2 mm) to not interfere with palpation of bony landmarks. The pad is fixed on the patient using athletic tape at the site of chiropractor/patient contact. Only forces perpendicular to the pressure pad can be measured, thus, great care was taken to select SMT where the main thrust is applied perpendicularly to the pressure pad on the patient. However, assuming that forces are not always applied precisely in the required direction, our measurements may tend to underestimate (but never overestimate) the actual forces by a small amount. We have not tried to correct for those potential underestimations.

On the thoracic spine, we have measured treatment forces in conjunction with cavitation signals of the spinal joints. Cavitation signals were recorded using small skin mounted accelerometers. Force and cavitation signals were synchronized electronically.

Figure 8 is a schematic representation of a force-time trace of SMT, including definitions for the four main parameters analysed in these studies. The preload force is the force required to move a joint to the end point of its passive range. This force is nearly constant for the last 500 ms preceding the thrusting force. The peak force is defined as the largest force recorded during SMT. The duration of the treatment thrust is defined from the onset of the thrusting force to the end of the thrust. The end of the thrust is defined as the first major change in slope after occurrence of the peak force or when the force reaches a value of zero. The treatment impulse is defined as the integral of the force-time trace over the treatment duration time. It corresponds to the shaded area shown in Figure 8.

Results (sacroiliac joint)

Figure 9 shows six force-time traces for SMT on the sacroiliac joint. All treatments were performed by one chiropractor using the Thompson technique with a drop piece. The six traces are

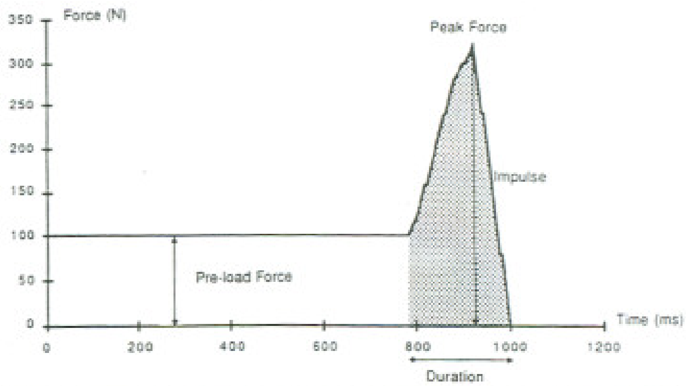

Figure 8 Schematic representation of a force-time history of SMT, and definitions for four selected variables used in the data analysis.

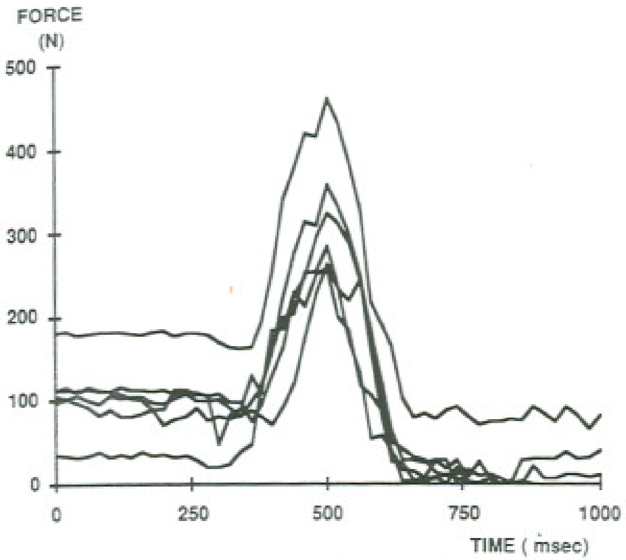

Figure 9 Force-time histories for SMT on the sacroiliac joint. Each curve represents the mean of three treatments on one symptomatic patient, given by the same chiropractor for all patients. Spinal manipulative thrusts were executed in a posterior to anterior direction using a reinforced unilateral contact on the sacroiliac joint. Patients were in a prone position, and a drop piece was used in all instances.

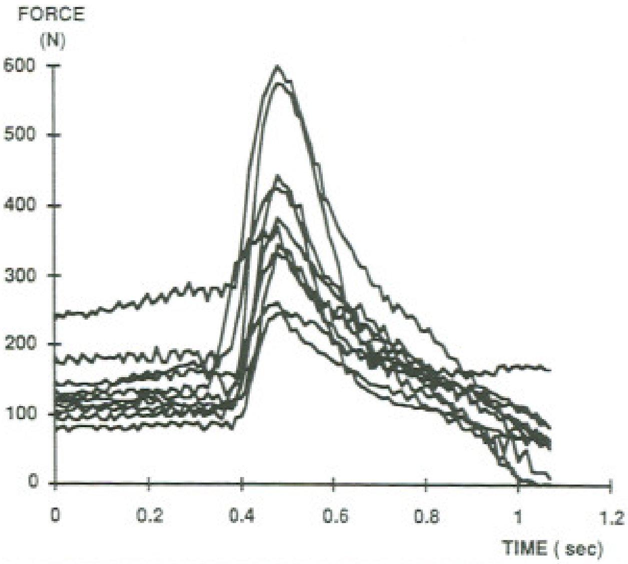

Figure 10 Force-time histories for SMT on the thoracic spine. Each curve represents a single treatment on one symptomatic patient, given by the same chiropractor as in Figure 9 for all patients. Treatments were performed in a posterior to anterior direction using a reinforced, unilateral hypothenar contact on the transverse process of T4. Patients were always in a prone position.

means of three separate treatments on each of six different patients. Preload forces range from about 30 N to 180 N, peak forces range from approximately 250 N to 450 N. We have measured force-time histories of SMT on the sacroiliac joint for 16 chiropractors on 46 symptomatic patients. The results shown in Figure 9 are representative for the general shape of these force-time histories, however, the absolute forces vary dramatically. For example, peak forces ranged from less than 200 N to over 1000 N for different chiropractors (1000 N = 220 lbs).

Force values obtained during SMT of the sacroiliac joint on symptomatic patients are not available in the literature, therefore, our results cannot be compared directly to other studies. However, Wood and Adams[12] and Adams and Wood[13] measured forces during sacroiliac joint SMT using a treatment simulator. The mean peak force measured in those studies was lower (256 N) than the mean peak force from the treatments shown in Figure 9 (328 N).

Results (thoracic spine)

Figure 10 shows 10 force-time traces for SMT performed on the thoracic spine. All treatments were given by one chiropractor (the same as in Figure 9) on 10 different patients. Treatments were administered using a straight posterior to anterior thrust with a reinforced unilateral hypothenar contact on the transverse process of T4.

The general shape of the force-time histories in Figure 10 are similar to those in Figure 9 for the sacroiliac joint treatments. On average, the preload and peak forces of SMT on T4 are larger than the corresponding values from the sacroiliac joint. Comparing the mean force-time histories of all (n = 18) sacroiliac joint and all (n = 10) thoracic spine SMT supports this statement (Figure 11). Interesting enough, the two mean force-time histories shown in Figure 11 are similar, except for a nearly constant shift in force corresponding approximately to the difference in preload force.

An analysis of Figures 9 and 10 reveals that peak forces are correlated to preload forces for SMT on T4 and the sacroiliac joint. This is illustrated in Figure 12 where preload forces from Figures 9 and 10 are plotted vs. the corresponding peak forces. A best fitting regression line (r^2-value of 0.603) indicates that over 60 percent of the variation in the peak forces may be associated with variations in the preload forces. Since the preload forces are applied slowly and carefully by each chiropractor before the manipulative thrust, it appears that it is the preload part of the treatment that can be altered consciously and that may affect the remainder of the treatment significantly. This may be born in mind when teaching SMT techniques to students. Force measurements during SMT on the thoracic spine (to our knowledge) are not available in the literature for comparison of our results.

Results (cervical spine)

Figures 13 and 14 show three force-time histories of SMT on the cervical spine from two different chiropractors, respectively. Each force-time history was obtained from the same patient on three different occasions using a unilateral contact at one level of the cervical spine and applying the manipulative thrust in a lateral to medial plane.[11]

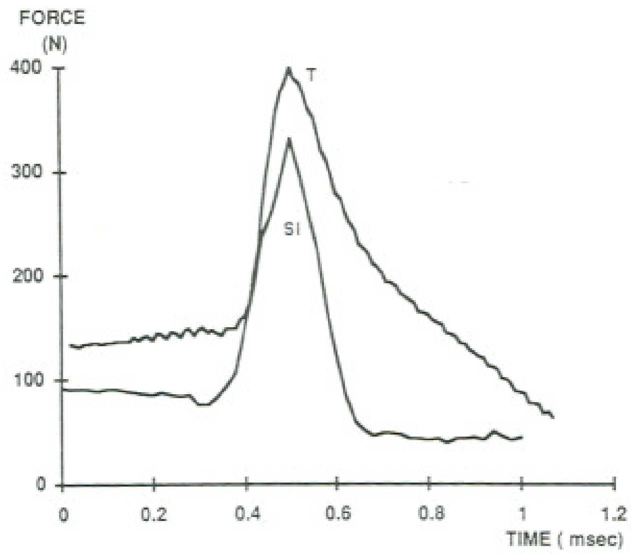

Figure 11 Mean force-time histories of SMT on the sacroiliac joint and the thoracic spine. The mean curve for the sacroiliac joint was obtained from one chiropractor treating six patients on three different occasions (n = 18); the mean curve for the thoracic spine was obtained from the same chiropractor treating 10 patients one time each (n = 10).

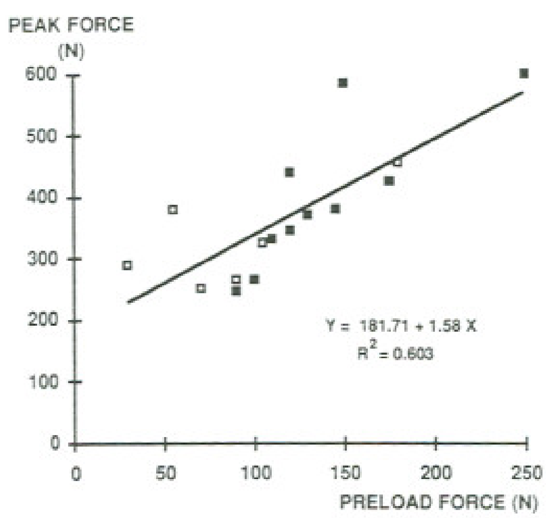

Figure 12 Preload forces vs. peak forces for SMT performed on the sacroiliac joint (open squares) and the thoracic spine T4 (filled squares). The regression line approximating the data indicates a direct positive relation between preload and peak forces for these treatments.

In contrast to thoracic spine and sacroiliac joint SMT, the treatments on the cervical spine were executed with no measurable preload force. Since the sensitivity of the system is about 1 N/cm², it is possible that small preload forces of approximately 5 N may have been exerted but were not registered. Furthermore, the peak forces in the cervical spine treatments are much lower than those observed during thoracic spine or sacroiliac joint SMT. In fact, on some occasions, the preload forces of those latter treatments were larger than the peak forces recorded for SMT on the cervical spine. Also, the duration of the treatment thrusts for cervical spine SMT was found to be substantially shorter than that for thoracic spine or sacroiliac joint SMT.

Indirect estimates of the forces exerted during SMT on the cervical spine (C2) have been performed by Triano and Schultz[14] using an inverse dynamics approach. Estimates of the mean peak forces (left side 111 N, right side 123 N) are virtually identical to our peak force measures (Figures 13 and 14); however, estimates of mean treatment duration times (200–300 ms) exceeded our values by a factor of 2–3.

Results (thoracic spine cavitation)

Spinal manipulative therapy often causes a cracking sound that has been associated with spinal joint cavitation.[15,16] Research on metacarpophalangeal joints has produced evidence that cavitation produces an increased space within a joint, and increases passive and active range of motion of the cavitated joint.[15,17] It is this type of evidence that has convinced many clinicians that cavitation identifies successful SMT.

Figure 15 shows a representative force-time history of SMT on T4 with a typical sound recording obtained using a skin mounted accelerometer on the spinous process of T3. The sound trace shows a low frequency triphasic signal that can be matched to the forces exerted by the chiropractor during SMT, and a high frequency signal with a frequency content similar to that found

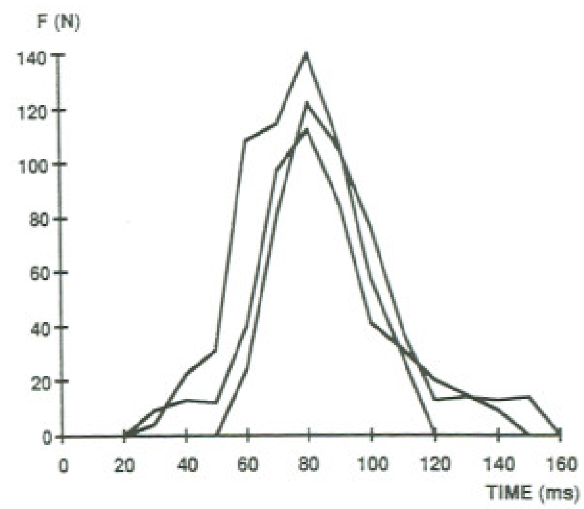

Figure 13 Force-time histories of SMT on the cervical spine. Each trace represents one treatment on one patient. All three treatments were performed by one chiropractor.

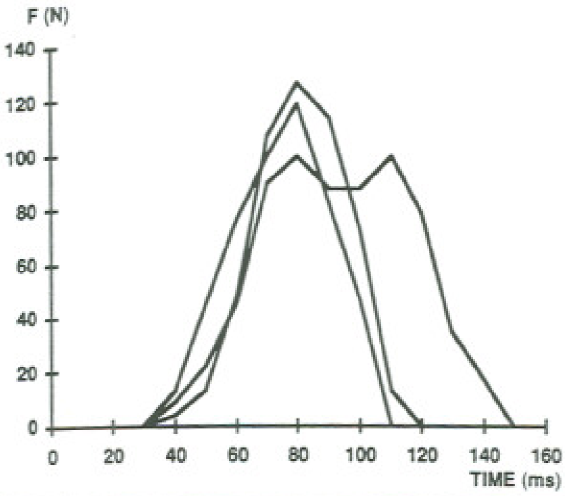

Figure 14 Force-time histories of SMT on the cervical spine. Each trace represents one treatment on one patient. All three treatments were performed by one chiropractor, but not the same chiropractor as the one shown in Figure 13.

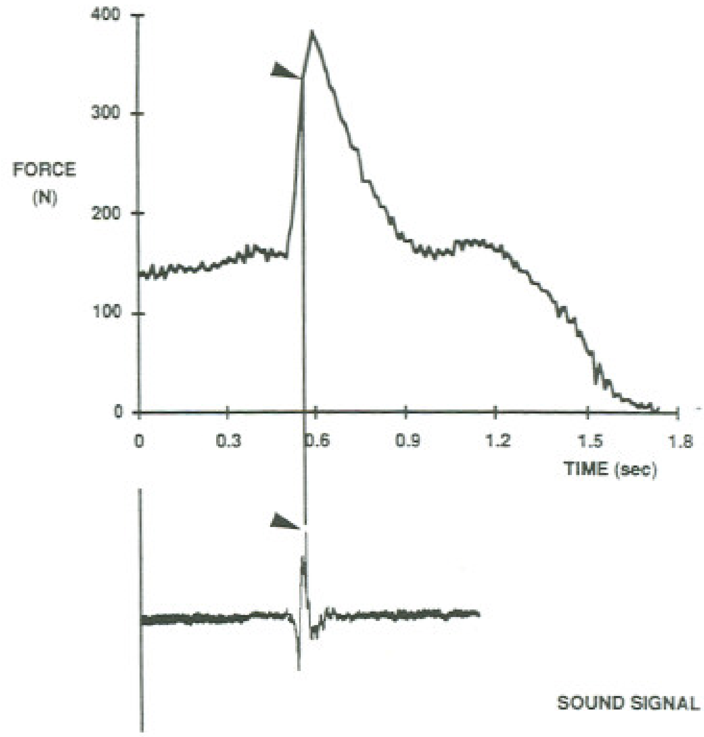

Figure 15 Representative force-time history of SMT on the thoracic spine with the corresponding cavitation (i.e. sound) signal. The arrow on the sound trace indicates the high frequency component of the signal that is associated with spinal joint cavitation. The arrow on the force-time trace indicates the point of cavitation.

for confirmed cavitation at the metacarpophalangeal joints.[16] The high frequency component of the sound signal was associated with cavitation of spinal joints and is indicated by an arrow on Figure 15.

In eight out of 10 cases, cavitation occurred before peak treatment forces were reached (e.g. Figure 15), however, in two cases cavitation occurred after peak forces had been reached. These two cases indicate that cavitation may not depend on the amount of force applied during SMT exclusively, but may possibly depend on other mechanical factors such as the speed of force application or the impulse applied during SMT.

Future

Our locomotion studies have shown that SMT on symptomatic patients causes quantifiable changes in movement mechanics. It is reasonable to assume that these changes are caused by changes in the musculoskeletal or neuromuscular system that was treated. Our long-term objective is to quantify and interpret these changes and associate them with spinal manipulative treatments. In a first step to quantify changes of the musculoskeletal and neuromuscular systems associated with SMT, we have measured the forces that chiropractors exert on patients during SMT. Some of these studies have pilot character and will be expanded in the near future. Some areas of the back, for example, the lumbar spine region, have been neglected in these studies and must be considered in future investigations. However, most importantly, future studies must attempt to quantify the changes in internal mechanics occurring during and after SMT. That means, displacements of vertebral bodies and internal forces acting on bones, ligaments, and muscles must be quantified directly during SMT. Only such an analysis will permit understanding of the mechanics of SMT and the effects of SMT on the rehabilitation process of back pain patients.

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