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Instantaneous Helical Axis Methodology to Identify Aberrant Neck Motion

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Abstract

Background—Neck pain afflicts 30-50% of the U.S. population annually; however we currently have poor diagnostic differentiation techniques to inform individualized treatment. Planar neck kinematics has been shown to be correlated with neck pain, but neck motion is much more complex than pure planar activities. Our objective was to define a methodology for determining aberrant neck kinematics and assess it.

Methods—We examined a complex neck kinematic activity of neck circumduction, computed the pathway of motion using the instantaneous helical axis approach in 81 patients with non-specific neck pain and in 20 non-matched symptom free subjects. Neck circumduction, or rolling of the head, represents a complex neck kinematic activity, investigating the innate coupled motion of the cervical spine at the end ranges of motion in all directions. Instance of discontinuities in the helical axis patterns, or folds, were identified and labeled as occurrences of aberrant motion.

Findings—The instances of aberrant motion, or folds, which are nearly non-existent in the healthy sample group, are present in both the pre and post treatment neck pain patients. Following a treatment intervention of the symptomatic patients, pain and neck disability index decreased significantly ($p<0.001$) concomitant with a decrease in the number of folds ($p=0.021$).

Interpretation—The present study highlights a new technique using an instantaneous helical axis approach to detect subtle abnormalities in the pathway of motion of the head about the trunk, during a neck circumduction exercise.

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Conflict of Interest Statement
The authors have no conflicts of interest to report.

Keywords

neck pain; helical axis; aberrant motion; kinematics; cervical spine

Introduction

Neck pain is a deleterious health outcome, which afflicts 30-50% of the US adult population annually(Carroll et al., 2008; Strine and Hootman, 2007). Neck pain is multifactorial with underlying causes ranging from neural tissue impingement to osteoligamentous pathology to neuromuscular control abnormalities(Moskovich, 1988; Pettersson et al., 1997). These diverse causes for neck pain lead to difficulties in diagnosis wherein many patients are labeled with non-specific neck pain. This may also be due to diagnosis tools or methods, which do not produce data capable of high-level diagnostic specificity for neck pain patients. For these patients the course of treatment is often similar regardless of underlying cause, which may be responsible for the general poor outcomes for patients with neck pain.

In an effort to understand the mechanisms associated with neck pain, a number of studies have investigated spinal kinematics in symptomatic and asymptomatic individuals, typically examining planar cervical motion(Feipel et al., 1999; Rix and Bagust, 2001; Youdas et al., 1992). Individuals suffering from neck pain often exhibit reduced range of motion (ROM) (Cagnie et al., 2007; Chiu and Sing, 2002; Grip et al., 2008; Osterbauer et al., 1996), which is frequently jerky or displays irregular motion patterns(Feipel et al., 1999; Sarig Bahat et al., 2010; Sjölander et al., 2008; Vogt et al., 2007; Woltring et al., 1994). However, much of the motion of the cervical spine is not planar, but is coupled among multiple axes.

In an effort to better understand three-dimensional cervical motion, many of the studies have utilized a helical axis approach to describe head motion about the torso. The helical axis is a precise three-dimensional vector that the head rotates about and translates along during motion. Öhberg et al. found significant differences in helical axis parameters between Whiplash Associated Disorder (WAD) patients and controls while performing simple head movements, such as flexion-extension and axial rotation(Ohberg et al., 2003). Woltring et al. also found that patients had more scattered helical axes while performing flexion-extension activities, and following manipulative therapy the helical axes from those suffering from WAD re-aligned similar to the healthy controls(Woltring et al., 1994). When performing more complicated tasks, such as ball catching, individuals with neck pain, either WAD or non-specific pain, had altered centers of rotation when compared with healthy subjects(Grip et al., 2008). Other groups have used helical axes to gain insight into motion patterns of the cervical spine, all of which highlight the helical axis approach's ability to quantify the complex motion of the cervical spine(Dugailly et al., 2010; Greaves et al., 2009; Moore et al., 2005; Osterbauer et al., 1996; Winters et al., 1993).

Although these previous studies have noted kinematic differences between symptomatic and asymptomatic individuals, many are either investigating planar motion or sensorimotor reactions. A neck circumduction exercise, or rolling of the head, potentially offers a novel diagnostic test to distinguish neck pain. Neck circumduction represents a complex neck kinematic activity, which investigates the innate coupled motion of cervical spine. Computing the helical axis of motion at infinitesimal time steps throughout the circumduction activity can provide insight into the precise three-dimensional pathway of motion of the cervical spine at the end ranges of motion in all directions and has the potential utility of discerning aberrant motion.

The aim of this study was to measure complex neck kinematics and describe the pathway of motion using the helical axis approach in an attempt to distinguish aberrant patterns of motion. The present study tested the methodology on neck-pain free subjects as well as on non-matched patients with non-specific neck pain before and after a treatment intervention. The objective was to define a methodology for assessing aberrant neck kinematics with the hope that this diagnostic method may in the future assist in distinguishing neck pain symptomology.

Methods

3D neck kinematics and symptomology were examined in a non-specific neck pain sample and a healthy sample. Head-to-torso kinematics was investigated in 101 subjects. 81 subjects (42.93 (10.41) years; 30 male) suffered from primary complaint of mechanical, non-specific neck pain, with average pain duration of 6.45 (7.72) years. Exclusion criteria for the symptomatic subjects included previous cervical spine surgery, fractures, and neck pain referred from peripheral joints or viscera. Patient kinematic data was collected at Northwestern Health Sciences University (NWHSU) as a part of two randomized clinical trials, which contain more detailed inclusion/exclusion criteria (Bronfort et al., 2012; Evans et al., 2012). Kinematic data from asymptomatic subjects was collected at the University of Minnesota (UMN) from 20 subjects (21.5 (3.4) years; 10 male) having no history of neck, back, or shoulder pain. IRB approval was granted by the participating institutions (NWHSU ID 1-87-01-11, UMN ID 1110M05921). Subjects rated their average pain (1-10) and completed the Neck Disability Index (NDI) survey based upon their week just past(Vernon and Mior, 1991). Relative position and orientation of the head with respect to the torso was computed via a CA-6000 Linkage system (OSI, CA) at a frequency of 100 Hz. The linkage system has been shown to be highly accurate and reproducible; reported by the company to be accurate to within 0.1 degrees in each direction and confirmed experimentally (Dvorak et al., 1992; Petersen et al., 2000). The inferior end of the linkage system, located over the spinous process of T1, was secured to a harness that was snuggly strapped around the torso. The superior end was connected to a helmet, which was tightened to minimize movement between the strap and the subject's hair and skin (Figure 1). Subjects were instructed to perform a circumduction exercise while standing with their arms by their side. Beginning from neutral position the subjects went into full flexion rolled their head to the left and around back to full extension, then to the right and to full flexion before returning to neutral position. Subjects were instructed to bend as far as they could in all directions and go at their own pace.

Two baseline trials were captured 1-2 weeks apart for all subjects; only the second trial was analyzed so as to remove any training bias. Each trial consisted of three cycles of circumduction. The final circumduction cycle was used for analysis. For those who were part of the symptomatic group another trial was captured at 12 weeks, following treatment intervention. Treatments, varied by individual, included a combination of exercise, manipulative therapy, and pharmaceutical intervention. However, treatment efficacy is not the focus of the present study. This study aimed to investigate a new methodology for detecting aberrant motion in a non-specific neck pain population using an instantaneous helical axis (IHA) approach.

The data were filtered with a 5th order low pass Butterworth filter with a cutoff frequency of 10 Hz. This filtering regiment was shown to be more conservative than previous studies (Grip et al., 2008; Woltring et al., 1994). IHA were calculated for each time step throughout the circumduction exercise between the subject's initial full flexion position and their final full flexion position(Spoor and Veldpaus, 1980; Woltring et al., 1985). The IHA vector tips were fit to a three-dimensional plane using a least squares method and transformed into spherical coordinates, where theta was the azimuthal angle. Aberrant motion was defined when the numerical derivative of theta was negative, indicating where the IHA folds back upon itself. A threshold of one degree of head rotation was set to define a 'fold'. This threshold value decreases the chance that noise in the data could appear as a fold. A visual representation for the quantification of a fold is displayed in Figure 2. The red vectors and markings on head position plot indicate a fold in the IHA surface, or an instances of aberrant motion.

Pain rating, NDI, number of folds, flexion/extension and lateral bending range of motion, and average head angular velocity were recorded. Descriptive statistics were used to evaluate the asymptomatic group and no direct statistical comparisons were made with the symptomatic group due to the differently matched demographics. Recall that the objective of this study was the definition of a new methodology, which may provide future diagnostic specificity. Thus, a paired t-test was performed within the symptomatic group comparing baseline and post-treatment to investigate the method's ability to assess patient's progress following an intervention ($\alpha=0.05$). In order to assess the repeatability in the aberrant motion quantification, the intra-class correlation coefficient (ICC) was calculated by comparing the number of folds between the last two cycles of the circumduction activity for the symptomatic subjects at baseline.

Results

The asymptomatic group had an initial pain rating of 0.15 (0.37) and an NDI rating of 0.95 (1.96). The baseline pain rating and NDI for the non-specific neck pain group was 5.30 (1.65) and 25.59 (8.42), respectively. Twelve weeks following treatment intervention the pain rating decreased significantly to 2.94 (2.05) ($p<0.001$) and NDI significantly decreased to 14.67 (10.59) ($p<0.001$).

The number of folds from the helical axis data, or instances of aberrant motion, decreased significantly within subjects following treatment in the symptomatic group from 4.00 (3.32) to 3.15 (2.17) ($p=0.021$). The asymptomatic group exhibited 0.63 (0.90) folds while performing the circumduction exercise. The intra-class correlation coefficient for the number of folds between the last two cycles of circumduction for the symptomatic group at baseline was 0.860.

The pre-treatment group had a significantly lower FE ROM than post treatment ($p<0.001$). LB ROM displayed this trend as well, although it was not found to be significant ($p=0.052$). Also, the symptomatic subjects performed circumduction faster following the treatment intervention ($p<0.001$).

Discussion

Many research studies have used helical axes to gain insight into the motion patterns of the cervical spine(Dugailly et al., 2010; Greaves et al., 2009; Grip et al., 2008; Moore et al., 2005; Ohberg et al., 2003; Osterbauer et al., 1996; Winters et al., 1993; Woltring et al., 1994). It is a useful tool to describe and quantify the complex motion of the cervical spine and has been used to comprehend the pathway of motion of the healthy cervical spine(Dugailly et al., 2010), as well as how these patterns are altered due to age, sex, and abnormalities(Greaves et al., 2009; Grip et al., 2008; Lee et al., 1997; Winters et al., 1993; Woltring et al., 1994). All of these studies computed the IHA for planar motions of the cervical spine and we propose that a more complex cervical spine motion may reveal greater information about the health of the neck.

The present study highlights a new technique using a helical axis approach to detect subtle abnormalities in the pathway of motion of the head about the trunk, during a complex multi-planar neck circumduction exercise. By computing the IHA throughout neck circumduction, aberrant motion can be identified by where the tips of the vectors fold back upon themselves. These folds, which were shown to be nearly nonexistent in the healthy sample group, are present in symptomatic subjects. The number of folds, or instances of aberrant motion, was shown to decrease in those suffering from non-specific neck pain following a treatment intervention wherein the individual's pain and NDI also decreased significantly. The underlying cause of a fold is unknown and could not be addressed in the current study. They may be based on anatomic or structural abnormalities in the cervical spine, or even sensorimotor changes related to altered activation patterns of the neck musculature. Further investigation including imaging of the cervical spine and electromyography are necessary to confirm the significance of the folds and these hypotheses.

The presence of folds was coincident with pain; while painful patients exhibited varying numbers of folds. It is important to point out, during post-hoc analyses; there was no direct correlation between level of pain or disability and the number of folds. This may be because the number of folds is not indicative of pain intensity, but rather the locations of these folds are related to the underlying source of the pain. In other words, an individual may have a high level of neck pain, but it is localized only to a few folds, where another could have a lower pain rating, but their kinematics are impacted at many stages of the circumduction exercise. Utilizing a paired analysis, the number of folds in the symptomatic group significantly decreased following an intervention where pain and disability also decreased significantly.

A visualization of representative data can be seen in Figure 4, where the healthy curve displays a smooth pattern with no folds. The symptomatic curves are of the same patient pre and post treatment intervention. Notice the decrease in number of folds and those that remain are in a similar location, however appear to have decreased in magnitude. The improvement within each subject showcases this technique's potential to track patient progression, which can be used to assess the validity of various treatment options. The folds provide a position and anatomically specific marker for poor motion.

Also, the high ICC value (0.860) in quantifying the number of folds within a session highlights this techniques repeatability. Woltring et al. took a similar qualitative look at the IHA patterns of a subject with WAD before and after spinal manipulation therapy during flexion/extension(Woltring et al., 1994). The orientation and location of the initial helical axes of the patient with WAD were exceedingly scattered. Specifically, there was large migration in the vertical location of the IHA and a large amount of out of plane motion was observed. Following treatment, the helical axes became more aligned and there was less fluctuation in location, similar to the healthy control. Grip et al. conducted a similar study of planar motion comparing asymptomatic individuals to both non-specific neck pain and WAD(Grip et al., 2008). They reported a trend towards increased IAR movement in the vertical direction (p=0.07) during flexion/extension; this observation was significant for left/right lateral bending (p=0.03).

Reduced range of motion was identified by others to be a function of neck pain(Cagnie et al., 2007; Grip et al., 2008; Ohberg et al., 2003; Osterbauer et al., 1996). The present study found similar results between the healthy and non-specific neck pain groups. Flexion/extension increased in the symptomatic group following treatment, however there was no significant increase in lateral bending, but a trend was observed (p=0.052). There was also a significant increase in angular velocity of the head following the treatment intervention. The asymptomatic group had higher angular velocities than each of the symptomatic trials.

Although no studies examined the circumduction exercise, it has been reported that angular velocity of the head is reduced in those suffering from neck pain during simple bending activities and more complex tasks such as catching a ball(Grip et al., 2008; Ohberg et al., 2003). Bahat et al. compared head kinematics between asymptomatic and chronic neck pain subjects while performing a series of targeting tasks; they recorded mean and peak velocities, as well as the number of peaks in the velocity profile, used as an indicator of the smoothness of motion (Sarig Bahat et al., 2010). They concluded that individuals suffering from chronic neck pain moved their heads at a lower mean velocity, reached lower peak velocities, and a greater number of peaks in their velocity profile.

A few methodological limitations of this research should be noted to contextualize the results and utility of the technique. First, although precautions were taken to ensure the harness and helmet were tightened securely, error may have been introduced due to clothing, hair, or skin slip. However, this methodology can be applied to data from other kinematic collection devices, which are less susceptible to these errors, such as infra-red motion capture systems, electromagnetic systems, and potentially dynamic fluoroscopy. In order to combat the error associated with linkage movement and errors in the helical axis quantification, the head position must change a minimum of one degree in the azimuthal plane in order to constitute a fold. This threshold was chosen to be an order of magnitude above the accuracy of the device allowing for each instance of aberrant motion not to be confused with noise or error in the system, while maintaining a potentially clinically relevant amount of motion. One limitation of our work is the healthy sample is not age or sex matched to our neck pain sample. For this reason, no statistical comparisons were made between the asymptomatic and symptomatic groups. However, post-hoc analyses showed no correlation between age and number of folds (Pearson's Correlational Coefficient = 0.0531). Only head to torso movements were recorded including all cervical levels in the aberrant motion measurement wherein it may be likely that a singular segment is structurally the nexus of that patient's neck pain. Also, it was not noted when or if patients experienced pain or discomfort while performing the exercise. Post-collection analysis was performed on the symptomatic subjects, therefore only one direction of circumduction was collected and analyzed. This represents an opportunity for future research to attempt to distinguish the origin of pain based on specific instances of aberrant motion.

Individuals suffering from neck pain have been shown to display altered kinematics. Specifically, they have decreased ROM in all bending directions, decreased head velocity, decreased smoothness of motion, and overall abnormal motion patterns. Our present work details a new technique to quantify these abnormalities by assessing the instantaneous helical axes patterns of individuals with neck pain while performing a neck circumduction exercise. This technique has the ability to count the number of instances of aberrant motion, detect the head position where these instances arise, and compute the duration of the folds. We hypothesize that the location and duration of these folds may be indicative of the underlying cause of pain due to structural abnormalities, injuries, or pathologies, which may enable more targeted treatment options. This hypothesis should be tested with future studies investigating the subject's pain level at different head locations while circumducting the head and measuring intersegmental kinematics. The preliminary work herein lays the foundation for a potential diagnostic tool for individuals with neck pain based on their kinematics.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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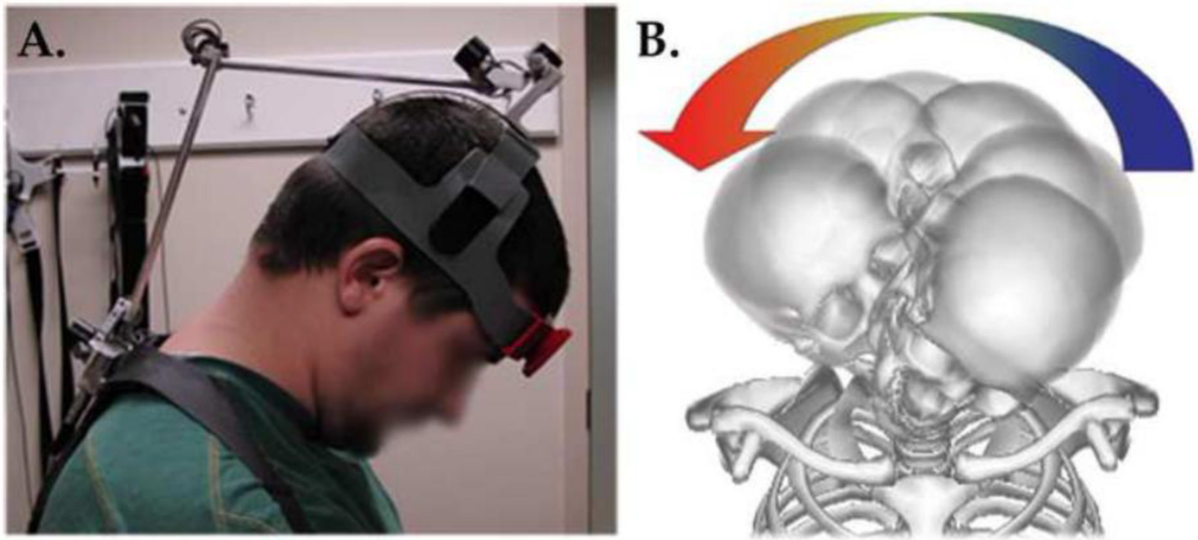

Figure 1. Test Set-Up

(A) Subject equipped with linkage system attached to head and strapped to torso. **(B)** Skeleton depicting the circumduction activity. Beginning from neutral position the subjects went into full flexion rolled their head to the left and around back to full extension, then to the right and to full flexion before returning to neutral position. Subjects were instructed to bend as far as they can in all directions and go at their own pace.

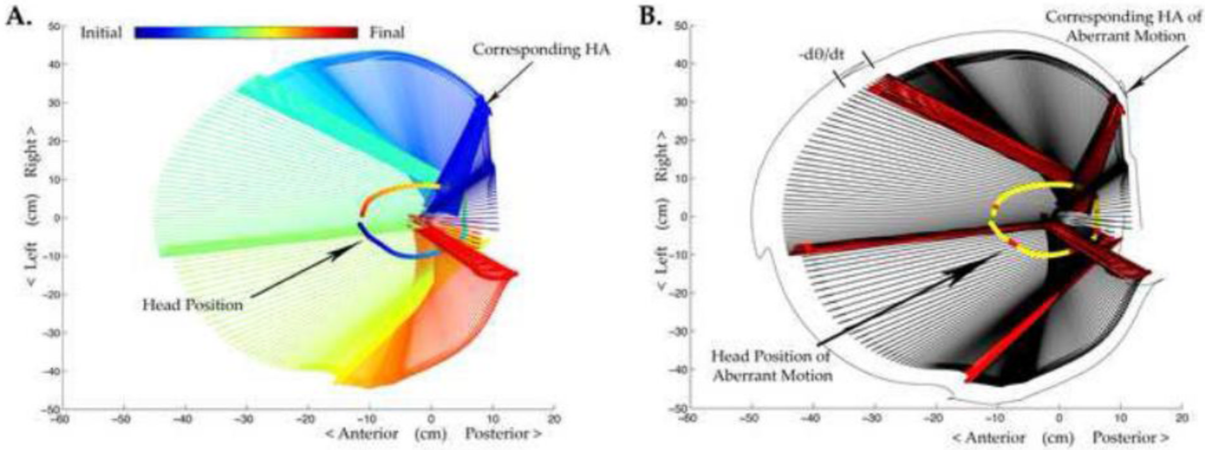

Figure 2. Quantification of Aberrant Motion

(A) Instantaneous Helical Axes and corresponding head position (blue to red) during the circumduction activity of symptomatic subject. **(B)** Isolation of aberrant motion (red) and corresponding head position. Folds were defined when the numerical derivative of theta, which is the azimuthal angle of the vector tips, was negative. Indicating where the IHA folds back upon itself.

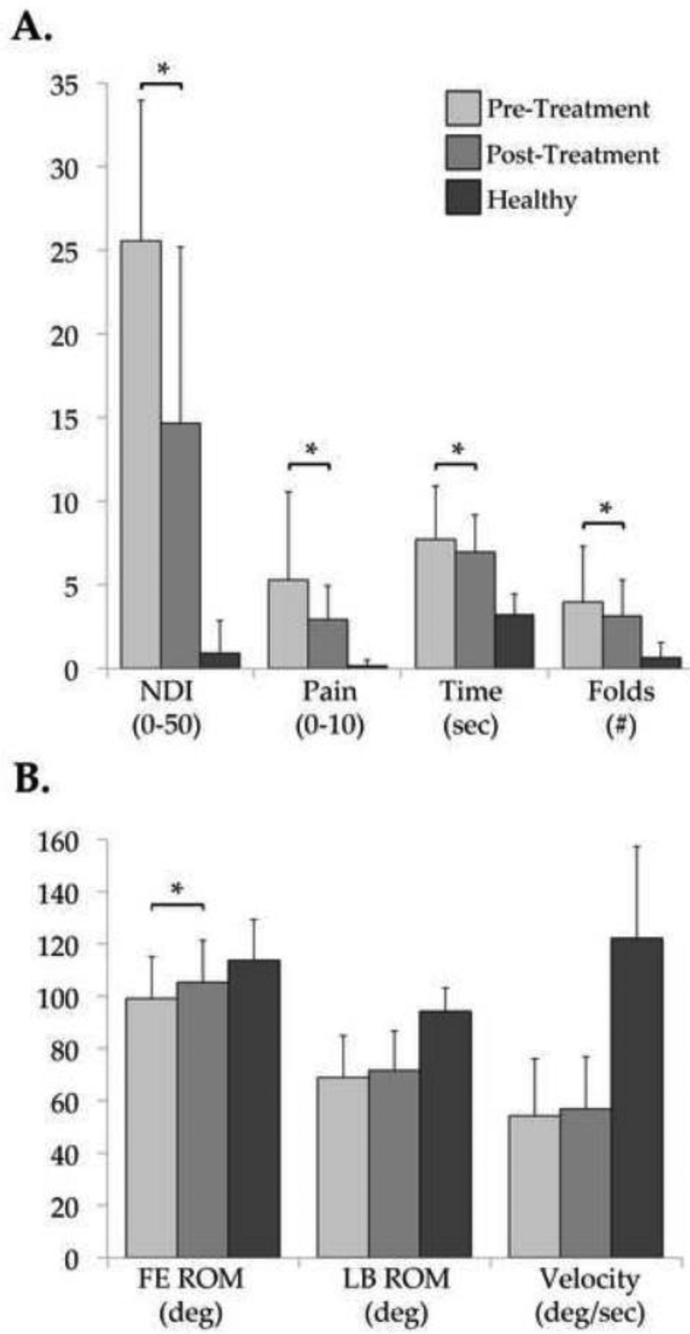

Figure 3. Summary Plots of Output Variables

Comparisons between the symptomatic group (n=81) before and following a treatment. Significant differences between pre and post-treatment groups assessed with paired t-test, * p<0.021.

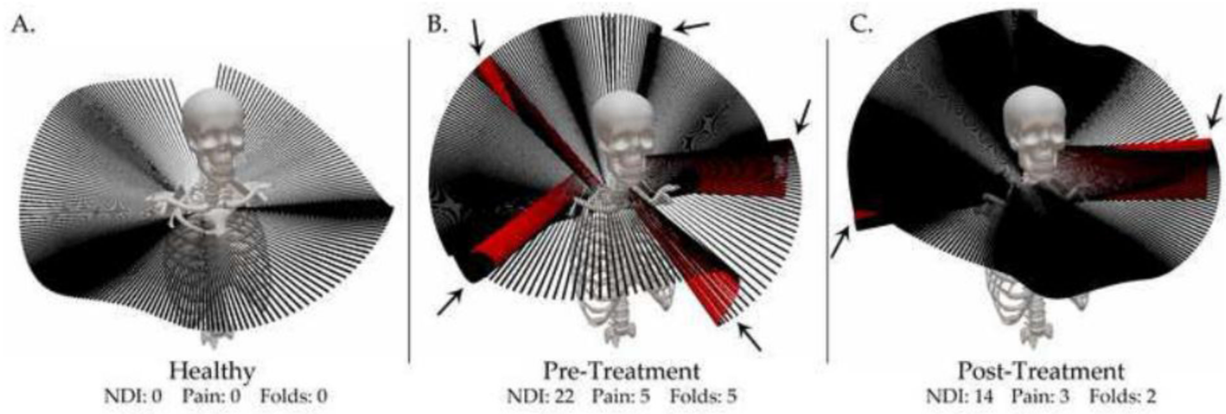

Figure 4. Representative Helical Axis Data of Healthy, Pre, and Post-Treatment overlaid on Skeleton with Arrows Identifying Folds

(A) HA vectors from an asymptomatic subject displaying no folds. **(B)** HA vectors from a symptomatic subject pre-treatment displaying 5 folds. **(C)** HA vectors from the same symptomatic subject post-treatment. Folds decreased along with pain and NDI. Videos of each example are available online. Skeletal model based on the work by Vasavada et al. (Vasavada et al., 1998).