Vrije Universiteit Brussel

FACULTEIT GENEESKUNDE EN FARMACIE i.s.m
FACULTEIT LICHAMELIJKE OPVOEDING EN KINESITHERAPIE
Master na Master in Manuele Therapie

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Finite helical axis for the analysis of cervical kinematics: a new approach using Convex Hull and Mean Angle.

Master thesis submitted as partial fulfillment of the Erasmus program of:

Anna Burioli

Academic year 2014 – 2015

Promotor: Prof. Dr. Erik Cattrysse

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ABSTRACT

Background

The finite helical-axes method can be used to describe the three-dimensional in vivo kinematics of the cervical spine. To date there are few attempts to investigate the kinematics in terms of quantity instead of quality.

The FHA approach, using Minimum Convex Hull (CH), Mean Angle (MA) and Path Lenght (PL) could give us values to discriminate between healthy and pathological subjects.

Methods

The Polhemus Liberty system was used as registration system, the data were then imported in a software to calculate the CH, MA e PL. Flexion-extension, lateral bending and rotation movements were analyzed.

Findings

The statistical analysis has shown statistically significant difference between healthy and pathological subjects ($p<0,05$) for each parameter in every kind of movement, except for the mean angle in the flexion-extension movement.

Three subgroups (Acute Neck Pain, Migraine and Non-Specific-Neck Pain-NSNP) were also analyzed and only for migraine and NSNP the difference between healthy and patological subjects was confirmed.

Interpretation

The validation of the FHA approach using CH, MA and PL to discriminate between healthy and pathological subjects could have several implications in the clinical field.

It could become an instrument that quantifies the joint kinematics behaviour and it could be introduced as an outcome measures in rehabilitative program for conditions characterized by movement impairments or it could be used to develop more sophisticated type of cervical prothesis.

Acknoweldegment

First of all I would like to thank Prof. Dr. Erik Cattrysse for being my promoter and for having dedicated me so much time in these four months. He really introduced me in the "research world" and after every conversation I felt a better professionist. He really surprised me for his patience and kindness in listening to my constant doubts and questions. I really can't explain how thankful I am for having the opportunity to live this experience.

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1.Introduction

In the last decade, the study of intra-articular kinematics has gained an orthopaedic interest In the context of joints' support or replacement, a clinical and ergonomic interest in comparing normal movements with pathological movements and an interest in understanding specific manual therapeutic mobilization/manipulation techniques (Baeyens et al.,2015). The studies that consider the analysis of joint kinematics should be objective and repeatable, in order to allow within- and between-subject comparisons, and this necessitates unambiguous, quantitative descriptions of joint movement (Woltring et al.,1985). For this reason, the biomechanics literature is replete with publications on planar and three-dimensional joint kinematics (Panjabi 1979,1982; Soudan et al., 1978; Bryant et al., 1984.).

For many years intra-articular joint kinematics has been described hypothetically in terms of the convex concave principle (Kaltenborn and Evjenth 1989, Mink et al. 1990, Mangus et al. 2002). However the applicability of the concept to all joints and all conditions has been questioned (Baeyens et al. 2000). As joint surfaces show large inter-individual variation, motions may also differ. Modern arthrokinematic research provides ways to analyse the two combined motions and associated translations three dimensionally by a six-degrees of-freedom analysis. These researches commonly involve analysis of rigid body dynamics. Discrete points (attached markers) define these rigid bodies. Popular measurement techniques includes ultrasonic digitizers, cine-photogrammetry, roentgen stereophotogrammetry and electromagnetic systems (Ohberg et al., 2008). For in vitro experiments, usually three angles are reported, typically Euler-Cardan angles or projection angles.

In this context, in 1992 the International Society of Biomechanics Standardization and Terminology Committee distributed a draft Recommendation for Standardization of Reportings of Kinematics (van der Helm and Dapena 1994). Although the description of motion in terms of Euler-Cardan or helical angles may be kinematically complete, therapeutic interpretation of the results may be difficult. The respective predefined axes mostly do not reflect the actual rotary axes of the joint. Furthermore, variations in the localization of the axes reduce the reproducibility of results and may lead to an over or underestimation of angle values, called "crosstalk effect" (Chao, 1980). For this reason, the Euler angles often require a predefined anatomical coordinate system according to the joint they describe and the three angles are sequence dependent. This problem is most evident in the case of large, coupled vertebral motions. Nowadays it is possible to evaluate the mobility of joints in vivo, with different motion capturing techniques. Among different parameters used for the analysis of joint movements, such as range of motion, angular velocity and jerkiness, Woltring (Woltrint et., al 1984) introduced the use of instantaneous helical axis (IHA) of rotation of a body segment with respect to the other. Most studies exploring the IHA tend to produce good qualitative results, but quantitative results are often lacking (Blankevoort et al., 1990; Baillargeon and Anderst, 2013). Graphical representations of the IHA have been used in many different studies and add to an easier interpretation. The location of the knee axis of motion has been extensively discussed from a clinical and orthopedic point of view (Asano et al., 2005; Mannel et al., 2004a,b; Marin et al., 2003; Sheehan, 2007; Van Sint Jan et al., 2002; Wismans et al., 1980; Woltring et al., 1985). Spine motion analysis using the IHA has shown to provide a useful method for the analysis of complex segmental and regional 3D-motions (Cripton et al., 2001; Dugailly et al., 2010; Kettler et al., 2004; Milne, 1993). To date there is no attempt to describe the localization of a group of IHA in space during a movement without the need for a 3D reconstruction of the bones of the joint. Since the helical axis is a differential quantity (measuring an infinitely small change in a variable), most users have approximated the IHA with the so called finite helical axis (FHA) which is estimated from a single finite displacement (Blankevoort et al., 1990), so the movements are analyzed in discrete steps. One can prove (Goldstein, 1970) there is an axis—the so-called “screw axis” or “instant axis”—such that the whole motion of a body in each moment can be described as a combination of a single translation along that axis, combiend with a single rotation around this axis. If the instant axis in each moment is defined (place and direction) together with the translation and the angular velocity, then the whole body motion is known, and the velocities of all points of the body can easily be computed.

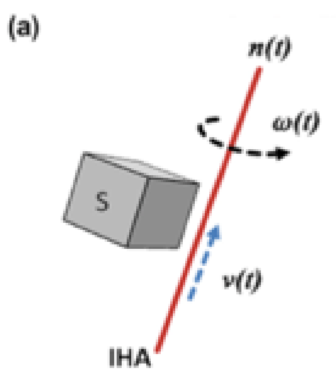

Fig.1 Representation of the instantaneous helical axis (IHA) of an object with an instantaneous angular velocity x(t) and linear velocity v(t). The inclination of the IHA is represented by vector n(t). (Cescon et al.,2013)

A new approach using the FHA was introduced by Cescon (Cescon et al., 2013). For each joint movement, the neutral position and the extreme position (flexion, extension, axial rotation, lateral bending) were identified and the FHA between the two of them was computed (FHA0). A number of planes perpendicular to FHA0 were defined and equally spaced along it. Each movement was divided in two phases (neutral to extreme and extreme to neutral) and each phase was equally divided in steps at a defined angle. For each of the movement steps the FHAi was identified and the intersections of each FHAi with each of the defined planes, were identified (Cescon et al., 2013).

Two “new” parameters were used to evaluate the features of the cervical kinematics. One is called Convex Hull (CH) and is the area through which all the axis pass at a specific section plane. We can then search and identify the section plane in which this area has the minimum value, finding the Minimum Convex Hull Area (cm²) that characterizes that movement. Therefore for each of the planes perpendicular to the FHA0 the intersection points of the FHAi were analyzed with the CH technique and the minimum area was identified (Cescon et al.,2013). The other “tool” that we have is the Mean FHA Angle (°) (MA) that is the mean value of the distribution of the angle between the FHA0 and each of the FHAi .

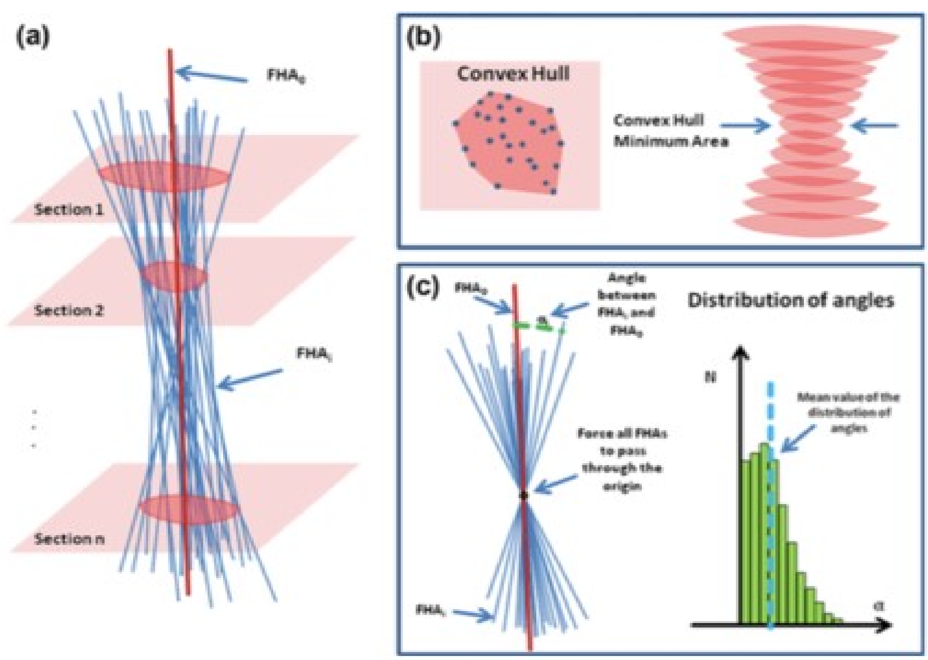

Fig.2 (a) Representation of the instantaneous helical axis during head rotation. FHA0 is the axis between neutral position and extreme position. Sections 1, 2, . . . n represent planes perpendicular to the mean axis and equally spaced (20 mm between adjacent planes). For each plane, the convex hull of the intersection of the helical axes (FHAi) was computed. (b) graphical representation of convex hull for a plane and identification of the convex hull with minimum area. (c) Distribution of angles between each FHAi and FHA0 (Cescon et al., 2013).

The angle step that seem to provide a good compromise between movement analysis resolution and error in the FHA parameters estimation was determined to be 10 degrees, in agreement with the results of the previous studies on cervical and knee joints (Cescon et al, 2013, Westphal et al., 2013). The selection of the optimal angle step is important when applying the use of FHA in clinical practice (for example for the analysis of cervical or knee kinematics) because a clinician could be interested in small variation of the axis behavior in a specific part of the motion or simply could be interested in observing the general behavior of a joint before and after a surgical intervention or con- servative treatment. The errors in the estimation of FHA strongly depend on the choice of angles, thus the noise level should always be considered when interpreting the results.

The aim of this study is to investigate the differences in the quantitative features of the cervical movements between healthy and pathological subjects, using the CH, MA and Path Lenght.

2. Methods

2.1 Measuring tool

The Polhemus Liberty system was used as registration system. (Polhemus Liberty, Colchester Vermont, USA). This is a three dimensional electromagnetic tracking device with a sampling frequency of 240 Hz. An electromagnetic field emitted by the source unit (central transmitter) is detected by two sensors to recognize their position and orientation in three dimensions. One sensor is attached on the frontal part of the head by means of a Velcro strap and the other on the sternum fixed by double sided tape. A third stylus sensor is used to mark seven bony landmarks in order to construct two referential frames using the most lateral parts of the right and left acromion, the deepest point of the fossa jugularis, the most caudal point of the right and left mastoid process and the protuberatia occipitalis externa. All data were stored on a computer as a TMOT file and on a external disc by another observer.

Use was made of the Polhemus interface software (PI Tracker management GUI © 2007-210 Alken inc. dba Colchester VT 05446 USA, PoMgr version 2.7.0. build 2.7.0 in a windows 7 environment (Guo, et al., 2012; Koerhuis, et al., 2003; Cattrysse, et al., 2012).

According to the literature a two sensor electromagnetic sensor registration has been found to have sufficient reliability and validity. (Koerhuis, et al., 2003; Gelais, et al., 2009; Audette, et al., 2010) .

Procedures

A standard protocol was used for instructions by one and the same observer. All subjects were seated in an upright position on a wooden chair with armrests with no metal parts. The central transmitter was placed in front of the subject on sternum level at a distance of 60 cm on a wooden table without any metal parts nearby. At first the reference frames were registered with the stylus. All subjects performed five movements. The participants were asked to execute the movements smoothly and comfortably with eyes open and without moving their shoulders and in a fixed sequence. Starting in neutral position, maximal rotation to the left and to the right, maximal lateral bending to the left and to the right, maximal flexion and extension. Each movement was executed three times and the same sequence was repeated three times. This resulted in fifteen recordings.

The first sequence was used as an assimilation trial (and secondary back-up), the second for data registration and the last sequence served as the primary back-up.

2.2 Data Analysis

The data were transposed to a .TXT file. Those data were then analyzed using a specific Mathlab routine to calculate the Minimum Convex Hull, the Mean Angle and the Path Lenght for every movement of every patient.

The Mathlab routine also provides a reproduction of the head's movement and it gives the possibility to define the section plane through which the FHAs are closer (fig. 3).

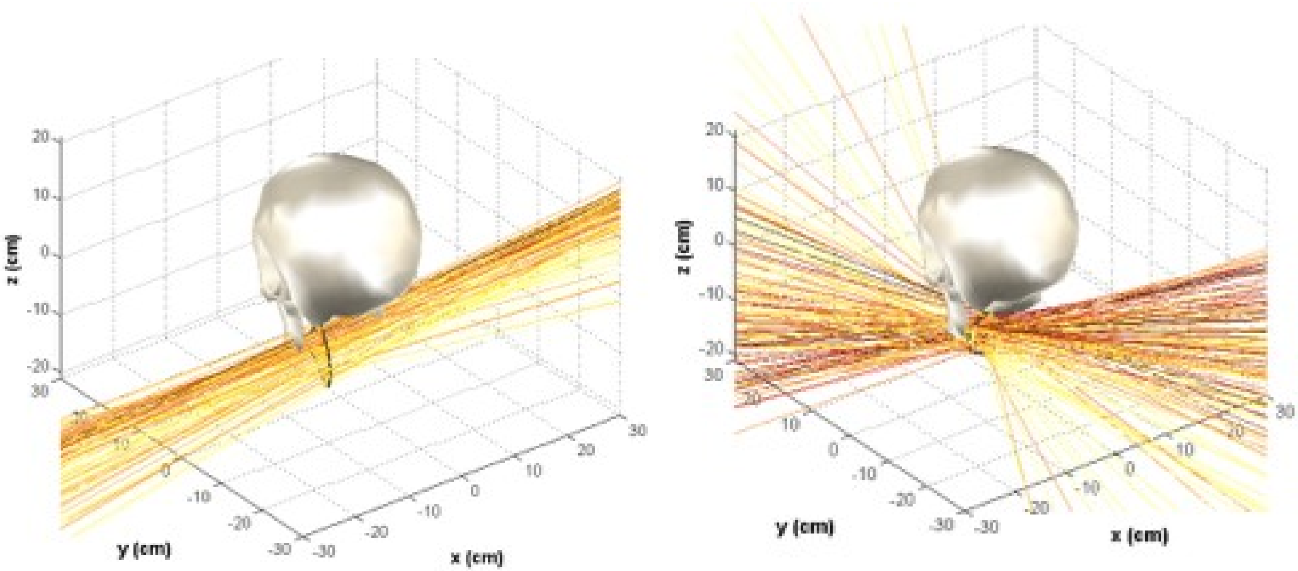

Fig.3 Representation of the movements of the head around the Euler axis: flexion extension and lateral bending.

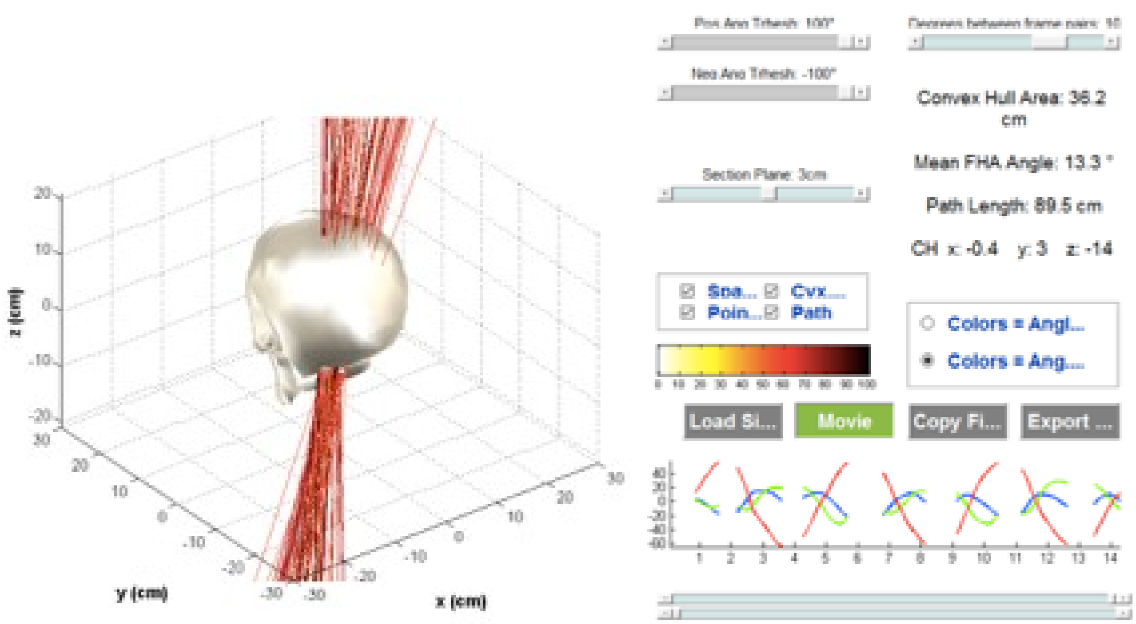

Fig.4 On the left the Representation of the movements of the head around the Euler axis of rotation, on the right the interface of the software used to compute CH, MA and PL.

At this point the results were exported in csv files that were then organized in Microsoft excel 2010 and stored as xls files.

Table 1. Final data set

	Flexion/Extension	Lateral bending (right-left)	Rotation	Total
Controls	379	468	483	1330
Patients	128	143	146	417
Total	507	611	629	**1747**

This table doesn't show the number of the patients but the number of the singular movement analyzed. In fact for some patients we were able to analyzed only 1 or 2 of the movements. The total movements analyzed are therefore 1747.

The results spread sheet was further exported and processed in IBM SPSS statistics version 23 (SPSS).

The Kolmogorov-Smirnov test was used for checking normality of the data distribution. Pearson/Spearman coefficients was calculated for correlation between age and CH, MA e PL and between gender and CH, MA e PL.

Since no variable was normally distributed, non-parametric testing was chosen.

Differences between and within groups (control and non-specific neck pain group) were analysed using the independent Mann-Whitney U test for non parametric data and analyses of covariance. Significance was determined at $p < 0.05$.

To investigate the potential correlation between the three parameters and the age and gender we used a Spearman's rho coefficient for testing the age (Table 2) and the gender (Table 3). The results are the following:

Table 2. Correlation between Age and Parameters.

AGE CORRELATION	PATH LENGHT	MINIMUM CONVEX HULL	MEAN ANGLE
FE CONTROL	-0,332** coeff 0,000 sig	-0,284** coeff 0,000 sig	-0,061 coeff 0,369 sig
FE PATIENTS	0,308* coeff 0,016 sig	0,215 coeff 0,097 sig	0,236 coeff 0,067 sig
LB CONTROL	0,211** coeff 0,001 sig	0,091 coeff 0,142 sig	0,242** coeff 0,000 sig
LB PATIENTS	0,199 coeff 0,096 sig	0,245 ** coeff 0,039 sig	0,352** coeff 0,003 sig
ROT CONTROL	0,161** coeff 0,003 sig	0,123* coeff 0,024 sig	0,126*coeff 0,021 sig
ROT PATIENTS	0,205 coeff 0,085 sig	0,285* coeff 0,015 sig	0,148 coeff 0,214 sig

**Correlation is significant at the 0.01 level (2-tailed). Spearman's rho coefficient.

*Correlation is significant at the 0.05 level (2-tailed). Spearman's rho coefficient.

FE = Flexion-extension movement

LB= Lateral bending movement

ROT= Rotation Movement

Coeff= Spearman's rho coefficient

Sig= Level of significance

Table 3. Correlation between Gender and Parameters.

GENDER CORRELATIONS	PATH LENGHT	MINIMUM CONVEX HULL	MEAN ANGLE
FE CONTROL	-0,097 coeff 0,152 sig	-0,137* coeff 0,043 sig	-0,035 coeff 0,611 sig
FE PATIENTS	-0,247 coeff 0,053 sig	-0,241 coeff 0,059 sig	0,354** coeff 0,005 sig
LB CONTROL	0,066 coeff 0,281 sig	0,051 coeff 0,401 sig	0,052 coeff 0,392 sig
LB PATIENTS	0,205 coeff 0,092 sig	0,333** coeff 0,005 sig	0,134 coeff 0,271 sig
ROT CONTROL	0,119 coeff 0,052 sig	0,151* coeff 0,013 sig	0,114 coeff 0,062 sig
ROT PATIENTS	0,013 coeff 0,918 sig	0,052 coeff 0,671sig	-0,176 coeff 0,144 sig

**Correlation is significant at the 0.01 level (2-tailed). Spearman's rho coefficient.

*Correlation is significant at the 0.05 level (2-tailed). Spearman's rho coefficient.

FE = Flexion-extension movement

LB= Lateral bending movement

ROT= Rotation Movement

Coeff= Spearman's rho coefficient

Sig= Level of significance

The analysis didn't reveal any correlation between age and gender or, if there was, the significance was very small.
For this reason we decided to keep all the data that we had, including the ones for which we didn't have informations about age and gender.
Differences between and within groups (control and non-specific neck pain group) were analyzed using the independent Mann-Whitney U test for non parametric data and analyses of covariance. Significance was determined at $p < 0.05$.
For each group we also reported a descriptive analysis of the three parameters.

3.Results

3.1 Flexion-Extension movement

Table 4. Descriptive analysis of Control Subjects in the FE movement

CONTROLS (N=379)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	15,8	554,2	227,371	91,7973
MINIMUM CONVEX HULL	10,1	1579,5	273,670	216,2725
MEAN ANGLE	1,6	9,4	3,345	0,9371

Table 5. Descriptive analysis of Patient Subjects in the FE movement

PATIENTS (N=128)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	45,9	458,5	**187,127*** (0,000)	72,9010
MINIMUM CONVEX HULL	13,8	917,3	**208,597*** (0,001)	149,9469
MEAN ANGLE	1,7	5,2	3,302 (0,926)	0,7624

*is significant (<0,05). Mann-Whitney U test between Controls and Patients. Between brackets the level of significance.

As we can see from Table 4 and Table 5 there's a statistically significant difference between the means as concern PL (sig: 0,000) and CH (sig:0,001). It appears in fact that the Path Lenght and the Convex Hull have a larger value in the Controls group. Even the Mean Angle is larger by comparing the means, but the difference is not statistically significant.

Table 6. Descriptive analysis of Acute Subgroup for the Flexion-Extension movement

ACUTE (21)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	99,1	458,5	217,881	94,8693
MINIMUM CONVEX HULL	60,5	917,3	284,205	212,7378
MEAN ANGLE	2,3	4,5	3,043	0,5671

Table 7. Descriptive analysis of Migraine Subgroup for the Flexion-Extension movement

MIGRAINE (61)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	64,2	326,1	178,579	54,6411
MINIMUM CONVEX HULL	26,2	499,5	174,018	80,2768
MEAN ANGLE	1,9	5,1	3,395	0,7568

Table 8. Descriptive analysis of NSNP Subgroup for the Flexion-Extension movement

NSNP (46)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	45,9	361,8	184,422	80,4362
MINIMUM CONVEX HULL	13,8	884,4	219,935	174,1499
MEAN ANGLE	1,7	5,2	3,296	0,8311

In the Tables 6,7 and 8 are reported the descriptive analysis of the three subgroups as concern the Flexion-extension movement: Acute Neck Pain patients, Migraine patients and NSNP patients. We compared the parameters of each of these groups with the controls group. In the Table 9 are reported the results of the comparison:

Table 9. Levels of significance between controls group and subgroups in the Flexion movement

SIG	ACUTE	MIGRAINE	NSNP
PATH LENGHT	0,329	**0,000***	**0,006***
MINIMUM CONVEX HULL	0,826	**0,000***	0,120
MEAN ANGLE	0,88	0,356	0,894

*is significant (<0,05). Mann-Whitney U test.

From the statistical analysis only PL and CH from the Migraine group and PL from the NSNP group present statistically significant difference between the means.

For all the results that didn't report a statistically significant difference, a power analysis was performed. The results are reported in the Addendum.

3.2 Lateral bending movement

Table 10. Descriptive analysis of Controls group for the Lateral bending movement

CONTROLS (468)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	11,3	918,9	206,756	101,5361
MINIMUM CONVEX HULL	10,1	1116,5	259,065	199,6234
MEAN ANGLE	2,7	81,8	10,554	7,2108

Table 11. Descriptive analysis of Patients group for the Lateral bending movement

PATIENTS (143)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	36,2	587,4	**172,364*** (0,000)	80,3576
MINIMUM CONVEX HULL	8,4	985,5	**217,89*** (0,014)	177,9171
MEAN ANGLE	1,1	70,8	**9,812*** (0,012)	7,0517

*is significant (<0,05). Mann-Whitney U test between Controls and Patients. Between brackets the level of significance.

As we can see from Table 10 and Table 11 there's a statistically significant difference between the means as concern PL (sig: 0,000), CH (sig:0,014) and MA (sig: 0,012). It appears in fact that the Path Lengh, the Convex Hull and the Mean Angle have a larger value in the Controls group. The trend is really similar to the Flexion-extension movement.

Table 12. Descriptive analysis of Acute Subgroup for the Lateral bending movement

ACUTE (23)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	90,1	587,4	212,013	116,9003
MINIMUM CONVEX HULL	54,4	969,2	295,013	252,6547
MEAN ANGLE	5,3	40,7	11,643	8,0330

Table 13. Descriptive analysis of Migraine Subgroup for the Lateral bending movement

MIGRAINE (65)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	37,2	324,4	164,428	55,8721
MINIMUM CONVEX HULL	42,9	651,4	207,918	123,0238
MEAN ANGLE	4,3	22,4	8,514	3,2363

Table 14. Descriptive analysis of NSNP Subgroup for the Lateral bending movement

NSNP (55)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	36,2	394,5	164,902	83,1327
MINIMUM CONVEX HULL	8,4	985,5	197,424	190,3042
MEAN ANGLE	1,1	70,8	10,581	9,3807

In the Tables 12,13 and 14 are reported the descriptive analysis of the three subgroups concerning the Lateral bending movement: Acute Neck Pain patients, Migraine patients and NSNP patients. We compared the parameters of each of these groups with the controls group. In the Table 15 are reported the results of the comparison:

Table 15. Levels of significance between controls group and subgroups in the Lateral bending movement

SIG	ACUTE	MIGRAINE	NSNP
PATH LENGHT	0,779	**0,000***	**0,002***
MINIMUM CONVEX HULL	0,694	0,136	**0,003***
MEAN ANGLE	0,889	**0,001***	0,386

*is significant (<0,05). Mann-Whitney U test.

From the statistical analysis only PL and MA from the Migraine group and PL and CH from the NSNP group present statistically significant difference between the means.
For all the results that didn't report a statistically significant difference, a power analysis was performed. The results are reported in the Addendum.

3.3 Rotation Movement

Table 16. Descriptive analysis of Controls group for the Rotation movement

CONTROLS (483)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	7,5	908,2	120,180	66,2581
MINIMUM CONVEX HULL	3,1	944,2	110,141	105,4265
MEAN ANGLE	1,1	16,2	4,760	1,7607

Table 17. Descriptive analysis of Patients group for the Rotation movement

PATIENTS (146)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	25,5	343,3	**95,914*** (0,000)	47,5257
MINIMUM CONVEX HULL	5,0	236,3	**73,953*** (0,000)	48,4933
MEAN ANGLE	2,2	8,6	**4,208*** (0,001)	1,1284

*is significant (<0,05). Mann-Whitney U test between Controls and Patients. Between brackets the level of significance.

As we can see from Table 10 and Table 11 there's a statistically significant difference between the means as concern PL (sig: 0,000), CH (sig:0,000) and MA (sig: 0,001). It appears in fact that the Path Lengh, the Convex Hull and the Mean Angle have a larger value in the Controls group. These results are congruent with the ones reported for the Flexion-extension and Lateral bending movement.

Table 18. Descriptive analysis of Acute Subgroup for the Rotation movement

ACUTE (24)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	49,2	170,5	98,075	29,4361
MINIMUM CONVEX HULL	23,7	169,4	80,225	36,5561
MEAN ANGLE	2,3	8,0	4,233	1,3097

Table 19. Descriptive analysis of Migraine Subgroup for the Rotation movement

MIGRAINE (66)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	37,1	343,326	91,326	47,5776
MINIMUM CONVEX HULL	27,8	236,3	76,941	47,3199
MEAN ANGLE	2,6	6,7	4,141	1,0035

Table 20.Descriptive analysis of NSNP Subgroup for the Rotation movement

NSNP (56)	MINIMUM	MAXIMUM	MEAN	SD
PATH LENGHT	25,5	241,2	100,395	53,5720
MINIMUM CONVEX HULL	5,0	217,7	67,743	54,1054
MEAN ANGLE	2,2	8,6	4,275	1,1997

In the Tables 18,19 and 20 are reported the descriptive analysis of the three subgroups concerning the Rotation movement: Acute Neck Pain patients, Migraine patients and NSNP patients. We compared the parameters of each of these groups with the controls group. In the Table 21 are reported the results of the comparison:

Table 21. Levels of significance between controls group and subgroups in the Rotation movement

SIG	ACUTE	MIGRAINE	NSNP
PATH LENGHT	0,067	**0,000***	**0,012***
MINIMUM CONVEX HULL	0,232	**0,002***	**0,000***
MEAN ANGLE	0,123	**0,008***	0,087

*is significant (<0,05). Mann-Whitney U test.

From the statistical analysis only PL, CH and MA from the Migraine group and PL and CH from the NSNP group present statistically significant difference between the means.
For all the results that didn't report a statistically significant difference, a power analysis was performed. The results are reported in the Addendum.

The results show that there is a statistically significant difference between controls and patients except for the Mean Angle in the Flexion-Extension movement.
For every comparison the Controls group appeared to have a larger value for each of the three parameters:

Table 22. Summary of the levels of significance

SIG	FLEXION-EXTENSION	LATERAL BENDING	ROTATION
PATH LENGHT	**0,000**	**0,000**	**0,000**
MINIMUM CONVEX HULL	**0,001**	**0,014**	**0,000**
MEAN ANGLE	0,926	**0,012**	**0,001**

4 Discussion

The finite helical axes method can be used to describe the three-dimensional in vitro kinematics of the spine. However, this method still suffers from large stochastic calculation errors and poorly conceived visualisation techniques. The aim of this study was to investigate if there was a quantitative parameter to compare healthy and pathological subjects. Therefore the CH, the MA and the Path Lenght were analyzed to estimate their applicability to differentiate.

The results show that there is a difference between the controls group and the patients group. Referring to the means, in every comparison the controls group showed a larger value of CH and PL and a more spread MA (see Table 4-5 for the FE, 10-11 for the LB,16-17 for the ROT).

The only parameter that doesn't seem to differ between patients and controls is the Mean Angle in the flexion-extension movement. This could be due to various factors.

Analyzing all the data it appeared that flexion-extension movement was often not readable from the computation software due to bugs so we had to eliminate various subjects from the research. Moreover the movement presented high variability, and therefore we argue that it would be preferrable to have a stricter experimental protocol for the examiners.

The fact that the data were collected by several different physical therapists and the results are statistically different shows a sort of inter-examiner applicability, but at the same time the results would have been more accurate and evident if the registration protocol had been controlled in a stricter way between operators.

Possibly for the same reason the results of the comparison between groups are not so congruent.

That could be also because of the big difference in the number of subjects between the samples, hence we decided to perform a power analysis, reported in the Addendum, in case the difference was just to small to be seen. This test showed that there were very high values of Beta both in the flexion-extension and lateral bending groups. So it could be that for these groups (see the Addendum) the difference was simply too small, probably because of the difference between the samples size.

In summary these results are congruent with the results from other previous studies.

In his study Kettler (Kettler et al., 2004) wanted to improve the used finite helical axes description, by use of a less error-prone calculation algorithm and a new visualisation technique, and to apply this improved method to the study of the three-dimensional in vitro kinematics of the spine. He used a three-dimensional, continuous motion data of spinal motion segments to calculate the position and orientation of the finite helical axes (FHAs). This method was used to demonstrate the ability of a prosthetic disc nucleus to restore the three-dimensional motion pattern of lumbar motion segments. Nucleotomy of the lumbar segments caused the axes to spread out, indicating complex coupled motions. The implantation of the prosthetic disc nucleus, reversed the effect, for the most part: the axes became oriented almost parallel to each other (Kettler et al 2004).

In the following years most of the studies dealt with the analysis of the direction and the orientation of the FHA.

In 2008 Schmidt (Schmidt et al.,2008) wanted to investigate the interaction between the FHA and the facet joints loads under combined loading and the study has shown that high facet forces might direct the FHAs to migrate posteriorly, especially for axial rotation (in the lumber spine). Thus that author suggested that patients immediately after surgery or patients with facet joint arthritis should reduce or avoid axial rotation, both alone or in combination with other load applications. The same year Grip (Grip et al., 2008) investigated the cervical helical axis and its center of rotation during fast head movements (side rotation and flexion/extension) and ball catching in patients with non-specific neck pain or pain due to whiplash injury as compared with matched controls. Various authors also wondered how surgery and more specifically disc prothesis or stabilization could alter the spinal cinematic. Once again the studies were conducted in terms of quality of the movement and not quantity. Zander in 2009 showed that, after the insertion of an artificial disc in the lumbar spine, the positions of the helical axes are altered, especially as far as lateral bending and axial torsion are concerned (Zander 2009). These findings were confirmed by more recent studies that use both IHA and FHA. In the cervical spine the IHA-direction was found to be rotated backwards and largely independent of the rotational angle, amount of axial pre-load, size of pre- torque, and Total Disk Arthroplasty (TDA) (Wachowsky et al., 2013). FHA analysis was also used to characterize the motion path of the instant center of rotation (ICR) at each cervical motion segment from C2 to C7 during dynamic flexion-extension in asymptomatic subjects and to compare ICR paths in asymptomatic subjects with patients with single-level arthrodesis. It appeared that symptomatic and arthrodesis groups were not significantly different in terms of average ICR position or in terms of the change in ICR location per degree of flexion-extension (Anderst et al.,2013).

Furthermore FHA has been used to analyze physiological movement and coupled patterns (Salem, 2013).

Ellingson in 2013 examined a complex neck kinematic activity of neck circumduction, computed the pathway of motion using the instantaneous helical axis approach to quantify the aberrant motions in pathological subjects. The findings showed that after the treatment the number of aberrant motion was reduced but even if this method quantify the conditions pre and post treatment, is not comparable with the approach used in this study. It may seem that the results are in contrast with the ones from this study because less aberrant movements may make people think that the cervical spine is more stable, but in reality the parameters taken in account are to different to be compared.

Range of motion, angular displacement, velocity, and acceleration of the three defined regions, and movement coordination between regions were used to determine and to compare spinal kinematics between neck pain and healthy subjects (Tsang et al.,2013) Assessment of the range of motion of the neck is not sufficient to reveal movement dysfunctions in chronic neck pain subjects. Significant differences between the two subject groups were only found in differential kinematics (angular velocity and acceleration) and movement coordination, but not in spatial kinematics (angular displacement). The differential kinematics of the cervical spine was found to be significantly lower in all three movement planes in the neck pain group compared with the control subjects (Tsang et al.,2013). ROM and jerkiness had already been used to compare healthy and injuried subjects (Cattrysse et al.,2011). In that previous study the patients had fusion surgery, results comparing the experimental group with the control group reveals that the range of the main motion component differs significantl. The root mean square value of the jerkiness (derivative of the acceleration) and deviation from the 6-polynomial smoothed function of the main as well as the coupled motion component express the qualitative aspects of kinematics and are significantly different between the experimental and the control group.

These studies show that quantitaves methods to analyze cervical kinematics had already been conducted but they are not comparable with the parameters used in this study.

It could be possible to related velocity to CH, MA and PL to see if the results are comparable with the ones from the two studies mentioned before.

In the 2013 the first studies concerning the use of the CH and the MA were conducted. At first, the aim of the studies was to introduce a novel approach for the quantification of the FHA behavior and to investigate the effect of noise and angle intervals on the estimation of FHA parameters (Cescon et al.,2013). Then authors started to try to get closer to the clinical potentional utilizations. A study to compare pre-mobilization and post mobilization FHA features was conducted on two healthy subjects both in terms of quality and quantity (Barbero et al.,2013). It seemed that the position of the FHA pre and post mobilization were almost the same, and the orientation had slightly changed.

Comparing the CH and the MA in the flexion and rotation movements, it appeared that in both patients there was an increase of the dispersion of the FHA and of the variation in the mean angle (Barbero et al., 2013).

Another study from Barbero (Barbero et al., 2014) investigated the arthrokinematics of the cervical spine after disc prosthesis and the results were that the ROM was significantly smaller in patients with prothesis, convex hull area is slightly smaller in patients with prothesis and mean angle deviation are slightly lower in patients with prothesis. So once again it seems that after disc prothesis insertion, the cervical spine became more stable (as in Kettler in vitro study). The latest studies concerning the features of the analysis of FHAs aim to shrink the gap between research and clinical practice. The challenge is now to understand if this approach can be used by clinicians as a new non-invasive tool in order to analyze both qualitatively and quantitatively joint motion. The studies on the subject are still analyzing only healthy subjects and refining the FHA analysis (Cescon et al, 2014) eventually including new ways of treating the data, like the alpha shape (McLachlin et al.,2016).

Alpha shape is a computational geometric technique used to envelop a finite set of points within a series of curves. Similar to a convex hull, these geometric shapes can be thought of as an elastic band surrounding a set of points. In the study McLachlin (McLachlin et al.,2016) compared in vitro healthy and injuried specimens and found out that ROM between the intact and injured states increased for all three simulated movements. However this injury model consisted of surgically sectioning both facet capsules, three-quarters of the annulus, and half of the ligamentum flavum, followed by rotating the disrupted specimen to the perched position. Obviously this is not the type of conditions that it was tested in these in vivo subjects, in which the anatomical structures could neither be traumatized nor taken apart.

It could be interesting to compare this methodology with the CH but on in vivo populations with specific pathologies.

So far, it seems that the cervical spine needs a certain amount of “instability” and that this spreading in the FHAs and MA is related to the health of the cervical spine.

If FHA behavior will be confirmed to discriminate between healthy and pathological subjects, CH and mean angle may be introduced as outcome measures in rehabilitative program for conditions characterized by movement impairments (i.e. musculoskeletal and neu- rological conditions). The same approach can also be suggested to test and improve athlete performance during specific tasks or for having a proper real time graphical representation of the FHA in the biofeedback for both healthy and pathological subjects.

Moreover, as done in Barbero studies (Barbero et al.,2014), the results of different treatment methodologies or the capacity of reproducing the physiological movement of the different type of prothesis could be investigated.

In the future studies it would be also interesting to take in consideration the patients complains (using the VAS scale or Neck Disability Index), to see if in the same subject the potential difference reported in the CH,MA and PL value after a treatment demonstrate a difference also in pain perception and the quality of life.

4.1 Strenghts and limitations of the study

The limitations of the study were briefly pointed out in the previous chapter. We saw in fact that due to the accuracy needed in the data registration, having more than one examiner could have influenced the study, both positively and negatively.

Having an instrument that allows us to perform accurate measurements without being concerned about inter-examiner realibility is an undeniable advantage: it clearly facilitates longer experimental runs, for one. At the same time, whatever the results with respect to statistical significance, we think that the examiner should check if a registration was somehow disturbed and not suitable for the analysis. For this reason the registrations have to be done in the most accurate way possible and the the examiners must be well trained.

The sensors used in the study are electromagnetic, thus their output depends on the shape of the electromagnetic field generated by the antenna. The electromagnetic field is sensitive to ferromagnetic elements in the room around the transmitter. We noticed that during pure translation of the sensor (of some tenth of centimeters) in any direction there could be an error in the orientation matrix like an apparent rotation due to magnetic field distortions. The possible causes for field distortion are usually neon lights, ferromagnetic fixation systems, electromagnetic fields from electronic equipment.

We also believe that more attention should be payed to the careful explanation and illustration of the three different movements to the patients. It is well known that all movements are 3-dimensional and as such include coupled movements but it’s important to have the patients perform a real lateral bending and not a rotation, while registring a rotation.

Moreover in the future studies we could check if considering only the middle part of the movement (avoiding acceleration and deceleration by the patients), leads to stronger data.

The size of the sample is one clear strength of this study. Until today all previous studies investigated the kinematics features only in very small samples and often only in healthy subjects. In our study also the “patients group” was really large. That implies that even if we found a large variability, this instrument could really be used for the purposes mentioned before and it could have a place in the clinical field.

5 Conclusion

The results of the present study indicate that in the analysis of the cervical kinematics, healthy people differ from pathological subjects in terms of Minimum Convex Hull, Mean Angle and Path lenght.

This new method could allow us to quantify the stability of the movement analyzing the dispersion of the FHA.

It now seems that a certain amount of “instability” or spread in the FHA-behaviour may be necessary is healthy kinematical pattern.

Further studies that investigate the CH, MA and PL can be developed in order to find out if these correlations are strong enough to make this instrument a valid method to discriminate between healthy and pathological subjects by measuring their CH, MA and PL values.

Addendum

FLEXION-EXTENSION MOVEMENT

Hypothesis retained	Sample size	Sig.	Effect Size	Beta (β)	Statistical Power (1-β)
MA PatientsVSControls	507	0,633	0,000	0,076	**0,924**
PL AcuteVSControls	400	0,646	0,001	0,074	**0,926**
CH AcuteVsControls	400	0,828	0,000	0,055	**0,945**
MA AcuteVSControls	400	0,144	0,005	0,309	0,691
MA MigraineVSControls	440	0,694	0,000	0,068	**0,932**
CH NSNPVSControls	425	0,106	0,006	0,366	0,634
MA NSNPVSControls	425	0,731	0,000	0,064	**0,936**

The value in bold font are >0,80.

LATERAL BENDING MOVEMENT

Hypothesis retained	Sample size	Sig.	Effect Size	Beta (β)	Statistical Power (1-β)
PL AcuteVSControls	491	0,810	0,000	0,057	**0,943**
CH AcuteVsControls	491	0,406	0,001	0,132	**0,868**
MA AcuteVSControls	491	0,482	0,001	0,108	**0,892**
CH MigraineVSControls	533	0,034	0,008	0,564	0,436

The value in bold font are >0,80.

ROTATION MOVEMENT

Hypothesis retained	Sample size	Sig.	Effect Size	Beta (β)	Statistical Power (1-β)
PL AcuteVSControls	507	0,105	0,005	0,368	0,632
CH AcuteVsControls	507	0,167	0,004	0,282	0,718
MA AcuteVSControls	507	0,149	0,004	0,303	0,697

The value in bold font are >0,80.

For every hypothesis retained with the Mann-Whitney U analysis, we calculated the statistical power to see the probability of commiting a Type II error in retatining the Null Hypothesis.

The complement of β error, 1- β, is the statistical power of a test. Power is the probability that a test will lead to rejection of the null hypothesis, or the probability of attaining statistical significance. If β=0,20, power=0,80. Therefore, for a statistical test at 80% power, the probability is 80% that we would correctly demonstrate a statistical difference and reject the null hypothesis if actual differences exist.

REFERENCES

1. Anderst W, Baillargeon E, Donaldson W, Lee J, Kang J. Motion path of the instant center of rotation in the cervical spine during in vivo dynamic flexion-extension: implications for artificial disc design and evaluation of motion quality after arthrodesis. Spine. 2013 May 1;38(10):E594–601.

2. Asano T, Akagi M, Nakamura T. The Functional Flexion-Extension Axis of the Knee Corresponds to the Surgical Epicondylar Axis. The Journal of Arthroplasty. 2005 Dec 1;20(8):1060–7.

3. Baeyens J-P, Cattrysse E, Van Roy P, Clarys J-P. Measurement of three-dimensional intra-articular kinematics: methodological and interpretation problems. Ergonomics. 2005 Nov 15;48(11-14):1638–44.

4. Baillargeon E, Anderst WJ. Sensitivity, reliability and accuracy of the instant center of rotation calculation in the cervical spine during in vivo dynamic flexion-extension. J Biomech. 2013 Feb 22;46(4):670–6.

5. Barbero M, Dunning J, Mourad F, Leoni D, Cattrysse E, Cescon C. The Effect of Manual Techniques on Cervical Kinematics. An Innovative Approach using Helical Axis. Book of Abstract of “XI Congresso Nazionale Gruppo di Terapia Manuale « The role of Manipulations in the treatment of Neuromusculoskeletal Disorders» 9-10 Novembre 2013 . Firenze, Hotel Londra”

6. Barbero M, Boscherini D, Cattrysse E, Cescon C. Arthrokinematics of the cervical spine after disc prosthesis. Book of abstract of “CERVICAL SPINE. Applied Anatomy and Biomechanics for Rehabilitation : an interactive cadaver-lab experience. Arezzo 31 January – 1 February 2014.

7. Blankevoort L, Huiskes R, Lange A de. Helical axes of passive knee joint motions. Journal of Biomechanics. 1990 Jan 1;23(12):1219–29.

8. Bryant JT, Wevers HW, Lowe PJ. One parameter model for error in instantaneous centre of rotation measurements. J Biomech 1984;17:317–23.

9. Cattrysse E, Moens M, Schaillée E, D'Haens J, Van Roy P. Changed cervical kinematics after fusion surgery. Eur Spine J. 2012 Jul;21(7):1353-9. doi: 10.1007/s00586-011-2112-z.

10. Cescon C, Cattrysse E, Barbero M. Methodological analysis of finite helical axis behavior in cervical kinematics. J Electromyogr Kinesiol. 2014 Oct;24(5):628–35.

11. Cescon C, Tettamanti A, Barbero M, Gatti R. Finite helical axis for the analysis of joint kinematics: comparison of an electromagnetic and an optical motion capture system

(PDF Download Available) [Internet] August 2015. Available from: https://www.researchgate.net/publication/281230338.

12. Cripton PA, Sati M, Orr TE, Bourquin Y, Dumas GA, Nolte L-P. Animation of in vitro biomechanical tests. Journal of Biomechanics. 2001 Aug 1;34(8):1091–6.

13. Dugailly PM, Sobczak S, Sholukha V, Van Sint Jan S, Salvia P, Feipel V, Rooze M. In vitro 3D-kinematics of the upper cervical spine: helical axis and simulation for axial rotation and flexion extension. Surg Radiol Anat. 2010 Feb;32(2):141-51. doi: 10.1007/s00276-009-0556-1.

14. Ellingson AM, Yelisetti V, Schulz CA, Bronfort G, Downing J, Keefe DF, Nuckley DJ. Instantaneous helical axis methodology to identify aberrant neck motion. Clin Biomech (Bristol, Avon). 2013 Aug;28(7):731-5. doi: 10.1016/j.clinbiomech.2013.07.006.

15. Goldstein, H. (1970) Classical Mechanics, Vol. 7, pp. 93-124. Addison-Wesley, Reading.

16. Grip H, Sundelin G, Gerdle B, Karlsson JS. Cervical helical axis characteristics and its center of rotation during active head and upper arm movements-comparisons of whiplash-associated disorders, non-specific neck pain and asymptomatic individuals. Journal of Biomechanics. 2008 Sep 18;41(13):2799–805.

17. Jan SVS, Salvia P, Hilal I, Sholukha V, Rooze M, Clapworthy G. Registration of 6-DOFs electrogoniometry and CT medical imaging for 3D joint modeling. Journal of Biomechanics. 2002 Nov 1;35(11):1475–84.

18. Kaltenborn F & Evjenth O (1989) Manual mobilization of the extremity joints. Basic examination and treatment techniques. 4 edn. Oslo

19. Kettler A, Marin F, Sattelmayer G, Mohr M, Mannel H, Dürselen L, et al. Finite helical axes of motion are a useful tool to describe the three-dimensional in vitro kinematics of the intact, injured and stabilised spine. Eur Spine J. 2004 Oct;13(6):553–9.

20. Mangus, B.C., Hoffman, L.A., Hoffman, M.A. and Altenburger, P., 2002, Basic principles of extremity joint mobilization using a Kaltenborn approach. Journal of Sport Rehabilitation, 11, 235–250.

21. Mannel H, Marin F, Claes L, Durselen L. Establishment of a knee-joint coordinate system from helical axes analysis-a kinematic approach without anatomical referencing. IEEE Transactions on Biomedical Engineering. 2004 Aug;51(8):1341–7.

22. Marin F, Mannel H, Claes L, Dürselen L. Correction of axis misalignment in the analysis of knee rotations. Hum Mov Sci. 2003 Aug;22(3):285–96.

23. McLachlin SD, Bailey CS, Dunning CE. Use of the alpha shape to quantify finite helical axis dispersion during simulated spine movements. J Biomech. 2016 Jan 4;49(1):112–8.

24. Metzger MF, Faruk Senan NA, O'Reilly OM, Lotz JC. Minimizing errors associated with calculating the location of the helical axis for spinal motions. J Biomech. 2010 Oct 19;43(14):2822–9.

25. Milne N. Composite motion in cervical disc segments. Clinical Biomechanics. 1993 Jul 1;8(4):193–202.

26. Mink, A.J.F., Ter Veer H.J. and Vorselaars, J.A.C.T., 1990, Extremiteiten: Functie-onderzoek en Manuele Therapie (Antwerpen: bohn Stafleu Van Loghum).

27. Ohberg F. The effect of anisotropic systematic errors in estimating helical angles. Comput Methods Biomech Biomed Engin. 2008 Apr;11(2):205-13. doi:10.1080/10255840802298927.

28. Panjabi MM. Centers and angles of rotation of body joints: A study of errors and optimization. Journal of Biomechanics. 1979 Jan 1;12(12):911–20.

29. Panjabi MM, Goel VK, Walter SD, Schick S. Errors in the center of and angle of rotation of a joint: An experimental study. J Biomech Eng 1982;104:232–7.

30. Salem W, Lenders C, Mathieu J, Hermanus N, Klein P. In vivo three-dimensional kinematics of the cervical spine during maximal axial rotation. Man Ther. 2013 Aug;18(4):339–44.

31. Schmidt H, Heuer F, Wilke H-J. Interaction between finite helical axes and facet joint forces under combined loading. Spine. 2008 Dec 1;33(25):2741–8.

32. Sheehan FT. The finite helical axis of the knee joint (a non-invasive in vivo study using fast-PC MRI). Journal of Biomechanics. 2007 Jan 1;40(5):1038–47.

33. Soudan K, Van Audekercke R, Martens M. Methods and difficulties, and inaccuracies in the study of human joint kinematics and pathokinematics by the instant axis concept. J Biomech 1978;12:27–33.

34. Tsang SM, Szeto GP, Lee RY. Movement coordination and differential kinematics of the cervical and thoracic spines in people with chronic neck pain. Clin Biomech (Bristol, Avon). 2013 Jul;28(6):610-7. doi:10.1016/j.clinbiomech.2013.05.009.

35. Van Der Helm, F.C.T. and Dapena, J., 1994, Proposals for definition of joint coordinate system of various joints, International Society of Biomechanics Newsletter, 53, 10 – 13.

36. Westphal CJ, Schmitz A, Reeder SB, Thelen DG. Load-dependent variations in knee kinematics measured with dynamic MRI. Journal of Biomechanics. 2013 Aug 9;46(12):2045–52.

37. Winters JM, Peles JD, Osterbauer PJ, Derickson K, Deboer KF, Fuhr AW. Three-dimensional head axis of rotation during tracking movements. A tool for assessing neck neuromechanical function. Spine. 1993 Jul;18(9):1178–85.

38. Wismans J, Veldpaus F, Janssen J, Huson A, Struben P. A three-dimensional mathematical model of the knee-joint. Journal of Biomechanics. 1980 Jan 1;13(8):681–5.

39. Woltring HJ, Huiskes R, de Lange A, Veldpaus FE. Finite centroid and helical axis estimation from noisy landmark measurements in the study of human joint kinematics. J Biomech. 1985;18(5):379–89.

40. Zander T, Rohlmann A, Bergmann G. Influence of different artificial disc kinematics on spine biomechanics. Clinical Biomechanics. 2009 Feb;24(2):135–42.

41. Wachowski MM, Wagner M, Weiland J, Doerner J, Raab BW, Dathe H, et al. Does total disc arthroplasty in C3/C4-segments change the kinematic features of axial rotation? Journal of Biomechanics. 2013 Jun 21;46(10):1739–45.