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"Facet joint displacement of C1 relative to C2 during a regional manual mobilisation into rotation: a 3D kinematic analysis."

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ABSTRACT

Background

Few studies investigated the kinematics of the upper cervical spine during manual mobilization. Some information regarding rotational movements is available, but also different features such as translational components must be examined to understand the complex inter-vertebral motion. This study aims to describe the amount, trajectories and reliability of atlanto-axial facet joint displacement during regional manual mobilization into rotation.

Methods and materials:

Twenty fresh human cervical specimens were investigated in a test-retest situation. Two manual therapists performed the manual mobilization, while a Zebris CMS20 ultrasound-based motion tracking system was performing a continuous motion registration. The amount and trajectories of C1-C2 displacement along the XYZ components were calculated. Intra and inter-rater reliability were estimated through ICC scores. Differences between the four measurements were evaluated with Friedman two-way ANOVA tests.

Results:

The mean NORM values of displacement were 15mm and 23mm for left and right facet respectively (range 2.58-41.55mm). Descriptive statistics displayed wide ranges and high standard deviations. No statistically significant Friedman two-way ANOVA test was found. ICC reached significance in approximately one third of the comparisons between testers, and in about all the test-retest comparisons for one of the examiners.

Conclusion:

The amount of displacement in the atlanto-axial joint is very variable among subjects. Although physiotherapists produce on average similar magnitude of displacement, this is only partially reproducible and predictable, according to the ICC scores and the trajectory analysis, that showed consistent directions only in the antero-posterior component.

Further research is recommended for a better comprehension of the kinematical mechanism underlying manual therapy manoeuvres.

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LIST OF ABBREVIATIONS

2D: Two dimensional

3D: Three dimensional

C0: Occiput

C1: Atlas

C2: Axis

HVLAT: High velocity low amplitude thrust

ICC: Intra-class correlation coefficient

ISB: International Society of Biomechanics

NORM=Norm vector, algebraic resultant of the XYZ components

p= p value

R1 = Re-Test 1; second test made by Tester 1

R2 = Re-Test 2; second test made by Tester 2

SD: Standard deviation

SPSS: Statistical Package for the Social Service version 24.0

T1 = Test 1; first test made by Tester 1

T2 = Test 2; first test made by Tester 2

UCS: Upper cervical spine

X: Medio-lateral axis

Y: Supero-inferior axis

Z: Antero-posterior axis

1. INTRODUCTION

Neck complaints are a huge problem in rehabilitation, as they are common and related to a high rate of disability and costs (Driessen *et al*., 2012; Hoy *et al*., 2010). Manual therapy is frequently recommended to treat these problems, as it is effective in a multimodal approach (Miller *et al*., 2010) or as a single treatment (Gross *et al*., 2015). The effectiveness of these interventions seems to be attributable to a short-term change in the connective tissue and neurophysiologic effects (Bolton *et al*., 2004), which improves modulation of pain and the motor and sympathetic nervous systems activity (Souvlis *et al*., 2004).

The importance and the growing popularity of cervical spine mobilization led some authors to study the kinematics of cervical spine during different diagnostic or therapeutic manual mobilization procedures. The methodological strategies adopted were both in vivo (Vincenzino *et al*., 1999; Takasaki *et al*., 2011) and in vitro (Cattrysse *et al*., 2011; 2010; 2009; 2008a; 2007a; 2007b).

In their experiments, Vincenzino *et al*. (1999) and Takasaki *et al*. (2011) examined the movement with a 2D approach, aiming at demonstrating the content validity of the assessed manual manoeuvre.

Cattrysse *et al*. (2007a; 2007b) described the intended main motion and non-intended coupled motion during flexion-extension, axial rotation and lateral bending mobilizations of the atlanto-occipital and atlanto-axial joints. Three manual approaches were used: one regional and two segmental mobilizations, using a manual fixation or an inferior cervical spine locking. The kinematic differences found between the techniques confirmed that in a therapeutic context it might be important to choose specific techniques according to the desired effect.

Segmental coupled movements of UCS during manual axial rotation mobilization were investigated in relation to individual features of alar ligaments and morphometry of atlanto-axial joints (Cattrysse *et al*., 2011). The relationship between anatomical and kinematics aspects was analyzed using single and multiple regression techniques. As these parameters were only partially correlated (R^2 values ranged between 0.26 and 0.73), the therapist may play a major role in the final effect of a specific technique.

The reproducibility of coupled movements of the UCS during cervical regional and segmental manual mobilization into rotation techniques was also examined. Cattrysse *et al*. (2009) considered the main axial rotation component and the coupling patterns as a separate entity, while Cattrysse *et al*. (2010) used the Euclidean norm. The Euclidean norm is the root of the sum of the squared values of each separate motion component, and therefore it is a mathematical representation of 3D motion. Interpreting the results of these two studies together it is possible to argue that therapists, even if they are able to reproduce segmental 3D motions, use different coupled components to do so.

Although the amount of motion expressed as rotation around the 3 axis (XYZ) has been assessed, the joint movement analyzed as displacement of the facet joints during mobilization techniques has been poorly studied. However, some information about the cervical facet joint displacement is available. Three studies investigated the displacement of atlanto-axial joint from neutral position to maximum active axial rotation (Mockenberg *et al*., 2009; Duan *et al*., 2006; Villas *et al*., 1999). While in neutral position the corresponding facets are almost overlapping, in rotated position a wide contact loss emerged. Villas *et al*. (1999) found an average of 78% of contact loss of the total articular surface in ten children. In the adult population, this parameter was around 70% (Mockenberg *et al*., 2009). The width of rotational facet displacement was between 6.16mm and 8.68mm in the experiment of Duan *et al*., (2006).

Pearson *et al*. (2004) reported a peak facet joint compression (displacement of upper facet towards the lower) of 2.6mm at C4–C5, and a maximum anterior sliding (displacement of upper facet surface along the lower) of 5.4mm during simulated whiplash. Panjabi *et al*., (2007) showed an average of translation peaks of 22.0mm in anterior sliding, 7.9mm in separation (displacement of upper facet away from the lower), 9.9mm in compression, and 3.6mm of lateral displacement during high-speed bilateral facet dislocation.

Onan *et al*. (1998) used the facet joint displacement to assess the stability of motion segments of human cervical spine, showing that an isolated facet joint allowed translation between superior and inferior surfaces up to 9mm.

Tucker and Taylor (1998) studied the facet joint displacement in relation to different degree of compromise of the spinal canal in normal rotation and in various atlanto-axial pathological states. An atlanto-axial subluxation up to 9mm reduces the area of the spinal canal, in neutral rotation, to 60% with no cord compromise. However, any rotation added at this amount of subluxation is likely to cause cord compression.

The recent study of Buzzatti *et al*. (2015) was the first that measured the amount of displacement between the centre of the facet joint surfaces to analyse the kinematics of atlanto-axial joint during a manual approach. They report an average of 6.0 mm of maximum induced displacement for the NORM (sum of the motion along X, Y and Z axis) throughout a rotational HVLAT.

To the best of the author's knowledge, no studies about the displacement of the facet joints during regional manual mobilization have been published. This paper aims to describe in particular the atlanto-axial facet joint displacement during manual mobilization into rotation, using an in vitro approach and recording the continuous motion through an ultrasound device, in order to give information about ROM and trajectory.

The purpose of this experiment is to provide a better understanding of biomechanics and behaviours of cervical segment during manual mobilization, that is important to define the impact of the techniques in term of cost-benefits, and the related risk for soft-tissue injuries.

2. METHODS AND MATERIALS

2.1 Specimens

In this experiment twenty fresh human cervical specimens, including the head and the vertebrae from T2 to C1 were used. 11 subjects were females and 9 males. The age of the specimens ranged from 59 to 95 years old, with a mean of 81 (±11). A dissection of the skin, subcutaneous tissue and muscles was performed, leaving muscles and ligaments' insertions intact. The specimens were kept frozen before examination, therefore the biomechanical properties of the tendons and ligaments were not affected (Panjabi *et al.*, 1989; Wilke *et al.*, 1998). Room temperature was between 15°C and 20°C and humidity above 60% to prevent the dehydration of the specimens.

2.2 Instruments

An adapted Zebris CMS20 ultrasound-based motion tracking system (Zebris Medical GmbH-Germany) was used to collect kinematical data of the UCS.

This device allows to calculate the travel time of ultrasonic pulses produced by a transmitter and collected by a measuring sensor (antenna). The resolution of the instrument ranges from 0.1mm to 0.01mm. The input data frequency of the instrument was 100 Hz. Previous studies demonstrated that this device can reproduce angles of movements with an accuracy of less than 0.1° for the main motion component and 0.2° for the coupled components (Cattrysse *et al.*, 2009).

The angles of movement were calculated according to the Zebris Winbiomechanics software® (version 0.2.7, Zebris Medical GmbH, Isny, Germany).

2.3 Methods

The second thoracic vertebra of the specimens was fixed on a wooden frame using fixation pins. The rest of the specimen was left free to move without any restrictions. Therefore, a clinical situation in which the patient is in a supine position on an examination table was closely reproduced. The transmitter and the antenna were attached on the transverse process of the atlas and the axis respectively. This allowed the registration of atlanto-axial joint movements. Before starting the mobilizations, the optimal positioning of the device was controlled for each specimen.

Three metal reference markers (left (L), right (R) and front (F)) were inserted in each segment to allow the Zebris software to define a local reference frame by digitization of these markers.

2.4 Manual technique

The optimal positioning of the fixation tools, together with the preliminary dissection allowed free mobility of the cervical spine through full range of motion.

Three consecutive regional cervical mobilizations into rotation were performed on each specimen. While the lower thoracic segments are relatively fixed by the weight of the thorax lying on the bed (or in the in vitro set-up by fixation in the wooden frame), the head is sustained and turned to the left and right, mobilizing the whole cervical spine.

This technique was performed by two physiotherapists with more than 10 years of experience in orthopaedic manual therapy. Moreover, before the experiment, both examiners were allowed to practice with one specimen to get more confident with the experimental conditions. The operators were blinded from the data analysis of the system, and they performed the experiment in a test-retest set up under random circumstances.

Figure 1 (A) = Set-up showing the fixation of the specimen in horizontal position mimicking the supine position of a patient; (B) = Therapist mobilizing the specimen in vitro; (C) = In vivo demonstration of regional axial rotation mobilization

2.5 3-D angles of motion

As said above, the definition of the local reference frame used by the Zebris system is based on three markers, left (L), right (R) and front (F).

These anatomical landmarks were chosen as follows:

- Atlas: left, right transverse processes and the central part of the anterior surface of the vertebral body
- Axis: left, right transverse processes and the anterior tubercle

While the international Society of Biomechanics (ISB) has defined the local reference frame for middle and lower cervical spine, there are no descriptions of how to define a local reference frame for the upper cervical segments (Wu *et al*., 2002).

However, the above described reference frames for atlas and axis were defined, and the labelling of the axes was chosen in congruency with the ISB-guidelines as follows:

- X-axis: from the right to left transverse process, segmental flexion-extension axis;
- Z-axis: from the anterior centre of the corpus perpendicular to X axis, segmental lateral bending axis;
- Y-axis: perpendicular to the X and Z axes, pointing upward, segmental axial rotation axis

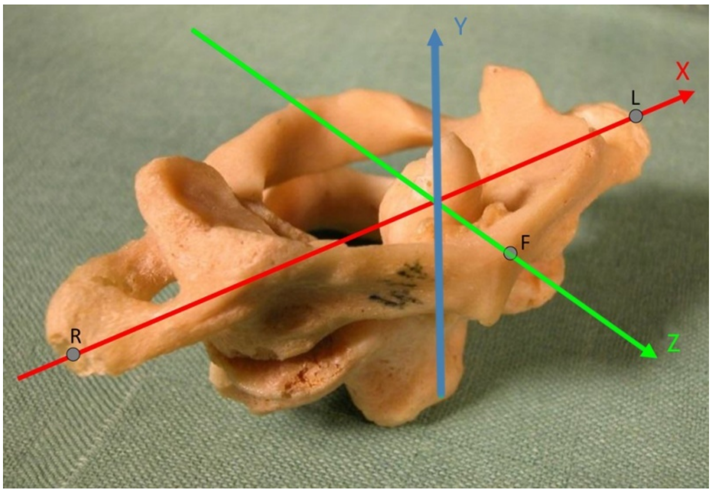

Figure 2 Bone embedded coordinate system on C1: X-axis (segmental flexion-extension); Y-axis (segmental axial rotation); Z-axis (segmental lateral bending). Location of metal reference markers L,R,F.

2.6 Displacement

The system initially was only able to calculate angles of motions of the UCS, and it was not possible to calculate the displacement because the system did not have data about the 3D morphology of the atlanto-axial facet joint surfaces. To obtain these information, a 3D-digitizer (3D-microscribe ® Immersion Corporation, USA) was adopted, with a two-step approach.

The metal reference markers were digitized on the full specimen, and later anatomical landmarks were digitized after segmentation. The location of these anatomical landmarks was the centre of the inferior facets of the atlas and the centre of the superior facets of the axis respectively. The GeoGebra© (v. 5.0 Beta, International GeoGebra Institute) geometry software allowed recalculating the 3D-Digitizer's coordinates in the Zebris system and input them in the software. As the position of these points represented the displacement between the facets, the software was consequently able to produce a displacement output break into XYZ components expressed in millimetres. A procedure to validate the process which allowed to input the facet joint coordinates acquired with the Microscribe 3D digitalizer into the Zebris software was performed **(Addendum 1).**

The overall displacement from neutral to end range position was calculated using Mathcad© professional software (v14, Parametric Technology Corporation, USA). The displacement displayed during the mobilization was defined as the difference between the maximum and the minimum values of the moving point position in each direction (X,Y,Z). To express the whole 3D amount of displacement the NORM vector ($|v|=\sqrt{x^2+y^2+z^2}$) was obtained from XYZ components.

To obtain the maximum distance achieved by C1 relative to C2, the initial distance between the facets in neutral position was added to the displacement during the mobilization. From here on out, the word “displacement” will be referred to the value thus calculated.

2.7 Trajectories

The present study examined the amount of displacement throughout the total range of motion. A separate analysis of left and right axial rotation would imply that the mobilizations have been started from a neutral position. An accurate 3D positioning and repositioning is difficult to achieve. This could have led to slight under or overestimations of both the angular movement and the displacement, due to the fact that a small portion of the movement towards one side may be included in the amount of motion towards the other side.

Nevertheless, right and left rotation can be considered separately when the aim is to examine the trajectories of the facet joints, as the focus is no more the magnitude of displacement, but only the direction.

To define the start and the end of these movements, angular data were used, and the intervals were manually tracked down from graphs.

In the following Mathcad model **(Figure 3)**, X ,Y, Z represent respectively flexion-extension, axial rotation and lateral bending. According to the reference frame, negative values of the Y component represent right rotation, while positive values represent left rotation. The intersections of the curve with the abscises axis were used to define the start of the movements, while the minimal and maximal values were used to define the end of right and left rotation respectively.

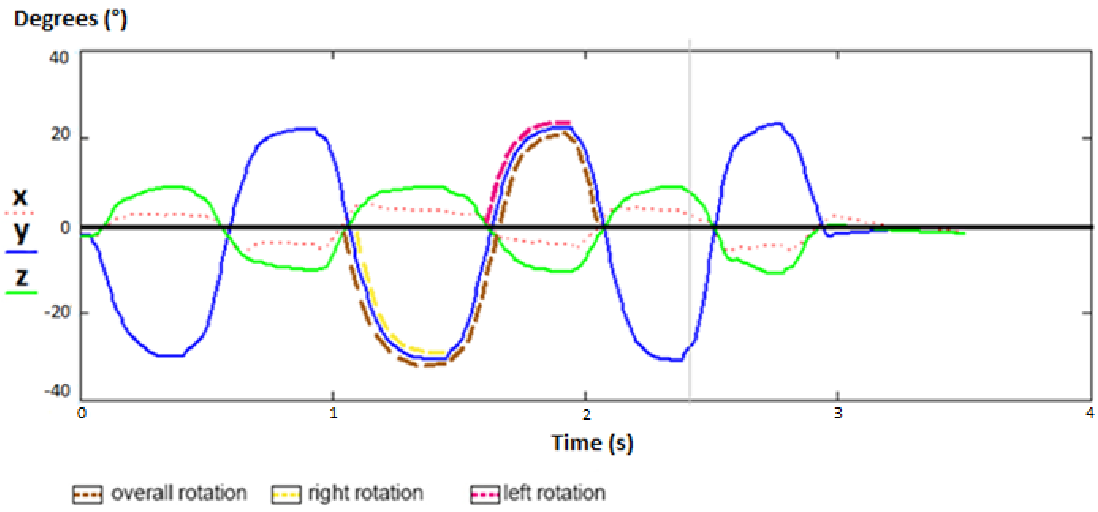

Figure 3 X= flexion-extension component in °; **Y=**axial rotation component in °; **Z=** lateral bending component in °

The target of the direction analysis was to depict four possible scenarios:

- the displacement follows a positive trajectory

- the displacement follows a negative trajectory
- two scenarios in which the displacement in the first part of the movement follows a positive direction while throughout the second part the opposite, and vice versa

In order to evaluate when each of these options occurred, mathematic calculations were performed (**Addendum 2).**

As previously mentioned, movements along the X axis represent medio-lateral movement, with positive value indicates leftward. Movement along the Y axis indicates superior-inferior movement, with positive values indicating upward, movement along the Z axis indicates anterior-posterior movement, with positive values representing forward.

2.8 Statistical analysis

The statistical software SPSS© (24th v, International Business Machines Corporation) was adopted to make all the statistical calculations.

Descriptive statistics was calculated to quantify the size of displacement across X, Y, Z axis and the NORM vector.

A Kolmogorov-Smirnoff goodness-of-fit test was performed to control for normal distribution of data. As the data were not normally distributed, a non-parametric "Friedman two-way ANOVA by ranks" test was used, in order to identify differences between the four measurements.

Intra-Class Correlation Coefficient (ICC) allowed the author to identify the strength of the correlation between different measurement, and so to quantify the intra-rater and inter-rater reliability. This index was classified as follow: <0.5="poor"; 0.50-0.75="moderate"; 0.75-0.90="good"; 0.90-1.00="excellent" (Portney and Watkin, 2000).

Significance was tested using the 5% rejection level ($p<0.05$).

3. RESULTS

From the starting eighty registrations, one was excluded from the statistical analysis because of a technical error occurred in the registration phase. No outliers were found using the "outlier labelling rule" with a 2.2 coefficient (Hoaglin and Iglewicz, 1987; Tukey, 1977).

3.1 Descriptive statistics

Descriptive statistics were calculated (**Table 1**) for the following variables:

- displacement of the facet joints along the X, Y and Z axis
- whole 3D displacement of the facet joints, represented by the previously described NORM vector
- degrees of angular motion around the Y axis (axial rotation)

Both left and right facet were taken into account, and their displacement values were considered separately.

During an overall UCS mobilization into rotation (48.53° on average), the mean left facet's displacement was 8.09 (±6.61)mm in the medio-lateral direction, 7.79 (±6.13)mm in the caudo-cranial direction, 7.90 (±6.48)mm in the anterior-posterior direction, and 15.37 (±8.66)mm regarding the NORM vector. During the same movement, the right facet's displacement was about 8.99 (±4.56)mm, 11.33 (±6.52)mm, 16.46 (±7.67)mm and 23.32 (±7.62)mm respectively. Considering the isolated X Y Z components, the values ranged from -3.34mm to 31.97mm.

The minimum and maximum NORM values for displacement were 2.58 mm (right facet) and 41.55 mm (left facet) respectively.

Table 1. Displacement of C1 relative to C2 along XYZ components and NORM resultant expressed in mm; the values are referred to an overall rotation; number of analyzed specimen=20; number of analyzed registrations=79)

		MIN	MAX	Mean	SD
Left facet	X	-1.55*	25.86	8.09	6.61
	Y	-0.80*	30.88	7.79	6.13
	Z	-0.74*	30.66	7.90	6.48
	NORM	3.33	41.55	15.37	8.66
Right facet	X	-0.69*	20.13	8.99	4.56
	Y	-3.34*	27.46	11.33	6.52
	Z	0.60	31.97	16.46	7.67
	NORM	2.58	37.48	23.32	7.62
Rotation ° Y axis		10.23	82.19	48.53	17.33

X = medio-lateral displacement (flexion-extension axis); **Y** = caudo-cranial displacement (axial rotation axis); **Z** = postero-anterior displacement (lateral bending axis); **NORM** = resultant of XYZ components; MAX = maximum values MIN = minimal values; SD = standard deviation; *the meaning of negative values is explained in **addendum 3**.

3.2 Trajectories

The **Table 2** shows the trajectories followed by the facet joints during the manual therapy technique.

The left facet had a preferential rightward, upward and forward trajectory during a right rotation, while in the left rotation it behaved the opposite. The right facet moved mainly leftward, upward and backward during a right rotation, while it followed a forward translation when the neck was rotated to the left side.

Table 2. Displacement trajectories: the direction is related to the initial position of the facet joint's centre. Number of analyzed registrations=79

		Left facet				**Right facet**			
		+ % (n)	- % (n)	+/-% (n)	-/+% (n)	+ % (n)	- % (n)	+/-% (n)	-/+%(n)
Right rotation	X	29 (23)	**53** (42)	11 (9)	6 (5)	**39** (31)	33 (26)	3 (2)	25 (20)
	Y	**46** (36)	16 (13)	9 (7)	29 (23)	35 (28)	**37** (29)	9 (7)	19 (15)
	Z	**65** (51)	5 (4)	15 (12)	15 (12)	5 (4)	**89** (70)	6 (5)	0 (0)
Left rotation	X	**41** (32)	30 (24)	14 (11)	15 (12)	**49** (39)	20 (16)	6 (5)	24 (19)
	Y	13 (10)	**34** (27)	27 (21)	27 (21)	29 (23)	20 (16)	18 (14)	**33** (26)
	Z	1 (1)	**72** (57)	14 (11)	13 (10)	**89** (70)	3 (2)	3 (2)	6 (5)

+ = positive direction; **-** = negative direction; **+/-** = the movement start in the positive direction and it end in the opposite; **-/+** = the movement start in a negative direction and it end in the opposite; **%** = percentage of displacements which follow the identified specific direction; (n)= number of registrations witch follow the specific identified direction; **X+** =leftward; **Y+** =upward; **Z+** = forward.

3.3 Test for normality and difference between registrations

In our experiment, there were four registrations, which are referred to the test-retest set up as follows:

- Test 1 (T1) is the first test made by Tester 1
- Test 2 (T2) is the first test made by Tester 2
- Re-Test 1 (R1) is the second test made by Tester 1
- Re-Test 2 (R2) is the second test made by Tester 2

To highlight differences between these four registrations, a Friedman two-way ANOVA by ranks test was used (**Table 3**). A non-parametric test was adopted because the Kolmogorov-Smirnoff goodness-of-fit test showed 10 of 32 non-normal distributed variables.

Table 3. Results of Friedman two-way ANOVA by ranks. Comparison between the four registrations (T1, R1, T2, R2). XYZ components and NORM during a mobilization into rotation; the values are referred to an overall rotation

X		**Y**		**Z**		**NORM**	
Left Facet	Right Facet	Left Facet	Right Facet	Left Facet	Right Facet	Left Facet	Right Facet
0.18	0.56	0.95	0.30	0.36	0.09	0.88	0.82

X = medio-lateral displacement (flexion-extension axis); **Y** = caudo-cranial displacement (axial rotation axis); **Z** = postero-anterior displacement (lateral bending axis); **NORM** = resultant of XYZ components; **T1** = first test made by tester 1; **T2** = first test made by tester 2; **R1** = second test made by tester 1; **R2** = second test made by tester 2

As no significant statistical difference was found, no other non-parametric tests were performed.

3.4 ICC

The inter-rater ICC values reached statistical significance in nine comparisons: three in the Y and Z components of the left facet, one in the Y component of the right facet, two in the NORM of the left facet. Scores ranged from poor (0.50) to moderate (0.74). Tester 1 showed a good intra-rater reliability only in two comparisons, while tester 2 reached significance in all the comparisons, with a reliability ranging from poor (0.46) to excellent (0.92).

Table 4. Intra-rater and inter-rater reliability of induced displacement of C1 relative to C2 (Expressed as Intra-class Correlation Coefficients); the values are referred to an overall rotation

			X		Y		Z		NORM	
			Left Facet	Right Facet	Left Facet	Right Facet	Left Facet	Right Facet	Left Facet	Right Facet
Inter rater	T1-T2	ICC	0.29	0.28	0.45	0.03	0.27	0.05	0.14	0.02
	T1-R2	ICC	0.47	0.55	**0.54***	0.32	**0.55***	0.30	**0.50****	0.31
	R1-T2	ICC	0.26	0.66	**0.55***	**0.59***	**0.74****	0.36	0.53	0.41
	R1-R2	ICC	0.26	0.34	**0.76 ****	0.50	**0.73 ****	0.47	**0.65***	0.54
Intra rater	T1-R1	ICC	0.42	0.45	0.28	0.52	**0.75****	**0.56***	0.44	0.47
	T2-R2	ICC	**0.92****	**0.77****	**0.89****	**0.76****	**0.77****	**0.46***	**0.79****	**0.76***

X = medio-lateral displacement (flexion-extension axis); **Y** = caudo-cranial displacement (axial rotation axis); **Z** = postero-anterior displacement (lateral bending axis); **NORM** = resultant of XYZ components; **T1** = first test made by tester 1; **T2** = first test made by tester 2; **R1** = second test made by tester 1; **R2** = second test made by tester 2; **ICC**=Intra-class Correlation Coefficient; *=p<0,05; **=p<0,01

4. DISCUSSION

The kinematical behaviour of the upper cervical spine segments during the execution of manual therapy techniques have been investigated by some authors in the last years. (Cattrysse *et al*., 2011; 2010; 2009; 2008a; 2007a; 2007b; Takasaki *et al*., 2011; Vincenzino *et al*., 1999).

Recently, Buzzatti *et al*.(2015) tried to analyse the kinematics of the vertebrae induced during a HVLAT using a new approach. Rather than consider the translational and rotational motion components separately, they focused on the amount of displacement between two points located on the centre of the facet joint surfaces. This approach is supposed to be able to provide more realistic, interpretable and representative information, as the movement is never only rotational or translational.

However, many manual techniques have yet to be studied to understand the underling kinematical mechanism. The present paper tried to analyze the behaviour of the C1-C2 facet joints during a regional cervical manual mobilization into rotation.

In the present study, the mean NORM values of displacement were 15mm and 23mm for the left and the right facet respectively. It has to be recalled that the current values refer to the sum of a right and a left rotation, while the studies described below considered these movements separately. Therefore, the data coming from the current study should be divided approximately by two before being compared.

In the experiment of Duan *et al*. (2006), the rotational facet displacement ranged between 6.16mm and 8.68 mm. Using the radiography presented in the study of Tucker and Taylor (1998), Buzzatti *et al*. (2015) estimated that the maximum 2D displacement of the centre of the facets is approximately 15mm when the head is moved from neutral position to 47° of axial rotation. Starting again from neutral position to maximum active axial rotation position, Villas *et al*. (1999) found an average of 78% of contact loss of the total articular surface in children. This parameter came to 70% in the adult population (Mockenberg *et al*., 2009). This latter study showed a maximum contact loss of 85.7%, suggesting that a big amount of displacement can be reached. The medio-lateral and the anterior-posterior diameters of the inferior articular facets of the atlas can be up to 21.7mm and 20.1mm respectively (Cattrysse *et al*., 2011; Cattrysse *et al*., 2008b; Sengul and Kadioglu, 2006). Therefore, these results seem to be coherent with our study, that showed a maximum medio-lateral displacement of 25.86mm and an antero-posterior displacement of 31.97mm (but approximately 12.93mm and 15.98mm if we consider only the rotation in one direction).

The differences among the values resulting from the different studies can be explained considering the different approaches: 2D versus 3D and in vivo versus in vitro.

In a 3D approach, all the movements along the three axes are taken into account, therefore higher values than the ones derived from a bi-planar analysis can be expected. In an in vitro study, some aspects such as muscles activity, active neural tissue and patient feedback are not present. In addition, the dissection of the specimens may have allowed wider movements, giving results slightly overestimating the actual in vivo situation.

The wide ranges and the high values of the standard deviations in the XYZ components, suggest a high variability among subjects. We can also notice differences between the behaviour of the right and the left facet. The mean displacement of the left facet was quite similar along the XYZ axis, while in the right facet the antero-posterior movement (Z) was nearly the double of the medio-lateral one (X). The right facet displayed also a bigger movement.

We can assume that these differences could be attributed to the anatomy of the subjects, to the execution of the technique, or to the choice of the reference frame. Cattrysse *et al*. (2011) demonstrated that main and coupled rotational motions can be only partially predicted by individual features of alar ligaments and morphometry of atlanto-axial joint. A similar study investigating the correlation between anatomical characteristics and displacement could be the next step in order to clarify this matter.

Friedman two-way ANOVA by ranks tests did not show differences between the four groups of data, therefore the displacement generated by the two examiners in the two tests did not differ significantly. This means that on average the amount of displacement that the two physiotherapists were able to produce was nearly the same.

In the present paper, inter-rater ICC was statistical significant in approximately one third of the calculations (range 0.50-0.76). One of the two examiners was able to reach a statistical significant intra-rater ICC in all the comparisons (range 0.46 to 0.92), while the other in two of eight.

Buzzatti *et al*. (2015), considering the same variables, found only seven significant intra and inter-rater ICC score (range 0.47-0.67), demonstrating that displacement during the execution of a HVLAT is not reproducible. The comparison between these studies suggests that displacement can be only partially replied during a regional and uniplanar mobilization, but it can be better reproduced than throughout a combined and complex technique.

Cattrysse *et al*. (2009) showed that the ROM of the intended axial rotation component has a good level of intra and inter-examiner reproducibility, while the coupled motions cannot be adequately replied. Cattrysse *et al*. (2010) demonstrated that combining all three motion components in one parameter (the Euclidean norm) excellent scores as well as inter-observer ICC values can be reached. It was supposed that the physiotherapists are able to reproduce the main intended and the 3D overall angular movement, but using different coupled motions. The results of the present study suggest that they use also different amount of displacement between facets.

This study was performed by two experienced manual therapists, but with different levels of familiarization with the technique. Contrary to expectations, the less experienced physiotherapist reached higher ICC scores. Therefore, we can suppose that in this specific manual technique familiarization is not determinant for reliability.

According to the results of this study, the facet joints' trajectories are very variable among subjects. Only the displacement along the antero-posterior Z axis was quite consistent. During a right rotational mobilization, the right facet is supposed to move backward and the left facet forward, while during a left rotation the opposite should occur. This was confirmed in the present experiment. During a right rotation, the left facet moved mainly forward (80%), and the right facet moved backward (95%). During a left rotation, the left facet moved backward (86%), while the right facet moved forward (95%). These percentages consider the case in which the facet moves only toward one direction, but also that one in which the facet moves, for a brief moment, in the opposite direction at first.

In order to clarify this matter, in the **addendum 4,** 2D representations of trajectories are displayed.

Considering the relationships between the UCS and important vital structures, the risks related to rotational cervical spine manual therapy is still a matter of concern.

Some reassuring results can be found in literature. The study of Tucker and Taylor (1998) demonstrated that, although a 47° rotation of atlanto-axial joint reduces the area of the spinal canal up to 61%, the residual area subtracting the cord is still 34%.

Also changes in blood flow in the vertebral arteries is still a debated matter (Mitchell, 2008). Three recent studies (Thomas *et al.*; 2013; Quesnele *et al*., 2014; Thomas *et al*., 2015), using magnetic resonance angiography, showed that blood flow is not negatively affected by sustained right and left rotated neck positions, and that total cerebral inflow also remain fairly constant, providing a good cerebral perfusion. It was assumed that the vertebral artery's double curve configuration at C1-C2 level is able to allow large amount of deformation, avoiding compression and damages.

Although the possible vertebral artery involvement cannot be directly estimated by this experiment, some important information could be provided by further studies, adopting a similar methodological approach, but focusing on the amount of C1-C2 displacement at the transvers foramen instead of on the centre of the articular surfaces.

4.1 Limitations

In addition to the previously mentioned limitation of an in vitro approach, the considered sample did not completely represent the population that usually receive manual therapy treatments, as the mean age was quite high. Possible morphological alterations caused by the age of the subject could have influenced the kinematical behaviour of the UCS (Trott *et al*., 1996).

5. CONCLUSION

The current study showed that the mean NORM values of displacement of the facet joints of C1 relative to C2 during a regional axial mobilisation into rotation were 15mm and 23mm on average for the left and the right facet respectively, ranging from 2.58 to 41.55 mm. These results are coherent with previous studies, in which a large contact loss between the atlanto-axial joint surfaces was displayed. However, comparisons should be made carefully, as different methodological approaches were used.

The wide ranges and high standard deviations emerged in this study show that the amount of inter-vertebral movements in the atlanto-axial joint during a regional mobilization into rotation is very variable among subjects. Even if on average physiotherapists produce similar magnitude of displacement, this is only partially reproducible and predictable, according to the ICC scores and to the trajectories analysis, which displayed consistent patterns only along the anterior-posterior component.

The debate related to changes in vertebral artery blood flow during rotational manual therapy techniques of the cervical spine is still open. This experiment cannot truly estimate the possible vertebral artery involvement, but this matter could be deepened by further studies using a similar methodological approach, but focusing on the displacement of C1-C2 at the transvers foramen.

More research is recommended in order to validate these results and to achieve a better comprehension of the complex kinematical mechanisms underlying the manual therapy manoeuvres.

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ADDENDA

ADDENDUM 1: validation procedure

A system in which the real value of displacement could be known was needed in order to compare this amount with the software's output.

A wooden model was thus adopted **(Figure 4)**. This unit is composed by a platform (representing C2), in which the antenna is positioned, and a movable cylinder (representing C1), in which is positioned the transmitter. These two parts are fixed each other through a screw which allows only axial rotation.

At first, three points (front (**F**), right (**R**), left (**L**)) were acquired in order to provide a reference frame for the Zebris system. Then other two points (centre of the facet joints) were acquired using a 3D digitizer. The cylinder representing C1 was rotated (α), in order to simulate a mobilization.

Figure 4: Wooden model

In **Figure 5** the distance between the left facet in the initial position (**LF**) and the centre of the circle (**O**) is labelled as "**a**". The distance between the left facet in the final position (**LF1**) and the centre of the circle is labelled as "**a1**".

The displacement is the distance between the initial and the final position, labelled as "**b**".

As "**a**" and "**a1**" are equal, fixed and known measures, the value of displacement can be easily calculated.

$$\boldsymbol{b=2a * sin\,\alpha}$$

The results of these calculations were compared with the software's output. The maximum detected difference for the NORM displacement was of 10.69%. This difference is acceptable, considering that the above mentioned wooden model is not a high precision tool. For example, instead of permitting only 2D translations (X; Z), it actually allowed little movements along the Y component.

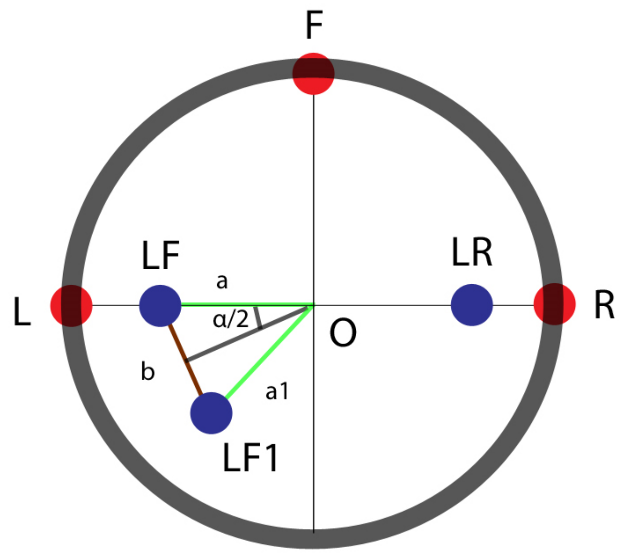

Figure 5 The red points are referred to markers acquired with the Zebris system in order to provide a reference frame (**L**=left; **R**=right; **F**=front). The blue points are referred to the coordinates of the centre of the facet joints acquired with the 3D digitizer (**LF**=left facet; **RF**=right facet). The cylinder was rotated in order to simulate a mobilization (**α**=angle° of rotation); **LF1**= final position of left facet coordinates; **O**= centre of the circle and of the reference frame; **a**= distance between the left facet in the initial position; **a1**= distance between the left facet and the final position; **b**= displacement

ADDENDUM 2: trajectory analysis

As said previously, the target of the direction analysis was to depict four scenarios:

- the displacement, according to the reference frame, follows a positive trajectory
- the displacement follows a negative trajectory
- two scenarios in which the displacement in the first part of the movement follows a positive trajectory, while throughout the second part a negative one, and vice versa

To evaluate mathematically when each of these options occurred, three operations were performed:

- difference between the minimal and the initial value of the curve representing the displacement
- difference between the maximal and the initial value
- difference between the final and the initial value

If we interpret the results of this operations together we are able to distinguish the four different scenarios (in **Table 5** the values highlighted in yellow are the peculiar results which allow to distinguish them) :

Table 5. Results of the three mathematical operations

	positive trajectory	negative trajectory	Initially positive, then negative trajectory	Initially negative, then positive trajectory
START - MIN	0	-	-	-
START - MAX	+	0	+	+
END - START	+	-	+	-

START=initial value; END=final value; MIN=minimal value, MAX=maximum value; START-MIN=first operation; START- MAX=second operation; END –START= third operation; +=positive value; -=negative value;

- the result of the first operation is 0 only when the trajectory is positive, because the minimum and the initial values are equal **(Figure 6A)**

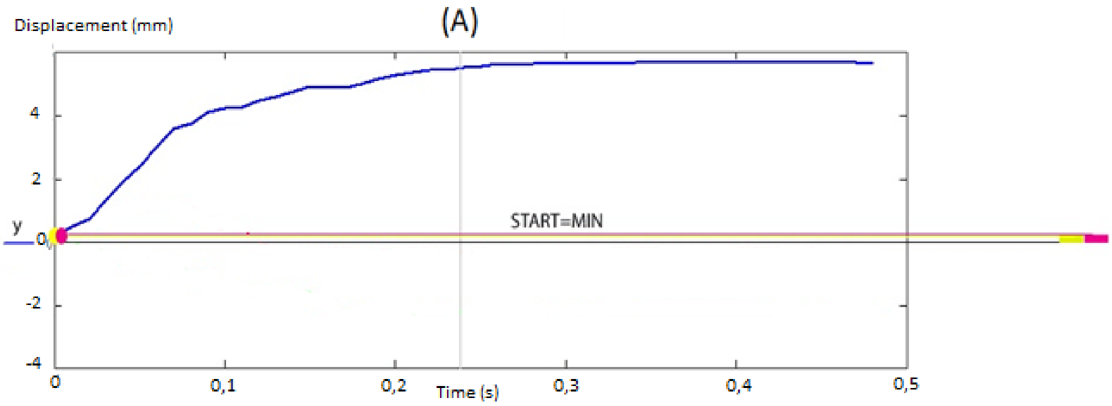

Figure 6A In this example only the Y component (blue line; caudo-cranial displacement) is displayed; yellow= initial value (START); purple= minimum value (MIN)

- the result of the second operation is 0 only when the direction is negative, because the maximum and the initial value are the same **(Figure 6B)**

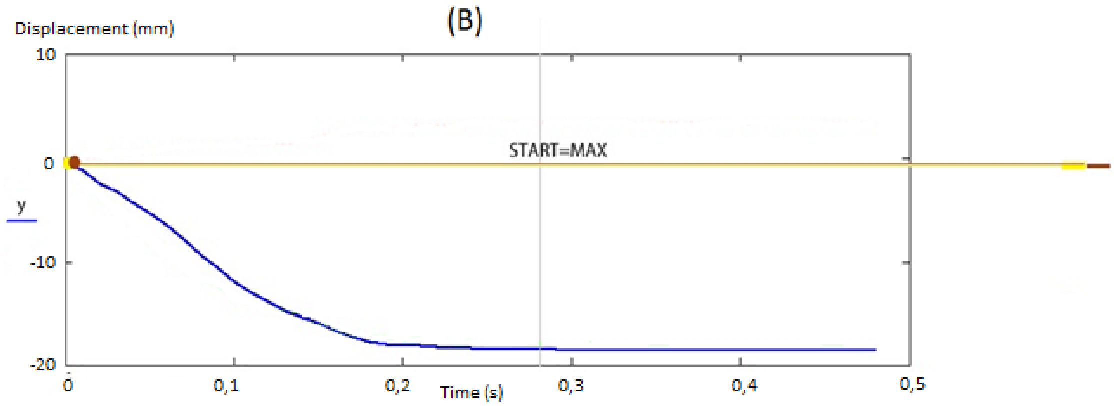

Figure 6B In this example only the Y component (blue line; caudo-cranial displacement) is displayed; yellow= initial value (START); brown= maximum value (MAX)

- when displacement follows a positive trajectory at first, but then it becomes negative, the final value is higher than the initial one, and the third operation result in a negative number **(Figure 6C)**

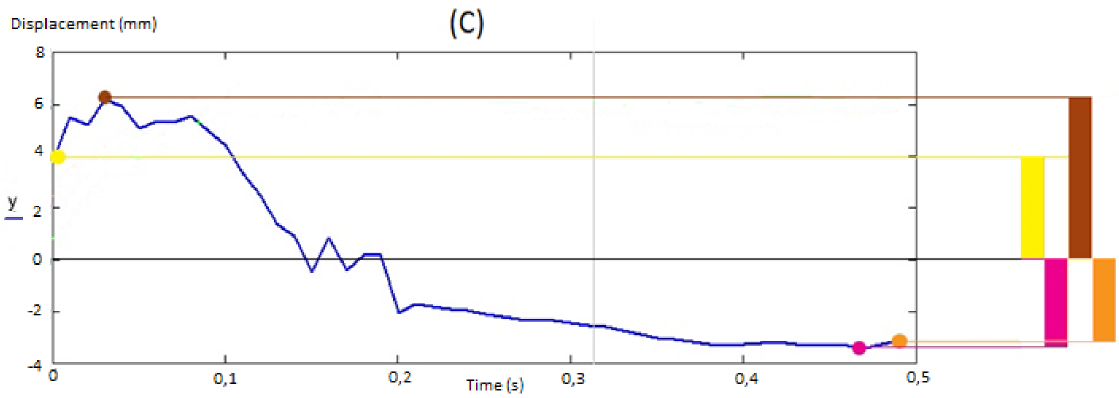

Figure 6C In this example only the Y component (blue line; caudo-cranial displacement) is displayed; yellow= initial value (START); purple=minimal value (MIN); brown= maximum value (MAX); orange=final value (END)

- in the fourth scenario the result of the third operation will be positive **(Figure 6D)**

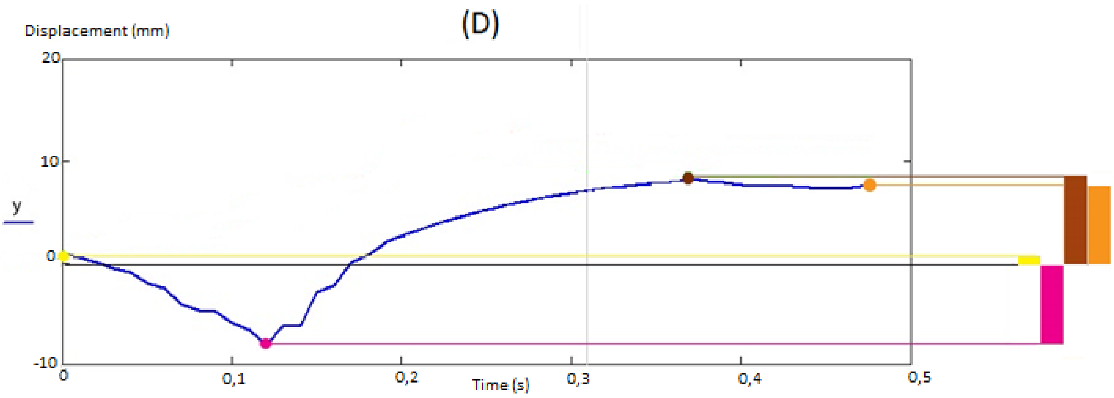

Figure 6D In this example only the Y component (blue line; caudo-cranial displacement) is displayed; yellow= initial value (START); purple=minimal value (MIN); brown= maximum value (MAX); orange=final value (END)

ADDENDUM 3: negative values of displacement

Descriptive statistics (**Table 1**) showed some negative values of displacement. This can be explained considering that the overall displacement (OD) between C1 relative to C2 was defined as the algebraic sum of displacement during the mobilization (DM) and the initial distance between the facets in neutral position (NP): ***OD=DM+NP.***

The displacement during the mobilization was defined as the difference between the maximum (MAX) and the minimum (MIN) values of the moving point position: ***DM=MAX-MIN.*** Therefore, this number is always positive.

The initial distance between the facets in neutral position was defined as the difference between the position of C1 (P_{C1}) and the position of C2 (P_{c2}) from the centre of the reference frame: $NP=P_{C1}-P_{C2}$. Thus this number can be negative.

Therefore, if the displacement induced during the manual therapy technique does not overcome the initial negative distance between the facets in neutral position, a negative number will be obtained.

ADDENDUM 4: trajectory graphs

Each coloured line is referred to one specimen. As too much lines would have affected the clarity of the graphs, only the T1 (first test made by tester 1) measurements are represented.

Looking at X Y graph **(Figure 7A, 7A1)**, it can be noticed that trajectories of displacement are not consistent among subjects, and a clear patter cannot be recognized. In the X Z **(Figure 8B-9B1)** or in the Z Y **(Figure 8C-9C1, 8D-9D1)** graphs the Z component displacement tends to follow roughly the same direction.

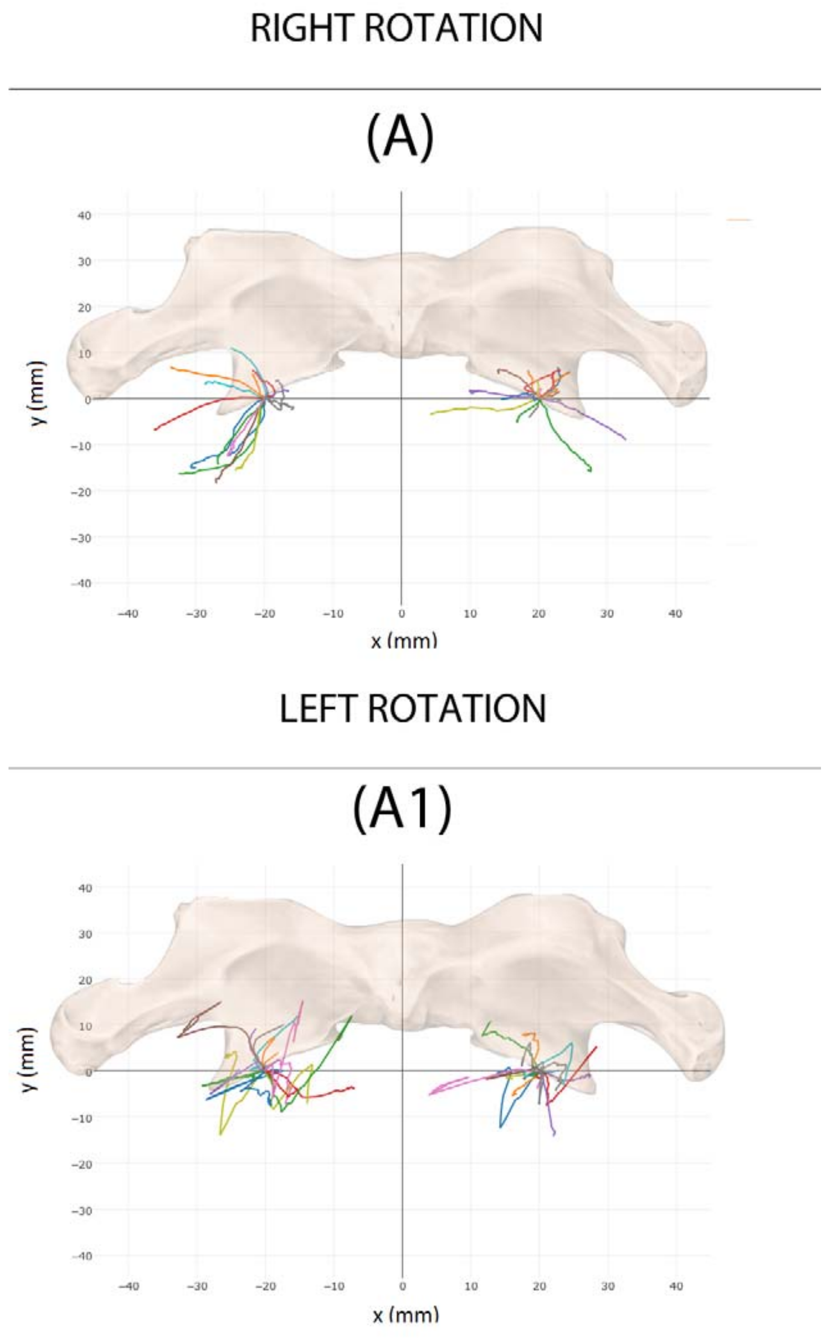

Figure 7 (A)-(A1)= X Y graphs, anterior view of C1

RIGHT ROTATION

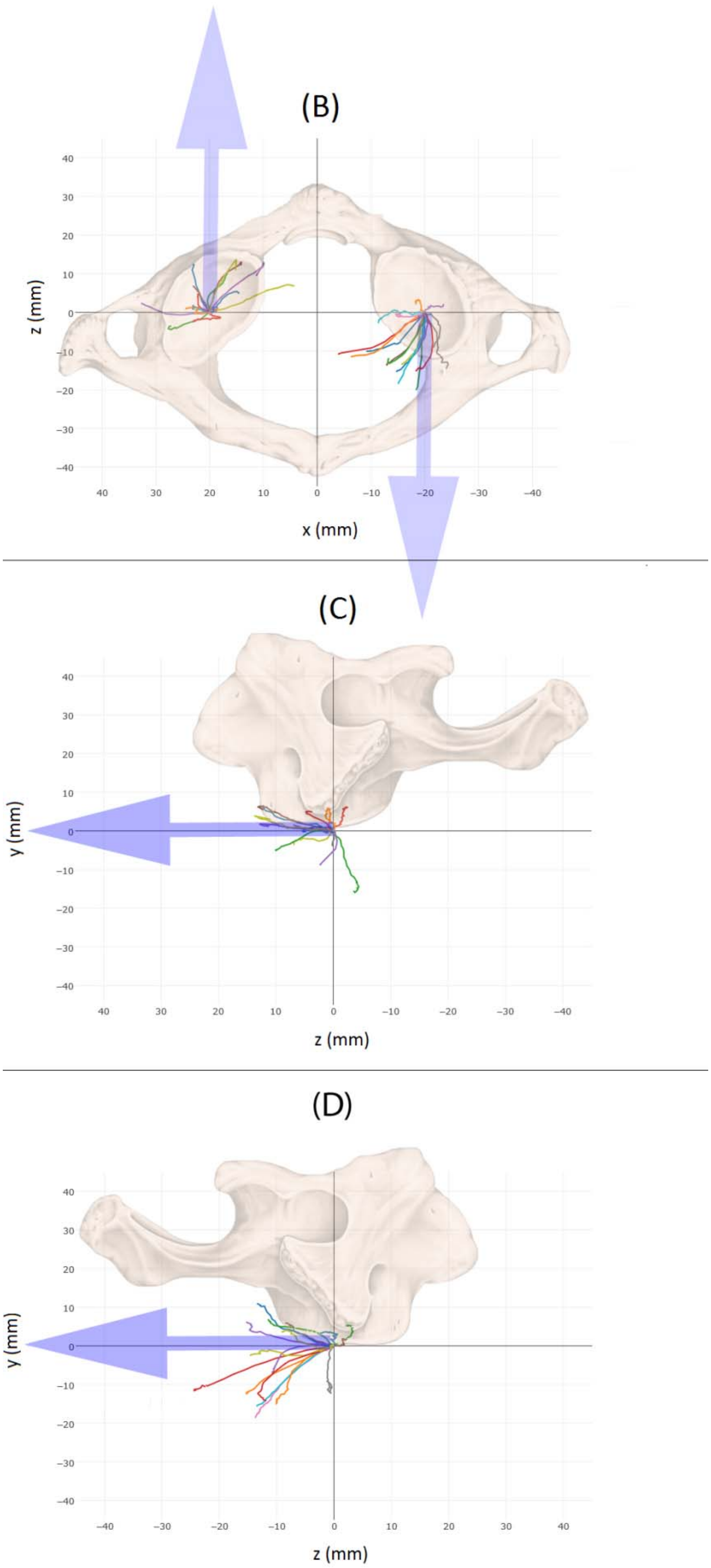

Figure 8 (B)=X Z graph, superior view; (C)=Z Y graph, left view; (D)=Z Y graph, right view

LEFT ROTATION

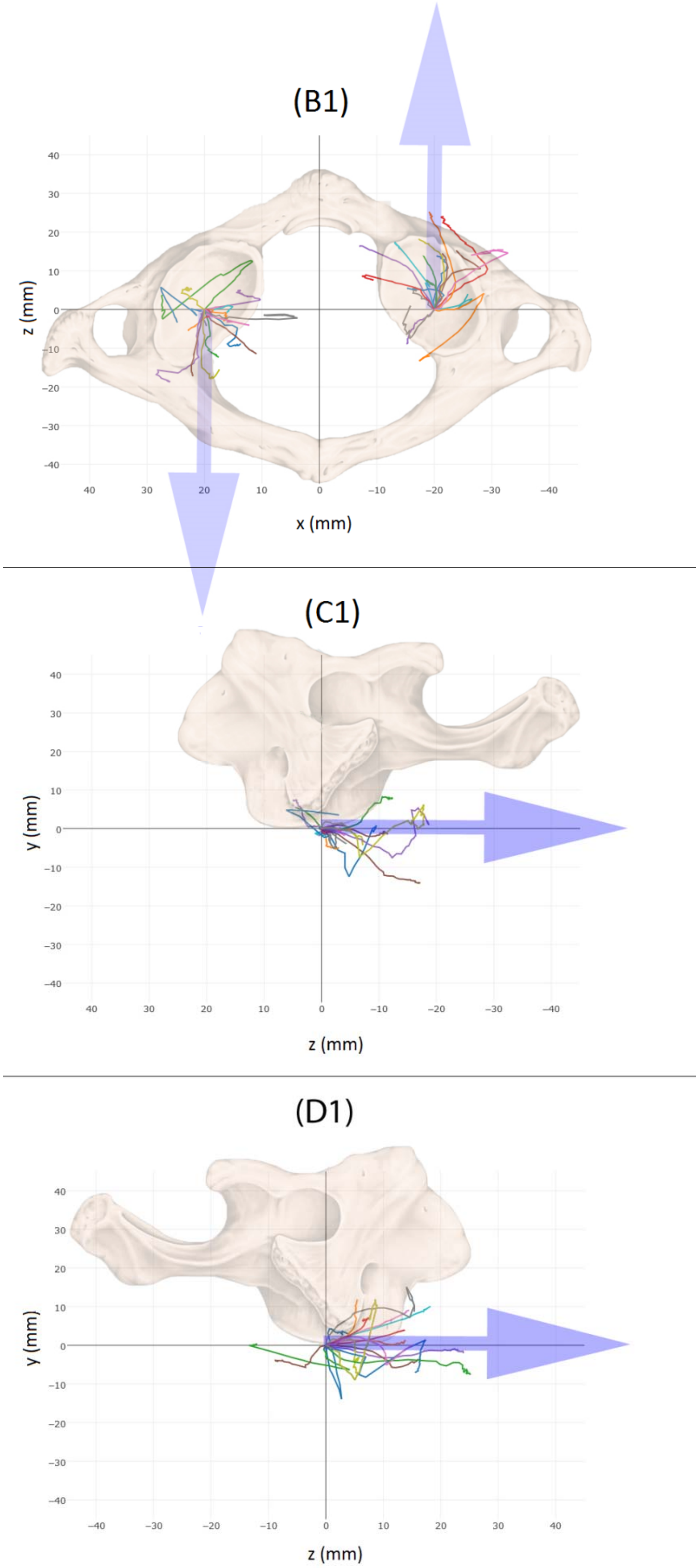

Figure 9 (B1)=X Z graph, superior view; (C1)=Z Y graph, left view; (D1)=Z Y graph, right view