Vrije Universiteit Brussel
FACULTEIT GENEESKUNDE EN FARMACIE
Master na Master in Manuele Therapie

UNIVERSITÀ DEGLI STUDI DI GENOVA
Master in riabilitazione dei disordini muscolo-scheletrici

Kinematic analysis of 3-dimensional mobilization techniques of the upper cervical spine: a reliability analysis and comparison of techniques.

Thesis presented as partial fulfilment of the Erasmus program of:

Giulia Sgarbi

Academic year: 2011 – 2012

Promoter: Prof. Dr. Erik Cattrysse

Abstract

Introduction: There are few studies which analyze the three-dimensional kinematic aspects of the upper cervical spine during manual mobilization. No previous experiments have been made during non-planar, i.e. combined mobilization of the atlanto-occipital joint. The present *in vitro* study aims to analyze the kinematic behavior of the upper cervical spine during a three-dimensional mobilization of the atlanto-occipital joint. Two different segmental manual techniques (manual fixation and locking technique) were compared in a test-retest situation of two manual therapists. Intra and inter-examiners reproducibility were analyzed.

Methods and material: Twenty fresh human cervical specimens were studied in a test-retest situation with two examiners. Two 3D mobilizations (flexion-right axial rotation and flexion-left axial rotation) of the atlanto-occipital joint were performed using two different manual techniques. The 3D kinematic aspects during segmental manual fixation were compared with those during segmental locking technique of C1-C2 segment. Segmental kinematics were registered using Zebris CMS20 ultrasound-based tracking system. The intra and inter-examiners reliability were analyzed

Results: The statistical analysis showed an acceptable intra- and inter-examiners reliability, mainly in the atlanto-occipital joint. However the intra-class correlation coefficient did not present any statistically significance in most parameters. The manual fixation enables to increase the flexion motion of 2,6° in the atlanto-occipital joint. At the same level, during the combined mobilization to the right direction with manual fixation, there is a statistical significant increase of 1.6° in the flexion motion compared to combined mobilization to the left direction. However the manual fixation nor the locking technique influence the axial rotation motion in the atlanto-occipital joint. The cross-correlation showed a controlateral pattern between main axial rotation and coupled lateral bending in the atlanto-occipital joint, but ispilateral pattern in the atlanto-axial joint. The main axial rotation was greater than the coupled lateral bending, mainly in C1-C2 segment.

Conclusion: Although we did not observe significant differences between examiners, the results do not suggest a statistically significant correlation between observers. The results may indicate that the experience and the familiarization of examiners with the exerted manual therapy techniques and the complexity of the upper cervical spine anatomy, could influence the reproducibility of the 3-dimensional kinematics of segmental complex mobilizations. The results of this in vitro study suggest that the use of different segmental manual techniques during complex mobilizations could partly result in different kinematics of the upper-cervical spine. Further in vivo studies may validated these results.

Acknowledgement

First of all I would like to thank Prof. Dr. Erik Cattrysse for the opportunity to participate in this project. His kindness, his precious advises and his professionalism have been fundamental during my stay in Bruxelles. Without his guidance I could not have completed this work.

I would also like to thank Dr. Steven Provyn, Drs. Aldo Scafoglieri, Drs. Jonathan Tresignie, Ann Vanhaelewijck and all the staff Experimental Anatomy Department of Vrije Universiteit Brussel, for all the support during difficult and stressed moments. They are really a team and I am proud to have been a part of it.

Gratitude's to all my teachers and colleagues of the Manual Therapy Master in Italy, for all the knowledge in the physiotherapy field. The theoretical part and practical experience accumulated these years shaped my professional life and give me the opportunity to meet wonderful people.

At last, but not least, a special thanks to my family, and the persons I love the most. Thank you for sustaining all my decisions and being there for me every day of my life.

Giulia Sgarbi

Index

List of Abbreviations

3D	Three dimensional
df	Degrees of freedom
C0	Occiput
C1	Atlas
C2	Axis
CC	Cross-correlation
ICC	Intra-class correlation coefficient
ISB	International Society of Biomechanics
Eucl. norm	Euclidean norm
FLL	Flexion-right axial rotation mobilization with locking technique
FLM	Flexion-left axial rotation mobilization with manual fixation
FRL	Flexion-right axial rotation mobilization with locking technique
FRM	Flexion-right axial rotation mobilization with manual fixation
Max X	Extreme position of flexion-extension movement
Max Y	Extreme position of axial rotation movement
Max Z	Extreme position of lateral bending movement
X	Flexion-extension axis
Y	Axial rotation axis
Z	Lateral bending axis
Sign	Statistical significance
sd	Standard deviation
SPSS	Statistical Package for the Social Service version 19.0
T2	Second thoracic vertebra
Zebris CMS20	Ultrasound-based motion analysis device (Zebris Medizintechnik Gmbh Isny, Germany)

List of Tables and Figures

Tab 2.1: Descriptive statistic of parameters in flexion-right axial rotation of C0-C1 with manual fixation

Tab 2.2: Descriptive statistic of parameters in flexion-left axial rotation of C0-C1 with manual fixation

Tab 2.3: Descriptive statistic of parameters in flexion-right axial rotation of C0-C1 with locking technique

Tab 2.4: Descriptive statistic of parameters in flexion-left axial rotation of C0-C1 with locking technique

Tab 2.6: Descriptive statistic of parameters in flexion-right axial rotation of C1-C2 with manual fixation

Tab 2.7: Descriptive statistic of parameters in flexion-left axial rotation of C1-C2 with locking technique

Tab 2.8: Descriptive statistic of parameters in flexion-left axial rotation of C1-C2 with locking technique

Fig.1: bone embedded coordinate system on C1: X-axis: segmental flexion extension, Z-axis: segmental lateral bending axis, Y-axis: segmental axial rotation axis

Fig.2: mathcad curves during (a) flexion-left axial rotation with manual fixation technique in C0-C1 segment (b):flexion-left axial rotation mobilization with locking technique in C0-C1 segment, xhk: flexion-extension axis, yhk: axial rotation axis, zhk: lateral bending axis, k: sampling size 20Hz

1. INTRODUCTION

Coupled spinal motion is the rotation or translation of a vertebral body around or along one axis that is consistently associated with the main rotation or translation about another axis. During movement, translation occurs when all elements within that segment move in the same direction with the same velocity. With movement, rotation occurs as a spinning or angular displacement of the vertebral body around some axis. Biomechanical coupling is 3-dimensional (3D), takes place within 6 degrees of freedom (df), and is often described using a Cartesian coordinate system. The 6 df describe translation along and rotation about each orthogonal axis. The 3D motions of the spine in humans correspond to axial rotation, lateral bending and flexion-extension forces. One specific movement activates movement in the other 5 component motions[1].

The kinematic analysis of the cervical spine has been studied by several authors using different approaches. Some in vivo studies have attempted to record normal cervical range of motion in different postures[2], comparing different instrumentations[3], or analyzing differences between ages and gender[4].

In some experiments[5,6], the three dimensional physiologic motions of the upper cervical spine (C0-C1, C1-C2) were recorded. Other authors have focused on coupling behavior of the occiput-atlanto-axial complex during planar motion, in *in vitro* or *in vivo* studies.

During axial rotation motion most of the studies reported a coupled lateral bending in the direction opposite of head rotation in C0-C1 segment[1,7,8,9,10,11,12,13,14,15]. Only Goel[16] and Cattrysse[17]described a coupled lateral bending in the same side of the main axial rotation movement. In the analysis of coupled motions around the sagittal plane all authors, except Goel, described a coupled extension in C0-C1 segment, whereas, in the C1-C2 segment there are differences. Some studies reported coupled extension motion[7,8,16] and other coupled flexion[9,10,11,12]. Some studies reported also coupled lateral translation of C0 in the same direction as the axial rotation[7,18], while the atlas translates superiorly during the initial stage of head rotation, and inferiorly as the magnitude of the main rotation increases[15]. Panjabi[8] reported also coupled translations in the sagittal plane in both segments directed posteriorly with no relationship to the direction of the applied torque.

Table 1. Range of motion in literature, mean ± standard deviation (sd) of main axial rotation motion and coupled movements in degrees in the upper cervical spine

AXIAL ROTATION

STUDY	C0-C1			C1-C2		
	AR	LB	F-E	**AR**	LB	F-E
Goel 1988[16]	2,4±1,2	I 3,0±1,8	F 3,8±2,8	23,3±11,2	I 6,5±3,0	E 3,0±2,5
Ishii 2004[7]	1,7±1,5	C 4,1±1,4	E 13,3±1,9	36,2±4,5	C 3.8±3,0	E 6,9±3,0
Panjabi 2001[8]	4,9	C 1,8	E 11,7	28,4	C 3.1	E 3,5
Panjabi1993[9]	4,9±4,8	C 4,9±4,8	E 5,4±3,2	34,3±7,2	C 5.4±2,6	**F** 2,8±3,5
Panjabi 1991[10]	3.3±2,3	C na	E na	37,4±9,0	C na	**F** na
Dugailly 2010[11]	5,0±3,4	C 2,3±2,0	E 0,8±3,5	46,1±12,5	C 0.5±5,2	**F** 0,7±5,3
Dugailly 2011[12]	5,0±3,4	C 2,3±2,0	E 0,8±3,5	46,1±12,5	C 0.5±5,2	**F** 0,7±5,3
Cattrysse 2007[13]	3,88±2,03	C 3,02±2,1	F-E 9,0±2,8	49,9±5,5	C 21.3±7,7	F-E 8,2±4,5
Cattrysse 2011[17]	na	na	Na	49,5±12,7	I 20.10±8,2	F-E22,8±6,5
Cattrysse 2008[14]	na	na	Na	54,4±12,6	C 21.1±12,3	F-E 9,7±2,0

C0-C1: atlanto-occipital joint, C1-C2: atlanto-axial joint, AR: main axial rotation motion, LB: coupled lateral bending motion, F-E: coupled flexion-extension motion, I: ipsilateral coupling behavior, C: controlateral coupling behavior, na: not available, **Bold**: range of motion and sd to one side

The main lateral bending moment is more complex and there is less consents across studies[1]. Panjabi[8], Goel[16], Cattrysse[13,14] reported coupled axial rotation to the same side as the applied lateral bending moment in both C0-C1 and C1-C2 segments, while, in other studies this happened only in the C0-C1 segment[19,10]. Other studies showed a coupled axial rotation to the opposite side as the main lateral bending motion[19,20] in both C0-C1, C1-C2 segments. Some authors found a coupled axial rotation greater than the main lateral bending at C1-C2 segment[9,14,19,20].

The coupled flexion-extension motion component is very small, in general the occiput will extend on the atlas, but the atlas will flex relative to C2[15]. However, Panjabi[8] and Goel[16] reported a coupled extension of the atlas. Two studies[8,20] showed coupled lateral translation motion in the same direction as the applied lateral bending moment, but another study[18]showed a coupled translation to the opposite side of lateral bending.

Table 2. Range of motion in literature, mean ± sd of main lateral bending motion and coupled movements in degrees in the upper cervical spine

LATERAL BENDING

STUDY	C0-C1			C1-C2		
	AR	**LB**	F-E	AR	**LB**	F-E
Goel 1988[16]	I 1.0±1.8	3.4±2.8	E 1.2±1.2	I 2.3±2.9	4.2±2.8	E 0.4±1.0
Panjabi 2001[8]	I 2.4	4.5±1.5	F-E <1.2	I 5.3	3.2±2.3	E 3.0
Panjabi 1993[9]	I 2.4±2.3	5.2±3.4	E 1.2±6.3	C 24.6±19.3	11.4±7.6	F 2.4±6.7
Panjabi 1991[19]	I nr	5.6±3.0	E na	C na	12.6±7.0	F na
Ishii 2006[20]	C 0.2±1.0	1.9±0.9	F-E<1.1	C 17.1±4.7	1.6±1.3	F-E<1.1
Cattrysse 2007[13]	I 5.4±4.3	2.9±2.4	F-E 2.6±1.4	I 8.7±6.3	7.1±4.8	F-E 7.2±4.1
Cattrysse 2008[14]	na	na	na	i 12.2±7.7	11.4±7.6	F-E 7.6±5.2

C0-C1: atlanto-occipital joint, C1-C2: atlanto-axial joint, LB: main lateral bending motion AR: coupled axial rotation motion, , F-E: coupled flexion-extension motion, I: ipsilateral coupling behavior, C: controlateral coupling behavior, i: inconsistent**,** na: not available, sd: standard deviation**, Bold**: range of motion ± sd to one side

During sagittal plane rotation (flexion-extension motion) some authors recorded coupled axial rotation and lateral bending movements, but in general they are minimal and inconsistent[11,12,18]. During the main flexion and extension motions, there are only coupled translations: anterior translation occurs during flexion, and posterior translation is coupled with extension[15](tables 3-4).

Table 3. Range of motion in literature, mean ± sd of main flexion motion and coupled movements in degrees

FLEXION

STUDY	C0-C1				C1-C2			
	AR	LB	**F**	T	AR	LB	**F**	T
Goel 1988[16]	0.1±1.3 controlateral	1.2±0.3	6.5±2.5		0.6±1.5 controlateral	0.4±1.0	4.9±2.0	
Panjabi 2001[8]	inconsistent		7.2±2.5	S	inconsistent		12.3±2.0	S
Panjabi 1991[19]	ipsilateral		14.4±3.2		controlateral		12.7±3.2	
Dugailly 2010[11]	1.7±3.3 controlateral	0.1±1.3	19.1±5.8 F-E		1.9±4.5 controlateral	0.7±1.6	14.3±3.3 F-E	
Dugailly 2011[12]	1.7±3.3 controlateral	0.1±1.3	19.1±5.8 F-E		1.9±4.5 controlateral	0.7±1.6	14.3±3.3 F-E	
Cattrysse 2007[21]	8±4 controlateral	5±3	12±4 F-E		6±1 controlateral	8±3	16±2F-E	

C0-C1: atlanto-occipital joint, C1-C2: atlanto-axial joint, F: main flexion motion, F-E: main motion on the sagittal plane, AR: coupled axial rotation motion LB: coupled lateral bending motion, T: trasversal coupling behavior, S: sagittal plane, ipsilateral: coupling behavior, controlateral coupling behavior, inconsistent coupling behavior, sd: standard deviation, **Bold**: range of motion ± sd to one side.

Table 4. Range of motion in literature, mean ± sd of main extension motion and coupled movements in degrees

EXTENSION

STUDY	C0-C1				C1-C2			
	AR	LB	**E**	T	AR	LB	**E**	T
Goel 1988[16]	1.9±2.5	1.4±1.3	16.5±7.6		0.3±3.0	0.6±1.6	5.2±2.9	
Panjabi 2001[8]	inconsistent		20.2±4.6	S	inconsistent		12.1±6.5	S
Panjabi 1991[19]	ipsilateral		14.4±3.2		controlateral		10.5±5.0	

C0-C1: atlanto-occipital joint, C1-C2: atlanto-axial joint, E: main extension motion, AR: coupled axial rotation motion LB: coupled lateral bending motion, T: trasversal coupling behavior, S: sagittal plane, ipsilateral: coupling behavior, controlateral coupling behavior, inconsistent coupling behavior, sd: standard deviation**, Bold**: range of motion ± sd to one side.

The behavior of the coupled pattern is dependent on the main motion of initiation, the posture of the spine, and the pathology of the segment. In his review Cook[1] tried to explain the controversies between authors and studies. One reason could be anatomical variation, structure and mechanical influences. The occipito-atlanto-axial complex exhibits intricate interactions between bony and soft tissue structures, and also the highest degree of variance in total range of motion compared with other cervical segments. Injuries and different spinal postures can also influence both coupling patterns and main motions[9,10,19]. Secondly, the instrument used during the measurement process may lead to variable results. Another reason could be the difference associated with *in vivo* and *in vitro* specimens[1].

The limitation of the studies *in vivo* are many. The *in vivo* loads that are applied to the spine by the subjects are unknown, thereby precluding calculations of the cervical spine flexibility and stiffness. Additionally, the loads can vary, depending on the motivation of individual subjects. Slippage at the skin beneath measurement devices also contributes to inaccuracies in the data. *In vivo* studies also encounter difficulties defining the neutral position in living subjects. Thus, wide variation in *in vivo* measurements of three-dimensional main and coupled motions can be expected. On the other hand the limitation to studying cervical spine motions with an *in vitro* model is the lack of musculature. These have been shown to exert significant stabilizing forces of the spine[8], and in some studies the absence of the chin, which has known to restrict the end of movement during flexion motion[9] .

In manual medicine the three-dimensional aspect (3D) of joint kinematics are assessed and treated based on specific concept of motion coupling[17] .

In manual therapy, segmental spine mobilization is proposed as a way of restricting the desired effect of the intervention to one specific motion segment. It is, however, not know whether and to what extent such a restriction can be achieved. Understanding the segmental three-dimensional kinematics of the upper cervical manual mobilization techniques is especially relevant in appreciating the possible risks and effects of such intervention[21].

In literature there are very few studies that analyze segmental ranges of movement of main and coupled motions during manual passive mobilization of the upper cervical spine.

In an in vitro study, Cattrysse et al.[14] analyzed the influence of the manual mobilization of the atlanto-axial joint on motion coupling patterns. Segmental motion coupling was recorded during manual mobilization through the full range of axial rotation and lateral bending. Although differences in methodological approaches, this study revealed that coupled patterns between axial rotation and lateral bending, observed during manually induced functional anatomical movements, showed similarities with the results of kinematic studies using pure moment of forces.

In two other in vitro studies, Cattrysse et al.[13,21] analyzed the three-dimensional aspects of manual flexion-extension, axial rotation and lateral bending mobilizations of the atlanto-occipital joint and atlanto-axial joint using an electromagnetic tracking device and a 3D-digitizer. The segmental motion of these joints were registered during three different manual techniques: regional mobilization, segmental mobilization with manual fixation and segmental mobilization with locking of the inferior cervical spine.

The results of the studies indicate that the manual fixation of the atlas did not significantly influence the flexion-extension movement in C0-C1 segment, compared to a regional mobilization, but reduced coupled axial rotation and lateral bending components on the mobilized segment, and reduced also the movements of axial rotation and lateral bending in the adjacent atlanto-axis joint. Also the locking technique reduced rotation in all axes, but the results were not statistically significant.[21]

During axial rotation mobilization of the atlanto-axial joint, the manual fixation and the locking techniques reduce the range of coupled motion components. The locking technique, however, enables an increase in the main motion. The coupling pattern is not influenced by the segmental mobilization technique. The segmental lateral bending mobilization techniques did not induce significant differences in the range of coupled motion compared to a regional mobilization technique. The fixation technique reduced the coupled flexion-extension motion in the atlanto-axial joint[13]. Thus, suggests that segmental mobilizations can reduce coupled components associated to the main movements but they did not influence the range of the main motion, suggesting that different techniques could be useful in different situations depending on the desired effects.

Although these experiments gather useful information to the manual planar mobilization techniques, in literature there are no studies analyzing the 3D-kinematics of three-dimensional non- planar, i.e. combined mobilization of the upper cervical spine.

This thesis aims to present an in vitro experimental study, conducted by two expert manual therapists, in which the kinematics of the upper cervical spine were recorded during manual three-dimensional mobilization, i.e. combined flexion-extension with axial rotation. And different techniques used in manual therapy were compared: segmental mobilization with manual fixation of the lower segment and while using a 3D-locking technique.

The purpose is to understand how different manual techniques can influence the kinematic of the upper cervical spine, what is the relationship between the three-dimensional main motion and the coupled components, how 3D-mobilizations differ from planar mobilizations and to analyze inter and intra therapist reproducibility of these effects.

Table 5. method and subjects of mentioned studies in literature

Study	method	subjects
Gelalis 2009	In vivo. MDT and inclinometer	10 healthy volunteers, mean age 29.3
Edmondston 2005	In vivo, Spine T goniometer	30 heathy volunteers, mean age 24.6
Karthu 1999	In vivo, kinematic MRI	20 healthy volunteers, mean age 29
Ishii 2004	In vivo, MRI	15 healthy volunteers, mean age 24.3
Ishii 2006	In vivo, MRI	12 healthy volunteers, mean age 23.6
Goel VK 1988	In vitro, stereophotogrammetry and optoelectronic device Selpot II	8 fresh human cervical spine, mean age 80
Panjabi 1988	In vitro stereophotogrammetry	10 fresh human cervical spine specimens
Panjabi 1991	In vitro, stereophotogrammetry	10 fresh human cadaveric specimens, mean age 51.7
Panjabi 1991	In vitro, stereophotogrammetry	10 fresh human cadaveric specimens, mean age 51.7
Panjabi 1991	In vitro, stereophotogrammetry	10 fresh human cadaveric specimens, mean age 52
Panjabi 1993	In vitro, stereophotogrammetry	7 fresh human cadaveric specimens
Panjabi 2001	In vitro stereophotogrammetry. C0-C7	17 fresh human cervical spines
Cattrysse 2007	In vitro, flock of bird: electromagnetic tracking system. C0-C1	6 cervical specimens: 5 embalmed, 1 fresh, mean age more than 50
Cattrysse 2007	In vitro, flock of bird: electromagnetic tracking system.	6 specimens: 5 embalmed, 1 fresh, mean age 60 or more
Cattrysse 2008	In vitro, flock of bird: electromagnetic tracking system, and 3D-digitiser	10 specimens:9 embalmed, 1 fresh, mean age more than 60
Cattrysse 2011	In vitro, adepted Zebris CMS20, ultrasound motion tracking	20 fresh specimens, mean age 80
Dugailly 2010	In vitro, computerized tomography	10 unembalmed cervical specimens
Dugailly 2011	In vitro, computerized tomography	10 unembalmed cervical specimens

1.1 Purpose

This study represents a 3D in vitro analysis on twenty fresh human spine specimens in a test-retest situation with two manual therapists.

The experiment combines an ultrasound device for continuous motion registration with manual applied mobilization technique in an *in vitro* set-up.

The purpose of the study is to analyze the kinematic behavior of the atlanto-occipital joint during a three-dimensional mobilization, comparing two different segmental manual techniques, and to analyze intra and inter-examiners reproducibility of these effects.

The three-dimensional mobilizations, flexion-right axial rotation and flexion-left axial rotation, have been performed at C0-C1 segment, however segmental motion components are analyzed on C0-C1 and C1-C2 segments.

The experimental part of this thesis has been performed in 2006 and includes method and material of studies of Cattrysse et al. (2007). For that reason the methodological part is the same. The following chapter, method and material, is similar to Cattrysse et al. (2008)[24].

2. Method and material

2.1 Specimens

In this experimental study twenty fresh human spinal specimens were included, 9 specimens from male and 11 from female subjects. Each specimen included the occiput, the cervical segments and the first two thoracic vertebrae. The mean age of the specimens was 80 years (± 11 years) with a range 59 to 97.
Room temperature was controlled between 15° and 20° and humidity was above 60% to prevent dehydration of the specimens during the test procedure.

2.2 Instruments

An adapted Zebris CMS20 ultrasound-based motion tracking system (Zebris Medical GmbH – Germany) was used in this study.
The accuracy of the system has been studied using a single hinge phantom. One transmitter and the receiver of the device were mounted on a high accuracy rotary stage (Time and Precision Ltd., Baringstoke, England) making it possible to produce angular displacements with an accuracy of 0.02° per step.
The standard deviations can be used as an indicative measure of error. An overall deviation of 0.04° occurs on the main axis on a total measurement range of 75° of motion of the phantom. Standard deviation of 0.25° and 0.29° occur on the other axes. Differences between the performed angular displacements and the angles calculated can be partly attributed to cross-talk effects. After applying a correction technique for misalignment between the axis of the phantom and the reference frame defined during the set-up of the Zebris system, based on an optimization technique, these standard deviations for the real and measured angles can be reduced to 0.20° and 0.13°. The system thus reproduces angles of movements with an accuracy of less than 0.1° for the main motion component and 0.2° for the coupled components .

2.3 Methods

In all specimens the dissection of the skin, subcutaneous tissue and muscles were performed, leaving the muscular insertions and ligaments intact. This procedure is necessary because, during the fixation of the ultrasound system on the segments, uncontrolled movements and coupled motions might occur. Moreover, leaving muscles, biomechanical changes can alter the results, but it has been demonstrated that the biomechanical properties of ligaments and tendons do not change due to conservation by freezing[22,23].

Specially fabricated fixation tools were inserted in the parietal part of the occiput (C0), the transverse process of the atlas (C1) and the transverse process of the axis (C2). The transmitters and the receiver of the Zebris system were mounted on these fixation tools. Before starting the mobilizations, the optimal positioning of the device was controlled for every specimen. Fixation pins were drilled cross-linked through the corpus of the second thoracic vertebra (T2). The specimen was mounted in a wooden frame by these fixation pins. In this way the specimen was positioned as if the subject was in a supine posture on an examination table to simulate a physiotherapy session. The dissection and the optimal positioning of the fixation tools permitted free mobility of the cervical spine through full range of motion in axial rotation, lateral bending, flexion-extension and combined directions[24].

During the experiment each specimen was manually guided through two complex mobilizations. First a flexion and right axial rotation mobilization were performed in C0-C1 segment, and subsequently a flexion and left axial rotation at the same cervical level. These two type of mobilization were executed with two different segmental techniques. The first by manually fixating the axis and, secondly, by using a three dimensional locking of the lower and mid-cervical segment up to C1-C2. These two different techniques are commonly used in the physiotherapic practice and are useful to focus the movement at the cervical segment that has to be treat. During the manual fixation technique, the therapist fixed the atlas manually by the posterior arc while mobilizing the head in flexion-axial rotation direction. In the locking technique, the inferior cervical spine were brought into a three dimensional end-range position combining flexion, lateral bending and controlateral axial-rotation up to the C1-C2 segment before mobilizing the atlanto-occipital joint[21]. During the execution of the experiment, the 3D ultrasound tracking sensors, fixed on the occiput and the first two cervical vertebrae, recorded the motion.

All the mobilization techniques were performed three times consecutively by two physiotherapists with several years of experience in manual therapy, in a test-retest situation. The test-retest order was assigned randomly for the two investigators, and they were blinded from the analysis data of the system during testing.

One of the examiner was familiar with the specific techniques from many years, while the other usually performed similar but not identical techniques, and familiarized with the techniques used in this study before the testing period.

Both examiners performed a trial with feedback of the tracking system in a test-retest situation on one specimen to familiarized with the mobilizing techniques and the test set-up[24].

2.4 3-D angles of motion

The angles of movement used in the present analysis are the angles reproduced from the Zebris-winbiomechanics software. A graphical representation of the calculated angles has been presented by Wang et al[25].

The definition of the local reference frame used by the Zebris system is based on a three markers: L, R and F. The point L, referred to left, was chosen on a marker inserted on the left transverse process of the axis, the point R, referred to right, was inserted on the right transverse process, and the point F, front, centrally on the anterior side of the corpus.

The International Society of Biomechanics (ISB) provides guidelines that define the local reference frame for the mid-cervical spine segment, but it does not define local reference frame on the upper cervical spine: atlas and axis[26].

By reason of the specific anatomy of the upper cervical vertebrae and the nature of the experiment, the centre of the corpus of the vertebra could not be defined.

The above described reference frames for atlas and axis were therefore defined and the labeling of the axes was chosen in congruency with the ISB-guidelines.

The axes are defined as follows:

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

The direction of the Z-axis was reversed to create a right handed orthogonal reference frame. For reasons of clearness of the graphical and numerical representation the sign of the angles around the Y-axis was changed. In this way, an axial rotation and a lateral bending movements to the same side are indicated by the same sign, on the contrary, an axial rotation and lateral bending to the opposite side are indicated with opposite signs. Left and right are respectively represented by + and – signs.

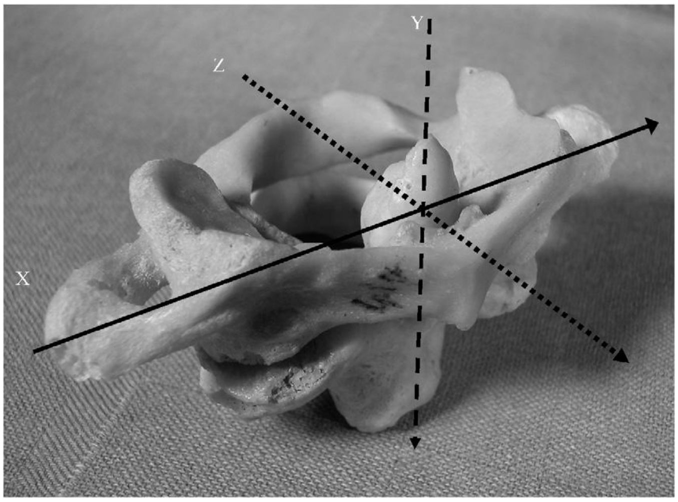

Fig 1. bone embedded coordinate system on C1: X-axis: segmental flexion-extension, Z- axis: segmental lateral bending axis, Y-axis: segmental axial rotation axis

2.5 Data analysis using Mathcad professional software

Unprocessed data were recorded as ASCII files and computed by Mathcad professional software. The first part of the data analysis consisted in the selection of the correct curves that represented the complex movements performed by two operators.

In the 3D mathcad model x ,y, z represent respectively flexion-extension, axial rotation and lateral bending.

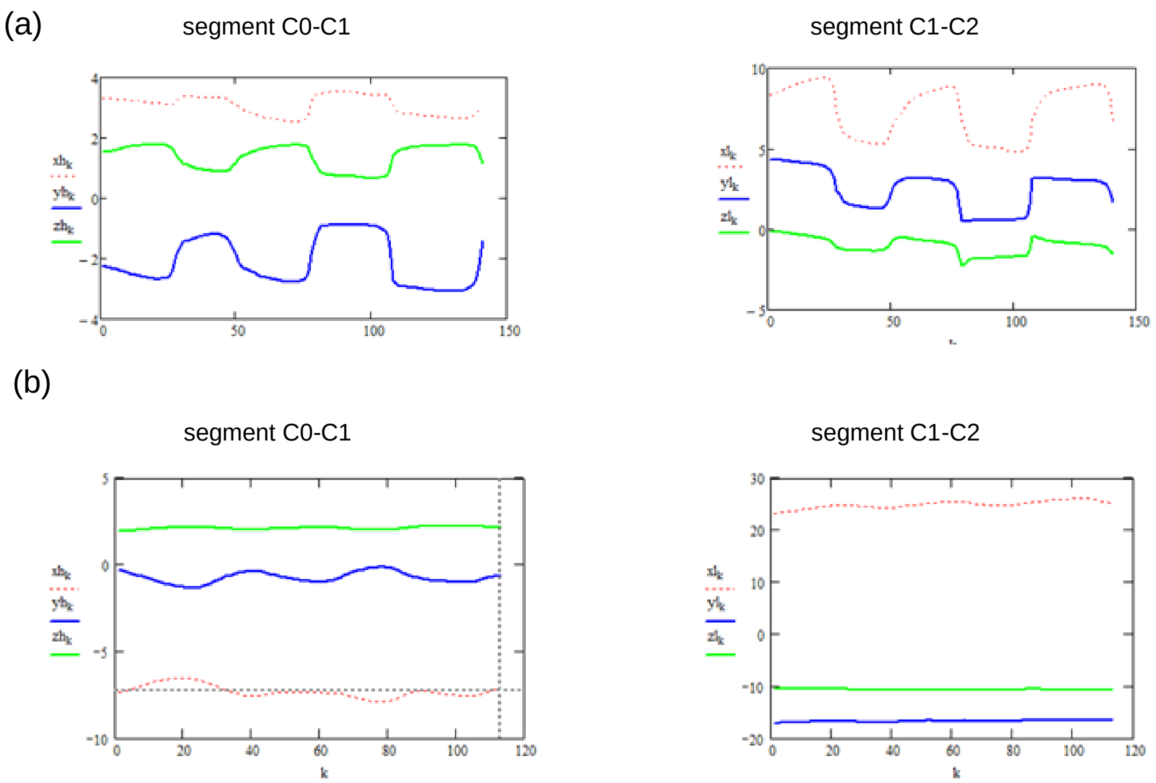

Fig 2. Kinematics curves for a single specimen during (a) flexion-left axial rotation with manual fixation technique in C0-C1 segment(specimen 173), (b):flexion-left axial rotation mobilization with locking technique in C0-C1 segment (specimen 167), xhk: flexion-extension axis, yhk: axial rotation axis, zhk: lateral bending axis, k: sampling size 20Hz.

In each specimen four tests were considered: test-retest of two examiners. The test-retest were performed for complex manual mobilizations in C0-C1 segment: flexion-axial rotation to the right, and flexion axial rotation to the left. Two different manual techniques were compared. Mathcad professional software calculated also the unintended movements that occurred in C1-C2 segment. The figure above (fig.2) shows an example for manual fixation and locking techniques. One of the test was not analyzed by Mathcad software, and was not considered in the statistical analysis because of bad signal of the data originated from the ultrasound Zebris system, due to technical problem.

At the end of Mathcad software calculations a sample of tests was randomly controlled a second time .

2.6 Data analysis of motion coupling patterns

The pattern of motion coupling between the main flexion-axial rotation and the coupled lateral bending movement component were analyzed. Six different parameters were defined to describe these coupling patterns in a objective way.

In the experiment no starting point was strictly defined, this implied that the range of motion was considered as the extreme position reached by each axis: flexion, axial rotation and lateral bending. In this study these parameters were labeled Max X, Max Y, Max Z, for extreme positions of flexion, axial rotation and lateral bending motions respectively.

The Euclidean norm, represented by the mathematical formula: $\sqrt{x^2+y^2+z^2}$, was calculated. It represents a vector which can be considered a mathematical representation of the overall amount of motion.

The cross-correlation (CC), parameter that describes the relationship between the axial rotation and the coupled lateral bending component, was calculated. The cross-correlation parameter can be regarded as the equivalent of a Pearson correlation coefficient.

The ratio between the axial rotation and the coupled lateral bending can be defined as the relative amount between the extreme position of axial rotation and lateral bending motions.

2.7 Statistical Analysis

Unprocessed data were recorded as ASCII files and computed by Mathcad professional software through a predetermined routine.

The statistical software SPSS (version 19.0) was used to make all statistical calculations.

A Kolmogorov-Smirnoff goodness-of-fit test was firstly performed to control the normal distribution of data of the six parameters and descriptive statistics were calculated (addenda 2). The reproducibility of the results was studied by analysis differences and correlations between test and retest results of two operators.

For each segmental mobilization techniques, locking and manual fixation, the differences between paired data of measurements were defined using an analysis of variance (ANOVA). Secondly, in the parameters that presented a statistically significant ANOVA, a paired Student's t-test between consecutive measurements was performed.

If the ANOVA between the extreme position of the three movements (Max X, Max Y, Max Z) showed significant differences between test-retest of the two operators, another variables was created by calculating the Euclidean norm. Thus, this parameter was not calculated for each type of mobilization.

The strength of the correlation between parameters in different measurement situations was estimated by the intra-class correlation coefficient (ICC). The classification of this index is included between 0 and 1, where <0 is "poor", 0-0.20 is "slight", 0.21-0.40 is "fair", 0.41-0.60 is "moderate", 0.61-0.80 is " substantial, 0.81-1.00 is "almost perfect" correlation.

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

3. Results

In the statistical analysis 192 variables were considered for each of the twenty specimens. The followed parameters were calculated: three extreme positions reached by the three motion components (Max X, Max Y, Max Z), the Euclidean norm, and two measures of relation (correlation and ratio) in C0-C1, C1-C2 segments, during two different complex mobilizations (flexion-right axial rotation and flexion-left axial rotation) comparing two different segmental fixation techniques (manual fixation and locking technique). The mobilizations were performed in the atlanto-occipital joint by two examiners a test-retest situation, and also the undesired movements in the atlanto-axial joint were registered and calculated.

An ANOVA was performed for all the parameters reported above (table 6). This reliability analysis was calculated to compare the results of the two examiners in the test-retest situation (t1-r1-t2-r2).

Analyzing the variables of the extreme position of the three different dimensions (flexion-extension, axial rotation and lateral bending: Max X, Max Y, Max Z), only three mobilizations do not show statistical differences for any of these variables in the ANOVA: flexion-right rotation of C0-C1 with locking technique (FRL 01), flexion-left rotation C0-C1 with manual fixation (FLM 01) and flexion-left rotation C0-C1 with locking technique (FLL 01). The ANOVA of the other mobilizations presents statistical significance in one or two variables.

A non statistically significant ANOVA means that the results of inter- and intra-examiner comparisons do not present differences and they could be considered as one measure.

For all the non statistical significant parameters in the extreme positions of direction of movements, the mean and the standard deviation within examiners were calculated and showed in the table 7. The strength of correlation between parameters was estimated by the intra class correlation coefficient (ICC) and the results are shown in table 8.

Table 6. Statistical significant and not significant parameters calculated with ANOVA in complex mobilizations

parameters	FRM 01	FLM 01	FRL 01	FLL 01	FRM 12	FLM 12	FRL 12	FLL12
MAX X	,946	,339	,131	,122	,400	**0,001****	**,035***	**,000****
MAX Y	**,017***	,167	,114	,122	,668	,639	,875	,649
MAX Z	,940	,555	,259	,915	**,001****	**,004****	,139	,368
EUCL. NORM	,194	nc	nc	nc	**,002****	**,05***	,81	**,014***
CC	,651	,536	,615	,960	,920	,261	,610	,184
RATIO	,401	,813	,223	,673	,242	,896	,352	,898

Max X: extreme position flexion movement, Max Y: extreme position axial rotation movement, Max Z: extreme position lateral bending movement, Eucl.norm: Euclidean norm, CC: cross-correlation between axial rotation and lateral bending motions, Ratio: relative amount between axial rotation and lateral bending motions, FRM: flexion-right axial rotation with manual fixation, FLM: flexion-left axial rotation with manual fixation, FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique, 01: C0-C1 segment, 12: C1-C2 segment.nc: not calculated

*: $p \leq 0,05$

**: $p \leq 0,01$

Table 7. mean values (sd) of the extreme position of the three direction of movement, expressed in degrees.

N= 20	Max X	Max Y	Max Z
FRM 01	3.06(4.5)	-	0.39(2.2)
FLM 01	1.4(4.6)	-0.3(5)	1,7(2.9)
FRL 01	0.4(5.7)	1.4(4.4)	-1.9(3.4)
FLL 01	-0.7(4.3)	-0.3(6.2)	1.2(3.2)
FRM 12	-0.04(5.3)	5.3(5)	-
FLM 12	-	0.5(3.9)	-
FRL 12	-	23(11.9)	2.7(6.3)
FLL 12	-	-21(8.4)	-1.1(8.4)

N: number of specimens, sd: standard deviation, Max X: extreme position flexion movement, Max Y: extreme position axial rotation movement, Max Z: extreme position lateral bending movement. FRM: flexion-right axial rotation with manual fixation, FLM: flexion-left axial rotation with manual fixation, FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique, 01: C0-C1 segment, 12: C1-C2 segment, -:statistical significant values in the ANOVA test, the mean was not calculated

Table 8. intra-class correlation coefficients of all parameters resulted not statistically significant with ANOVA

Parameters	C01 Right		Left		C12 Right		Left	
	Manual	Lock	Manual	Lock	Manual	Lock	Manual	Lock
	ICC				ICC			
MAXX	**0,62****	**0,76****	**0,47***	0,15	**0,67****	**-**	**-**	**-**
MAXY	**-**	0,33	**0,68****	**0,79****	0,30	**0,47***	-0,30	0,10
MAXZ	-0,32	-0,31	-0,20	-0,39	**-**	0,32	**-**	**0,54****
Eucl. norm	**0,50***	nc	nc	nc	**-**	**0,72****	**-**	**-**
CC	-0,09	0,40	0,35	0,17	**0,54****	0,17	**0,47***	**0,50***
Ratio	**0,43***	0,17	-0,15	0,11	-0,13	0,09	-0,42	0,13

ICC: intra-class correlation coefficient, Manual: manual fixation technique, Lock: locking technique, right: right axial rotation, left: left axial rotation Max X: extreme position flexion movement, Max Y: extreme position axial rotation movement, Max Z: extreme position lateral bending movement, Eucl.norm: Euclidean norm, CC: cross-correlation between axial rotation and lateral bending motions, Ratio: relative amount between axial rotation and lateral bending motions, 01: C0-C1 segment, 12: C1-C2 segment.nc: not calculated, - parameters statistical significant with ANOVA

*: $p \leq 0,05$

**: $p \leq 0,01$

3.1 Extreme positions and Euclidean norm

Regarding the atlanto-occipital joint, the extreme positions of flexion (Max X) does not show different inter- and intra- examiner comparisons for the different mobilizations in the ANOVA. The means(sd) are distributed from -0,7°(4,3°) to 3,06°(4,5°). A negative value means an extension movement. The ICC vary between 0,15 and 0,76 (from slight to substantial reproducibility), however one of the ICC values in locking technique is not statistically significant.

Also the extreme position of lateral bending (Max Z) does not show different inter- and intra-examiners comparisons in all different mobilizations in ANOVA, but the ICCs, distributed between -0,39 and -0,20, are very low and all of them are not statistically significant. The means of Max Z are distributed between -1,9°(3,4°) and 1,7°(2,9°), in which a negative value means a right lateral bending movement.

The extreme position of axial rotation movement (Max Y), calculated with ANOVA, shows an acceptable inter- and intra-examiner reproducibility, except for the flexion-right axial rotation with manual fixation (FRM 01).

The ICC vary between 0,33 and 0,79. However, only during the flexion-left axial rotation with manual fixation as well as with locking technique (FLM and FLL 01) the ICC is statistically significant. The mean is distributed from -0,3°(6,2) to 1,4°(4,4°).
Regarding the atlanto-axial joint the extreme axial rotation position (Max Y) shows a good intra- and inter-examiners reproducibility, with ANOVA, however the ICC is significant (0,47) only for the flexion-right axial rotation with locking (FRL 12).The mean is distributed from 0,5°(3,9°) to 23°(11,9°).
The extreme flexion position (Max X) presents a good intra- and inter- examiners reproducibility only in flexion right axial rotation with manual fixation (FRM) and reports a mean of -0,04°(5,3°) and a substantial ICC (0,67).
The extreme lateral bending position (Max Z) is not statistically significant in ANOVA during the locking technique. The means are distributed between -1,1°(8,4°) and 2,7°(6,3°) and the ICC goes from moderate to substantial (0,54-0,64).

For the other parameters that demonstrated statistically significant results in the ANOVA test, a pair wise analysis of the results by Student's t-test for paired samples were performed. The results are presented in table 9 . The Student's t-test is used to compare the mean of two groups. In this case all the combinations between test and retest of the two examiners were calculated: t1-r1-t2-r2. This means that 6 pairs were compared: t1-r1,r1-r2, t2-r2, r2-r1, t2-t1, t1-r2.

Table 9: significance in Student's t-test in the parameters resulted statistical significant in the ANOVA

Parameters	t1-r1	t2-r2	r1-t2	r2-r1	t2-t1	t1-r2
Max Y FRM 01	Not sign	**Sign0,037**	Not sign	**Sign 0,040**	Not sign	**Sign 0,002**
Max Z FRM 12	**Sign 0,005**	**Sign 0,006**	Not sign	Not sign	Not sign	**Sign 0,001**
MaxZ FLM 12	**Sign0,004**	**Sign 0,042**	Not sign	Not sign	Not sign	**Sign 0,004**
MaxX FLM 12	Not sign	Not sign	**Sign 0,031**	**Sign 0,001**	**Sign0,003**	**Sign 0,001**
Max X FLL12	Not sign	Not sign	**Sign 0,012**	**Sign 0,008**	**Sign 0,001**	**Sign 0,002**
Max XFRL 12	Not sign	Not sign	**Sign 0,006**	Not sign	Not sign	Not sign
Eucl FRM 12	Not sign	Not sign	**Sign 0,003**	**Sign 0,003**	**Sign 0,054**	Not sign
Eucl FLM 12	Not sign	Not sign	**Sign 0,024**	**Sign 0,013**	Not sign	Not sign
Eucl FLL 12	**Sign 0,014**	Not sign	**Sign 0,015**	Not sign	Not sign	Not sign

Max X: extreme position flexion motion, Max Y: extreme position axial rotation motion, Max Z: extreme position lateral bending motion, Eucl: Euclidean norm, Ratio: relative amount of axial rotation and lateral bending, FRM: flexion-right axial rotation with manual fixation, FLM: flexion-left axial rotation with manual fixation, FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique, 01: C0-C1 segment, 12: C1-C2 segment, t1: test of the first examiners, r1: retest of the first examiners, t2: test of the second examiners, r2:retest of the second examiner, Sign: significant p≤0,05, Not sign: not significant ≥0,05.

Max X Student's t-tests performed for flexion left and right rotation mobilization with locking technique and left rotation with manual fixation in C1-C2 segment (FRL, FLL, FLM 12) shows no differences for the intra-examiners comparisons (t1-r1, t2-r2). The other variables concerning the extreme position of movements do not present a statistically significant intra- and inter-examiners reliability.

Consequentially, the Euclidean norm was calculated for all the complex mobilization that showed statistical differences in Max X, Max Y or Max Z with the ANOVA test. The statistical analysis respected the same procedure used for the extreme positions: ANOVA and subsequent Student's t-test, if indicated.

The ANOVA calculated for the Euclidean norm is not statistically significant during flexion- right axial rotation of C0-C1 segment with manual fixation (FRM 01) and flexion right axial rotation C1-C2 with locking (FRL 12) with a moderate and substantial ICC (0,50-0,72).

The Student's t tests, calculated for the Euclidean norm (table 9), during flexion-right and left axial rotation with manual fixation in C1-C2 segment (FRM, FLM 12) do not show differences in test-retest of both examiners. This parameter in flexion-left axial rotation of C1-C2 segment with locking (FLL12) shows a good intra reproducibility only in the second examiner.

3.2 Cross-Correlation

The cross-correlation describes the relationship between the axial rotation and the coupled lateral bending component. The cross-correlation parameter can be regarded as the equivalent of a Pearson correlation coefficient. This cross correlation coefficient has a maximum value of ±1 indicating a perfect degree of association between axial rotation and lateral bending movement. A negative value means that axial rotation and coupled lateral bending move in a opposite direction, i.e. controlateral, and a positive value means that the two movements run in the same direction, i.e. ispilateral.

In all mobilizations techniques there are no differences for intra- and inter- examiners comparisons in both C0-C1 and C1-C2 segments with ANOVA. However the ICC is significant only in the atlanto-axial joint and it varies between 0,47 and 0,54.

Tables 10-10(II) report the means and standard deviation of cross-correlation calculated for t1, r1, t2, r2 during the execution of the two complex mobilizations with locking and with manual fixation. In this study the variation of cross-correlation parameter is generally from -1.00 to +1.00. The negative and positive values were calculated separately to not cause error during the calculation of the overall mean value.

Regarding the tables, it seems that the mean values of cross-correlation of atlanto-occipital joint tends to be generally a negative value, while in the atlanto-axial joint it is generally a positive value.

The mean negative and the positive values for C0-C1 segment vary from -0,55 to -0,90 and from 0,53 to 0,93.

The mean negative and the positive values for C1-C2 segment vary from -0,05 to -0,83 and from 0,39 to 0,83.

Table 10. Means and standard deviations for negative values of cross correlation in C0-C1 and C1-C2 segments

CC	**t1**			**r1**			**t2**			**r2**		
Mob.	**n**	**Mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**
FRM01	13	-0,79	0,2	14	-0,71	0,2	14	-0,71	0,19	11	-0.67	0.30
FLM01	**13**	**-0,90**	**0,08**	13	-0,85	0,18	12	-0,73	0,21	10	-0,78	0,18
FRL01	14	-0,58	0,28	12	-0,71	0,26	9	-0,60	0,24	**13**	**-0,55**	**0,28**
FLL01	11	-0,73	0,26	11	-0,65	0,30	11	-0,82	0,21	12	-0,79	0,30
FRM12	7	-0,75	0,28	**6**	**-0,83**	**0,22**	6	-0,49	0,38	5	-0,58	0,27
FLM12	10	-0,55	0,38	7	-0,54	0,28	7	-0,59	0,22	12	-0,65	0,27
FRL12	6	-0,48	0,42	**8**	**-0,05**	**0,64**	5	-0,63	0,29	3	-0,55	0,29
FLL12	8	-0,74	0,31	12	-0,70	0,26	10	-0,65	0,21	12	-0,65	0,27

Table 10(II). Means and standard deviations for positive values of cross correlation in C0-C1 and C1-C2 segments

CC	**t1**			**r1**			**t2**			**r2**		
Mob	**n**	**Mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**
FRM01	7	0,57	0,31	6	0,75	0,23	6	0,66	0,27	9	0,69	0,32
FLM01	7	0,71	0,35	7	0,63	0,33	8	0,67	0,27	10	0,68	0,27
FRL01	6	0,58	0,28	8	0,64	0,32	**11**	**0,53**	**0,33**	7	0,71	0,28
FLL01	9	0,55	0,29	9	0,75	0,32	9	0,70	0,27	**7**	**0,93**	**0,06**
FRM12	**13**	**0,81**	**0,28**	14	0,69	0,30	14	0,71	0,23	15	0,65	0,27
FLM12	10	0,55	0,35	13	0,47	0,38	**13**	**0,39**	**0,36**	8	0,43	0,40
FRL12	14	0,67	0,35	12	0,23	0,57	15	0,57	0,25	17	0,66	0,29
FLL12	12	0,69	0,30	8	0,60	0,34	10	0,50	0,28	7	0,46	0,33

CC: cross correlation, t1: test of first operator, r1: retest of the first operator, t2: test of the second operator, r2: retest of the second operator. n: number of specimens, mean: mean of negative(table10) and positive (10 II) values between specimens for each mobilization and each examiners separately. Mob: type of mobilization, FRM: flexion-right axial rotation with manual fixation, FLM: flexion-left axial rotation with manual fixation, FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique,01: C0-C1 segment, 12: C1-C2 segment. Bold: maximum and minimum mean value

3.3 Ratio

The ratio between the axial rotation and the coupled lateral bending can be defined as the relative amount between the extreme position of axial rotation and lateral bending motions.

The calculation of ANOVA for the ratio parameters does not show statistical significance in all different mobilizations for atlanto-occipital joint, as well as for the atlanto-axial joint.

In this variable the values of ICC are not significant, except for flexion-right axial rotation in C0-C1 with manual fixation (FRM 01) where the ICC is moderate (0,43) (table 8). As for the cross-correlation parameter, also for the ratio, the means and standard deviation were calculated for the test-retest of each examiner in all different mobilizations reported in this study. The means for controlateral and ipsilateral coupling specimens were calculated separately for negative and positive values (tables 11,11(II)).

The mean of negative and the positive values(sd) for C0-C1 segment vary from -0,7(0,44) to-5,6(13,9) and from 0,6(0,48) to 11,5(34,9).

The mean of negative and the positive values for C1-C2 segment vary from -1,6(0,6) to -13,4(20,2) and from 0,6(0,48) to 31,8(64,7).

The extreme position of axial rotation motion exceeds the extreme position of coupled lateral bending, mainly in the C1-C2 segment.

Table11: Means and standard deviations for negative values of ratio in C0-C1 and C1-C2 segments

Ratio	t1			r1			t2			r2		
Mob.	**n**	**Mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**
FRM01	9	-0,96	0,47	8	-1,3	0,99	8	-1,7	1,9	6	-1,02	0,6
FLM01	9	-5,3	11,9	7	-2,3	1,6	8	-4,3	9,4	9	-3,3	4,1
FRL01	12	-1,5	2,3	7	-2,3	2,0	**13**	**-5,6**	**13,9**	11	-1,4	2,9
FLL01	10	-1,9	3,1	**10**	**-0,7**	**0,44**	12	-3,4	7,7	10	1,8	2,7
FRM12	5	-1,6	2,1	**6**	**-1,6**	**0,6**	6	-2,1	1,6	9	-2,3	1,9
FLM12	7	-1,8	0,9	7	-1,9	1,4	7	-4,5	6,7	9	-1,9	1,3
FRL12	7	-2,7	1,9	8	-4,6	3,1	9	-9,4	9,6	9	-6,7	4,6
FLL12	9	-2,4	1,06	9	-4,1	3,3	10	-10,2	12	**7**	**-13,4**	**20,2**

Table11(II): Means and standard deviations for positive values of ratio in C0-C1 and C1-C2 segments

Ratio	t1			r1			t2			r2		
Mob.	**n**	**Mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**	**n**	**mean**	**sd**
FRM01	11	4,2	5	12	3,5	5,7	12	2,9	5,4	**14**	**11,5**	**34,9**
FLM01	11	1,7	1,8	13	1,1	1,1	12	1,5	2,2	11	3,3	3,1
FRL01	8	1,3	1,1	13	5,5	14,7	7	1,7	2,0	9	3,7	7,2
FLL01	10	0,9	1,2	**10**	**0,6**	**0,48**	8	3,7	7,9	9	7,5	19,8
FRM12	15	3,9	3,7	14	1,6	0,96	14	7,9	9,2	11	5,7	9,7
FLM12	13	3,0	2,5	13	1,6	0,8	13	3,2	4,6	11	2,5	1,8
FRL12	13	4,3	6,9	12	8,0	14,3	11	9,3	9,1	**11**	**31,8**	**64,7**
FLL12	**11**	**1,7**	**1,5**	11	1,9	2,2	9	14,9	29,6	12	5,8	6,0

Ratio: relative amount between extreme axial rotation position and extreme lateral bending position, t1: test of first operator, r1: retest of the first operator, t2: test of the second operator, r2: retest of the second operator. n: number of specimens, mean: mean of negative(table11) and positive (11II) values between specimens for each mobilization and each examiners separately. Mob: type of mobilization, FRM: flexion-right axial rotation with manual fixation, FLM: flexion-left axial rotation with manual fixation, FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique,01: C0-C1 segment, 12: C1-C2 segment. Bold: maximum and minimum mean value

3.4 Analysis of differences between techniques

The statistical analysis with ANOVA shows no significant results for the intra- and inter- examiners reliability comparison in most of the extreme position for each motion component. However most of the cases present a non statistical significance in the intra-class correlation coefficient (ICC). For that reasons only few comparisons using the Student's t-test between means can be performed as shown in the table 12.

Table 12: Student's t t-test between means of the C0-C1segment, manual vs locking fixation technique, right rotation vs left rotation during manual fixation

Manual vs locking	**Mean(sd)**	**Sign**
Max X01: FRMvsFRL	2,6(2,9)	0,001*
Max Y01: FLMvsFLL	-0,02(3.6)	0,976
Right vs left rotation	**Mean(sd)**	**Sign**
Max X01: FRMvsFLM	1,6(2,9)	0,02*

Manual: manual fixation technique, Locking: locking technique, right: right axial rotation movement, left: left axial rotation movement, sd: standard deviation, Sign: significant ,*:p≤0,05, Max X: extreme position flexion movement, Max Y: extreme position axial rotation movement, FRM: flexion-right axial rotation with manual fixation, FLM: flexion-left axial rotation with manual fixation, FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique, 01: C0-C1 segment, 12: C1-C2 segment. *:≤0,05

The analysis of differences between means was performed to compare the two different segmental fixation techniques, (manual fixation compared to locking technique), and the opposite direction of axial rotation movement, (right and left). Table 11 shows a statistical difference of 2,6° in the flexion movement during the manual fixation in the atlanto-occipital joint, and a statistical difference of 1.6° at the same level during the flexion-right axial rotation, compared to flexion-left axial rotation. Otherwise axial rotation movement is not influenced by the type of segmental fixation.

4. Discussion

This study represents a 3D *in vitro* analysis on twenty fresh human spine specimens in a test-retest situation with two manual therapists.

The experiment combines an ultrasound device for continuous motion registration with manual applied mobilization technique in an *in vitro* set-up.

An overall accuracy for angular rotation of 0.6° for Zebris ultrasound system was found by Natalis and Koning[27]. The results of the validation procedure of the Zebris CMS20 device used in this study are in agreement with these findings and offer an adequate precision for analyzing segmental motions during manual mobilization[26].

The purpose of the study was to analyze the kinematic behavior of the atlanto-occipital joint during two three-dimensional mobilizations, flexion-right axial rotation and flexion-left axial rotation, comparing two different segmental manual techniques that were used to fixed the atlanto-axial joint. However, before comparing techniques inter- and intra-therapist reproducibility had to be analyzed.

The inter- examiner reliability is the variation in measurements when taken by different observers but with the same method or instrument. Intra-examiner or test-retest reliability is the variation in measurement taken by the same observer or instrument on the same item and under the same condition.

Reproducibility of manual and more specifically segmental mobilization techniques remains a debatable matter. In his study Cattrysse at all[26] showed differences in intra-examiner reproducibility between observers.

In this experiment, the ANOVA results, obtained in all the six parameters analyzed in the atlanto-occipital joint, show an acceptable level of intra- and inter-examiners reproducibility, but not for all parameters considered in the atlanto-axial joint. For the parameters that showed differences in the ANOVA, the Student's t-test for paired sample was calculated. According to Cattrysse[26] 5 parameters out of 9 presented an acceptable intra-examiner reproducibility, (Max X FLM, FLL, FRL and Euclidean norm FRM and FLM in C1-C2 segment).

This study was performed by two experienced manual therapists, but with different levels of familiarization with the applied techniques. This could explain the acceptable intra-examiners reproducibility and the low inter-observer reliability.

The differences found with ANOVA in the atlanto-axial joint could be contributed to the fact that the different complex mobilizations were performed on the C0-C1 segment, whereas the lower segment C1-C2 was fixed, using two different segmental techniques. In that case the attention of the examiners was pointed on the mobilized segment.

Although an acceptable level of reliability was observed, the intra-class correlation coefficients (ICC) were not statistically significant in the majority of the parameters. The ICC shows the strength of the correlation between parameters in different measurements situations and it is classified from poor, <0, to almost perfect,1, correlation. The significant ICCs within parameters vary from 0,43 to 0,79, i.e. from moderate to substantial correlation. This result can be explained by the fact that the occipito-atlanto-axial complex exhibits the highest degree of variance in total range of motion when compared with other cervical segments, and also by the fact that there may be less control of the mobilized segment by the therapist during a 3-dimensional mobilization, with respect the execution of a planar mobilization.

The analysis of differences between means of the extreme position of flexion, axial rotation and lateral bending motions was performed to compare differences between the two different segmental fixation technique, manual fixation compared to locking technique, and between opposite direction of axial rotation movement, right and left. Due to non significant ICCs in the most of the considered parameters, only few comparisons between techniques can be performed. The analysis with Student's t-test showed a statistical difference of 2,6° in the flexion motion during the manual fixation in the atlanto-occipital joint compared to the locking technique. At the same level, the flexion-right axial rotation mobilization showed a statistical difference of 1.6° in the flexion motion compared to the flexion-left axial rotation, using the same manual fixation technique. Whereas the axial rotation movement is not influenced by the type of segmental fixation in C0-C1 segment.

Regarding of extreme positions reached in the three motion component during different types of mobilization, it seems that the coupled lateral bending motion in C0-C1 segment is not influenced by the locking nor by the manual fixation technique (mean from 0,39° to1,9°), while the manual fixation technique seem to reduce the axial rotation motion in C1-C2 segment (0,5°-5,3°in manual fixation versus 21°-23° in locking technique). However these values do not show a strong intra class-correlation between operators and they are not statistical significant.

Cattrysse et al[21] showed a reduction of associated axial rotation and lateral bending motions during the manual fixation technique without influencing the main motion component of flexion-extension in C0-C1 segment, and a reduction of all movement component in the atlanto-axial joint with the locking technique.

Moreover in another study, Cattrysse at al[13]. observed a reduction of coupled lateral bending and flexion-extension motion during an axial rotation mobilization using manual segmental fixation technique. In the same study[13], during lateral bending mobilization of C1-C2 segment the manual fixation technique reduced the effect on the coupled flexion-extension component.

There are many differences between the previous studies[13,21] and the present experiment. First of all the number and the type the of specimens. In his study Cattrysse used ten human spinal specimens, nine of those were embalmed. In this experiment twenty fresh human spinal specimens were used. Secondly the previous studies analyzed only the intra-examiner reproducibility of one observer. The acceptable intra-examiner reproducibility and significance in the ICC values, permitted to perform a more extensive comparison between techniques.

Secondly, in this study two different 3-dimensional mobilizations were performed: flexion- right axial rotation and flexion-left axial rotation. In the mentioned studies planar mobilizations were performed.

The relationship between the axial rotation and the coupled lateral bending components is described by the cross correlation (CC) analysis. In this experiment the CC was calculated separately for test and retest of both operators, and for each type of mobilizations. It seems that the means of cross-correlation, of atlanto-occipital joint tend to be a negative value, representing a controlateral coupled lateral bending, while in the atlanto-axial joint the means tend towards a positive value, showing an ispilateral coupled lateral bending motion.

The controlateral pattern of axial rotation with lateral bending in C0-C1 segment is confirmed in previous studies[1,7,8,9,10,11,12,13,15] but this does not occur for the C1-C2 segment. In general, a controlateral pattern of coupled lateral bending is observed during planar main axial rotation or main flexion-extension movement.

In agreement with other studies[9,14,19,20], in this experiment the ratio showed an extreme axial rotation position greater than the extreme lateral bending.position both in the ispilateral and controlateral coupling specimens, mainly at C1-C2 segment. This can be explained by the fact that the major motion taking place in the C1-C2 segment is axial-rotation.

In literature there are no studies analyzing the 3D-kinematics of three-dimensional non-planar, i.e. combined mobilization of the upper cervical spine. In all previous studies that analyzed the upper-cervical spine, only planar movements were performed, and very few studies analyzed the effect of manual mobilization techniques. This could explain the complexity and the differences of the results for such complex mobilization techniques.

5. Conclusions

This study is a kinematic analysis of 3-dimensional mobilization techniques of the upper cervical spine.

The experiment was performed in the atlanto-occipital joint by two expert manual therapists in a test-retest situation.

The results, calculated with ANOVA, indicate an acceptable intra- and inter-examiners reliability in C0-C1 segment, while in the lower C1-C2 segment there is less inter-operators reproducibility. Five out of nine parameters, that presented differences between examiners with ANOVA, showed an acceptable intra-examiner reproducibility in Student's t-test.

Although this, the strength of reliability, calculated with the intra-class correlation coefficient (ICC), is not significant in most cases.

The results of this in vitro study indicate that, in the atlanto-occipital joint, the manual fixation enables to increase the flexion motion of 2,6°, and, at the same level, there is an increase of 1,6° in the flexion motion, when the flexion-right axial rotation mobilization is performed, with manual fixation. Both the manual fixation and the locking technique do not influence the axial rotation motion in the atlanto-occipital joint.

Regarding the mean of extreme position reached by the three motion componenst in the different mobilization techniques, it seems that the coupled lateral bending motion in C0-C1 segment is not influenced from both locking and manual fixation techniques (mean from 0,39 to1,9), while the manual fixation technique seem to reduce the axial rotation motion in C1-C2 segment (0,5°-5,3°in manual fixation versus 21°-23° in locking technique). However these results do not show a strong intra class-correlation between operators and they are not statistically significant, indicating a bad reliability and as such inconsistent results.

The Cross-correlation, calculated for each test-retest, shows a controlateral coupled lateral bending motion in C0-C1 segment in most of the specimens, in agreement with previous studies, and an ipsilaterlal coupled lateral bending in C1-C2 segment. The ratio shows a grater axial rotation motion compared to the coupled lateral bending, especially in the C1-C2 segment both for ipsilateral and controlateral coupling specimens.

The experience and the familiarization of examiners with the exerted manual therapy techniques and the complexity of the upper cervical spine anatomy, could influence the reproducibility of the 3-dimensional kinematics of segmental complex mobilizations.

A manual fixation technique can increase the main flexion motion, without affecting the axial rotation motion. Moreover, the direction of the axial-rotation motion can influence the main flexion motion.

The results of this in vitro study suggest that the use of different segmental manual techniques during complex mobilizations could partly result in different kinematics of the upper-cervical spine.

In literature there are no studies analyzing the 3D-kinematics of three-dimensional mobilization of the upper cervical spine.

Further *in vivo* studies may validated these results.

References

1. Cook C, Hegedus E, Showalter C, Sizer Jr PS. Coupling behavior of the cervical spine: a systematic review of the literature. J manipulative Physiol. Ther. 2006 Sep; 29(7): 570-5
2. Edmondston SJ, Henne SE, Loh W, Ostvold E. Influence of cranio-cervical posture on three-dimensional motion of the cervical spine. Manual Therapy 2005 Feb, 10(1):44-51
3. Gelalis ID, De Frate LE, Stafilas KS, Pakos EE, Kang JD, Gilbertson LG. Three-dimensional analysis of the cervical spine motion: reliability of a computed assisted magnetic tracking device compared to inclinometer. Eur Spine J 2009 Feb; 18(2):276-81
4. Trott PH, Pearcy MJ, Rusron SA, Fulton I, Brien C. Three-dimensional analysis of the active cervical motion: the effect of the age and gender. Clin Biomech 1996 Jun;11(4):201-206
5. Panjabi MM, Dvorak J, Duranceau J, Yamamoto I, Gerber M, Rauschning W, Bueff HU. Three-dimensional movements of the upper cervical spine. Spine 1988 Jul;13(7):726-30.
6. Karthu JO, Parkkola RK, Komu ME, Kormano MJ, Koskinen SK. Kinematic magnetic resonance imaging of the upper cervical spine using a novel positioning device. Spine 1999 Oct 1; 24(19):2046-56
7. Ishii T, Mukai Y, Hosono N, Sakaura H, Nakajima Y, Sato Y, Sugamoto K, Yoshikawa H. Kinematics of the upper cervical spine in rotation: in vivo three-dimensional analysis. Spine 2004 Apr 1;29(7):E139-44.
8. Panjabi MM, Crisco JJ, Vasavada A, Oda T, Cholewicki J, Nibu K, Shin E. Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. Spine (Phila Pa 1976). 2001 Dec 15;26(24):2692-700.
9. Panjabi MM, Oda T, Crisco JJ, Dvorak J, Grob D. Posture affects motion coupling patterns of the upper cervical spine. J Orthop Res. 1993 Jul;11(4):525-36.
10. Panjabi MM, Dvorak J, Crisco JJ, Oda T, Wang P, Grob D. Effecs of alar ligament transection on upper cervical spine rotation. J Orthop Res. 1991 Jul;9(4):584-593

11. 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) 32:141–151
12. Dugailly PM, Sobczak S, Moiseev F, Sholukha V, Salvia P, Feipel V, Rooze M, Van Sint Jan S. Musculoskeletal modeling of the suboccipital spine: kinematics analysis, muscle lengths, and muscle moment arms during axial rotation and flexion extension. Spine (Phila Pa 1976). 2011 Mar 15;36(6):E413-22.
13. Cattrysse E, Baeyens JP, Clarys JP, Van Roy P. Manual fixation versus locking during upper cervical segmental mobilization: Part 2: an in vitro three-dimensional arthokinematic analysis of manual axial rotation and lateral bending mobilization of the atlanto-axial joint. Man Ther.2007;12(4):353-62
14. Cattrysse E, Baeyens JP, Kool P, Clarys JP, Van Roy P. Does manual mobilization influence motion coupling patterns in the atlanto-axial joint? J Electromyogr Kinesiol. 2008 Oct;18(5):838-48
15. Harrison DE, Harrison DD, Troyanovich SJ. Three-dimensional spinal coupling mechanics: Part I. A review of the literature. J Manipulative Physiol Ther. 1998 Feb;21(2):101-13. Review.
16. Goel VK, Clark CR, Gallaes K, Liu YK. Moment-rotation relationships of the ligamentous occipito-atlanto-axial complex. J Biomech. 1988;21(8):673-80
17. Cattrysse E, Provyn S, Kool P, Clarys JP, Van Roy P. Morphology and kinematics of the atlanto-axial joints and their interaction during manual cervical rotation mobilization. Man Ther. 2011 Oct;16(5):481-6
18. Oda T, Panjabi MM, Crisco JJ 3rd. Three-dimensional translational movements of the upper cervical spine. J Spinal Disord. 1991 Dec;4(4):411-9.
19. Panjabi MM, Dvorak j, Crisco JJ. Flexion, extension, and lateral bending of the upper cervical-spine in response to alar ligament transections. Journal of spinal disorders.1991 Jun;4(2):157-167
20. Ishii T, Mukai Y, Hosono N, Sakaura H, Fujii R, Nakajima Y, Tamura S, Iwasaki M, Yoshikawa H, Sugamoto K. Kinematics of the cervical spine in lateral bending: in vivo three-dimensional analysis. Spine (Phila Pa 1976). 2006 Jan 15;31(2):155-60

21. Cattrysse E, Baeyens JP, Clarys JP, Van Roy P. Manual fixation versus locking during upper cervical segmental mobilization. Part 1: an in vitro three-dimensional arthrokinematic analysis of manual flexion-extension mobilization of the atlanto-occipital joint. Manual Therapy 12(2007) 342-352
22. Panjabi MM, Krag M, Summers D, Videman T. Biomechanical time-tolerance of fresh cadaveric human spine specimens. Journal of Orthopaedic Research 1985;3:292-300
23. Wilke Hj, KrishChack S, Claes LE. Formalin fixation strongly influences biomechanical properties of the spine. Journal of Biomechanics 1996;29:1629-31
24. Cattrysse E, Provyn S, Kool P, Gagey O, Clarys JP, Van Roy P Reproducibility of kinematic motion coupling parameters during manual upper cervical axial rotation mobilization: a 3-dimensional in vitro study of the atlanto-axial joint. J Electromyogr Kinesiol. 2009 Feb;19(1):93-104
25. Wang FS, Teng CC, Lin KH. Measurement of the cervical range of motion pattern during cyclic neck movement by an ultrasound-based motion system. Manual Ther 2005;10(1);68-72
26. Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, Whittle M, D'Lima DD, Cristofolini L, White H, Shmid O, Stokes H. ISB recommendation on definitions of joint coordinate system of various joint motion-part 1: ankle, hip and spine. J Biomech 2002;35(4):543-8
27. Natalis M and Koning A. Non invasive, accurate and reliable measurement of the cervical spine motion with a 3D real-time ultrasound motion analyzer. Ultraschall Med 1999;20(2):70-3

Addenda

Addendum 1:Literature research

Web of science and Pubmed databases were used for the research of articles related to the present experiment. The research was made using mesh terms, free words, and their combinations and the use of some synonyms (reported below). Related citations were examined in Pubmed.

Key words:

-upper-cervical: cervical spine, cervical vertebrae, “upper cervical spine”, “upper cervical vertebrae”, “upper cervical joints”, atlanto-occipital joint, cranial cervical joint, atlanto-axis joint

-kinematics: kinematics, kinematics analysis, biomechanics, arthrokinematics, three dimensional kinematics, three dimensional biomechanics

-coupled motion: coupled mobilization, coupled movement, coupling behavior

-mobilization: complex mobilization, manual mobilization, mobilization, manual therapy, manual treatment

Research strategy:

cervical AND coupled motion

“upper cervical” AND coupled motion

“upper cervical” AND coupled motion AND mobilization

“upper cervical” AND coupled motion AND kinematics analysis

“upper cervical” AND kinematics analysis AND mobilization

Limits: languages: English, French, German,

Ages: all adult 19+

Species: human

Results:

- PUBMED

In the first search 53 articles were found, 42 were excluded after reading the title and abstracts. Another 5 articles were found from related citations. 16 articles were selected

- WEB OK KNOWLEDGE

In the search with web of knowledge 68 articles were found. 48 articles were excluded after reading the title, abstract or the full text. 15 articles were already found in the previous search with Pubmed. 5 articles were selected.

Addendum 2: Descriptive Statistic

Tab 2.1 Descriptive statistic of parameters in flexion-right axial rotation of C0-C1 with manual fixation

Descriptive statistic					
FRM 01	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-11,89	17,48	3,1505	6,3159
Max X r1	20	-11,02	11,37	2,712	4,86425
Max X t2	20	-15,05	25,4	3,653	8,4816
Max X r2	20	-13,31	11,8	2,7565	6,31539
Max Y t1	20	-12,57	6,13	-0,9565	4,6449
Max Y r1	20	-11,47	9,59	0,289	5,20842
Max Y t2	20	-16,5	17,15	1,2205	7,29209
Max Y r2	20	-15,29	20,69	4,309	6,61279
Max Z t1	20	-10	8,18	0,3375	4,26599
Max Z r1	20	-13,13	6,38	1,004	4,31271
Max Z t2	20	-8,64	7,25	0,06	4,60174
Max Z r2	20	-14,3	14,06	0,169	6,53608
CC t1	20	-0,98	0,97	-0,311	0,71294
CC r1	20	-0,97	0,98	-0,2765	0,72503
CC t2	20	-0,97	0,95	-0,3005	0,68273
CC r2	20	-0,99	0,98	-0,0565	0,75941
Ratio t1	20	-1,68	13,65	1,8999	4,50612
Ratio r1	20	-2,81	19,96	1,558	5,03699
Ratio t2	20	-6,23	19,23	1,0882	4,90407
Ratio r2	20	-1,78	132,75	7,7637	29,50688
Eucl t1	20	3,39	468,18	86,6356	109,10319
Eucl r1	20	2,21	254,77	74,365	90,55274
Eucl t2	20	0,69	969,97	153,8113	226,49747
Eucl r2	20	0,24	731,64	146,2112	172,81687
Valid	20				

Tab 2.2 Descriptive statistic of parameters in flexion-left axial rotation of C0-C1 with manual fixation

Descriptive statistic					
FLM 01	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-12	19,05	3,012	6,1615
Max X r1	20	-12,01	19,67	1,4175	6,80451
Max X t2	20	-16,62	23,74	2,034	8,6932
Max X r2	20	-13,03	9,68	-0,768	7,62822
Max Y t1	20	-18,24	7,27	-2,317	6,8074
Max Y r1	20	-15,36	8,89	-0,9805	6,29926
Max Y t2	20	-14,89	16,64	0,136	6,71913
Max Y r2	20	-17,9	21,47	1,6895	8,40711
Max Z t1	20	-16,25	9,26	1,5725	5,83527
Max Z r1	20	-20	8,78	1,6495	6,14304
Max Z t2	20	-8	12,42	3,052	4,90368
Max Z r2	20	-14,95	7,01	0,6125	5,0337
CC t1	20	-1	0,97	-0,346	0,81413
CC r1	20	-0,99	0,97	-0,3315	0,76733
CC t2	20	-0,97	0,97	-0,172	0,74422
CC r2	20	-0,97	0,98	-0,052	0,78883
Ratio t1	20	-37,22	4,91	-1,403	8,68385
Ratio r1	20	-5,7	3,69	-0,0953	2,09695
Ratio t2	20	-27,79	7,25	-0,8462	6,68564
Ratio r2	20	-13,78	10,05	0,3562	4,9124
Valid	20				

Tab 2.1, 2.2:
FRM: flexion-right axial rotation with manual fixation , FLM: flexion-left axial rotation with manual fixation, 01: C0-C1 segment , Max X: extreme flexion position, Max Y, extreme axial rotation position, Max Z: extreme lateral bending position, CC: cross-correlation between axial rotation and lateral bending motion component, Ratio between axial rotation and lateral bending motion components, t: test, r: retest, 1: first examiner, 2: second examiner

Tab 2.3 Descriptive statistic of parameters in flexion-right axial rotation of C0-C1 with locking technique

Descriptive statistic					
FRL 01	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-14,3	17,53	1,837	7,53312
Max X r1	20	-9,45	8,93	0,561	5,27737
Max X t2	20	-12,89	20,89	1,2745	9,35241
Max X r2	20	-12,9	11,22	-2,1415	7,28699
Max Y t1	20	-13,87	6,15	-0,8335	5,06451
Max Y r1	20	-13,3	12,62	0,4295	5,54844
Max Y t2	20	-11,58	38,49	1,502	10,6843
Max Y r2	20	-6,89	27,28	4,369	8,08752
Max Z t1	20	-11,68	41,32	-0,038	10,56059
Max Z r1	20	-13,47	8,84	-1,1025	4,88566
Max Z t2	20	-11,53	13,47	-1,551	6,22078
Max Z r2	20	-19,16	6,83	-4,7725	7,25663
CC t1	20	-0,99	0,97	-0,233	0,6192
CC r1	20	-0,99	0,93	-0,171	0,74165
CC t2	20	-0,96	0,98	0,0215	0,65083
CC r2	20	-0,95	0,97	-0,1115	0,68011
Ratio t1	20	-8,54	3,17	-0,3961	2,39457
Ratio r1	20	-6,04	54,5	2,7582	12,42692
Ratio t2	20	-51,75	6	-3,0319	11,69787
Ratio r2	20	-10,15	22,88	0,9003	5,79412
Valid	20				

Tab 2.4 Descriptive statistic of parameters in flexion-left axial rotation of C0-C1 with locking technique

Descriptive statistic					
FLL 01	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-7,92	15,49	2,3385	5,84743
Max X r1	20	-12	8,09	-1,6515	6,26002
Max X t2	20	-21,44	16,55	-0,384	9,65211
Max X r2	19	-16,36	7,4	-3,7374	6,39498
Max Y t1	20	-16,1	3,31	-2,766	5,39985
Max Y r1	20	-10,98	6,74	-0,969	4,29917
Max Y t2	20	-12,62	43,35	1,438	11,36383
Max Y r2	19	-15,65	26,56	1,3579	9,0024
Max Z t1	20	-35,92	10,73	0,691	9,76285
Max Z r1	20	-16,88	10,46	2,2555	6,0169
Max Z t2	20	-17,71	11,91	0,9025	7,62211
Max Z r2	19	-11,85	6,8	1,2958	5,7163
CC t1	20	-0,97	0,93	-0,1535	0,70917
CC r1	20	-0,99	1	-0,0235	0,78256
CC t2	20	-1	0,99	-0,139	0,81354
CC r2	19	-0,99	1	-0,1584	0,89005
Ratio t1	20	-10,81	3,69	-0,5385	2,75116
Ratio r1	20	-1,49	1,85	-0,0401	0,87103
Ratio t2	20	-27,43	23,46	-0,552	8,41472
Ratio r2	19	-9,48	60,43	2,5743	14,21758
Valid	19				

Tab 2.3, 2.4:

FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique, 01: C0-C1 segment , Max X: extreme flexion position, Max Y, extreme axial rotation position, Max Z: extreme lateral bending position, CC: cross-correlation between axial rotation and lateral bending motion component, Ratio between axial rotation and lateral bending motion component, t: test, r: retest, 1: first examiner, 2: second examiner

Tab.2.5 Descriptive statistic of parameters in flexion-right axial rotation of C1-C2 with manual fixation

Descriptive statistic					
FRM 12	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-11,53	10,57	1,442	5,67534
Max X r1	20	-8,41	10,22	0,766	4,43457
Max X t2	20	-17,39	19,16	-1,0045	9,304
Max X r2	20	-16,49	18,21	-1,387	9,28736
Max Y t1	20	-6,76	22,53	6,303	6,86344
Max Y r1	20	-7,66	13,47	4,3135	5,91361
Max Y t2	20	-15,33	24,24	6,657	10,40366
Max Y r2	20	-18,91	25,72	4,0195	10,88788
Max Z t1	20	-4,44	15,2	3,171	4,69711
Max Z r1	20	-10,33	9,71	-0,474	4,91894
Max Z t2	20	-7,06	10,73	1,618	4,67427
Max Z r2	20	-8,91	6,59	-1,6275	4,6732
CC t1	20	-0,96	1	0,265	0,81823
CC r1	20	-0,99	0,99	0,237	0,77412
CC t2	20	-0,97	0,97	0,348	0,63283
CC r2	20	-0,91	0,99	0,347	0,61169
Ratio t1	20	-5,29	14,75	2,5235	4,16904
Ratio r1	20	-2,79	3,51	0,6706	1,77533
Ratio t2	20	-4,83	32,25	4,9545	9,03612
Ratio r2	20	-6,24	34,38	2,1202	8,30724
Eucl t1	20	7,26	551,02	148,1726	166,90084
Eucl r1	20	12,66	295,87	94,3083	81,91785
Eucl t2	20	9,72	744,04	253,7595	209,03128
Eucl r2	20	46,23	716,01	236,0367	173,20351
Valid	20				

Tab.2.6 Descriptive statistic of parameters in flexion-left axial rotation of C1-C2 with manual fixation

Descriptive statistic					
FLM 12	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-13,96	9,44	2,55	5,33463
Max X r1	20	-9,38	11,01	2,2455	4,40294
Max X t2	20	-13,31	8,87	-2,087	7,56001
Max X r2	20	-13,06	8,11	-3,289	6,95026
Max Y t1	20	-8,8	17,57	2,615	8,44785
Max Y r1	20	-10,32	14,88	-0,2775	6,55884
Max Y t2	20	-15,47	14,44	0,4375	7,86975
Max Y r2	20	-23,72	19,02	-0,721	10,68459
Max Z t1	20	-3,08	18,17	3,883	4,66892
Max Z r1	20	-14,65	9,54	-0,1645	5,51019
Max Z t2	20	-5,09	12,83	1,834	5,16353
Max Z r2	20	-11,01	7,59	-0,7885	5,08203
CC t1	20	-0,98	0,98	-0,001	0,67302
CC r1	20	-0,89	0,98	0,118	0,60683
CC t2	20	-0,84	0,97	0,052	0,57696
CC r2	20	-0,92	0,97	-0,2215	0,63385
Ratio t1	20	-3,52	8,6	1,3185	3,20438
Ratio r1	20	-3,78	4	0,3991	2,05509
Ratio t2	20	-18,75	17,92	0,5342	6,53541
Ratio r2	20	-4,01	6,62	0,5355	2,79593
Eucl t1	20	24,4	596,1	143,9605	142,14831
Eucl r1	20	13,7	308,46	93,2744	86,94786
Eucl t2	20	2,82	335,36	146,3718	97,72179
Eucl r2	20	2,01	612,39	190,838	164,833
Valid	20				

Tab 2.5, 2.6:
FRM: flexion-right axial rotation with manual fixation , FLM: flexion-left axial rotation with manual fixation, 12: C1-C2 segment , Max X: extreme flexion position, Max Y, extreme axial rotation position, Max Z: extreme lateral bending position, CC: cross-correlation between axial rotation and lateral bending motion component, Ratio between axial rotation and lateral bending motion component, t: test, r: retest, 1: first examiner, 2: second examiner

Tab 2.7 Descriptive statistic of parameters in flexion-right axial rotation of C1-C2 with locking technique

Descriptive statistic					
FRL 12	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-39,86	17,32	-5,5545	14,52753
Max X r1	20	-45,1	10,95	-8,871	14,13157
Max X t2	20	-18,88	24,04	-0,388	11,72917
Max X r2	20	-27,01	28,76	-2,5575	13,25806
Max Y t1	20	-2,96	41,14	22,6625	11,32441
Max Y r1	20	1,09	41,76	22,5815	10,9415
Max Y t2	20	-61,95	49,36	21,4635	28,06973
Max Y r2	20	-48,17	49,62	25,8015	20,816
Max Z t1	20	-15,1	26,28	6,6145	12,0579
Max Z r1	20	-15,79	28,18	3,372	12,04103
Max Z t2	20	-33,91	20,63	1,8325	11,11688
Max Z r2	20	-22,32	19,57	-1,052	8,16264
CC t1	20	-0,99	0,99	0,3285	0,65863
CC r1	20	-0,98	0,99	0,235	0,72323
CC t2	20	-0,97	0,99	0,2735	0,59336
CC r2	20	-0,85	0,97	0,48	0,52785
Ratio t1	20	-5,39	24,68	1,8484	6,45657
Ratio r1	20	-10,6	46,12	2,9753	12,76195
Ratio t2	20	-26,19	27,29	0,8515	13,24454
Ratio r2	20	-16,62	223,17	14,4769	51,02336
Eucl t1	20	96,89	2554,88	1048,6432	583,76536
Eucl r1	20	94,24	2630,95	1041,1729	657,2768
Eucl t2	20	244,2	3977,87	1460,8051	898,0517
Eucl r2	20	33,56	3526,77	1315,2898	899,14603
Valid	20				

Tab 2.8 Descriptive statistic of parameters in flexion-left axial rotation of C1-C2 with locking technique

Descriptive statistic					
FLL 12	**N**	**Minimum**	**Maximum**	**Mean**	**sd**
Max X t1	20	-19,37	27,03	10,8395	11,17964
Max X r1	20	-15,15	34,98	9,9275	13,87583
Max X t2	20	-17,32	14,33	2,222	8,60499
Max X r2	19	-12,05	22,52	1,0505	10,74494
Max Y t1	20	-46,6	-4,1	-19,689	10,94506
Max Y r1	20	-58,48	40,55	-21,2735	19,5728
Max Y t2	20	-38,61	22,38	-18,389	15,58652
Max Y r2	19	-59,77	24,54	-24,9258	17,96784
Max Z t1	20	-30,08	25,97	-0,8175	13,69386
Max Z r1	20	-21,74	40,98	-3,48	15,98767
Max Z t2	20	-16,3	41,49	1,5165	11,85234
Max Z r2	19	-24,48	13,69	-1,9805	9,98724
CC t1	20	-0,99	0,99	0,1175	0,78204
CC r1	20	-0,98	0,99	-0,178	0,71815
CC t2	20	-0,89	0,97	-0,077	0,64218
CC r2	19	-0,95	0,81	-0,2432	0,61705
Ratio t1	20	-4,82	5,18	-0,1233	2,50658
Ratio r1	20	-11,19	8,12	-0,7817	4,1561
Ratio t2	19	-40,79	93,25	1,7135	25,07756
Ratio r2	19	-57,21	19,47	-1,2263	15,81951
Eucl t1	20	120,83	2640,18	916,5052	539,32247
Eucl r1	20	409,03	3704,47	1352,9042	905,72508
Eucl t2	19	88,76	3616,45	1136,0451	832,3123
Eucl r2	20	53,08	1894,55	779,9825	506,62584
Valid	18				

Tab 2.7, 2.8:
FRL: flexion-right axial rotation with locking technique, FLL: flexion-left axial rotation with locking technique, 01: C0-C1 segment , Max X: extreme flexion position, Max Y, extreme axial rotation position, Max Z: extreme lateral bending position, CC: cross-correlation between axial rotation and lateral bending motion component, Ratio between axial rotation and lateral bending motion component, t: test, r: retest, 1: first examiner, 2: second examiner