EVALUATING THE RELATIONSHIP BETWEEN EXTERNAL MARKERS AND INTERNAL VERTEBRAL KINEMATICS IN THE CERVICAL SPINE

N. DE BEER, L. CHRISTELIS AND A.F. VAN DER MERWE

Abstract

The objective of this study was to examine the relationship between external markers typically used in external motion capturing devices and the true vertebral kinematics in the cervical spine. Twenty one healthy subjects were subjected to low dosage X-rays in five different positions, while radio opaque markers were attached to the skin at each vertebral level. Distance and angle parameters were constructed for vertebral prediction from skin surface markers. The causes of variation in these parameters were identified by investigating the correlations of these parameters with anthropometrical variables. Strong correlations of the parameters were observed in flexion, but in extension, especially full extension, the correlations were poor to insignificant. In neutral, half flexion, and full flexion it is possible to predict the vertebral position from surface markers by using the parameters and anthropometrical variables. In half extension this prediction is less accurate and in full extension alternative methods should be investigated for external motion capturing.

Keywords: cervical vertebrae, external markers, spinal motion capturing.

1.   INTRODUCTION

The field of artificial intervertebral disc design and manufacturing has developed and grown to include investigations into the use of Additive Fabrication Technologies for manufacturing customised implants. Human computer movement simulation forms an integral part of this process chain. Every computer simulation model first requires an understanding of how the natural disc and spinal elements function together in order for it to resemble natural human motion. In an attempt to develop such an understanding, vertebral kinematics need to be analysed in such a way as to provide inputs for simulation models.

For this purpose, in vivo spinal motion capturing techniques can be used to gain a better understanding. These techniques have advanced from functional assessment and superimposed flexion and extension radiographs to technologies that gather detailed and accurate data on normal spinal movement patterns, including axial rotation and lateral bending. Such systems include:

- optical tracking—where a set of specialised cameras measure the positions of reflective or light emitting markers (Gracovetsky et. al., 1995), (Henmi et. al., 2006), (Cerveri et. al., 2004),
- inertial systems—that determine absolute orientation (Simcox et. al., 2005), (Lee et. al., 2003), (Goodvin et. al., 2006), (Plamondon et. al., 2007), (Jasiewicz et. al., 2007),
- goniometric systems or exo-skeleton systems—where rods linked together with potentiometers articulate at the joints of the body, (Mannion et. al., 2000), (Troke et. al., 2005), (Mannion & Troke, 1999),
- electromagnetic systems that calculate position (X, Y, and Z Cartesian coordinates) and orientation (yaw, pitch and roll) by the relative magnetic flux (Jasiewicz et. al., 2007), (Van Herp et. al., 2000), (Amiri et. al., 2003), and
- ultrasonic systems—where spatial coordinates are determined from the pulses of ultrasound transmitters positioned relative to a fixed system of microphones (Demaille-Wlodyka et. al., 2007), (Vogt et. al., 2007), (Dvir & Prushansky, 2000), (Vogt & Banzer, 1999), (Castro et. al., 2000).

Motion is often measured as a total range of motion (ROM), for example from the head to the seventh cervical (C7) vertebra, as opposed to measurements at each vertebral level. Grant (Grant, 2002) criticises this approach, since the maximum ROM of a specific cervical segment is not necessarily reflected by the ROM from full flexion to full extension of the neck as a whole. A specific segment can reach its maximum range of flexion or extension before the neck reaches its final position. Kinematic assessment at vertebral level yields important and necessary information and, according to Zhang and Xiong (Zhang & Xiong, 2003), is crucial for the purposes of obtaining kinematical data for modelling of the intervertebral disc0. Therefore in this study motion capturing systems were evaluated in light of their abilities to capture motion specifically at vertebral level.

All external motion capturing systems share a common disadvantage: the external markers are subject to movement of the skin and tissue between the vertebrae and the markers and therefore its credibility to reflect the true vertebral motion at each level is questioned. Several studies mention this problem and warn that the true vertebral motion is concealed by skin and soft tissue effects (Zhang & Xiong, 2003), (Henmi et. al., 2006), (Cerveri et. al., 2004), (Lee et. al., 2003), (Dvir & Prushansky, 2000), (Hassan et. al., 2007), (Fujii et. al., 2007), (Lee, 2001). Except for C7, the spinous processes of the cervical spine are less prominent than in the lumbar region. The surface markers in the cervical region are therefore subject to more motion of skin and soft tissue.

Nattrass et al. (1999) argues that only radiographic techniques are able to determine movement of the vertebrae with acceptable accuracy in vivo. Radiographs evaluating flexion and extension motion at segmental level are most commonly used to assess spinal mobility and several measurement techniques have been developed to capture motion from radiographs (Piché et. al., 2006), (Frobin et. al., 2002), (Schuler et. al., 2004). Common shortcomings to X-ray imaging (radiographs, fluoroscopy, and computed tomography (CT)) are patient exposure to ionizing radiation and the fact that radiographs and fluoroscopy can only capture motion in two dimensions, giving no information on, for example coupled movements. In other cases, magnetic resonance imaging (MRI) can provide 3D imaging, but is considered a more costly alternative (Lee, 2001), (Ishii et. al., 2004), (Ishii et. al., 2006), (Ackerman et. al., 1997). It would seem that an ideal solution would be to have all the practical advantages of external motion capturing systems (low cost, safety, simplicity, and portability) combined with the capabilities of internal imaging technologies. Consequently, there is interest in ascertaining what the relationship is between external measures and internal vertebral motion.

1.1   Previous studies

One of the earliest studies asking similar questions was conducted in 1989 by Bryant et al. (Bryant et. al., 1989). They developed a model by which the measured skin profiles were transformed into equivalent profiles of vertebral centroids. This model was only done in one position, with the spine in its natural curve. Lee et al. (1995) developed a non-linear regression model that transferred skin marker coordinates into corresponding vertebral body positions. This model took some anthropometrical values into consideration, but focused only on the lumbar spine. (Zhang & Xiong, 2003) approached this problem differently, and developed a mathematical model that interpreted motion in terms of centres of rotation (COR), located for each motion segment from skin markers. The model did not take any anthropometric data into consideration, but the effect of skin motion artefacts was lessened by filtering out noise and non-circular motion components. This study only considered rotation and did not take translation into account. Cerveri et al. (2004), addressed three dimensional intervertebral motion obtained from skin markers. They constructed a kinematical model that used video recording and three skin surface markers at each motion segment to estimate vertebral rotations. A recent study by Ma et al. (2008) developed a Bayesian network dynamic model to estimate the kinematics of the intervertebral joints of the lumbar spine. Radiographic images in flexion and extension were used as extreme value inputs and the intermediate motion was obtained from skin surface markers of an electromagnetic motion capturing system. The model was validated by comparing the predicted position of the vertebrae in the neutral position with those obtained from the radiographic image in the neutral posture. A correlation of 0.99 and a mean error of less than 1.5° was achieved.

Although a variety of studies have been done on this topic, their focus was mostly on the lumbar spine. Therefore this study has focused its efforts on finding similar results for the cervical spine.

2.   MATERIALS & METHODS

The relationship between surface marker motion and vertebral motion was investigated by observing flexion and extension with a radiographic method and radio opaque markers to study the vertebrae and external surface markers simultaneously through one medium. A sample size of 21 subjects (11 male, 10 female, range: 21-26 years old (average 23.09 years)) was used. The participants were all asymptomatic (no experience or history of cervical pain or trauma and no abnormal posture). The study was approved by the Committee for Human Research of Stellenbosch University.

Lateral cervical spine X-rays were taken in five different motion positions: neutral (N), half flexion (HF), full flexion (FF), half extension (HE), and full extension (FE). To address concerns about radiation exposure, the Statscan Critical Imaging System from Lodox was used. A Lodox lateral cervical scan has an effective dose of 2.1 µSv (Ma et. al., 2008) and the five scans of each participant were well within in the allowable effective dose per year of 1 mSv (Anonymous, 2003).

The experimental sessions were conducted in the morning to account for diurnal variation. A physiotherapist identified the C2–C7 spinous processes of each participant by means of palpation and steel balls (Ø 4mm) were attached to the skin at each indentified vertebral level. Length, weight, neck girth (measured immediately superior to the thyroid cartilage), skin fold (using a standardised measurement place), and percentage skin stretch were measured in each participant. The skin stretch was measured as the difference in distance from C2–C7, in a neutral position and a full flexed position. There is no standard skin fold measurement in the cervical spine. A place for measurement was therefore chosen and standardised for all subjects. The head was first moved in a slight extended position to make it easier to capture the skin fold. A skin fold calliper was used to measure the skin fold at the fifth cervical vertebrae. With the left hand a piece of skin in this region was grabbed and with the calliper in the right hand this was measured. The calliper was held horisontally. The reading after two seconds was recorded. In some subjects the reading varied considerably and therefore whenever the three different readings differed more than a millimetre, the measurement was stopped and redone.

The scans from each individual underwent pixel aspect ratio correction to compensate for differences in position from the X-ray source. Coordinates of selected anatomical landmarks were identified from the radiographic scans by inspection and used for kinematic calculations. The absolute rotation was determined for each vertebra in each position.

The angle was obtained from the straight line through the anterior aspect of a vertebra. This method is similar to the method used by Dvorak et al. (1991), except that the anterior vertebral corners were used instead of the posterior corners. Intervertebral rotation between vertebral pairs was calculated according to literature by means of the Anterior Vertebral Angle (AVA) method (Frobin et. al., 2002). Relative vertebral translation, on the other hand, was calculated for each vertebra using the method of Frobin et al. (2002).

In order to describe the relation between the external markers and vertebrae, two parameters were constructed as shown in Figure 1. The distance (D) between the surface marker and the vertebrae, and the absolute angle (ß) between the vertical and a line connecting the centres of the vertebra and surface marker.
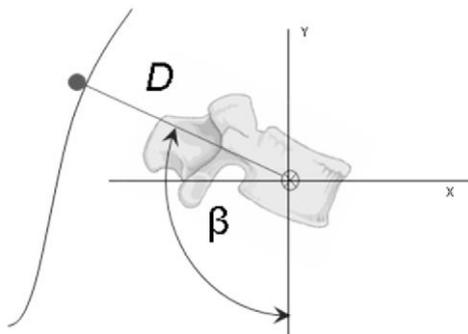

Figure 1 – Defining distance and angle parameters

3.   RESULTS AND DISCUSSION

Ideally D would remain the same throughout all the motion, as if the ball bearing was attached to the vertebra with a rod of length D, and thus following the same translation and rotation as the vertebrae. Figure 2 shows that this is not the case. D changes throughout the different positions with respect to the initial position of surface marker placement. The differences observed for D may be explained by the difference in skin curvature and cervical spine curvature, the effect of the skin fold, and the markers shifting up during flexion and extension. It seems that D may be a useful parameter for predicting the vertebrae from the skin surface, provided that the curvatures remain consistent for each individual.
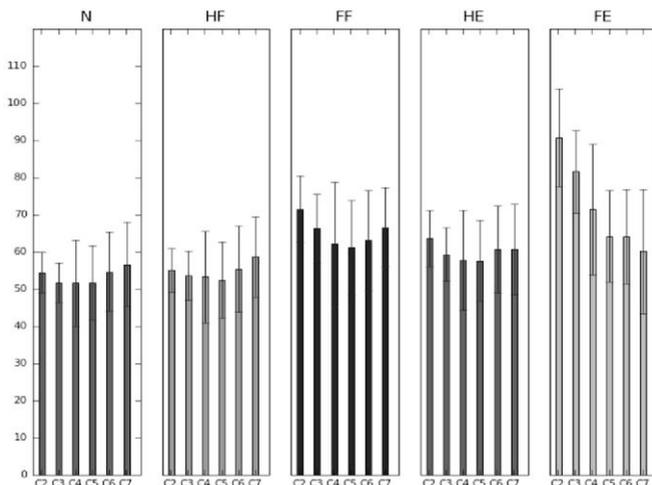
Figure 2 – D curvatures in different positions and vertebral level of 21 subjects

Figure 3 shows the curve that the cervical spine and the external markers form. The curvatures of different individuals were scaled for comparison.

In general, the marker profiles followed similar patterns for N, HF, FF. Greater variation occurred in the extension positions (HE and particularly FE). For half extension a pattern emerged after grouping the curvatures according to gender. Females mostly exhibited a skin fold at C3-C4 vertebral level, while the males exhibited a skin fold at the levels from C4 to C6 which influenced the skin curvature accordingly.
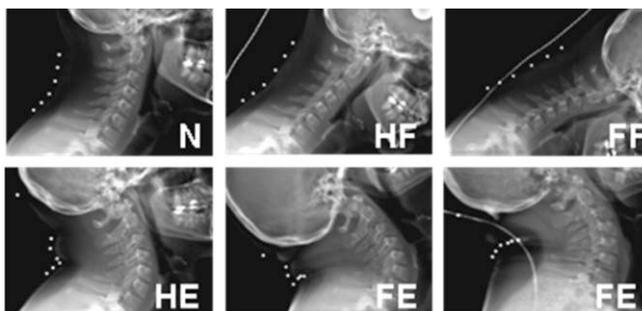

Figure 3 – Images showing the skin surface curvature and the spine curvature in different positions

In the case of full extension (FE), results were even more dramatic with different profiles being observed for different individuals with no discernable pattern, as shown in Figure 3. The curvatures were grouped according to gender, ROM and skin fold respectively, but none of the groupings showed any consistency or pattern. Figure 4 shows the closely followed trend in full flexion and the disorder in full extension.
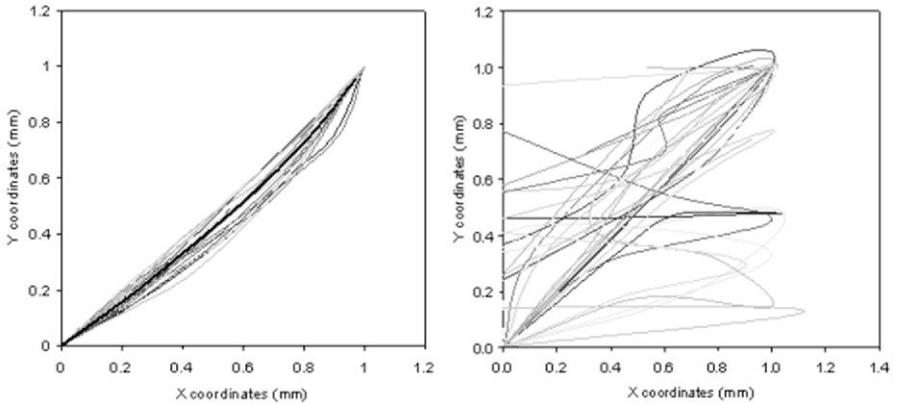
Figure 4 – Skin surface curvature in full flexion (left) and full extension (right)

The angle ß gives further information on the position of the surface marker with respect to the vertebra. In Figure 5 the average rotation for a position and vertebral level is presented.
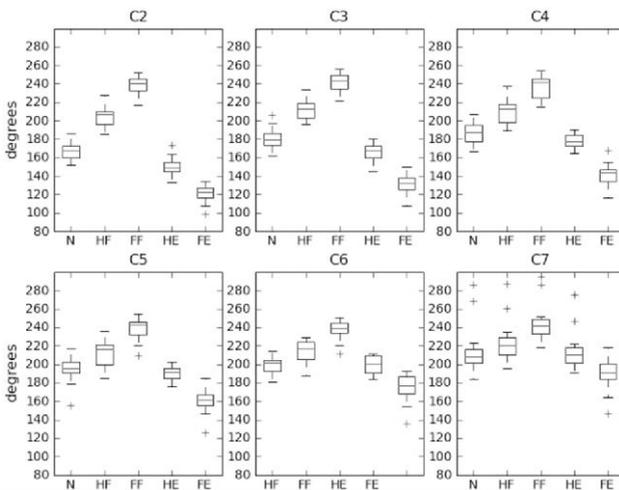
Figure 5 – ß for each position and vertebral level; all subjects (n = 21)

Due to the skin that stretches and folds during motion, the surface markers shifted up and rotated with respect to the vertebrae. ß is therefore different to the vertebral rotation. In the flexed positions this difference was less than in the extended position. In Figure 6, the difference between ß-neutral and ß of the position investigated, was subtracted from the difference of the vertebral rotation from the neutral to the investigated position. The negative values in the flexed positions therefore indicate that the surface marker rotated more than the vertebrae.
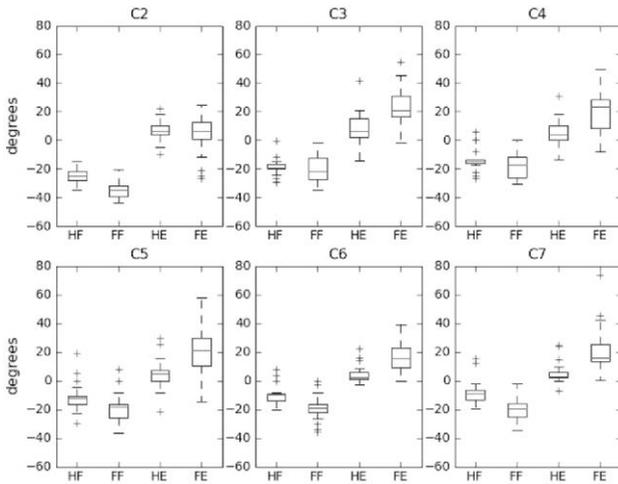
**Figure 6 – Difference in vertebral rotation and surface marker rotation (n = 21)**

The standard deviation of D ranged between 5.44 and 16.68 mm. ranges from 8.91° to 23.96°. To improve the use of D and ß for the prediction of vertebral positions from external markers, the causes of variation in D and ß must be known.

3.1 Variance in D and ß explained

D and ß were correlated with all the anthropometric variables to see which variables have the strongest influence on these parameters. All analyses were done at a significance level of 5%. All data were tested for normality with Shopiro-Wilk analysis (Walpole et al., 2002). Only skin fold values and were not normally distributed.

The relationship between gender and D and ß was observed with analysis of variance (ANOVA) (normally distributed data) and the Mann-Whitney U test (non-normal data) (Walpole et al., 2002). With p-values of below 0.05 the null hypothesis assuming no mean difference between males and females could be rejected in D for all positions, except full extension. was only rejected in C6 and C7 in N, HF, HE and FE.

The relationship between D and ß and the continuous variables of Table 1, were observed with correlation coefficients. In the case of normal data Pearson's correlation coefficient (r_p) was used and in the non-normal exceptions Spearman's rank correlation coefficient (r_s) (Walpole et al., 2002).

The anthropometric variables correlated well with D in the neutral position as shown in Table 1. Length, weight, girth and stretch played a definite and overall significant role in explaining the variation in D.

All the significant correlations were positive correlations, implying that an increase in, for example neck girth, would result in a linear increase of D.

	Length		Weight		Girth		% Stretch		Skin fold		CROM	
	(r_p)	p-value	(r_p)	p-value	(r_p)	p-value	(r_p)	p-value	(r_s)	p-value	(r_p)	p-value
C2	0.5897	0.0049	0.6999	0.0004	0.7810	0.0000	0.4594	0.0362	0.37	0.10	-0.4147	0.0616
C3	0.5505	0.0097	0.7375	0.0001	0.8627	0.0000	0.5025	0.0203	0.53	0.01	-0.3108	0.1702
C4	0.5156	0.0239	0.6592	0.0021	0.8351	0.0000	0.5081	0.0263	0.40	0.09	-0.4372	0.0613
C5	0.3818	0.0967	0.5787	0.0075	0.7133	0.0004	0.6626	0.0015	0.33	0.16	-0.3789	0.0995
C6	0.5418	0.0136	0.7430	0.0002	0.8646	0.0000	0.6622	0.0015	0.49	0.03	-0.4632	0.0397
C7	0.5984	0.0042	0.6146	0.0030	0.5640	0.0078	0.6791	0.0007	0.27	0.23	-0.0741	0.7495

The significant correlations between D and the anthropometrical variables in the other position are summarized in Figure 7. Further tables (not shown here) were also constructed for other positions. The correlations in HF indicated similar results as in the N position, except for a stronger correlation with skin fold and correlation to stretch only for C6 and C7. Similar results were observed for FF although with slightly weaker correlations. In HE girth and weight remained consistently correlated with D across all vertebral levels, but the correlation value decreased due to the arbitrary surface marker motion caused by the skin folds. From the scans it is clear that the skin folds influenced the motion of the surface marker, but no significant correlation between skin fold and D was observed. It was expected that the magnitude of the skin fold would give an indication of the motion of the surface marker in extension. In FE the overall correlation of anthropometric variables with D was statistically insignificant and no anthropometric variables correlate consistently with D.

In general the correlation between anthropometric variables and D was good, especially for variables such as girth, weight and also to a lesser extent length. The correlation of cervical ROM (CROM) with D, are generally lower than expected. It was thought that in the extreme positions ROM would play a significant role in determining variation in D. This may be an indication that the difference in vertebral curvatures due to ROM was consistent with the difference in surface marker curvatures, therefore having no effect on D. It could also be that there is a relation between ROM and D, but that it is not linear. CROM, did however feature in the regression model and is taken into account along with girth, to predict vertebrae in FF.

Unfortunately, the anthropometric variables correlated poorly with ß as shown in Figure 7. Only CROM and girth correlated with ß and it was only statistically significant in C6 and C7. Only in FE and with CROM was the correlation significant in all vertebral levels.
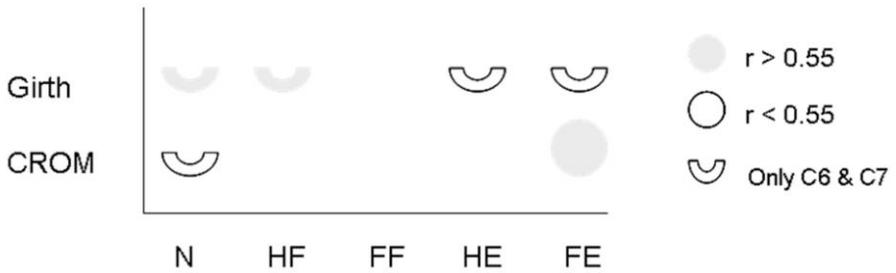
Figure 7 – Summary of correlations between anthropometrical variables and ß

A best fit general regression was done for both parameters to see what combination of variables at different positions and vertebral levels, would contribute to predict D most accurately. All the statistically significant results are presented in Table 2.

The predictions for D are good. In N position in the different levels up to 86% of the variation could be explained by the regression. In HF this value ranged between 53% and 87%. In FF the regression for D was good and between 62% and 85% of variation could be accounted for throughout the vertebral levels. In E the regression was still statistically significant, but on average less than 50% of variation could be accounted for by the regression model.

For ß the regression was poor and only statistically significant in a few cases. Although only 30% of the variance can be accounted for, the results are similar across four of the vertebral levels in this position. CROM was significant in all the vertebral levels and the combination of skin fold and CROM also yielded good R^2's, explaining on average 47% of the variance in ß in FE.

	Gender		Length		Mass		Girth		Stretch		Skin Fold		CROM		R^2	
	D	β	D	β	D	β	D	β	D	β	D	β	D	β	D	β
N C2							0.78								0.59	
N C3							0.86								0.73	
N C4			-0.32				1.08								0.71	
N C5			-0.47	0.72			0.83	-0.48	0.47						0.67	0.34
N C6		-0.91	-0.44				0.92	-0.36	0.39				-0.2		0.86	0.5
N C7					0.36				0.49					-0.45	0.5	0.16
HF C2	0.58						1.2								0.53	
HF C3	1.22						2.2				-0.63				0.62	
HF C4							0.84								0.69	
HF C5							0.89								0.79	
HF C6			-0.25				0.91	0.65	0.24				-0.16	0.6	0.87	0.39
HF C7			0.29						0.52		0.36				0.71	
FF C2							0.92	0.46					0.33		0.65	0.26
FF C3							0.9	0.51					0.3	0.66	0.62	0.34
FF C4							0.91	0.58					0.35	0.62	0.62	0.32
FF C5	-1.07		0.47		-1.28				1.44		1.28		0.41		0.76	
FF C6					-0.93	-0.85	1.39		0.22		0.43		0.21	0.44	0.85	0.37
FF C7	-0.79		0.54		-1.22				0.35		1.17		0.51		0.76	
HE C2							0.59								0.32	
HE C3							0.87						0.26		0.58	
HE C4							0.64								0.37	
HE C5		-0.99	-0.59	-0.81			1.07								0.49	0.27
HE C6	-0.47	-1.4	-0.71	-0.9			0.88								0.66	0.65
HE C7		-0.98		-0.89					0.56		0.34				0.43	0.26
FE C2	-0.54	0.5					0.64							-0.64	0.26	0.41
FE C3			0.67										0.35		0.32	
FE C4	1.7		0.87				1.59				-1.01	0.34		-0.52	0.44	0.35
FE C5												0.42		-0.55		0.49
FE C6			-0.66		-0.7		1.32		0.5			0.28	0.46	-0.7	0.52	0.58
FE C7									0.62				0.43	-0.75	0.39	0.54

4.   CONCLUSION

The question of whether surface markers can represent the motion of the vertebrae in the cervical spine was investigated by observing the kinematic behaviour of the markers and vertebrae on the same medium and instance. Parameters D and ß were constructed to show the relationship with the surface marker and the vertebrae. These parameters could be used to predict the vertebrae from the skin surface markers if the variation in these parameters is accounted for.

Strong correlations between D and anthropometrical variables were observed that accounted for on average 70% of the variation, especially in the N and F positions. Overall, the variable that correlated the strongest was neck girth. Unfortunately in FE correlations and regression fits were poor. The correlations with the second parameter were poor in most positions. In FE exhibited a strong negative correlation with CROM.

Further work to make external motion capturing of cervical intervertebral kinematics a viable option would require refinement of the work presented here, especially in describing the effect that the identified anthropometrical factors has on. The current variation in would cause vertebral predictions from surface markers to be inaccurate.
Ideally, a motion capturing device should yield information about the full ranges of motion. Therefore, before such refinement is possible, an alternative option for external motion capturing of the full extension position needs to be researched. In the absence of reliable results for the relationship between external markers and the internal vertebrae for the extension position, internal imaging technologies will continue to be essential for such interpretations – at the cost of the practical advantages that external motion capturing offer.

5.   ACKNOWLEDGEMENTS

6.   REFERENCES

Ackerman SJ, Steinberg EP, Bryan N, BenDebba M. Trends in Diagnostic Imaging for Low Back Pain: Has MR Imaging Been a Substitute or Add-on? Radiology 1997; 203:533-538

Amiri M, Jull G, Bullock-Saxton J. Measuring range of active cervical rotation in a position of full head flexion using the 3D Fastrak measurement system: an intra-tester reliability study. Man Ther 2003;8(3):176–179.

Anonymous, Ionizing radiation safety standards for the general public. Position statement of the Health Physics Society. Adopted: September 1992 Revised: June 2003.

Bryant JT, Reid JG, Smith BL, Stevenson JM. Method for determining vertebral body positions in the sagittal plane using skin markers. Spine 1989 14: 258–265.

Castro WHM, Sautmann A, Schilgen M, Sautmann M. Noninvasive three-dimensional analysis of cervical spine motion in normal subjects in relation to age and sex: an experimental examination. Spine 2000; 25(4):443-449.

Cerveri P, Pedotti A, Ferrigno G. Non-invasive approach towards the in vivo estimation of 3D inter-vertebral movements: methods and preliminary results. Med Eng Phys 2004; 26:841–853.

Demaille-Wlodyka S, Chiquet C, Lavaste JF, Skalli W, Revel M, Poiraudeau S. Cervical range of motion and cephalic kinesthesis: ultrasonographic analysis by age and sex. Spine J 2007;32(8):E254–E261.

Dvir Z, Prushansky T, Reproducibility and instrument validity of a new ultrasonography-based system for measuring cervical spine kinematics. Clin Biomech 2000;15(9):658-664.

Dvorak J, Panjabi MM, Novotny JE, Antinnes JA, (1991) In vivo Flexion/Extension of the normal cervical spine. J Orthopeadic Research 9:828-834.

Frobin W, Leivseth G, Biggemann M, Brinckmann P, Saggital plane segmental motion of the cervical spine. A new precision measurement protocol and normal motion data of healthy adults. Clin Biomech 2002;17:21-31.

Fujii R, Sakaura H, Mukai Y, Hosono N, Ishii T, Iwasaki M, Yoshikawa H, Sugamoto K. Kinematics of the lumbar spine in trunk rotation: in vivo three-dimensional analysis using magnetic resonance imaging. Euro Spine J 2007; 16(11):1867-1874.

Goodvin C, Park EJ, Huang K, Susaki K. Development of a real-time three-dimensional spinal motion measurement system for clinical practice. Med Bio Eng Comput 2006; 44(12):1061-1075.

Gracovetsky S, Newman N, Pawlowsky M, Lanzo V, Davey B, Robinson L. A database for estimating normal spinal motion derived from noninvasive measurement. Spine 1995 20:1036–1046.

Grant R. Physical therapy of the cervical and thoracic spine. 3rd ed. Churchill

Livingstone, 2002.

Hassan EA, Jenkyn TR, Dunning CE. Direct comparison of kinematic data collected using an electromagnetic tracking system versus a digital optical system. J Biomech 2007;40:930–935.

Henmi S, Yonenobu K, Masatomi T. A biomechanical study of the activities of daily living using neck and upper limbs with an optical three dimensional motion analysis system. Mod Rheumatol 2006; 16:289-293.

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: 29(7): E139–E144.

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 2006: 31(2): 155–160.

Jasiewicz JM, Treleaven J, Condie P, Gwendolen J, Wireless orientation sensors: Their suitability to measure head movement for neck pain assessment. Man Ther 2007; 12:380-385.

Lee RYW. Kinematics of rotational mobilisation of the lumbar spine. Clin Biomech 2001;16(6):481-488.

Lee RYW, Laprade J, Fung EHK. A real-time gyroscopic system for three-dimensional measurement of lumbar spine motion. Med Eng Phys 2003; 25(10):817-824.

Lee YH, Chiou WK, Chen WJ, Lee MY, Lin YH. Predictive model of intersegmental mobility of lumbar spine in the sagittal plane from skin markers. Clin Biomech 1995; 10(8):413-420.

Ma HT, Yang Z, Griffith JF, Leung PC, Lee RYW. A new method for determining lumbar spine motion using Bayesian belief network. Med Biol Eng Comput 2008; 46:333–340.

Mannion A, Troke M. A comparison of two motion analysis devices used in the measurement of lumbar spinal mobility. Clin Biomech 1999; 14:612-619.

Mannion AF, Klein GN, Dvorak J, Lanz C. Range of global motion of the cervical spine: intraindividual reliability and the influence of measurement device. Euro Spine J 2000; 2(9):379–385.

Nattrass CL, Nitschke JE, Disler PB, Chou MJ, Ooi KT. Lumbar spine range of motion as a measure of physical and functional impairment: an investigation of validity. Clin Rehab 1999; 13:211–218

Piché M, Benoît P, Lambert J, Barrette V, Grondin E, Martel J, Paré A, Cardin A. Development of a computerized Intervertebral motion analysis of the Cervical Spine for clinical application. J Manipulative and Physiol Ther 2006;30(1).

Plamondon A, Delisle A, Larue C, Brouillette D, McFadden D, Desjardins P, Lariviëre C. Evaluation of a hybrid system for three-dimensional measurement of trunk posture in motion. Appl. Ergonomics 2007; 38:697-712.

Schuler TC, Subach BR, Branch CL, Foley KT, Burkus JK, Segmental Lumbar Lordosis: Manual versus Computer-Assisted Measurement Using seven Different techniques. J Spinal Disord Tech, 2004; 17:372-379.

Simcox S, Parker S, Davis GM, Smith RW, Middleton JW. Performance of orientation sensors for use with a functional electrical stimulation mobiliy system. J Biomech 2005; 38:1185 – 1190.

Troke M, Moore AP, Maillardet FJ, Cheek E. A normative database of lumbar spine ranges of motion. Man Ther 2005;10:198–206.

Van Herp G, Rowe P, Salter P, Paul JP. Three-dimensional lumbar spinal kinematics: a study of range of movements in 100 healthy subjects aged 20 to 60+ years. Rheumatology 2000; 39:1337-1340.

Vogt L, Banzer W. Measurement of lumbar spine kinematics in incline treadmill walking. Gait and Posture 1999; 9:18–23.

Vogt L, Segith C, Banzer W. Movement behaviour in patients with chronic neck pain. Physiotherapy Res Int 2007; 12(4):206–212.
Walpole RE, Myers RH, Myers SL, Ye K. Probablility & Statistics for Engineers & Scientists, 7th Edition, 2002, Prentice Hall.

Zhang X, Xiong J. Model-guided derivation of lumbar vertebral kinematics in vivo reveals the difference between external marker-defined and internal segmental rotations. J Biomech 2003;36:9–17