Definition of spinal joint coordination laws for repositioning a digital human model based on MRI observations in four different postures

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Keywords: Spinal coordination law, Non-standard anatomical postures, Digital human model repositioning.

Introduction

Thanks to recent studies about the relationship between joint center locations, external body shape and landmarks positions, we can build a personalized kinematic human model in standing posture. It is though challenging to position it into a seated posture. This is particularly true for positioning pelvis and spine due to the high number of degrees of freedom (DOF) involved and very low number of anatomical landmarks available for palpation/motion capture. This is an under-determined problem. A priori knowledge is needed to find anatomically correct solutions. One way is to reduce the DOFs of spine model by either not allowing all intervertebral joint rotate freely or introducing relationships between them. (Alemi et al. 2021) reduced spinal DOFs from 51 to 5 by defining kinematic constraints and showed that a 5DOF-simplified model could produce smooth spine motions. Monnier et al., (2007) used the relationships between spinal joint angles, called spinal coordination laws, to prevent unrealistic postures in motion reconstruction process. However, evidence based statistical models are missing. The objective of this paper is to investigate the variation of spinal joint angles when changing posture and to identify spinal coordination laws.

Methods

In this research, a previously collected data by Beillas et al., (2009) from MRI observations of three females and six males in four postures (standing, seated, supine and 45° forward-flexion), were used. In their study, positional MRI and custom designed adjustable fixtures were used to define and impose the four postures. We defined a spinal model with 17 spherical joints, from S1L5 to T1C7, and we personalized the segment lengths for each participant. Since postural changes between the four studied positions were mainly in the sagittal plane, only flexion-extension was allowed for each joint. All joints were aligned when joint angles were zeros. Then, the intervertebral joint angles were obtained by minimizing the distance between the joint positions of the subject-specific kinematic models and those from MRI image. One factor ANOVA was used to analyze the effect of posture on joint angles. We also defined two overall spinal parameters to characterize the global spinal posture: 1) distance between T1C7 and S1L5 (trunk_d) for trunk compression, 2) angle between L5S1-midHip and S1L5-C7T1 (trunk_a) for trunk flexion. Statistical relationships between overall spinal parameters and joint angles were analyzed.

Results

Figure 1 shows the reconstructed spines corresponding to the four postures for one male participant (M01). Significant differences between four postures were observed only for S1L5 (F=9.19, p=0.0002), L5L4 (F=7.28, p=0.0007), L4L3 (F=2.95, p= 0.0475), and T7T6 (F=3.13, p=0.0391) joint angles (Table 1). Taking standing posture as reference, joint angle changes were calculated for forward-flexion, seated and supine postures. Regression equations of joint angle changes for S1L5, L5L4, L4L3 and T7T6 were obtained (Table 2).

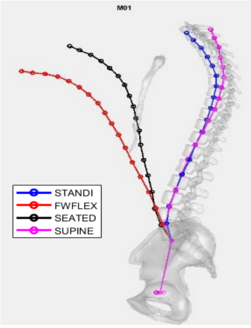

Figure 1. Reconstructed spinal models for four postures for a male participant (M01)

Table 1. Means (± standard deviations) of spine joint angles for the four postures and the global spinal postural parameters trunk_a (flexion-extension) and trunk_d (compression). Angles are in degrees, positive for flexion and negative for extension. *FWFLEX=forward-flexion, SEATED=seated, STANDI=standing, SUPINE= supine

Posture	S1L5	L5L4	L4L3	T7T6	Trunk_d(mm)	Trunk_a
FWFLEX	35.21 ± 8.33	- 11.74 ± 7.38	-3.70 ± 5.18	7.62±7.11	445.81±19.73	37.51±12.52
SEATED	34.37 ± 5.86	-10.84 ± 3.71	-8.07 ±4.29	7.65±4.84	450.98± 15.32	29.62±5.40
STANDI	24.82 ± 7.58	-19.98 ± 3.59	-10.46 ±5.12	9.92±4.78	440.30±15.66	10.80±5.61
SUPINE	21.10 ± 5.57	-18.42 ± 4.96	-7.90 ± 5.00	2.03±5.72	453.82±20.08	5.15±7.06

Table 2 Regression equations of joint angle changes. D_Trunk_d (%) is the variation of trunk_d normalized by its value in standing posture, and D_Trunk_a is the change of trunk_a with respect to the standing posture.

Joint	Constant	D_Trunk_d (%)	D_Trunk_a	Adjusted R^2 (%)	MSE
S1L5	3.09	1.12	0.36	68.84	22.67
L5L4	0.41	1.32	0.28	45.87	20.12
L4L3	1.96	0	0.14	25.33	15.24
T7T6	7.54	0	0.25	20.29	60.22

Discussion and Conclusions

Only three lumbar joints (S1L5, L5L4, L4L3) and one thoracic joint (T6T7) were found to contribute to spinal posture changes, suggesting a kinematic model with these four joints would be enough to describe spinal curvature. This highlights the importance of lower lumbar joints in spine postural changes especially for flexion-extension. Kuai et al., (2018) showed that S1L5, L5L4, L4L3 joints contributed to total spinal motion more than other lumbar joints. Alemi et al. (2021) found that, comparing to thoracic joints, lumbar joints contribute more to overall spine flexion-extension. In this study, evidence-based spine coordination laws have been obtained. Results will be applied to reconstruct seated postures using a whole body model. High R-squared value for the variation of S1L5 and L4L5 angles imply that the two global spinal postural parameters could be enough to predict these variables using linear regressions. However low R-squared value for L4L3 and T7T6 suggest that other predictors might be needed to characterize the global spinal posture.

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