Spline-based repositioning for the vertebral column of the GHBMC Human Body Finite Element Model

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I. INTRODUCTION

Finite Element (FE) Human Body Models (HBM) have become powerful numerical tools for injury prediction. However, as they are developed in just a few standardised positions, this restricts their use. As it is not viable to develop these HBMs for all possible positions, posture-specific HBMs need to be generated by reconfiguring existing ones. Frechede *et al*. [1] describe a spine predictor, implemented in the PIPER (Position and Personalize Advanced Human Body Models for Injury Prediction) tool, which approximates the cervical and thoraco-lumbar spine as cubic splines and predicts the vertebral positions for flexion/extension and lateral flexion of the spine for different HBM postures.

A spline-based technique is presented in [2] for the positioning of the vertebral column of the FE-HBMs in the sagittal plane. The work in this paper improves upon this spline-based technique and is capable of dealing with all three types of motion – flexion, abduction and twisting – for the cervical, thoracic and lumbar sections of the vertebral column. Each section is fitted with a different cubic spline, the shape of which can be changed by moving the control points. Subsequently, the new position of the vertebral column can be obtained from the transformed location of the end vertebrae, which means the position of intermediate vertebrae can be derived using spline interpolation.   The work presented here is implemented in the PIPER framework [3], in addition to the spine predictor tool of [2], and can be used to reposition the upper body for flexion and lateral flexion, as well as for rotation of the spinal segments. In addition, the PIPER framework includes display/visualisation and input/output, as well as other modules, such as smoothing, that can be applied subsequently. The method described in this paper will be available under the Open Source GPL v2 license within the PIPER framework.

II. METHODS

The cervical, thoracic and lumbar sections of the vertebral column involve three types of motion: flexion, abduction and twisting. The algorithm for these three types of motion is similar across the three sections, which is controlled by two input parameters: the key vertebrae for morphing, and the angle of rotation. In Fig. 1 (a), K1, K2, K3, K4 mark the four vertebrae used for cubic spline generation. K5 is the Lumbo Sacral Joint (LSJ) through which the rotation axis passes
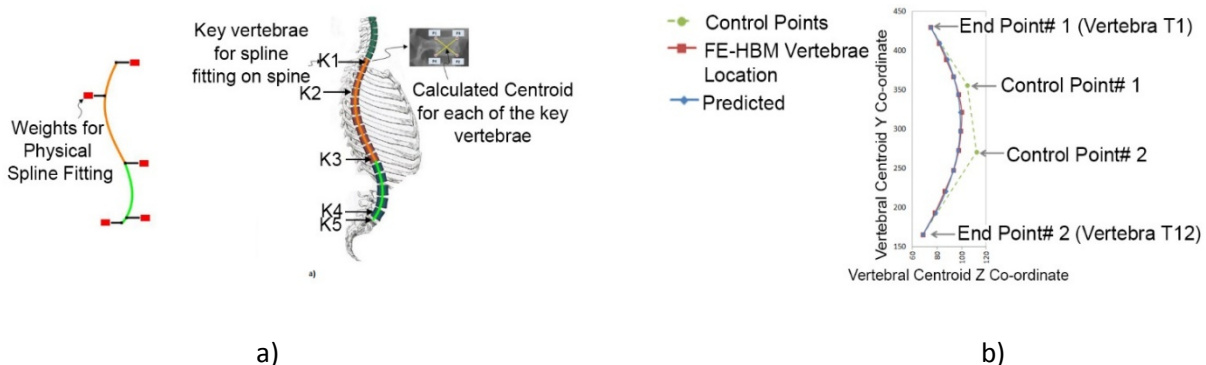

a)   b)

Fig. 1. (a) Weights for physical spline fitting; (b) key vertebrae identified for spline fitting.

Repositioning of Lumbar, Thoracic and Cervical Spline

For the natural spline to be calculated, the key vertebrae are first identified and mapped in the lumbar, thoracic or cervical sections. After the calculation of the natural spline, the intermediate points on the vertebral spine curve are mapped to the computed natural spline, which is done by calculating the arc length for the entire lumbar region and then defining the ratio of arc length between each successive vertebra.

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For the flexion of the lumbar region, the location of the Lumbo-Sacral-Joint (LSJ) is estimated by the position of landmarks on S1 and L5 vertebrae, and the calculated joint position is used as a centre of rotation during transformation of key vertebrae. In the next step the rotation angle for the whole cubic spline is calculated, which depends on the rotation of the preceding vertebra. Key vertebrae T1, T4, T12 and L5 are used to estimate control points for the cubic Bezier spline. As per Fig. 1(b), End Point 1, Control Point 1 and Control Point 2 are rotated about the LSJ by an angle gamma (γ), two-thirds of gamma and one-third of gamma angle, respectively. To remap the transformed positions of vertebral centroids, their position is computed on the original spline. The centroids are later regenerated on the transformed/rotated spline using this position, which helps to generate the transformed state for the spine. To generate the vertebral nodes in the transformed position from their respective centroids, the vertebrae are transformed rigidly to the new location and orientation. Flexion for thoracic and cervical parts is carried out using the same technique as used for the lumbar part.

Lateral flexion for all the three parts is also done using the same method about the lateral flexion axis (instead of the flexion-extension axis). Twisting of vertebral nodes is carried out based on *a priori* knowledge [4-5] of maximum permissible relative angular rotation between consecutive vertebrae. Twisting is done in proportion to the maximum permissible twist at each intervertebral joint. Once the spine is repositioned, the upper body of the HBM is repositioned using a technique similar to that presented in [2] [6].

III.   INITIAL FINDINGS

Figure 2 shows results of the spline-based repositioning technique where the HBM twisted by 25° in the lumbar region, laterally flexed by 20° in the thoracic region, and flexed in the cervical region. The last figure shows the model after a combination of the three motions. The process takes about 4 minutes on a machine running Windows 7 with 16GB RAM, Intel Xeon E5-1620 CPU, NVDIA GTX 780 GPU.

a)   b)   c)
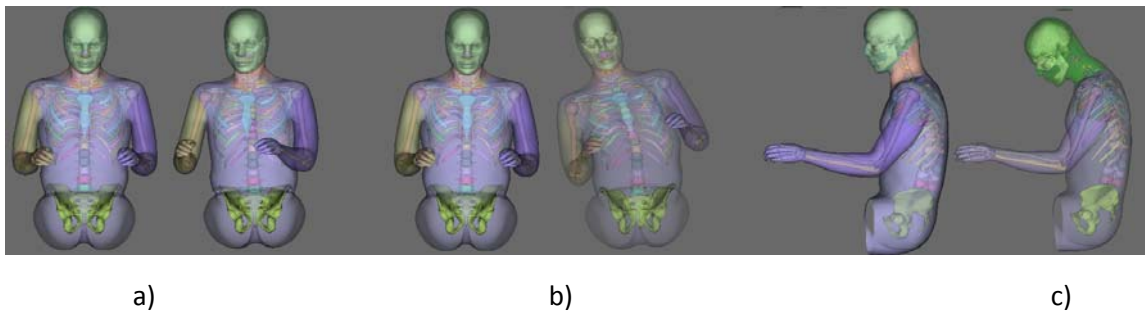
Fig. 2. a) After twisting the lumbar region by 25°; b) lateral flexion of the thoracic region by 20°; c) after flexion of the cervical region by 25°.

IV.   DISCUSSION

The spline-based technique presented in this paper can serve as a viable method for positioning the vertebral column of the human body, as the spline methods employed are a good approximation for the human spine. Since the cervical, thoracic and lumbar regions can be independently repositioned through spline-based interpolation, the method is likely to give additional control during repositioning of the upper body. Another advantage of this technique is that the relative locations of the organs of the thoracic region are maintained in the repositioned model, in spite of the complexity of the placement of organs in the thoracic and abdominal region.

V.   ACKNOWLEDGEMENT

VI.   REFERENCES

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