Spine Posture Estimation Method from Human Images Using 3D Spine Model

– Computation of the rough approximation of the physical forces working on vertebral bodies –

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Abstract

This paper describes a method for estimating a human spine posture from human images using a human spine model that is possible to compute the rough approximation of the physical forces working on vertebral bodies. The spine posture estimation model is composed of the vertebral bodies, each of which is modeled as a rigid body, and the intervertebral discs that are modeled as springs. Our method uses the positions of the neck and waist in addition to the positions of the head, torso, and arms estimated from the actual human images. The spine model is deformed so as to locate the top and the bottom vertebrae of the spine model to the estimated neck and waist positions. According to the experiments based on one real MR image dataset of one subject person, our methods estimated the positions of the vertebrae within positional shifts of about 6.3 mm and the rotational variation of about 3.1 degrees. We also confirmed the methods calculated the reasonable estimation of the physical forces working on the vertebral body.

1. Introduction

Spine posture is very important to keep us healthy and comfortable in our daily life, because if we keep poor posture for a long time, or lift up a heavy object quickly, the spine will be damaged due to the stress working on the spine. Therefore, it is very important to develop a method for analyzing the loads working on the vertebra. Nabhani et al. [1] proposed the method for computing the force working on the vertebra assuming that a subject is in upright posture, because the positions and directions of vertebrae cannot be measured easily from an actual posture.

In this paper, we propose a method for estimating the positions and the orientations of the vertebrae from human images taken by conventional video cameras. Since the positions and the orientations of the vertebrae are determined by the equilibrium of the weight of the head, torso, and arms, and the compressive and tensile forces of the intervertebral discs, our method can estimate the physical forces working on the vertebral body roughly as well as the spine posture.

According to Schultz et al. [2], the force and the torque acting on one vertebral body depend on the positional relations between the center of mass of the vertebral body and the centers of mass of the head, torso, and arms. Then we need to acquire the positions of the head, torso, and arms of a subject from the human images. For this task, the methods for estimating the whole body are available [3, 4, 5, 6].

On the other hand, there are few discussions about the method for estimating the spine posture from the human images. Badler et al. [7] proposed the spine and torso models and the motion generation method using them for computer animation. However, since this model is deformed based on kinematics, it is difficult to apply this model to the physical force computation.

In Section 2, we present the spine posture estimation model. The spine posture estimation process is described in Section 3. The physical force computation is also explained briefly. In Section 4, we show the experimental results for evaluating the accuracy of the estimated positions and the orientations of the vertebrae. In this experiments, one set of real MR images are used. Then we show the preliminary experiments of the physical force computation. Section 5 contains the conclusions and future work.

2. Spine posture estimation model

Our spine posture estimation model consists of twelve thoracic vertebrae and five lumbar vertebrae, and the intervertebral discs. The vertebrae are modeled as surface objects since the vertebrae are dealt with as rigid bodies in

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the model deformation process. The intervertebral disc is approximated by eight springs which connect the adjacent vertebrae.

A set of X-ray CT images provided by the Visible Human Project [8] are used to construct the spine model. The surface of the vertebral bodies are determined by applying the marching cubes method to the voxel data obtained by simply thresholding the CT images. The contacting points of the vertebrae and the associated springs are manually adjusted considering the center of mass of the vertebra and the symmetry of the arrangement of the springs.

3. Spine posture estimation method

Figure 1 shows the processing flow of the spine posture estimation. The inputs are a sequence of human images of a subject taken by video cameras.

3.1. Neck and waist positions estimation

The whole body model consists of nine parts of ellipsoids that represent the head, upper and lower bodies, upper arms and forearms, and thighs and legs. We define the neck and waist positions, r_{neck} and r_{waist} as the top of the ellipsoid corresponding to the upper body part and the center of mass of the ellipsoid corresponding to the lower body part, respectively. Although the whole body model was manually fit to the human images manually in this paper, the basic posture estimation method can be used to do it. After the model fitting, r_{neck} and r_{waist} indicate the neck and waist positions of the subject. The centers of mass of the head, arms, and bodies, r_{h}, r_{l}, r_{r}, and r_{b}, are approximated by the centers of mass of the corresponding ellipsoids.

3.2. Spine model deformation

Before the model deformation process, the model is translated and rotated to make the position and the orientation of the bottom vertebra of the model and those of the waist coincide. Then the top vertebra is moved toward the neck position by a short distance. This movement is carried out iteratively until the top vertebra reaches at the neck position. After n times iterations, the top vertebra position $r_{\text{top}}(n)$ is expressed by the following formula,

$$r_{\text{top}}(n) = r_{\text{top}}(n-1) + \delta \boldsymbol{d}, \tag{1}$$

where $\boldsymbol{d}$ satisfies $\boldsymbol{d} = r_{\text{neck}} - r_{\text{top}}(0)$, and $\delta \boldsymbol{d}$ means the small displacement along the direction of $\boldsymbol{d}$. $r_{\text{top}}(0)$ is the initial position before the model deformation process.

Each time the top vertebra is moved by $\delta \boldsymbol{d}$, the state of equilibrium of the model is calculated. As shown in Fig.2, we consider two types of forces working on a vertebra, the weight $\boldsymbol{W}_i$ of the volume between the centers of mass of the $(i-1)$-th and the i-th vertebrae and the force of repulsion $\boldsymbol{Fd}_i$ and $\boldsymbol{Md}_i$ of the springs connected to the i-th vertebra. We denote the force and the torque working on the i-th vertebrae as $\boldsymbol{F}_i$ and $\boldsymbol{M}_i$. Then $\boldsymbol{F}_i$ and $\boldsymbol{M}_i$ are expressed by the following equations,

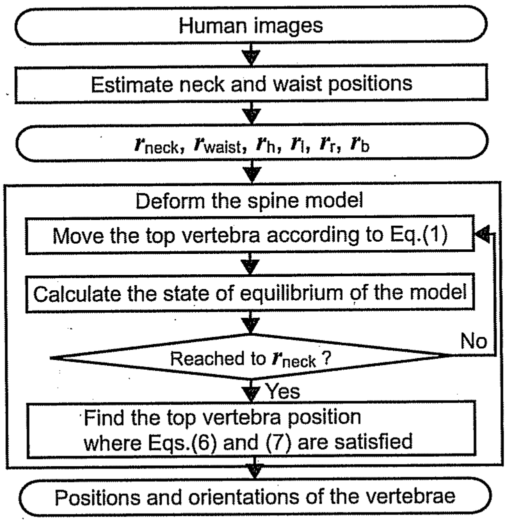

Figure 1. Processing flow of the spine posture estimation.

$$\boldsymbol{F}_i = \boldsymbol{W}_i + \boldsymbol{Fd}_i, \tag{2}$$

$$\boldsymbol{M}_i = \boldsymbol{r}_i \times \boldsymbol{W}_i + \boldsymbol{Md}_i, \tag{3}$$

where $\boldsymbol{r}_i$ represents the center of mass of the volume. The symbol '×' represents the outer product of two vectors. Since we model the torso as a combination of ellipsoids, $\boldsymbol{W}_i$ can be calculated by integral easily. k_{ij} is the spring constant.

As expressed in Eqs.(2) ~ (3), $\boldsymbol{F}_i$ and $\boldsymbol{M}_i$ depend on the positions and the orientations of the $(i-1)$-th and the $(i+1)$-th vertebrae as well as the ones of the i-th vertebra. Then $\boldsymbol{F}_i$ and $\boldsymbol{M}_i$ can be expressed by the following formulae,

$$\boldsymbol{F}_i = \boldsymbol{F}_i(\boldsymbol{r}_{i-1},\ \boldsymbol{\theta}_{i-1},\ \boldsymbol{r}_i,\ \boldsymbol{\theta}_i,\ \boldsymbol{r}_{i+1},\ \boldsymbol{\theta}_{i+1}), \tag{4}$$

$$\boldsymbol{M}_i = \boldsymbol{M}_i(\boldsymbol{r}_{i-1},\ \boldsymbol{\theta}_{i-1},\ \boldsymbol{r}_i,\ \boldsymbol{\theta}_i,\ \boldsymbol{r}_{i+1},\ \boldsymbol{\theta}_{i+1}), \tag{5}$$

where we denote the center of mass of the i-th vertebra as $\boldsymbol{r}_i$, and the orientation in Euler angle as $\boldsymbol{\theta}_i$. $\boldsymbol{F}_i$ and $\boldsymbol{M}_i$ must satisfy the following equations because of the equilibrium of the model,

$$\boldsymbol{F}_i(\boldsymbol{r}_{i-1},\ \boldsymbol{\theta}_{i-1},\ \boldsymbol{r}_i,\ \boldsymbol{\theta}_i,\ \boldsymbol{r}_{i+1},\ \boldsymbol{\theta}_{i+1}) = \boldsymbol{0}, \tag{6}$$

$$\boldsymbol{M}_i(\boldsymbol{r}_{i-1},\ \boldsymbol{\theta}_{i-1},\ \boldsymbol{r}_i,\ \boldsymbol{\theta}_i,\ \boldsymbol{r}_{i+1},\ \boldsymbol{\theta}_{i+1}) = \boldsymbol{0}. \tag{7}$$

Therefore, the positions and the orientations of the $N-2$ vertebrae excluding the top and the bottom vertebrae are determined by solving the $2 \times (N-2)$ sets of nonlinear equations. These equations can be solved using the Newton-Raphson method.

We assume that the top vertebra of the model supports the weight of the head and arms as expressed in the following formulae,

$$\boldsymbol{F}_{\text{top}} = \boldsymbol{W}_{\text{h}} + \boldsymbol{W}_{\text{l}} + \boldsymbol{W}_{\text{r}} + \boldsymbol{Fd}_{\text{top}}, \tag{8}$$

$$\boldsymbol{M}_{\text{top}} = r_{\text{h}} \times \boldsymbol{W}_{\text{h}} + r_{\text{l}} \times \boldsymbol{W}_{\text{l}} + r_{\text{r}} \times \boldsymbol{W}_{\text{r}} + \boldsymbol{Md}_{\text{top}}, \tag{9}$$

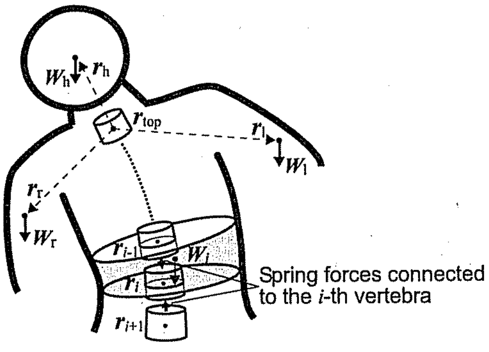

Figure 2. Forces and moments acting on a vertebra.

where $\boldsymbol{W}_h$, $\boldsymbol{W}_l$, and $\boldsymbol{W}_r$ represent the weight of the head and arms, and $\boldsymbol{r}_h$, $\boldsymbol{r}_l$, and $\boldsymbol{r}_r$ the vectors of the center of mass of the body parts. $\boldsymbol{F}_{top}$ and $\boldsymbol{M}_{top}$ do not satisfy the conditions expressed by Eqs.(6) and (7) because the position of the top vertebra is determined according to Eq.(1). Therefore, we find the top vertebra position so that Eqs.(6) and (7) are satisfied by translating the top vertebra along the line that passes through its center of mass and that is parallel to a plumb line.

The forces working on the upper surface of the vertebral body can be calculated from Eqs.(2) and (3). But, at this time, $\boldsymbol{Fd}_i$ and $\boldsymbol{Md}_i$ are derived by summing only the forces generated by the springs connecting to the upper surface of the vertebral body.

4. Experimental results and discussion

4.1. Evaluation about the accuracy of the model deformation method using MR images

We evaluated the accuracy of the method for deforming the spine model. In this experiment, we used three sets of MR images. The first two datasets A and B were the coronal and sagittal images in which a subject was lying straightly on the bed of MRI. The other dataset C was the coronal images in which the subject was lying with his body bending to the right. Acquisition parameters of the MRI images were: 512 × 512 pixels, 0.586 mm pixel size, 7 slices. The reconstruction pitch was 15 mm for the image datasets A and C, 8 mm for the image dataset B.

Table 1. The comparison results of the positions and the orientations of the vertebrae measured from MR images and estimated by our methods.

Vertebra	Δx (mm)	Δy (mm)	SSD (mm)	$\Delta\theta$ (deg)
T2	9.1	1.4	9.3	12.6
T3	11.0	-4.0	11.7	4.3
T4	13.2	-1.7	13.4	2.2
T5	11.7	-1.9	11.8	2.9
T6	10.0	-1.0	10.0	0.2
T7	8.5	-1.4	8.6	0.1
T8	7.0	-0.6	7.0	1.7
T9	4.3	-0.3	4.3	3.1
T10	1.2	0.2	1.2	6.0
T11	0.1	1.7	1.7	4.1
T12	-1.4	0.9	1.6	2.4
L1	0.1	3.2	3.2	3.3
L2	0.4	2.7	2.7	0.9
L3	1.1	3.4	3.5	1.1
L4	1.7	4.3	4.6	1.5
M $\pm\sigma$	5.2 ± 4.9	0.5 ± 2.2	6.3 ± 6.0	3.1 ± 3.0

From the datasets A and B, we measured the center of mass, vertical height, sagittal diameter, transverse diameter of a vertebra, and distance between vertebrae, and we constructed an spine model reflecting the structure of the spine of the subject based on these parameters. We also measured the vertebra positions of the subject bending his body to the right from the dataset C. The neck and waist positions were determined by the obtained vertebra positions. Then the spine model was deformed, and we compared the estimated results of the vertebrae with the vertebra positions measured from the dataset C. Because we took only the coronal images about the bending posture, we could not obtain the coordinate of a vertebra in the direction of the sagittal axis. Therefore, we assumed that the coordinate of a vertebra in the direction of the sagittal axis does not change during the deformation process, and the movements of the vertebrae was limited on the plane parallel to the coronal plane.

We employ the Young's modulus of 500 MPa and the Poisson's ratio of 0.3 as the material property of the intervertebral discs. The spring constant k_i were determined as the approximations of these values.

Table 1 shows the comparison results of the positions and orientations of the vertebrae measured from MR images and estimated by our methods. In this table, Δx and Δy mean the errors along the left-right direction and along the longitudinal direction, respectively. SSD means the sum of squared differences. The unit of the values is millimeter. The abbreviation 'T' and 'L' represent thoracic and lumbar vertebra, respectively.

We implemented our proposed method on a conventional PC (Pentium 4 2.8 GHz). Total computation time was 77.6 seconds. The model deformation was repeated 65 times until the top vertebra reached to the neck position obtained from the MR images. 70 times iterations was performed on the average to solve the sets of nonlinear equations expressed in Eqs.(6) and (7).

4.2. Calculation of the forces working on the upper surface of the vertebral body

We calculated the physical force on the upper surface of the lumbar vertebra 'L5' by applying the methods to the real human images. Fitting the whole human body model to the human images was carried out manually. The subject was slowly lifting up the weight of about 4.1 kg to his

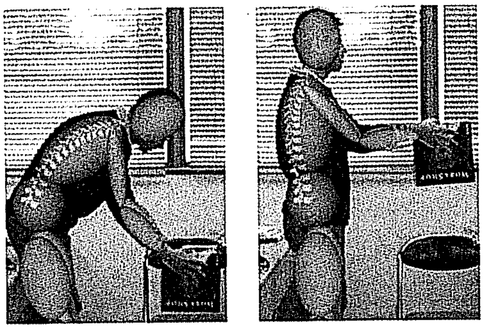

Figure 3. Examples of the estimated spine postures.

elbow height. It was assumed that the weight of the head, torso, and arm of the subject were about 3.6 kg, 25.7 kg, and 3.3 kg, respectively. These are the similar conditions in the numerical computation performed by Schultz et al. [2]. The subject was the same person whose MR images were used in the experiment stated in Section 4.1. Then the model constructed in the above experiment were used again in this experiment.

Figure 3 shows the examples of the estimated spine postures. The estimated spine postures are overlaid on the figures. The violet ellipsoidal regions represent the whole body model. The computation result of the force working on the lumbar vertebra 'L5' was about 336 N. The experiment was carried out on the same computer resource (Pentium4 2.8 GHz) used in Section 4.1. Total computation time was about 49 seconds.

4.3. Discussion

As shown in Table 1, our methods estimated the positions of the vertebrae within positional shifts of about 6.3 mm and the rotational variation of about 3.1 degrees. From MR images, the center of mass of the vertebra 'T4' shifted in 6.2 cm from its original position after the subject bent his body to right. The method estimated the 'T4' shifted in 4.8 mm (Table 1). Therefore, the error of the estimated 'T4' is about 22 %. Since this experiment was performed using one set of MR images, we have to validate the method more precisely using a large number of MR image sets.

The computation result of the force working on the lumbar vertebra 'L5' was about 336 N. According to the Schultz's simple model not having the dorsal muscles, the force is about 390 N [2]. Therefore, it is turned out that our model is reasonable for calculating the rough estimation of the force working on the vertebra.

We have to consider two kinds of errors, those of the neck and waist position estimation based on the fitting of the whole body model to the human images, and those of construction and fitting of the spine model. The latter are examined in the experiments stated in Section 4.1, whose results are discussed in the above paragraph. However, the former are not examined in this paper since we could not obtain the gold standard of the neck and waist positions from only one camera view. We should measure the positions using stereo vision to evaluate them.

5. Conclusion

In this paper, we have proposed a spine model and a method for estimating the spine posture from human images taken by video cameras. According to the preliminary experiments based on one real MR image data set of only one subject person, the methods estimated the positions of the vertebrae within positional shifts of about 6.3 mm and the rotational variation of about 3.1 degrees. We also confirmed that the methods calculated the reasonable approximation of the physical forces working on the vertebral body.

Future work includes: (1) validation of accuracy of the model deformation method using a large set of MR image sets, (2) application to a large set of human images and the discussion about the method for evaluating the estimated spine posture, and (3) precise validation of the calculated physical forces on the vertebra from the viewpoint of anatomy and biomechanics.

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