

REVIEWED LNCS VERSION OF ICPR-WDIA PAPER:

Posture Analysis and Range of Movement Estimation using Depth Maps

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We updated the paper based on the following reviewers' comments and included new explanations in some subsections of the paper.

The article describes a semi-automatic method to detect back problems on humans, especially a shape analysis of the spine. According to the article, this method is ready to be applied in practice.

In the spine curvature analysis the explanation of equation (4) is incomplete. How are h_1 and h_2 derived?

The definition of these landmarks has been clarified in the new version of the paper.

In eq.(2), how to give the values (0 or 1) for $w_{i,j}$? I mean how to judge that point T_i and C_j correspond to the same point?

As it is an optimization process, this value is optimized while assigned possible transformation of the two point clouds. This does not need to be redefined.

I do not understand "range of movement". The authors should give a further explanation about this term. This confusion makes section 2.4 difficult to read.

As suggested by the reviewer we extended the explanation regarding range of movement to make the procedure clear.

In (2) T is not a translation matrix but a 3-D vector.

We updated the definition of the term T accordingly.

Moreover, in the new version of the paper some paragraphs have been extended including extra details of the procedure. Finally, the whole paper has been carefully checked for minor inconsistencies.

Posture Analysis and Range of Movement Estimation using Depth Maps

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Abstract. World Health Organization estimates that 80% of the world population is affected of back pain during his life. Current practices to analyze back problems are expensive, subjective, and invasive. In this work, we propose a novel tool for posture and range of movement estimation based on the analysis of 3D information from depth maps. Given a set of keypoints defined by the user, RGB and depth data are aligned, depth surface is reconstructed, keypoints are matching using a novel point-to-point fitting procedure, and accurate measurements about posture, spinal curvature, and range of movement are computed. The system shows high precision and reliable measurements, being useful for posture reeducation purposes to prevent musculoskeletal disorders, such as back pain, as well as tracking the posture evolution of patients in rehabilitation treatments.

Keywords: Depth maps, Physiotherapy, Posture Analysis, Range of Movement Estimation, Rehabilitation, Statistical Pattern Recognition

1 Introduction

World Health Organization has categorized disorders of the musculoskeletal system as the main cause for absence from occupational work and one of the most important causes of disability in elders in the form of rheumatoid arthritis or osteoporosis. It is estimated that 80% of world population will suffer from musculoskeletal disorders during their life.

The body posture evaluation of a subject manifests, in different degrees, his level of physic-anatomical health given the behavior of bone structures, and especially of the dorsal spine. For instance, common musculoskeletal dysfunctions or disorders (MSDs) such as scoliosis, kyphosis, lordosis, arthropathy, or spinal pain show some of their symptoms through body posture. This requires the use of reliable, noninvasive, automatic, and easy to use tools for supporting diagnostic. However, given the articulated nature of the human body, the development of this kind of systems is still an open issue.

The solution more frequently applied to measure body posture consists of the synchronization of multiple cameras, applying stereo vision techniques [3, 5]. This kind of systems use to be expensive and invasive. Moreover, it uses to require specific and restricted illumination conditions. The main alternative is accelerometers. These systems

also use to be expensive, invasive, and inaccurate because of the spatial measurements of multi-axial articulations. Most of these systems only treat specific areas of the body with little configurability, which implies that therapists cannot use their own methods of analysis. A recent alternative is the use of the depth maps provided by the Microsoft Kinect device [1]. The Kinect camera uses a structured light technique to generate real-time depth maps containing discrete range measurements of the physical scene [2].

In this work, we present a novel semi-automatic system that uses RGB-Depth information to elaborate a clinical postural analysis through the examination of anthropometric values. Given a set of keypoints defined by the user, our proposed method performs the following steps: a) RGB and depth data are aligned, b) noise is removed and depth surface is reconstructed, c) user keypoints and predefined protocols are matched using a novel point-to-point fitting procedure, d) static measurements about posture and spinal curvature are accurately computed, and d) dynamic range of movement is robustly estimated. Compared to standard alternatives and supported by clinical specialists, the system shows high precision and reliable measurements to be include in the clinical routine.

The paper is organized as follows: Section 2 present the system for posture analysis and range of movement estimation. Section 3 presents the validation of the proposal, and finally, Section 4 concludes the paper.

2 Posture analysis system

We designed a full functional system devoted to help in the posture reeducation task with the aim of preventing and correcting musculoskeletal disorders. The system is composed by three main functionalities: a) static posture analysis (SPA), b) spine curvature analysis (SCA), and c) range of movement analysis (RMA). The architecture of the system is shown in Figure 1. First, a pre-processing step to remove noise and reconstruct surfaces is performed. Next, we describe each of these stages.

2.1 Noise removal and surface reconstruction

After aligning RGB and depth data [7, 11], and even though the used depth information is compelling it is still inherently noisy. Depth measurements often fluctuate and depth maps contain numerous holes where no readings are obtained. In order to obtain a valid and accurate depth map, we perform a depth preprocessing step to eliminate erroneous information caused by noise and to reconstruct surfaces not well defined. We perform the following methodology:

Noise removal: For each point we compute the mean distance from it to all its neighbors. By assuming that the resulted distribution is Gaussian with a mean and a standard deviation, all points whose mean distances are outside an interval defined by the global distances mean and standard deviation are considered as outliers.

Surface reconstruction: We use a resampling algorithm [10], which attempts to recreate the missing parts of the surface by higher order polynomial interpolation be-

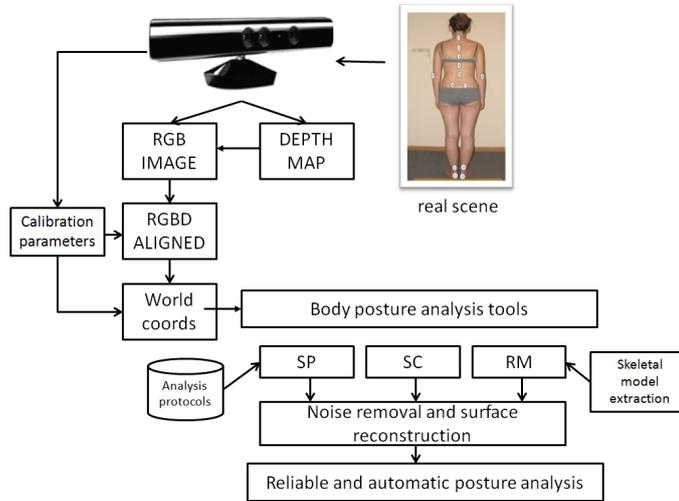


Fig. 1. Posture analysis system.

tween the surrounding data points. By performing resampling, these small errors can be corrected. Figure 2 shows an example of this process ¹.

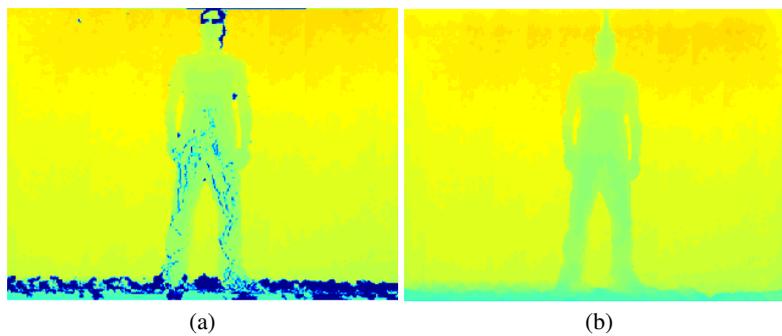


Fig. 2. (a) Original depth map. (b) Filtered and resampled.

Once the system is calibrated, data is aligned, and depth maps are filtered, the user can access to the three posture facilities.

¹ We experimentally found that our approach for noise removal and background reconstruction obtained better results than standard approaches based on accumulating temporal images (e.g. 30 frames of a stationary subject) for noise reduction and hole filling.

2.2 Static posture analysis (SPA)

This module computes and associates a set of three-dimensional angles and distances to keypoints defined by the user. These keypoints correspond to manual interactions of the user with the RGB data displayed in the screen (which internally is aligned with the corresponding depth data). The module also allows the therapist the possibility of designing a protocol of analysis. That is, a predefined set of angular-distance measurements among a set of body keypoints, all of them defined and saved by the user for posterior automatic matching. Figure 3 shows an example of a predefined protocol (the set of manual annotated keypoints together with the list of distance and angle relations to be computed).

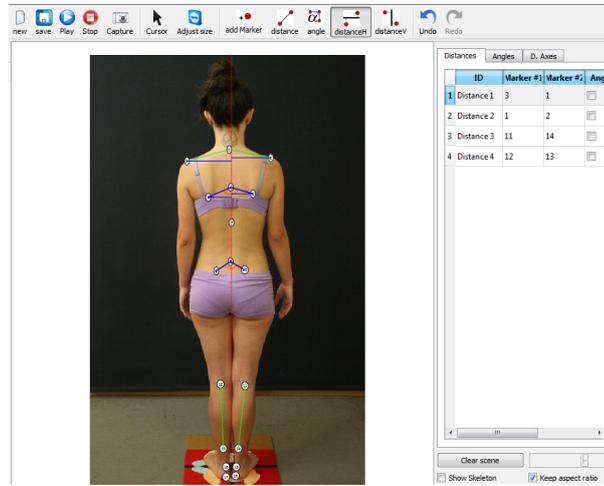


Fig. 3. Static posture analysis example.

In order to obtain an intelligent and automatic estimation of posture measurements, we define a correspondence procedure among manually placed virtual markers and protocol markers. We formulate markers matching as an optimization problem. Suppose a protocol analysis (template) T composed by N markers, $T = \{T_1, T_2, \dots, T_N\}$, $T_i = (x_i, y_i, z_i)$, and the current analysis C composed by the same number of markers, $C = \{C_1, C_2, \dots, C_N\}$ (predefined template and current set of keypoints defined by the user, respectively). Our goal is to make a one-to-one correspondence so that we minimize the sum of least square distances among assignments as follows:

$$\operatorname{argmin}_{C'} \sum_{i=1}^N \|C'_i - T_i\|^2, \quad (1)$$

where C' is evaluated as each of the possible permutations of the elements of C . For this task, first, we perform a soft pre-alignment between C and T using Iterative Closest

Point (ICP) [8], and then, we propose a sub-optimal approximation to the least-squares minimization problem. ICP is based on the application of rigid transformations (translation and rotation) in order to align both sequences C and T . This attempts to minimize the error of alignment $E(\cdot)$ between the two marker sequences as follows:

$$E(\mathcal{R}, \mathcal{T}) = \sum_{i=1}^N \sum_{j=1}^N w_{i,j} \|T_i - \mathcal{R}(C_j) - \mathcal{T}\|^2, \quad (2)$$

being \mathcal{R} and \mathcal{T} the rotation and translation 3D vectors, respectively. $w_{i,j}$ is assigned 1 if the i -th point of T described the same point in space as the j -th point of C . Otherwise $w_{i,j} = 0$. Two things have to be calculated: First, the corresponding points, and second, the transformation $(\mathcal{R}, \mathcal{T})$ that minimizes $E(\mathcal{R}, \mathcal{T})$ on the base of the corresponding points. For this task, we apply Singular Value decomposition (SVD). At the end of the optimization, the new projection of the elements of C is considered for final correspondence. Then, Eq. 1 is approximated as follows: Given the symmetric matrix of distances M of size $N \times N$ which codifies the set of $N \cdot (N - 1)/2$ possible distances among all assignments between the elements of C and T , we set a distance threshold θ_M to define the adjacency matrix A :

$$A(i, j) = \begin{cases} 1 & \text{if } M(i, j) < \theta_M \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

Then, instead of looking for the set of $N!$ possible assignments of elements of C and T that minimizes Eq. 1, only the possible assignments (C_i, T_j) that satisfies $A(i, j) = 1$ are considered, dramatically reducing the complexity of the correspondence procedure².

2.3 Spine curvature analysis (SCA)

The objective of this task is to evaluate sagittal spine curvatures (curves of the spine projected on the sagittal plane) by noninvasive graphic estimations in kyphotic and lordotic patients. Kyphosis and lordosis are, respectively, conditions of over-curvature of the thoracic spine (upper back) and the lumbar spine (lower back). The methodology proposed by Leroux et al [4] offers a three-dimensional analysis valid for clinical examinations of those conditions. In order to perform this analysis we proceed as follows. First, the therapist places the markers on the spine. Then, a few markers are selected and the 3D curve that represents the spine is reconstructed by linear interpolation (Figure 4(c)). Finally, the anthropometric kyphosis K_a and lordosis L_a are obtained.

The geometric model to compute K_a is represented in the Figure 4(a). F divides the curve representing the thoracic spine in two asymmetric arcs with different radius. Note that the F component begins at the farthest marker (apex, corresponding to T5) and it ends at the intersection with the T2-to-T12 line. h_1 and h_2 are the distances from manual annotation of T2 to the intersection and the distance from the intersection to

² We experimentally found that high values of θ_M obtain optimal results and reduces the computational cost in comparison to other approaches, such as Shape Context [6].

annotated landmark T12 (as shown in Figure 4, respectively). Then, the summation of two angles, φ_1 and φ_2 , represents the kyphosis curve value, where:

$$\begin{aligned}\varphi_1 &= 180 - 2 \cdot \arctan\left(\frac{h_1}{F}\right), \\ \varphi_2 &= 180 - 2 \cdot \arctan\left(\frac{h_2}{F}\right).\end{aligned}\quad (4)$$

L_a is calculated in a similar way, though the therapist should note the markers in the lumbar spine region. The capacity analysis of the spine is reinforced by a three-dimensional environment for a thorough examination by the therapist (Figure 4(d)). An example of spine interaction and computation are shown in Figure 4(a) and (b), respectively.

2.4 Range of movement analysis (RMA)

In order to complement the posture analysis procedure, we compute the range of movement of different body articulations. This means, for a particular articulation (joint), we detect and track its movement, and then we compute which is the range of angles that this joint performs for a particular period of time. For this purpose, we perform user detection using the Random Forest approach with depth features of Shotton et al [9] and compute the skeletal model. This process is performed computing random offsets of depth features as follows:

$$f_\theta(D, \mathbf{x}) = \mathbf{D}_{(\mathbf{x} + \frac{\mathbf{u}}{D\mathbf{x}})} - \mathbf{D}_{(\mathbf{x} + \frac{\mathbf{v}}{D\mathbf{x}})}, \quad (5)$$

where $\theta = (\mathbf{u}, \mathbf{v})$, and $\mathbf{u}, \mathbf{v} \in \mathbb{R}^2$ is a pair of offsets, depth invariant. Thus, each θ determines two new pixels relative to \mathbf{x} , the depth difference of which accounts for the value of $f_\theta(D, \mathbf{x})$. Using this set of random depth features, Random Forest is trained for a set of trees, where each tree consists of split and leaf nodes (the root is also a split node). Finally, we obtain a final pixel probability of body part membership l_i as follows:

$$P(l_i|D, \mathbf{x}) = \frac{1}{\tau} \sum_{j=1}^{\tau} P_j(l_i|D, \mathbf{x}), \quad (6)$$

where $P(l_i|D, \mathbf{x})$ is the PDF stored at the leaf, reached by the pixel for classification (D, \mathbf{x}) and traced through the tree j , $j \in \tau$. Computing the intersection borders among mean shift clusters estimated after Random Forest procedure, we obtain a three-dimensional skeletal model composed by nineteen joints. The physician then selects joint articulations and automatically obtains their maximum opening and minimum closing values measured in degrees for a certain period of time (Figure 4(e)).

3 Results

3.1 Software details

The video data uses a 8 bits VGA resolution at 30Hz, and we capture frames at 640×480 pixels, like the infrared camera. Regarding the implementation we used the Kinect SDK framework. We also used the PCL-Library to treat cloud points, and to support a free and three-dimensional visualization we used the VTK library. The user interface has been developed in multi-platform Nokia Qt technology.

3.2 Data and validation

In order to measure the precision of the proposed methodology in the different modules of the system, a battery of 500 simple tests has been labeled by three different observers, with an inter observer correlation superior to 99% for all planes (X, Y, Z). Each test contains a set of angles and distances in order to simulate an analysis protocol for the study of posture, placing twelve infrared led markers on the body of the subject. A total of 20 subjects participated in the validation of the method. In order to perform automatic validation of the tests, infrared markers are detected by means of thresholding a HSV infrared-filtered image.

Results for different distance of the device to the scene are shown in Table 1. AAV and 'o' correspond to the average absolute value and degree, respectively. This analysis validates the accuracy of the SPA and RMA in millimeters and degrees, respectively. Note the high precision in both tests. In addition, in order to validate the curvature analysis of the spine (SCA), we used a group of 10 patients and performed the Leroux protocol [4], placing nine markers over the spine. The relationship between lateral radiographic and anthropometric measures was assessed with the mean difference. It has used Cobb technique on the lateral radiograph in order to obtain the coefficients of kyphosis and lordosis. The results of the SPA validation are shown in Table 3.2. Moreover, after discussing with specialists in physiotherapy they agreed that the accuracy of the results is more than sufficient for diagnostic purposes.

Distance subject-device (m)	1,3	1,9	2,2
AAV (o movement)	2,2	3,8	5,2
AAV (mm)	0,98	1,42	2,1
AAV (o angles)	0,51	1,04	1,24
AAV (%)	0,46	0,77	1,3
Standard Error (%)	1,01	1,18	1,71

Table 1. Pose and range of movement precision.

	Khyphosis range	Lordosis range
AAV (o)	5	6

Table 2. Validation of spinal analysis.

4 Conclusion

We presented a system for semi-automatic posture analysis and range of movement estimation using depth maps. The aim of the system is to assist in the posture reeducation task to prevent and treat musculoskeletal disorders. Given a set of keypoints

defined by the user, RGB and depth data are aligned, depth surface is reconstructed, keypoints are matching using a novel point-to-point fitting procedure, and accurate measurements about posture, spinal curvature, and range of movement are obtained. The system showed high precision in terms of distance, degree, and range of movement estimation. Supported by clinical specialists, the system shows high precision and reliable measurements to be include in the clinical routine.

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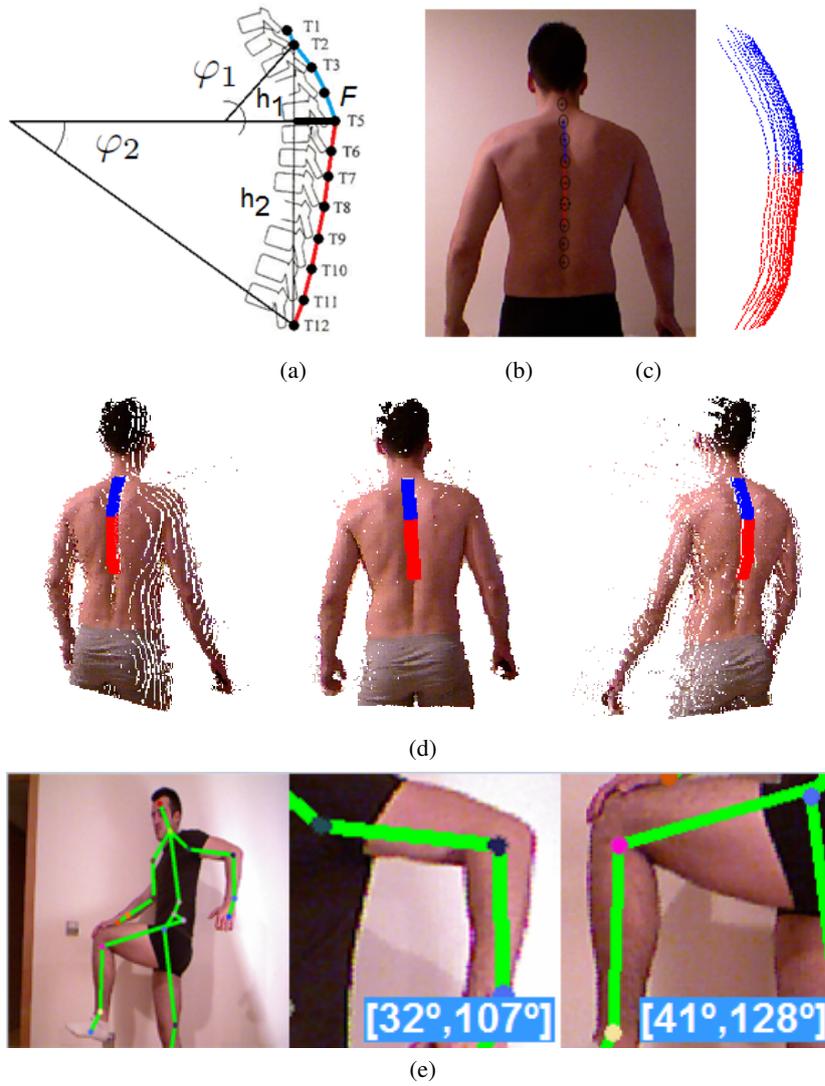


Fig. 4. (a) Geometric model to obtain anthropometric kyphosis, and lordosis value. (b) Sample of analysis. (c) Automatically reconstructed 3D spinal cloud. (d) Three-dimensional examination environment. (e) Skeletal model and example of selected articulations with computed dynamic range of movement.