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Comparison of two alignment methods prior to principal component analysis, for vertebra positions prediction from cutaneous markers

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1. Introduction

Predictions of internal vertebra positions from external data (e.g., skin shape or cutaneous markers) could be useful to drive spine osteoarticular models for motion analysis or to assess spinal alignment for clinical applications. These predictions are often limited to a single standing posture. Recently, a simple method based on linear regressions has shown its robustness to posture, with an average of 11.0 ± 3.7 mm root-mean-square errors (RMSE) on vertebra positions over the whole spine, in different sitting postures (Tomezzoli et al. 2024). This approach requires the expression of vertebra positions as polar coordinates in local frames originating at the skin, and the computation of composite predictors such as distances or back shape curvatures. Alternatively, principal component analysis (PCA) can be used to predict variable values from a multidimensional dataset without making assumptions about the variable interrelationships. The information contained in the dataset is automatically summarized onto a few PCA components, each constructed as a combination of the original variables. When applied to spatially organized data e.g., a collection of points extracted from two X-rays, alignment of the two point-clouds is recommended prior to PCA (Nerot et al. 2016). However, alignment is a compromise. For example, round and straight back shapes cannot be entirely superimposed. A segment from skin to vertebra, identical on those X-rays, will be rotated and therefore projected differently into x and y coordinates using trigonometric relationships. As PCA is based on additive, linear models, fitted on an array of unconnected inputs, the PCA's ability to

predict vertebra positions from markers coordinates might be compromised. The aim of this study is to assess the robustness to posture of a classical PCA-based algorithm (named c-PCA below), for predicting vertebra positions from cutaneous markers, then to assess the possibility of improving these predictions locally, for a few vertebrae, by optimizing alignment to cutaneous markers facing them (l-PCA).

2. Methods

2.1 Dataset

An existing open-access dataset was reused (Tomezzoli et al. 2024). Healthy participants (13 females, 23.6 ± 4.4 years, BMI 21.9 ± 1.5 kg/m²) were pre-equipped with radio-opaque cutaneous markers positioned by manual palpation, then 63 sagittal X-rays were taken, representing 3 sitting postures (slouched, erect and their usual posture) for each participant. The dataset comprised the coordinates of cutaneous markers and of the posterosuperior corner of the 25 vertebral bodies. In our study, the variables to be predicted were vertebra x, y coordinates (25×2) and the predictors were the coordinates of cutaneous markers with no missing data (19×2): spinous processes from the 5th cervical (C5) to the 9th thoracic vertebrae (T9), jugular notch, xiphoid process, anterior and posterior iliac spines, external auditory meatus, and occipital prominence.

2.2 Post-processing

A cross-validation process was carried out to predict vertebra positions, the dataset being repeatedly split into a training set (60 X-rays from 20 participants) and a validation set (3 X-rays from the remaining participant).

In the c-PCA method, each alignment was performed using all 19 cutaneous markers. Firstly, every X-ray of the training set was aligned to one X-ray in the usual sitting posture, arbitrarily chosen as the reference: the two cloud barycentres were first superimposed by translation, then the 3D rotation that minimized the least-squares distance between the points of the two cloud was determined. The PCA Matlab function was then used to compute the mathematical relationships between vertebra and cutaneous marker coordinates. Secondly, the vertebra positions of each of the 3 validation set X-rays were predicted based on these relationships, after aligning them on the average cutaneous markers disposition in the PCA. Thirdly, predicted vertebrae positions were repositioned on the initial X-ray by a final alignment on its own cutaneous markers. The distances between predicted and actual vertebra positions were computed for each X-ray.

The process was identical in l-PCA, except that all alignments were performed using a partial dataset

arbitrarily constituted, for this preliminary study, of the 7 cutaneous markers facing T1 to T7 spinous processes (Figure 1). The whole dataset was however entered in PCA predictions, to fully capture its information content.

Finally, RMSE in vertebra position prediction were calculated at each of the 25-vertebra level across the 63 X-rays. Average RMSE were computed across the cervical, thoracic, and lumbar spine, across T1 to T7 and across the whole spine. The number of PCA dimensions required to capture 99% of the dataset variance was also retrieved.

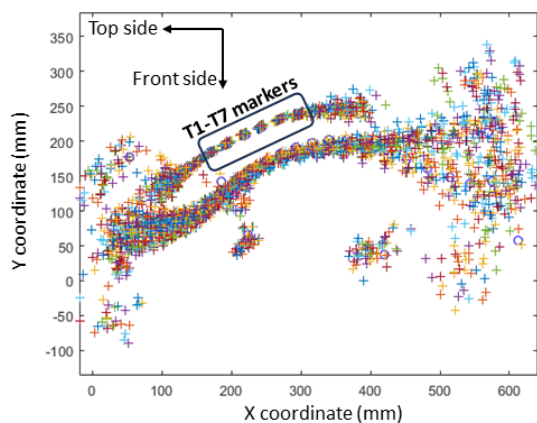


Figure 1. Alignment performed on T1 to T7 spinous processes' cutaneous markers, prior to l-PCA. Each radiograph ($n=60$) is plotted in one colour. Both cutaneous markers and vertebra positions are displayed

3. Results and discussion

The average RMSE in vertebra position predictions across the entire spine was higher when using c-PCA, $23.0\pm 12.4\text{mm}$ (Table 1), than when using regressions previously established on the same dataset ($11.0\pm 3.7\text{mm}$) (Tomezzoli et al. 2024). T1 to T7 vertebral position prediction was improved by l-PCA, reaching an average RMSE of $10.0\pm 1.7\text{mm}$ instead of $14.6\pm 5.0\text{mm}$ with c-PCA. Moreover, 10 to 11 PCA components were necessary to capture 99% of the variance of this 88 input-dataset when using l-PCA, instead of 17 to 18 with c-PCA, showing simplified prediction. As the set of markers used for alignment was the only difference between c- and l-PCA, it can be concluded that the choice of the alignment method is of paramount importance when performing predictive PCA on spatially organized data.

Improved RMSE in vertebra position were expected for vertebrae facing T1-T7 cutaneous markers, with l-PCA. Surprisingly, RMSE were decreased across all spine segments, suggesting that alignment on T1-T7

markers is more favorable than alignment on all available cutaneous markers. Explanatory hypotheses can be proposed: T1-T7 is the most rigid spine segment, is almost central to the spine, and its spinous processes are close to the skin. This result does not preclude the interest of local alignments on other partial datasets, which should be assessed.

Table 1. Average RMSE (mm) with c-PCA or l-PCA

Vertebrae	Alignment on	
	All cutaneous markers	T1-T7 cutaneous markers
Cervical	11.6 ± 2.2	9.6 ± 1.4
Thoracic	21.0 ± 8.5	12.2 ± 3.0
Lumbar	40.3 ± 3.7	20.0 ± 0.9
T1-T7	14.6 ± 5.0	10.0 ± 1.7
All	23.0 ± 12.4	13.3 ± 4.6

4. Conclusions

This preliminary work shows the importance of adequate alignment before vertebra position predictions by PCA. Local alignment could be effective in improving PCA robustness to spinal posture and should thus be further explored.

5. Conflict of Interest Statement

The authors declare that there is no conflict of interest.

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