REGISTRATION OF PEDOBAROGRAPHIC IMAGES

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ABSTRACT

In this study, we compare the performance of six fully automatic methods of within-subjects pedobarographic image registration: principal axes, modal matching, min(XOR), min(MSE), contours-based and frequency-based. These algorithms were tested on 30 control image pairs considered in previous studies. The accuracy was assessed by visual inspection and using the image similarity measures: exclusive-or (XOR) and mean squared error (MSE). Visually, we did not find differences in the registration accuracy among the min(XOR), min(MSE), contours-based and frequency-based algorithms. On the other hand, using the similarity measures, we found out that the best XOR value was achieved by the contours-based algorithm, closely followed by the min(XOR). Additionally, the best MSE value was achieved by the min(MSE) algorithm, nearly followed by the frequency-based algorithm. Finally, the algorithms based on principal axes and modal matching revealed low robustness.

1. INTRODUCTION

Plantar pressure distribution provides significant information for clinicians and researchers about the structure and function of the foot, general mechanics of gait and is a helpful means to evaluate patients with foot complaints. In fact, plantar pressure distribution allows the comparison of the loads in the limb, either between injured and non-injured or pre- and post-traumatic or -operative states, enables the comparisons between patients and control groups and provides detailed information specific to each region of contact [1].

Image registration, the process of optimally aligning homologous structures represented in images, is necessary for clinicians and researchers, as, after registration, some tasks such as, image comparison, identification of the main plantar pressure areas and classification of the foot type can be easily done. In addition, pedobarographic image registration supports pixel-level statistics, which makes possible the extraction of biomechanically-relevant information from plantar pressure images more effectively than traditional regional techniques [2].

Several studies on pedobarographic image registration have been made. For instance,

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using principal axes transformation [3], modal matching [4-6], principal axes combined with steepest descent gradient search [7], optimization based on evolutionary algorithms [8], registration based on foot size and foot progression angle [9], contours matching [10], and optimization of the cross-correlation (CC) and phase correlation computed in frequency domain [11].

In this work, we compare the accuracy of six fully automatic registration algorithms: principal axes based (PA); modal matching; min(XOR) and min(MSE) [8]; contours-based [10] and frequency-based [11]. These algorithms were tested on within-subjects pedobarographic image registration using a set of 30 control image pairs and considering rigid geometric transformations (shift and rotation). The accuracy was assessed by visual inspection and using the image similarity measures XOR and MSE.

2. METHODS

In this section, we briefly describe the similarity measures adopted, the registration algorithms tested and the dataset used. In all this section, we consider the template image I_0 and the source image I_1 (the image we wish to align having the template image as reference), both in the discrete form and with dimensions $N \times M$ pixels. For each image, $I(x, y)$ represents the intensity (gray level) of the pixel at position (x, y).

2.1 Similarity measures

The MSE is given by:

$$\text{MSE} = \frac{1}{N \times M} \sum_x \sum_y \left(I_0(x, y) - I_1(x, y) \right)^2 . \tag{1}$$

Thus, the lower is the MSE value, the better registered are the pressures, and consequently, the better registered are the input images.

We compute the XOR as the percentage of non-overlapped pixels:

$$\text{XOR} = \frac{|I_0 \oplus I_1|}{|I_0| + |I_1|} \times 100 , \tag{2}$$

where $|.|$ is the cardinal function and $\oplus$ is the exclusive-or operator. The XOR considers binary images: 0 (zero) if the intensity is 0 (zero) and 1 (one) otherwise. By minimizing the XOR, the shapes become better overlapped.

2.2 Registration algorithms

The registration algorithm based on the principal axes is well known and can be described as follows. The first step is to compute the centroid of each image. Then, the second central moment matrix of each image is assembled:

$$M = \begin{bmatrix} I_{xx} & I_{xy} \\ I_{xy} & I_{yy} \end{bmatrix}, \tag{3}$$

where I_{xx}, I_{xy} and I_{yy} are the second central moments. The following step is the eigenvalues/eigenvectors decomposition of the matrix *M*. The eigenvectors give the direction of the principal axes. Afterwards, the amplitude of the angle formed by the principal axes of one image with the principal axes of the other image gives the rotation angle (see Figure 1). The difference between the centroids of both images gives the shift.

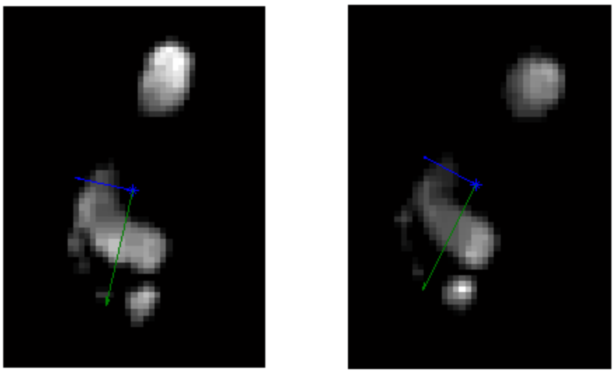

Fig. 1: Two pedobarographic images, their centroids and principal axes directions.

The modal matching-based registration algorithm was initially proposed in [12] and adopted to pedobarographic registration in [6]. The first step is to compute the physical model (mass and stiffness matrix) of each object, using a finite element per object. Then, the eigenvalues/eigenvectors of the matrices are determined and ordered. After that, the modes (eigenvectors) are matched based on their differences and finally the geometric transformation is determined. In this work, we used the feet contours extracted from the images as the objects that are supposed to register.

The min(MSE) and min(XOR) algorithms are based on the minimization of the image similarity measures MSE and XOR, respectively. To search for the optimal value, both algorithms use an evolutionary optimization algorithm [8]. The optimization algorithm starts from an initial guess and, from generation to generation, it chooses the geometric transformation parameters that minimize the similarity measure considered.

The contours-based algorithm presented in [10] can be described in four steps: (1) extract the external ordered contours of the feet, (2) assemble the contours' affinity matrix based on geometric features, (3) determine the matching of the contours' points using an optimization algorithm based on dynamic programming and with ordering preserving constraint, and (4) compute the geometric transformation parameters based on the matching found. In [10] a pseudo-optimization algorithm is also implemented to optimize the image similarity measures considered, starting from the alignment previously determined.

The last registration algorithm considered is the frequency-based presented in [11]. This algorithm can compute the optimal geometric transformation based on the maximization of the cross-correlation (CC), maximization of the phase correlation (PC) or minimization of the sum of squared difference (SSD). These similarity measures are computed in a direct manner using the Fourier transform properties and convolution theorem. The results obtained by optimizing each of the three image similarity measures considered are similar, so we just considered the CC as the image similarity measure.

The CC correlation between the images I_0 and I_1 is given as:

$$\mathrm{CC} = \sum_x \sum_y I_0(x,y) I_1(x,y). \tag{4}$$

The cross-correlation can be given in function of a shift (a,b) and as a convolution:

$$\mathrm{CC}(a,b) = \sum_x \sum_y I_0(x,y) \overline{I_1}(a-x, b-y) = \{I_0 * \overline{I_1}\}(a,b), \tag{5}$$

where $\overline{I_1}(x,y) = I_1(-x,-y)$ and $*$ represents the convolution. From the convolution theorem, one can obtain:

$$\mathbf{F}\{I_0 * \overline{I_1}\} = k \cdot \mathbf{F}\{I_0\} \cdot \mathbf{F}\{\overline{I_1}\}, \tag{6}$$

where **F** represents the Fourier transform and *k* is a constant that depends on the specific Fourier transform normalization. Thus, computing the inverse of the Fourier transform of the product of the equation 6, the cross-correlation can be obtained for all shifts. Then, the coordinates of the point that has the higher value represent the optimal integer shift. Based on the Fourier transform properties and converting the image spectrums to log-polar coordinates systems, the rotation angle can also be determined [11].

2.3 Dataset

We compare the registration algorithms on a dataset used in previous studies [8, 10-11]. The dataset consists of 30 pairs of peak pressure images and were originally collected at 500 Hz using a 0.5 m Footscan system (RSscan, Olen, Belgium).

2.4 Implementation

The modal matching, principal axes, contours-based and frequency-based algorithms were tested in the same notebook PC (AMD Turion64 2.0 GHz microprocessor, 1.0 GB of RAM and running Microsoft Windows XP). The principal axes based algorithm was implemented in MATLAB 7.04 and the modal matching, contours-based and frequency-based algorithms were implemented in C++. We did not implement the min(XOR) and min(MSE) algorithms, instead we use the results presented in [8] for the same dataset. In that work, the algorithms were implemented in MATLAB 7.4.

3. RESULTS

From visual inspection, the contours-based, frequency-based, min(XOR) and min(MSE) registration algorithms seemed to achieve high and identical registration accuracy. On the other hand, for some image pairs, the principal axes based algorithm seemed to achieve good registrations, but for other image pairs the registrations were clearly not so good. Finally, the modal matching algorithm revealed high sensibility to the values of its parameters and to the input image pairs. In fact, we could not find a set of parameters' values that work properly with all input image pairs.

The experimental accuracy, using the MSE and XOR as similarity measures, and the required processing times are indicated in Table 1. In this Table, we do not include the results of the modal matching registration algorithm by the reasons previously indicated. It should be noted that, since the required computational times are highly dependent on the implementation considered, they should be carefully compared. Complementary to the numeric data of Table 1, a registration example is shown in Fig. 2.

Table 1: Registration accuracy and processing time (SD-standard deviation).

	MSE		XOR		Time
ALGORITHM	$[N/cm^2]^2$	SD	%	SD	[s]
Before Registration	23.6	22.8	17.9	7.92	
Principal axes (on original pressure images)	8.71	10.1	14.4	3.51	0.100
Principal axes (on binarized pressure images)	7.02	6.29	13.4	2.73	0.110
Contours-based [10]	5.80	3.07	11.7	2.63	0.025
Contours-based (with pseudo-optimization) [10]	4.52	2.32	11.1	2.52	0.053
Frequency-based [11]	4.06	2.11	12.3	1.73	0.033
Min(MSE) [8]	3.98	2.09	12.5	1.78	9.010
Min(XOR) [8]	5.45	3.29	11.6	1.73	9.000

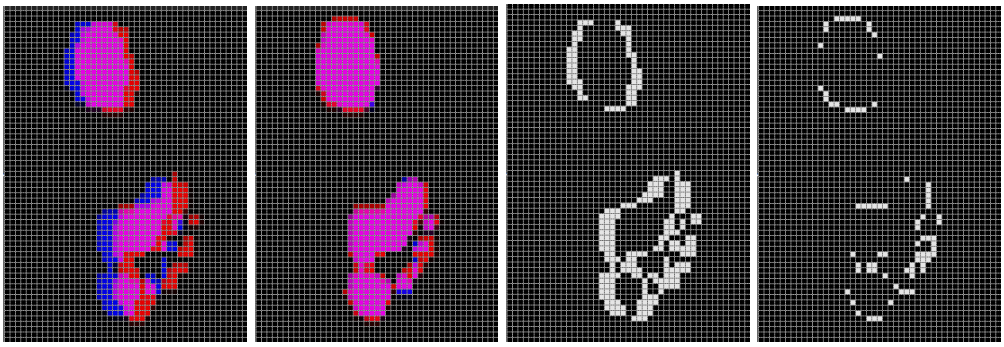

Fig. 2: Registration example using the contours-based algorithm. From the left to the right: overlapped binary images before registration, overlapped binary images after registration, XOR image before registration and XOR image after registration.

4. DISCUSSION

The experimental results validate the min(MSE), min(XOR), contours-based and frequency-based algorithms in the registration of pedobarographic images. The contours-based and min(XOR) algorithms reached the best XOR values, which means that they are more suitable to register the shapes than the other algorithms. Using the MSE as the similarity measure, the min(MSE) and frequency-based algorithms achieved the best values. Therefore, they are more appropriate to register the intensity (pressure).

The registration algorithm based on the alignment of the principal axes revealed low robustness. The results obtained using the binary pedobarographic images are slightly better than the results obtained using the original images. The modal matching based algorithm showed that it is not adequate to register plantar pressure images in a fully automatic way, as it is very sensitive to the input image pairs and to the parameters' values.

The principal axes, contours- and frequency-based algorithms revealed low processing times. On the other hand, the processing times for the min(XOR) and min(MSE) are considerably higher than the processing times of the other algorithms.

As main conclusion, we can point out that the min(XOR), min(MSE), contours-based and frequency-based registration algorithms are very accurate on within-subject registration, which allows their implementation in clinical and laboratorial applications. The computational processing speed of the contours-based and frequency-based algorithms also allows their utilization in “real-time applications”.

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REFERENCES

1. Rosenbaum, D. and H. Becker, *Plantar pressure distribution measurements. Technical background and clinical applications.* Foot and Ankle Surgery, 1997. 3(1): p. 1-14.
2. Pataky, T.C., et al., *New insights into the plantar pressure correlates of walking speed using pedobarographic statistical parametric mapping.* Journal of Biomechanics, 2008. 41(9): p. 1987-1994.
3. Harrison, A.J. and P.J. Hillard, *A moment-based technique for the automatic spatial alignment of plantar pressure data.* Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 2000. 214(3): p. 257-264.
4. Bastos, L.F. and J.M.R.S. Tavares. *Improvement of modal matching image objects in dynamic pedobarography using optimization techniques*. in *Third International Workshop on Articulated Motion and Deformable Objects, AMDO 2004*. 2004. Palma de Mallorca, Spain: Springer Berlin / Heidelberg.
5. Pinho, R.R. and J.M.R.S. Tavares. *Dynamic pedobarography transitional objects by Lagrange's equation with FEM, modal matching and optimization techniques*. in *International Conference on Image Analysis and Recognition (ICIAR 2004)*. 2004. Porto, Portugal: Springer Berlin / Heidelberg.
6. Tavares, J.M.R.S., J.M.G. Barbosa, and A.J. Padilha. *Matching image objects in dynamic pedobarography*. in *11th Portuguese Conference on Pattern Recognition (RecPAD 2000)*. 2000. Porto, Portugal.
7. Pataky, T.C. and J.Y. Goulermas, *Pedobarographic statistical parametric mapping (pSPM): a pixel-level approach to foot pressure image analysis.* Journal of Biomechanics, 2008. 41(10): p. 2136-2143.
8. Pataky, T.C., J.Y. Goulermas, and R.H. Crompton, *A comparison of seven methods of within-subjects rigid-body pedobarographic image registration.* Journal of Biomechanics, 2008. 41(14): p. 3085-3089.
9. Keijsers, N.L.W., et al., *A new method to normalize plantar pressure measurements for foot size and foot progression angle.* Journal of Biomechanics, 2009. 42: p. 87-90.
10. Oliveira, F.P.M., J.M.R.S. Tavares, and T.C. Pataky, *Rapid pedobarographic image registration based on contour curvature and optimization.* Journal of Biomechanics, 2009. 42(15): p. 2620-2623.
11. Oliveira, F.P.M., T.C. Pataky, and J.M.R.S. Tavares, *Registration of pedobarographic image data in frequency domain.* Computer Methods in Biomechanics and Biomedical Engineering, 2010(in press).
12. Sclaroff, S. and A.P. Pentland, *Modal matching for correspondence and recognition.* IEEE Transactions on Pattern Analysis and Machine Intelligence, 1995. 17(6): p. 545-561.