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AUTOMATED SPATIO-TEMPORAL ALIGNMENT OF PLANTAR PRESSURE IMAGE

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INTRODUCTION

The analysis of plantar pressure data provides information on the role of the foot and ankle during gait and other activities. The information gather can be used to define suitable rehabilitation programs through alterations of footwear, foot orthoses, exercise programs and weight-bearing restrictions. It can also assist the diagnosis and rehabilitation of impairments associated with various musculoskeletal, integumentary and neurological disorders. Particularly, it has a vital role in the assessment and prevention of ulceration of patients with diabetes and peripheral neuropathy.

Generally, the plantar pressure data can be converted into a discrete rectangular array at a point in time or over a period of time, giving rising to static images or to image sequences. The number of trials required to obtain reliable representations of the plantar pressure pattern is an important factor in dynamic data acquisition: three to five walking trials enhances the reliability of the pressure measurements [1]. Hence, the automatically spatio-temporal, i.e. simultaneously in time and space, alignment of sequence trials is important to build a representative plantar image sequence for the subject under study, as it is more reliable than a single trial and supports comparisons among plantar pressure image sequences on a pixel-by-pixel basis.

Here, the use of automated computational method for the spatio-temporal alignment of plantar pressure image sequences [2-3] is discussed. Using the method, the spatial position and orientation of a foot in an image sequence are changed to match the foot represented in a second sequence, and simultaneously the temporal scale of the first sequence is transformed with the aim of synchronizing the two input sequences. As such, the spatial correspondence of the foot regions along the sequences as well as the temporal synchronizing is obtained.

METHODS

Twenty-six non-pathological subjects were recruited for this study (7 men: 18.4±0.5 years old; and 19 women: 20.4±2.3 years old). Each subject performed two barefoot walking series at normal speed (one addressing the left foot and the other the right foot) each one defined by three trials, which gave a total of 156 image sequences that were acquired using an EMED system (Novel GmbH, Germany, spatial resolution: 2 sensors/cm^2, pressure sensibility: 5 kPa, 25 Hz).

The spatio-temporal transformations that best aligned the pairs of sequences were obtained by minimizing the mean squared error (MSE) among the plantar pressure values. Since only intra-subject alignment was involved, a rigid geometric model was used for the geometric spatial transformations. For the temporal alignments, polynomial models up to 4th degree and B-splines based transformations of 1st and 3rd degree with several knots spacing were used.

The accuracy of the resultant alignments was assessed in two ways: using synthetically deformed image sequences and using the real sequences. In the first case, the accuracy was assessed by comparing the transformations obtained with the transformations applied, which were used as "gold standard". In the later, the alignment quality was assessed based on the MSE values after the alignment (lower MSE values mean better alignments). For each temporal model selected, and for each foot of each subject, two alignments were made: sequences 2 and 3 were aligned with sequence 1. In total, 104 image sequence pairs were aligned for each temporal model. The MSE was computed for all alignments, and the resultant values were statistically compared using the paired *t*-test.

RESULTS

Two temporal deformations were used to simulate the natural variations on walking speed from trial to trail: a linear $f_1(i) = 1.15i$; and a curved $f_2(i) = 0.9i + 2\sin(i/3)$, where i is the image index in the original sequence [2]. The natural foot position and orientation variations were simulated by applying a rigid spatial transformation to the feet represented in all sequences, defined by a rotation of -15 degree around the center of each image.

Table 1 shows the mean difference of the image indexes (temporal error) and spatial position of the image pixels (spatial error) between the applied and obtained spatio-temporal transformations. For the temporal alignment, low differences were obtained when using the B-spline models. For the control temporal deformation f_1, the best result was obtained by using linear B-splines with knot spacing equal to 1 (one) image $(p < 0.05)$, which was already expected since the applied temporal deformation was linear. When the temporal scale was deformed by the control deformation f_2 instead, the best results were obtained by using cubic B-splines with knot spacing equal to 3 and 1 (one) $(p < 0.001)$. The spatial alignments were achieved high accuracy for all models. For instance, when using cubic B-splines with a knot spacing equal to 3, the mean spatial error was 0.005 pixels for the control deformation f_2, which corresponds to 0.035 mm as the width of each image pixel was around 7.07 mm for the device used.

Table 1: Mean temporal and spatial errors obtained for the temporal control deformations f_1 and f_2, and a rotation of -15º for the spatial deformation [2] (kd - distance between knots in terms of image indexes).

Temporal alignment model used to recover the applied deformation	Applied control deformations			
	Rigid and f_1	Rigid and f_2	Rigid and f_1	Rigid and f_2
	Mean temporal error [images]		Mean spatial error [pixels]	
Polynomial of 1^{st} degree	0.360	1.434	0.043	0.089
Polynomial of 4^{th} degree	0.020	0.271	0.002	0.022
B-spline (1st degree, kd = 5)	0.016	0.157	0.002	0.012
B-spline (1st degree, kd = 3)	0.015	0.063	0.003	0.006
B-spline (1st degree, kd = 1)	0.001	0.014	0.002	0.008
B-spline (3rd degree, kd = 5)	0.014	0.018	0.002	0.005
B-spline (3rd degree, kd = 3)	0.005	0.003	0.002	0.005
B-spline (3rd degree, kd = 1)	0.004	0.003	0.003	0.007

A comparison of the alignment quality of each temporal model used, given by the MSE mean values, is depicted in Figure 1. The experiments were carried out using a rigid transformation model for the spatial alignment and eight temporal models for the temporal alignment: 1^{st} and 4^{th} degree polynomial, and linear and cubic B-splines with distances between knots equal to 1 (one), 3 and 5 image indexes. The results with B-splines were better than the ones found using the 1^{st} and 4^{th} degree polynomial models $(p < 0.001)$, and the best results were reached by using the temporal model based on cubic and linear B-splines with a distance between knots equal to 1 (one) image, without statistical significant differences between their results $(p = 0.115)$. Figure 2 shows two alignment examples [3].

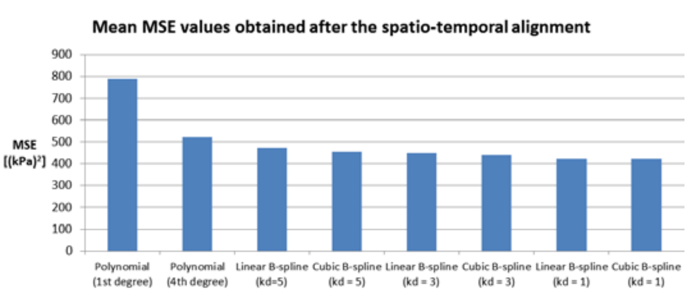

Figure 1: MSE mean values obtained after the spatio-temporal alignment using eight temporal transformation models. The values indicated are from 104 alignments per temporal model [2] (only the pixels with non-zero values were used in the MSE calculation; kd - distance between knots in terms of image indexes).

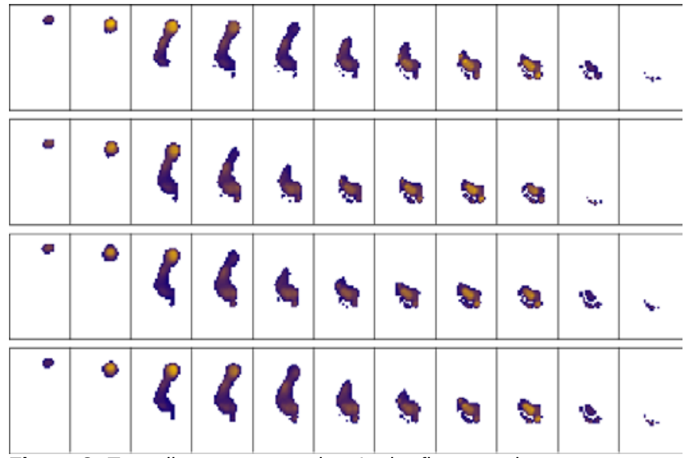

Figure 2: Two alignment examples: In the first row, the sequence used as reference; in the second row, the sequence to be aligned; in the third row, the aligned sequence using a 1^{st} degree polynomial temporal transformation model; and finally, in the last row, the aligned sequence using a 4^{th} degree polynomial temporal transformation model [3].

DISCUSSION

The method used revealed to be very accurate in the spatio-temporal alignment of plantar pressure image sequences; mainly, when cubic B-splines were used in the temporal modeling (Table 1). The accuracy of the temporal alignment was very high for the cubic and linear B-splines with a distance between knots equal to 1 (one) and 3 image indexes. In these cases, the mean temporal error was around 0.2 milliseconds (ms), with each image representing a period of 40 ms.

The spatial alignment accuracy was very high in the experiments based on control spatio-temporal deformations. The worst mean spatial error of any of the temporal models based on B-splines evaluated here was approximately equal to 0.08 mm, which corresponds to 0.012 pixels and is several times inferior to the resolution of the acquisition device used. From the results in Table 1, it can also be concluded that an increase in the accuracy of the temporal alignment originates an increase in the accuracy of the spatial alignment.

By assessing the quality of the alignments of real plantar pressure image sequences with the minimization of the MSE, it can be concluded that the B-splines produced better results than the 1^{st} and 4^{th} degree polynomials (Figure 1). The lowest MSE values, which correspond to the best alignments, were achieved by temporally align the sequences using cubic and linear B-splines with a distance between the knots equal to 1 (one) image. Although statistically significant in most of the cases, the differences among the MSE values were low for the six B-splines models used.

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