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Matching incomplete time series with dynamic time warping: an algorithm and an application to post-stroke rehabilitation

Paolo Tormene [1], Toni Giorgino [1,*], Silvana Quaglini, Mario Stefanelli

Laboratory for Biomedical Informatics, Computer Engineering and Systems Science, Università di Pavia, Via Ferrata 1, I-27100 Pavia, Italy

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Summary

Objective: The purpose of this study was to assess the performance of a real-time ("open-end") version of the dynamic time warping (DTW) algorithm for the recognition of motor exercises. Given a possibly incomplete input stream of data and a reference time series, the open-end DTW algorithm computes both the size of the prefix of reference which is best matched by the input, and the dissimilarity between the matched portions. The algorithm was used to provide real-time feedback to neurological patients undergoing motor rehabilitation.
Methods and materials: We acquired a dataset of multivariate time series from a sensorized long-sleeve shirt which contains 29 strain sensors distributed on the upper limb. Seven typical rehabilitation exercises were recorded in several variations, both correctly and incorrectly executed, and at various speeds, totaling a data set of 840 time series. Nearest-neighbour classifiers were built according to the outputs of open-end DTW alignments and their global counterparts on exercise pairs. The classifiers were also tested on well-known public datasets from heterogeneous domains.
Results: Nonparametric tests show that (1) on full time series the two algorithms achieve the same classification accuracy (p-value $= 0.32$); (2) on partial time series, classifiers based on open-end DTW have a far higher accuracy ($\kappa = 0.898$ versus $\kappa = 0.447$; $p < 10^{-5}$); and (3) the prediction of the matched fraction follows closely the ground truth (root mean square $< 10\%$). The results hold for the motor rehabilitation and the other datasets tested, as well.
Conclusions: The open-end variant of the DTW algorithm is suitable for the classification of truncated quantitative time series, even in the presence of noise. Early recognition and accurate class prediction can be achieved, provided that enough

* Corresponding author. Tel.: +39 0382 985981; fax: +39 0382 526088.
E-mail address: toni.giorgino@gmail.com (T. Giorgino).
[1] These authors contributed equally to this work.

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variance is available over the time span of the reference. Therefore, the proposed technique expands the use of DTW to a wider range of applications, such as real-time biofeedback systems.

1. Introduction

Rehabilitation is a challenge in the clinical course of patients affected by an acute neurological event. In particular, rehabilitation after stroke is known to benefit from early start of physical therapy, both in terms of quality of recovery [1,2] and cost-effectiveness [3]. However, obstacles of various nature are met in practice. They range from the difficulty in finding a slot in a rehabilitation structure, to the necessity of motivating the patient — often affected by post-event depression.

Additionally, long waiting lists consume resources: patients that are unable to come back at their home (e.g. because they were living alone) are often kept in the acute ward until a place becomes available in a post-acute rehabilitation structure [4]. This is expensive, because the patient stays in the costly acute ward longer than necessary. There is consequently a motivation for systems that enhance the autonomy of patients in their rehabilitation path.

Current guidelines for stroke prevention and treatment, e.g. the Stroke Prevention and Educational Awareness Diffusion (SPREAD) guideline (cf. recommendations 14.18, 14.25, 15.27 in [5], edition 2007), hint about the potential utility of systems that could foster earlier and prolonged rehabilitation, both in the clinic and at home. The basic idea is to provide patient with self-rehabilitation facilities, able to give them an immediate feedback for rewarding them and/or improving their performance. In the hospital these systems could enhance the traditional rehabilitation practice (which may be limited by lack of personnel and space) by allowing patients to perform more rehabilitation sessions than those regularly scheduled; at home, they could allow therapy to be continued — possibly under remote supervision — implementing the so important continuity of care.

Information technologies are natural candidates to realize rehabilitation aids that can be used locally or with the remote assistance of therapists. In addition to economic and organizational reasons, computerized interventions are appealing because they enable the acquisition of quantitative data on the progress of the therapy (lack of quantification is another well-known problem in the rehabilitation field). A computer-based rehabilitation aid could easily track the therapy and provide a systematic record of its progress.

Rehabilitation after a stroke may involve cognitive training, motor therapy, or both. The neurological rehabilitation system we developed (Product Concept NR) manages the two aspects [6]; this paper focuses on motor therapy and, in particular, on the rehabilitation of the upper limb, because upper limb disability is a frequent outcome of the event.

The paper presents an algorithm that processes body motion signals in order to verify the correct execution of rehabilitation exercises: the repetitions of the upper limb movement have to be counted and classified, evaluating their adherence to a known "correct" reference path, previously recorded with the supervision of a physiotherapist. The problem tackled is to provide feedback to patients in real-time, *before* the exercise is complete and the corresponding time series have been acquired in full. For this purpose, the stream of data from the motion measuring system has to be compared several times per second with suitable references. The output of the algorithm is eventually used to display how close the input is to the proper path.

We want to stress that, while the algorithm is actually embedded into the system for upper limb post-stroke rehabilitation, it is general indeed, and it can be exploited for several kind of template-based time series classification.

2. Movement recognition from the sensorized garment

The algorithm discussed in this paper was designed for detecting arm movements in real-time from a sensorized shirt [6,7]. Motion detection is based on an innovative strain sensor technology, directly printed on garments. Conductive elastomers (CE) are polymer-based materials which exhibit electrical conductivity and can be deposited without significantly altering the mechanical properties of the underlying fabric [8,9]. After vulcanization, the stripes show an electrical resistance around 10—100 kΩ/cm that depends on the printed geometry and varies according to the instantaneous stretch imposed on the fabric. The same material realizes connections to a pocket-sized device (SEW2, Centre Suisse d'Electronique et de Microtechnique) that wirelessly transmits the resistance (strain) measurements to a *patient station* providing feedback to the