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Short communication

Normalizing temporal patterns to analyze sit-to-stand movements by using registration of functional data

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Abstract

Functional data analysis techniques provide an alternative way of representing movement and movement variability as a function of time. In particular, the registration of functional data provides a local normalization of time functions. This normalization transforms a set of curves, records of repeated trials, yielding a new set of curves that only vary in terms of amplitude. Therefore, main events occur at the "same time" for all transformed curves and interesting features of individual recordings remain after averaging processes.

This paper presents an application of the registration process to the analysis of the vertical forces exerted on the ground by both feet during the sit-to-stand movement. This movement is particularly interesting in functional evaluations related to balance control, lower extremity dysfunction or low-back pain.

Keywords: Low-back pain; Functional assessment; Sit-to-stand movement; Functional data; Registration; Nonlinear time normalization; Warping function

1. Introduction

Continuous time functions are commonly used in biomechanical research to study the temporal patterns of human movement; examples include such records as the joint angles, ground reaction forces or estimated forces or moments at a given joint. Usually, this kind of data are not directly analyzed, but discrete variables are obtained from these continuous recordings (e.g. peak magnitude of variables of interest) and temporal variables are defined from the timing of selected events.

The representation of a continuous time function through a set of discrete variables implies a reduction in the amount and quality of the recorded information. Moreover, increases in variability of the movement patterns as a consequence of timing variations across multiple performance trials may be expected (James, 2004). This variability can contribute to the statistical cancellation effect associated with the aggregation of the data (Bates et al., 2004). The main features of each individual pattern can then be hidden when averaged patterns are obtained.

Some attempts to control the variability associated with variations in the timing of interesting events have been made. Most of them are based on a linear transformation of time over the whole range of the movement. This time normalization leads to inaccurate data when either the beginning or the end of the movement are not well-defined. Moreover, even after a linear normalization, local timing differences can remain and nonlinear procedures could be necessary (Kurz and Stergiou, 2004).

Functional data analysis (FDA) techniques provide an alternative for representing movement and

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movement variability as a function of time. Instead of transforming a continuous time recording into a set of discrete variables, FDA techniques work with the whole function as a piece of data (Ramsay and Silverman, 2000). Neither previous determination of singular events nor definition of discrete variables is necessary. The field of FDA is quite new and there is still a lot of work to be done, but several applications in different fields have been developed in recent years. Examples include such applications as the bone shape analysis (Shepstone et al., 1999), the study of human growth (Ramsay et al., 1995), the motor control of speech (Lucero and Koening, 2000), handwriting movements (Ramsay, 2000) or the analysis of the fingers' pinch force (Ramsay et al., 1995).

Registration is a very interesting tool for functional data analysis and it provides a local nonlinear normalization of time functions. This normalization transforms a set of curves, records of repeated trials, yielding a new set of curves that only vary in terms of amplitude. Therefore, main events occur at the same time for all transformed curves and interesting features of individual recordings remain after averaging processes (Ramsay and Li, 1998).

The purpose of this paper is to investigate the role of variability in the timing of events when determining individual or group patterns of human movements and to quantify the effect of the nonlinear time normalization in order to decrease such variability. An application to ground force recordings in the sit-to-stand (STS) movement allows us to show the effectiveness of this technique.

2. Materials and methods

An experiment has been designed and carried out to measure vertical forces exerted on the ground by both feet during the sit-to-stand movement. In order to evaluate our methodology, three groups have been considered. The cases group (P) includes 27 volunteers (23 male, 4 female), all of them with a history of chronic, non-specific low-back pain. Two criteria were used to select the subjects: a non-zero score on the Jensen pain scale (Jensen et al., 1989) and a moderate score on the Oswestry low-back pain disability questionnaire (Fairbank et al., 1980). The second is the control group (H) with 59 healthy volunteers (41 males, 18 females). Finally, a group of subjects pretending to be having back-pain problems was included in the study. This group (M) consisted of 12 volunteers (8 males and 4 females) who had suffered a previous low-back pain episode at least 2 years before the experiment but with no current symptoms. They were instructed to remember the disability associated with back pain and to sham limitations in the STS movement. This group was included in the study in order to introduce more variability in the movement patterns. Subjects were informed of the purpose and procedures of the experiment, and their informed consent was obtained.

During the experiment each subject performed five trials of STS movement. Before the trials, each subject stood on force plates in order to measure the total vertical force. The subjects were instructed to rise at their own preferred speed until reaching a relaxed standing position.

Two force platforms *DinascanIBV* were used to register ground reaction forces on both feet during the experiments. *DinascanIBV* is a trademark of the IBV, Institute of Biomechanics of Valencia (Spain).

A sample frequency of 50 Hz was used. These recordings were added in order to obtain the resulting force. Normalization with the subject's weight was made and ground reaction force was expressed as a percentage of body weight.

2.1. Data processing

The data analysis performed consists of three steps: (A) a smoothing process, (B) nonlinear time normalization (the registration process), and (C) measurement of the effect of the registration process on functional variability.

2.1.1. The smoothing process

For each subject, we had five trials of the experiment. As the functional datum for trial i is a set of discrete measured values $\{(t_j, y_j)\}_{j=1,\ldots,m}$, our first task was to convert these values to a function $x_i(t)$ computable for any t. Each trial has a different time interval associated, $[0, T_i]$. In order to have a common time interval, $[0, T]$, for all the functions we completed the raw data by adding a suitable number of pairs $(t, 100)$. It has been set to $T = 7$ because this was the greatest measured value.

In what follows, we will refer to any of these $x_i(t)$ as $x(t)$. We would like to point out that we did not use an interpolation process because we assumed that the discrete values may include some observational error. Instead, we have used a smoothing technique to transform the raw data $\{(t_j, y_j)\}_{j=1,\ldots,m}$ to a function $x(t)$ possessing a certain number of derivatives. Actually, we have obtained them by means of a least-squares fitting method. Such a method determines the best choice of the coefficients c_k, $k = 1, \ldots, K$, in the representation of the function as a linear combination of K basis functions. From several possibilities we chose a polynomial spline basis$\{\Phi_k(t)\}_{k=1,\ldots,K}$, where each $\Phi_k(t)$ is a piecewise cubic function, and we obtained the coefficients c_k of the expansion $x(t) = \sum_{k=1}^{K} c_k \Phi_k(t)$ by minimizing the least-squares criterion $\mathrm{SMSSE}(y/c) = \sum_{j=1}^{n} (y_j - \sum_{k=1}^{K} c_k \Phi_k(t_j))^2$ (Ramsay and Silverman, 1997, Chapter 3, pp. 44–51).