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An alternative approach to normalization and evaluation for gait patterns: Procrustes analysis applied to the cyclograms of sprinters and middle-distance runners

Leslie Decker[a,b,*], Christine Berge[a], Sabine Renous[a], Xavier Penin[c]

[a]FRE CNRS 26 96, Department of Ecology and Management of Biodiversity, National Museum of Natural History, 57 rue Cuvier (Post Office Box 55), 75231 Paris Cedex 05, France
[b]Movement, Action, Performance Laboratory, National Institute for Sports and Physical Education, 11 avenue du Tremblay, 75012 Paris, France
[c]Department of Orthodontics, Faculty of Dental Surgery, René Descartes University (Paris 5), 1 rue Maurice Arnoux, 92120 Montrouge, France

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Abstract

In order to compare gait patterns, a common procedure is to normalize strides both in time and magnitude. The stride duration is usually normalized to a time percentage before averaging curves. As the timing of event occurrences may shift across strides, the shape of the averaged curves is distorted and therefore the standard deviation is overvalued. Stride magnitude normalization is performed by means of dimensionless numbers. However, there is little agreement on which body size correction methods should be used. The Procrustes method describes curve shape and shape change in a mathematical and statistical framework, independently of time and size factors. The present study aims to explore how this technique may be used for time- and magnitude-stride normalization to reflect individual and group mean responses. The Procrustes method, which combines quantitative and visual features, is applied to the shape of the ankle and knee cyclograms. Superimposition of 25 cyclograms (10 for sprinters (SP) and 15 for middle-distance runners (MDR)) was supplemented by statistical procedures (principal component analysis, discriminant function) to extract the main key events, which vary according to the athletic specialities. In comparison with the MDR (poulaine-shaped cyclogram), the ovoid cyclogram of SP reveals the following gait indicators: a short braking phase, a rapid initial lower limb swing in the forward direction, a fast upward movement of the knee and ankle, and an active foot contact. The Procrustes approach could be used to describe other quasi-periodic movements through relative motion plots (e.g., cyclograms, angle–angle diagrams, phase plane portraits).

Keywords: Human gait; Running kinematics; Cyclogram; Geometric morphometrics; Multivariate statistics

1. Introduction

Traditionally, gait analysis data were based on the kinematics of a stride cycle normalized to a duration composed of 100 equally spaced time increments allowing comparison with other stride cycles of different durations (Winter and Yack, 1987). However, this method does not guarantee this assumption (West and Griffin, 1999) and neglects the time variability of the different phases within the stride. This is probably the case for the analysis of speed changes in gait (Forner Cordero et al., 2003). Therefore, the timing of event occurrences could shift slightly across gait trials (Sadeghi et al., 2000, 2003) and generate discrepancies, such as an increase in the standard deviation in gait data, and consequently the lesser probability of finding significant differences (Forner Cordero et al., 2006).

Recent studies have attempted to adopt algorithms to time series databases (Das et al., 1998; Keogh and Pazzani, 1998). These algorithms allow similar curves to fit together even if they are not in phase (e.g., dynamic time warping; Berndt and Clifford, 1994; Wang and Gasser, 1997). The

*Corresponding author. FRE CNRS 26 96, Department of Ecology and Management of Biodiversity, National Museum of Natural History, 57 rue Cuvier (Post Office Box 55), 75231 Paris Cedex 05, France.
Tel.: +33 6 21 79 63 05; fax: +33 1 69 04 17 26.
E-mail address: decker@mnhn.fr (L. Decker).

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main drawback is the high computational complexity of this technique for the comparison of a large number of time series. Curve registration—an alignment technique—can also normalize time-related events occurring during the gait cycle (Kneip and Gasser, 1992; Ramsay and Silverman, 1997). By reducing inter-subject variability, it could provide a technique suitable for application a priori to any statistical analysis (Sadeghi et al., 2000). According to Kneip and Gasser (1992), this method may be applied to individuals sharing a common pattern, notwithstanding variations in both amplitude and phase between individual curves. Recently, Forner Cordero et al. (2006) presented a method in which the gait is defined by sequentially occurring ''state variables''. This method provides a means of preserving the variability within the cycle and of avoiding time warping of curves. However, the author noted that this technique is influenced by measurement noise and sampling frequency, which could cause errors in the identification of subtle adaptations in the stride time. A solution to the scaling problem regarding stride-amplitude normalization can be found by using dimensionless numbers (Alexander and Goldspink, 1977; McMahon, 1984). For instance, step length can be dividing by a quantity of the same dimension (e.g., the stature or the lower limb length; Hof At, 1996). This method assumes geometrical and dynamical similarities among individuals, which constitutes a questionable hypothesis. Though many methods of size correction methods have been proposed, there is little agreement on which method should be used. This issue is crucial since different size correction methods usually yield different results.

The purpose of the present study was to determine how the Procrustes[1] method (Bookstein, 1991) can be used as an alignment technique (1) to better express the mean gait pattern and (2) to extract the main key events varying in response to the different athletic specialities. This method, which was initially designed to allow quantitative analyses of biological shapes using geometric morphometrics (e.g., Berge and Penin, 2004; Penin and Baylac, 1995; Penin et al., 2002), is applied here to an investigation of the ''dynamic shapes'' (''cyclograms'',[2] Rocha Barbosa et al., 1996) created during locomotor cycles at stabilized speed. Many studies devoted to animal locomotion (Rocha Barbosa et al., 1996; Snyder, 1962; Sukhanov, 1968; Walker, 1971) and human locomotion (Blanchi et al., 1982; Gajer et al., 1997; Milliron and Cavanagh, 1990; Yokoi et al., 1987) have explored and demonstrated the benefits to be derived from representing the relative movement of the upper and lower limbs, by considering as a fixed point a mobile referential (the shoulder and the hip, respectively). This mode of representation provides both a good visual reading of the continuous cyclical movement patterns and a quantitative expression of certain gait descriptors, such as specific instants in time (e.g., swing ankle position at contralateral foot contact on landing), time-to-event (e.g., time to mid-stance phase following foot strike), and magnitude of variables of interest (e.g., cyclogram height or length). The originality of this paper lies in the methodology used, i.e. Procrustes superimposition of all cyclograms, supported by statistical procedures (principal component analysis (PCA) and discriminant function) in order to establish whether overall shape changes in the ankle and knee cyclograms might provide potential gait indicators in different specialized running techniques (middle-distance running and sprint).

2. Materials and methods

2.1. Subjects

Four sprinters (SP) and four middle-distance runners (MDR) participated in the experiment. Subjects had an average age of 22.25 ± 3.65 years, height of 179.87 ± 3.91, lower limb length of 91.00 ± 4.50 cm and body mass of 70.5 ± 5.45 kg. These athletes were highly skilled male runners with a specific training program ranging from 8 to 12 h per week during the season. SP usually competed in 100 m races and MDR in 800 m races. The ranges of best performances for these events were 10.52–11.28 s for the 100 m sprint, and 1.45–2.03 min for the 800 m race.

2.2. Experimental protocol

The experiment was performed at the University of Evry Val-d'Essonne and the Club d'Athlétisme V.E.N.S.E. Approval for this experiment was obtained according to the legal regulations of the French National Ethics Committee for Health and Life Sciences.

Each athlete performed four running sequences with an active and complete recovery of 8 min between each run. The runners, provided with skin markers placed on the different joints on the right lower limb (external malleolus, external tibial tuberosity, and great trochanter), were videotaped using a digital camera at 50 fields s^{-1} (i.e., 28 frames per cycle for MDR and 22 for SP) in lateral view over a distance of 10 m between the 50 and 60 m marks of a 100-m race for SP and between 150 and 160 m of a 200-m race for MDR. In this way, data kinematics were recorded at a specific and stabilized speed (i.e., the competition speed according to the athlete's target time) for both categories of runners. The 10 m section to be filmed was marked by transmission radio cells in order to record the runners' average speed over this distance during each running sequence.

Some trials were not included: (1) when a significant increase in chronometric time was observed over the 10-m distance with respect to other individual trials (result of fatigue) and (2) when the running cycle was incompletely collected (i.e., at least two successive right-leg supports).

2.3. Processing method

A schematic diagram illustrates the methodological procedure (Fig. 1). Classically, all the frames are used as landmarks to draw cyclograms. As the number of frames varies according to the cycle duration, it is not possible to superimpose classical cyclograms for statistical analysis. With the Procrustes method, frames are selected to represent ''equivalent spatiotemporal'' or ''isodynamic'' landmarks for all cyclograms.

[1] In Greek mythology, Procrustes was a legendary highwayman from Attica who offered hospitality to passing strangers. He tied them to an iron bed, stretching them if they were too short and chopping off their legs if they were too tall.

[2] The term ''cyclogram'' was first introduced by Grieve (1968) to refer to joint angle–angle diagrams (e.g., Chapman and Medhurst, 1981; Goswami, 1998).