NONLINEAR ANALYSIS OF RACE WALKING GAIT: MOVEMENT VARIABILITY, ENTROPY AND MOTOR SKILLS ASSESSMENT

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The aim of this study was to explore the issue of motor skills characterisation, by assessing the regularity of motor patterns during race walking gait. Seven competitive race walkers' action was analysed through an optoelectronic system and a force platform. Sample entropy, a nonlinear dynamics tool, was adopted to evaluate the regularity of a selection of kinematic and kinetic variables. Results allowed to characterise athletic skill and to evidence the changes that may occur over time. In particular, the subtle anomalies of an injured subject were detected. Sample entropy appeared a valid means for individual monitoring in sports and gave clues for possible injury prevention.

KEY WORDS: sample entropy, motor skills, variability, injury prevention, race walking.

INTRODUCTION: Motor skills may be defined as the ability of obtaining the desired goal with a high degree of certainty and maximum proficiency. When a particular movement has to be learned or consistently improved, only the capability of producing a stable performance under different conditions reflects an effective achievement. Hence, many repetitions of the same task should be analysed (Bartlett et al., 2007): every time a subject repeats the same movement, a certain amount of changes may be registered over successive trials, even if the outcoming kinematic/kinetic variables appear as pseudo-periodic time series (Stergiou et al., 2004). Movement variability (MV) is inherently present both between and within individuals and may be associated to the extreme complexity and redundancy of movement organisation. Although fluctuations due to MV may appear as noise, recent investigations have supported the idea that inter-trial variability does not contain only randomness but also informative content about the system health, about its evolutions, and about its flexibility and adaptability to variable external conditions (Bartlett et al., 2007; Stergiou et al., 2004). Therefore, the most challenging issues are not only the quantification and handling of MV, but also the insight into its origin and meaning (Bartlett et al., 2007). Differently from conventional statistics (e.g. SD, CV, ICC), which only quantify the overall variability, nonlinear dynamics tools may also help in evaluating the information MV conveys. Among them, sample entropy (*SampEn*) is considered particularly suitable for the analysis of biological signals whose variability is of both deterministic and stochastic origin (Richman & Moorman, 2000; Stergiou et al., 2004). *SampEn* measures the predictability of the signal: the higher *SampEn*, the less regular and predictable time series. Changes in the regularity of motor patterns may be related to changes in motor strategies and may thus reveal the effects of training, pathologies, skills learning (Bartlett et al., 2007; Stergiou et al., 2004).
The aim of this work was to assess MV during sports activities and to gain more insight into its relation with athletes' skills and their evolutions. Sample entropy was applied to race walking (RW), a motor task that appears as being rather stereotyped and repeatable. The relation between athletic ability and pattern regularity was investigated. Furthermore the potentialities of *SampEn* and its applicability to individual monitoring and injury prevention in sports were evaluated.

METHOD: Four male and 3 female healthy race walkers (age: 19.7±2.1 years; height: 1.75±0.10 m, weight: 58.3±8.3 kg) of (inter)national rank were the subjects of this study. Their season best over the 5 km and 10 km events ranged, respectively, between 19'58"00 and 24'04"61, and between 40'56"74 and 48'34"43. All subjects underwent from 6 to 12 training sessions a week. Athletes were assigned to 2 groups according to their skill level, based on competition results and an expert trainer's evaluation. Three race walkers were in group MS (more skilled), and 4 in group LS (less skilled). Subjects were properly informed about testing procedures and written informed consent was obtained.

An 8-TVCs optoelectronic system (Elite2002, BTS, Italy), working at 100 Hz, and a force platform (AMTI OR6-7-1000, USA), whose sampling rate was 500 Hz, were used to capture 3D kinematics of body segments and ground reaction force (GRF) during race walking stance. The accuracy of the motion capture system was assessed before each experimental session: a maximum mean error of 1.0 mm concerning the length of a 600 mm rigid bar was accepted.

The SAFLo (Frigo et al., 1998) marker set was chosen. It is a total body protocol that matches experimental needs for practicality and freedom of movement, to reliability of measures. After a 20 min warm up routine, subjects were prepared by gluing 19 retroreflective hemispherical markers and were asked to race walk across a 15 m long walkway. The dimensions of the laboratory were large enough to let athletes circle continuously and reach an adequate, approximately constant speed about the force platform. Athletes were invited not to alter their progression by looking at the plate, and only the trials in which they randomly put their left or right foot on it were recorded. As many as 20 suitable passages, performed at self-selected training pace and supervised by an expert trainer, were collected for each subject's left and right side. 2 testing sessions, recorded in different periods of the agonistic season were available for 4 athletes (3 from MS and 1 from LS).

Anthropometric measures and specially designed algorithms were used to estimate (Pedotti & Frigo, 1992) and filter (D'Amico & Ferrigno, 1990) 3D coordinates of internal joint centres and joint angles. Lower limb joint angles (hip: A_{hs}; knee: A_{ks}; ankle: A_{as}) and GRF (vertical: R_v; antero-posterior: R_{ap}) in the sagittal plane, were considered for this study. They were selected at this stage, because they are considered the most reliable and representative measures of lower limb kinematics and kinetics during gait (Queen et al., 2006). Individual kinematic and kinetic time-series were created by aligning the 20 available curves so that they composed a continuous sequence of RW stances. The regularity of each time series was evaluated (for every variable, subject and side) by using sample entropy (Richman & Moorman, 2000). Given a series, *Y(t)*, of *T* points (*t=1, …, T*), *SampEn(m; r; T)* measures the logarithmic probability that two similar sequences of *m* points extracted from *Y(t)*, remain similar (i.e. within tolerance given by *r*) on the next incremental comparison (i.e. for *m+1* sequences). *SampEn* tends to 0 for regular or periodical time series, while the higher *SampEn* the more unpredictable patterns (Richman & Moorman, 2000; Stergiou et al., 2004). *m* was set to 1 and *r* to 0.1·SD (where SD is the overall standard deviation of the time series), because the analysed waveforms showed an apparent great regularity (Richman & Moorman, 2000; Stergiou et al., 2004). Two analyses on the regularity of time series were carried out. First, *SampEn* values from more and less skilled groups were compared. Then, the evolution of pattern regularity both in a subject (s6, from MS) that underwent athletic pubalgia between the two testing sessions, and in the other 3 race walkers (control group, CG) was studied. Wilcoxon and Mann-Whitney tests (α=0.05) were used to assess within and between groups differences.

RESULTS: Sample entropy of the considered time series is reported in Figure 1a (MS vs. LS groups). *SampEn* (median and IQR) of MS was greater than the one of LS for the hip angle, 014 (0.11) vs 0.07 (0.01), for the ankle angle, 0.15 (0.07) vs 0.06 (0.05), and for vertical GRF, 0.21 (0.04) vs 0.17 (0.04). Antero-posterior GRF showed increased unpredictability for less skilled athletes, 0.22 (0.05) vs 0.19 (0.02). No relevant differences emerged for knee joint waveforms, but the median value was greater for MS. Figure 1b reports the trend of *SampEn* between two subsequent testing sessions (March and September). The percentage median changes in the control group for A_{hs}, A_{ks}, A_{as}, R_{ap}, R_v were, respectively, –20.6%, –43.5%, –23.2%, –0.7%, –5.4%, and resulted significant for every variable except R_{ap}. The injured subject manifested a decrease of *SampEn* that, for A_{hs} and A_{ks}, was about 4 times larger (–87.0% and –76.9%) than other athletes' one.

DISCUSSION: Results showed that *SampEn* was pretty low for every considered variable, and confirmed the apparent regularity of kinematic and kinetic patterns during race walking gait (Richman & Moorman, 2000; Stergiou et al., 2004). The predictability of skilled athletes' time series concerning joint angles was substantially comparable, with a slight, non significant, proximal to distal decrease. These observations did not agree with previous studies on normal and pathological gait (Stergiou et al., 2004), which reported an inverse trend (i.e. increased *SampEn* for proximal districts). Race walking rules may be the cause of the different behaviour: RW impose an unnatural position of the knee, which must be kept locked during heel strike and load acceptance, until the leg has passed the vertical upright position. The task of absorbing the initial impact, of accepting the body weight and inertial forces, and of limiting the vertical excursion of the centre of mass is mostly shifted to the hip and to the pelvis. Therefore, the change from normal gait may imply an increased control over proximal joints and, consequently, a reduced complexity of related waveforms. Less skilled individuals manifested statistically significant differences from more skilled ones. *SampleEn* of A_{hs} and A_{as} was noticeably lower than in group MS. This may suggest that LS needed to add further control on those joints for compensating the extended knee and for maintaining a correct technique. These findings concurred with the ones of other authors, who mostly investigated the influence of pathologies or aging effects (Stergiou et al., 2004): greater values of entropy may be interpreted as a better flexibility and adaptability to unpredictable environmental changes. Namely, subjects that possess an improved coordinative ability and mastery of movements, have a better, less rigid control over the body's degrees of freedom. Results concerning the knee joint seem to support this hypothesis. In fact, when the articular pattern was imposed by external constraints (i.e. RW rules about knee locking), time series regularity was comparable in the two groups. Force variables manifested increased magnitude of *SampEn*, compared to kinematic variables. GRF may be seen as the final outcome of the whole movement, so both the higher values of *SampEn*, and the greater predictability of R_v for less skilled individuals were not unexpected. It must be remarked that differently from the nonlinear dynamics tool adopted in this research, traditional methods (e.g. ICC) had not been effective in characterising athletic ability from motor variables (Preatoni, 2007).

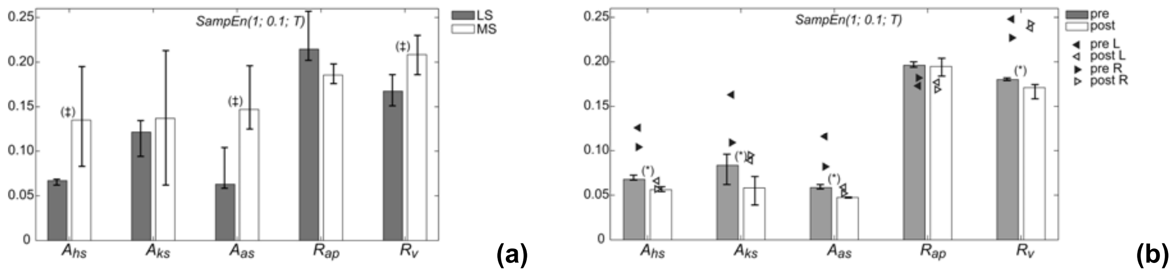

Figure 1: Sample entropy calculated over the 5 selected variables (median and 25-75th percentiles): (a) comparison between more (white bars) and less (dark bars) skilled individuals (‡Significant MS-LS difference, α=0.05); (b) *SampEn* values of two testing sessions (pre & post). Changes concerning an injured subject (triangles) are compared to a reference group (bars). L and R stand for left and right. *Significant pre-post changes within control group (α=0.05).

The longitudinal analysis evidenced very interesting aspects, too. Race walkers revealed a decrease in *SampEn* over time, more accentuated for kinematic variables than for GRF. Although significant for R_v, the percentage differences concerning ground reactions in the sagittal plane were small (few % points) for every subject. In contrast, joint angle patterns manifested increased predictability passing from March to September. This suggests that motor variability had changed over time by involving the genesis of the movement in terms of joint angles rather than affecting the global output of the movement (i.e. GRF). Entropy measures appeared as being able to detect these evolutions, which may relate to many factors: training programs, athletic condition, skills learning, etc. The subject who suffered from athletic pubalgia (s6) had changes in pattern regularity that were different from the control group (CG), although s6 was considered fully recovered and underwent the same training program. The *SampEn* for s6 concerning A_{hs} and A_{as} decreased about 4 times more than in the CG; furthermore, changes in A_{ks} predictability evidenced a remarkable asymmetry between the left and right limb. Therefore, all the reported results outlined that, although s6 was "apparently normal" and the global performance (i.e. competition results, progression velocity and GRF) appeared unchanged, important modifications took place in motor organisation. These changes might be associated to many causes. However, a pathology that typically affects motor structures (the groin region) of great importance for race walking action was present. Either its insurgence or its consequences might be associated to the remodelling of motor strategies. In particular, it seemed that, during the second testing session, s6 exerted an increased control over lower limbs. Less complexity in angular time series may imply greater control over degrees of freedom of the locomotor system. This was confirmed by another study we conducted (Preatoni, 2007), which revealed more stable phasing relations between joint coupling and a more controlled execution technique.

CONCLUSION: The aim of this study was to explore the issue of movement variability and motor skills during race walking stance phase, by utilising sample entropy measures on kinematic and kinetic variables. MV is always present when the same action is repeated and even elite athletes can not reproduce identical motor patterns after many years of training. Environmental changes, training procedures, latent pathologies or incomplete recoveries may affect the organisation of the neuromuscular system. Sometimes these influences are evident; in some other cases, like in the present research where competitive athletes are analysed, they are subtle and not easily detectable by using traditional analyses. Nevertheless, MV may be functional and the information it conveys may be important for performance monitoring. *SampEn* evidenced very interesting potential, besides the quantification of MV. It appeared as being able to: (i) characterise athletic ability by differentiating the performance of more and less skilled athletes; (ii) evidence changes of motor organisation over time; (iii) show individual peculiarities that may relate to underlying injury and training procedures. *SampEn* may be an effective tool for sports biomechanics and may turn useful on the field, too. In fact, it may provide coaches with useful information for individual monitoring, and has the merit of being a synthetic index of the neuromuscular organisation. However, further efforts should be made to gain more insight into the relation between those measures and the phenomenon of interest. For instance, referring to the exposed case study, it would be very useful to understand whether the pre-injury pattern irregularity was the cause of the injury, or, in contrast, whether the increased control during the post-injury session was an abnormal behaviour induced by the pathology. The answers to these issues might be found only by systematically monitoring athletic activities and by creating consistent databases.

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