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Nonlinear metrics assessing motor variability in a standardized pipetting task: Between- and within-subject variance components

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ABSTRACT

The aim of this study was to estimate the between days test–retest reliability of nonlinear metrics used to quantify motor variability in a repetitive pipetting task. On three separate days, 14 healthy subjects performed pipetting as a general model of repetitive tasks. The task consisted of transferring liquid 20 times with a cycle time of 2.8 s from a pickup tube to eight target tubes placed on a table in front of the subjects. The motion of hand, arm and the pipette tip was tracked in 3D and the shoulder elevation and elbow flexion angle were obtained. Motor variability was assessed using nonlinear metrics based on information theory and recurrence quantification analysis. Between- and within- (between-days) subject variance components were computed using a one-way random effect model, and intra-class correlation coefficients (ICC) were calculated from the variance components as standardized measures of reliability. Most of the metrics displayed a considerable between-days variance component and therefore the ICC showed a slight to moderate reliability. The reported data on between- and within-subject variability can be used to design future studies using nonlinear motor variability metrics on kinematics data.

1. Introduction

The pioneering work of Bernstein introduced motor variability as a general property of human movement (Bernstein, 1967). In biomechanics, motor variability has been related to the abundance of degrees of freedom to perform a defined motor task (Dingwell and Marin, 2006). A number of studies have proposed that motor variability has functional relevance (Latash et al., 2002; van Emmerik and van Wegen, 2002); for instance, a decreased motor variability may be associated with adverse effects of aging or diseases (Lipsitz, 2006; Vaillancourt and Newell, 2002).

Linear statistical metrics such as the standard deviation and the coefficient of variation have often been used to quantify the size of variability in time series of biomechanical variables, e.g., 3D kinematic properties of upper arm movement (Madeleine et al., 2008). However, linear metrics of variability may not be sufficient to fully identify the dynamics of movement control systems (Newell et al., 1993), and need to be complemented by metrics associated with the structural dynamics of motor variability (Slifkin and Newell, 1999). The Takens theorem supports a theoretical framework for deriving system dynamics based on an observation of an outcome which is known to be a function of the system dynamics (Takens, 1981). Based on this premise, nonlinear methods have been developed to reflect the system dynamics numerically (Dingwell and Marin, 2006; Webber Jr. and Zbilut, 2005).

These methods have revealed changes in the dynamics of the biomechanical time series related to e.g., aging and muscle fatigue (Buzzi et al., 2003; Farina et al., 2002; Webber et al., 1995). Nonlinear metrics are also relevant within biomechanics as the size and structure of variability are found to be linked to musculoskeletal discomfort and pain (Newell et al., 1993; Søndergaard et al., 2010). However, a causal link between possible changes in metrics of motor variability and development of musculoskeletal disorders cannot be established unless such a causal link is verified in a prospective cohort study (Manolio et al., 2006). This, in turn, requires that the between-day test–retest reliability of the candidate motor variability metrics is known. Further, information on between- and within-subject variability of the metrics is required to determine a proper sample size in studies comparing groups or conditions within a group (Cohen, 1988).

In this study, a selection of nonlinear motor variability metrics were used to quantify the kinematic properties of shoulder elevation and elbow flexion angles in a standardized pipetting task, as

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an experimental model of a repetitive motor task involving the upper extremities. We determined the variability between subjects and between days within subjects of the selected metrics as measures of their reliability, for the main purpose of providing a basis for proper design of future studies of motor variability in repetitive tasks similar to pipetting.

2. Methods

The study was conducted on 14 right-handed females (mean ± SD, aged 25 ± 4.6 years; height, 168.4 ± 7.8 cm; body mass, 62.1 ± 6.8 kg), with prior experience in pipetting. Subjects were nurses and university students in nursing and health education programs. Only females were included, partly because motor control strategies have been found to differ between males and females (Côté, 2012), thus encouraging gender-stratified studies (Messing et al., 2009), and partly because pipetting and other repetitive precision tasks in working life are mainly performed by females (Nordander et al., 2009). The study was conducted in accordance with the Declaration of Helsinki, and was approved by the Ethical Review Board in Uppsala, Sweden (Dnr. 2012/344).

2.1. Experimental protocol

Prior to conducting the experiment, subjects attended the lab and were familiarized with the repetitive motor task, i.e., pipetting (see below), including both a demonstration and a brief test of the procedure. The subjects practiced on the exact same setup that was subsequently used for data collection. Within two weeks from the familiarization, the subjects initiated a 3-day procedure. The three days were separated by at least two days while the setup remained identical across days. On each of the three experimental days, the subjects started with a warm-up period including 100 trials of the pipetting task described below. The pipetting task consisted of repeated arm movements between a pickup tube (Ø: 20 mm) and one of eight target tubes (Ø: 6 mm), placed within an array of total 10 × 10 tubes of identical size. Each cycle started with the aspiration of liquid (water) from the pickup tube, transferring it to a specified target tube (see below), and returning to the pickup tube to begin the next cycle. The center of the array of target tubes was placed on the midline of each subject, 10 cm from the near edge of the table (see Fig. 1).

The subjects sat on a chair fixed to the ground. The torso was strapped with belts to the backrest of the chair (Morasso, 1981). The table and pickup tube were adjusted to be at elbow height and one arm-length distance, respectively.

The task involved transferring liquid 20 times to each of the eight target tubes. In each cycle, the target tube was randomly chosen by a customized computer program turning on a light-emitting diode mounted below the target tube, thus the sequence of chosen targets was different in each day of the experiment. The computer program also controlled that each target had been selected exactly 20 times when the total of 160 cycles (8 targets × 20 repetitions per target) was completed. The work pace was set at 2.8 s per cycle and controlled by a metronome.

2.2. Data acquisition

Motion was tracked in 3D using two synchronized electromagnetic tracking systems (Fastrak, Polhemus, USA) at a sampling rate of 30 Hz. Detailed description of the receiver placements and measurements has been reported in (Srinivasan et al., 2015a). Briefly, the systems tracked 6 degrees of freedom sensors placed on the right arm-hand system and a three-segment biomechanical model was used to obtain the shoulder, elbow and wrist joint angles according to the ISB recommendations (Wu et al., 2005). Also placed on the pipette was a sensor from which the 3D position of the pipette tip was determined. The shoulder elevation and elbow flexion angle time series were chosen for further analysis as repetitive shoulder and elbow movements are known risk factors for development of musculoskeletal disorders in the upper extremities (van Tulder et al., 2007). We selected shoulder and elbow movements but abstained from addressing the wrist because musculoskeletal disorders are more prevalent in the shoulder and upper arm regions than in the lower arm and wrist in occupations characterized by low-level repetitive work (Nordander et al., 2009).

2.3. Data analysis

The motion tracking data was filtered using a 4th order, low-pass Butterworth zero-lag filter with a cut-off frequency of 3 Hz. The continuous shoulder and elbow angle time series were divided into cycles. A cycle was defined between two successive instants when the pipette tip was inside the pickup tube with a minimum velocity. Unsuccessful cycles due to mistakes were excluded from the analysis (0.45 ± 1.03 unsuccessful cycles averaged across subjects and days). The shoulder and elbow angle time series were sorted on a cycle to cycle basis and were divided into three sets for each of the eight targets. Each set contained an approximately equal number of consecutive and concatenated cycles, as the computation of nonlinear metrics requires data time series with a minimum length to provide a stable estimate (see the next section and discussion for details). A similar concatenation procedure was adopted to compute nonlinear metrics in previous studies where the nonlinear metrics applied to surface electromyography and knee angular movement during the stance phase of stair descent walking and the nonlinear metrics have shown a good capability to distinguish patients from a healthy subject group (Rathleff

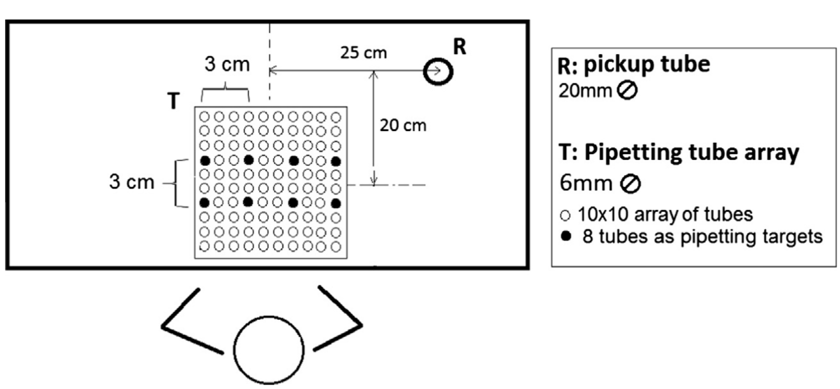

Fig. 1. Illustration of the workstation. Subject performed repetitive arm movements between the pickup tube and eight randomly selected target tubes.