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# Complexity and variability of the center of pressure time series during quiet standing in patients with knee osteoarthritis

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ABSTRACT

*Background:* While several studies have investigated the traditional linear measures in patients with knee osteoarthritis, no study has yet reported the non-linear structure of postural sway in these patients.
*Methods:* We used two non-linear methods, recurrence quantification analysis (percent of determinism-%DET) and central tendency measure, to respectively investigate differences in the complexity and variability of sway dynamics between two groups of knee osteoarthritis patients (n = 27) and healthy controls (n = 27) under different conditions of postural and cognitive tasks. The experimental conditions included standing on (1) rigid surface with open eyes; (2) rigid surface with closed eyes; (3) foam surface with open eyes; and (4) foam surface with closed eyes. All these conditions were performed isolated (single-task) and while performing concurrent cognitive task (dual-task).
*Findings:* The results showed greater %DET and lesser central tendency measure (both in mediolateral direction) in patients compared with healthy subjects. Moreover, in both groups, the %DET increased and central tendency measure decreased with increasing postural difficulty while %DET decreased and central tendency measure increased when moving from single- to dual-task conditions.
*Interpretations:* The complexity loss was observed in patients compared with healthy controls. The observed increase in the variability coupled with a decrease in the complexity could be explained by the exploratory behavior of postural control system to gather information during difficult postural conditions relative to the easy ones. Moreover, the observed increase in the complexity coupled with the decrease in the amount of variability may enhance the flow of information to facilitate the perceptual control of standing balance during dual-task conditions.



## 1. Introduction

Static evaluation of postural sway (i.e., quiet standing tasks) using force platform posturography is a common method for quantifying patients' balance performance in clinical and rehabilitative settings (Sarabon et al., 2013). Based on the traditional linear measures of postural sway (i.e., amplitude and velocity measures), good postural stability is generally related to small center of pressure (COP) fluctuations (Tallon et al., 2013). Given the results of increased amplitude/velocity of COP sway in knee osteoarthritis (OA) patients compared with healthy matched controls, previous studies have reported postural instability in this patient population (Hirata et al., 2013; Kim et al., 2011; Masui et al., 2006; Shaheen and Ayad, 2008). However, the results obtained by traditional linear measures should be interpreted with caution since many studies have questioned the content, construct, and predictive validities of these linear measures (Cavanaugh et al., 2005; Stergiou et al., 2004).

Recently, non-linear methods have been developed to extract new features related to underlying physiological systems (Pachori et al., 2009). Based on the concepts addressed in dynamical system theory, non-linear measures provide important information on the temporal structure of postural sway (including the complexity and variability) that are not captured using traditional linear measures (Hornero et al., 2006; Rhea et al., 2011; Tallon et al., 2013). Complexity is the result of non-linear interactions between system components and supposed to increase the adaptability of human postural system to perturbations imposed on the human body (Tallon et al., 2013). The complexity decreases with age and disease and in the literature has expanded to the so-called theory of "complexity loss" (Ramdani et al., 2013; Rhea et al., 2011). Moreover, variability is inherent within the human postural control (Hong et al., 2008). Traditionally, variability of the COP was

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attributed to noise as well as considered as a consequence of measurement error (Harbourne and Stergiou, 2003). However, based on the dynamical system theory of postural control, optimal variability allows the postural control for exploration of new solutions in challenging conditions (Deffeyes et al., 2009). Among the non-linear techniques that have been used to quantify the temporal structure of postural sway, recurrence quantification analysis (RQA) and central tendency measure (CTM) have some advantages over other methods. Indeed, they do not require the deterministic or stochastic underlying dynamics and can be applied to non-stationary data of COP time series (Kamath, 2013; Ramdani et al., 2013; Riley et al., 1999; Tallon et al., 2013). RQA which is based on the concept of recurrence plot can be used to quantify the complexity of COP time series by computing the percent determinism (denoted as %DET) so that more deterministic pattern corresponds to less complex behavior (Schmit et al., 2006). Alternatively, CTM which is based on the concept of second-order difference (SOD) plot can be used to study the degree of variability of the COP time series so that higher CTM corresponds to lower variability in the SOD plot (Pachori et al., 2009). Indeed, the SOD plot provides a visual representation of the points density clustered around the center (Kamath, 2013).

While some studies have investigated the linear sway measures of patients with knee OA, no study has yet reported the non-linear structure of postural sway in this specific patient population. In this study, we used two non-linear methods, RQA and CTM, to respectively investigate differences in the complexity and variability of the COP dynamics between two groups of knee OA patients and healthy matched controls. We expected less complexity (greater %DET) and more variability (lower CTM) in the dynamical structure of postural sway of OA patients compared with healthy matched controls.

Moreover, the relation between postural control and cognitive activity has received considerable attention in recent years (Schmit et al., 2006). Investigation to determine the effects of cognitive loading on postural control may be especially relevant to knee OA patients since cognitive deficit as evident by poor performance in attention and memory tests has been reported in a variety of patients with chronic pain-related disability including OA (Dohrenbusch et al., 2008; Moriarty et al., 2011). Therefore, the second aim of this study was to investigate the effects of cognitive loading on temporal structure of postural sway in patients with knee OA compared with healthy matched controls. To the extent that the cognitive task draws attention from postural control, we expected postural sway to become less complex (higher %DET) and more variable (lower CTM) under cognitive loading in patients with knee OA while less or no change may expect for healthy matched controls.

## 2. Methods

### 2.1. Participants

The sample comprised 27 patients with knee OA (mean age, height and body mass index: 54.8 with standard deviation (SD) of 6.4 yr, 162.4 with SD of 8.4 cm and 27.9 with SD of 2.9 kg/m$^2$, respectively; 19 females, 8 males) and 27 asymptomatic controls (mean age, height and body mass index: 54.4 with SD of 6.2 yr, 162.8 with SD of 8.7 cm and 28 with SD of 3.2 kg/m$^2$, respectively; 19 females, 8 males). Before participation, all subjects were informed about the procedure and asked to sign an informed consent form approved by the Ethics Committee at Ahvaz Jundishapur University of Medical Sciences, Ahvaz, Iran.

Patients were recruited from several orthopedic clinics in Ahvaz. The control group comprised staff at Ahvaz Jundishapur University of Medical Sciences and family members of patients with knee OA. Inclusion criteria for the patients were (1) clinical and radiologic diagnosis of unilateral or bilateral knee OA based on the criteria of the American College of Rheumatology by an orthopedic specialist (Hinman et al., 2002); (2) knee pain on most days of the previous month; and (3) independency in activities of daily living including walking and self-care activities. Exclusion criteria were (1) existence of rheumatoid arthritis, cardiovascular disease, vestibular disorder, uncorrected visual impairment, radiculopathy; (2) symptomatic OA in other weight bearing joints including ankle and hip; and (3) knee surgery in previous 12 months. The control group should be able to walk independently and should have no musculoskeletal or neurological disorders.

### 2.2. Postural and cognitive tasks

The COP data was measured using a strain gauge Bertec 4060-10 force platform and Bertec AM-6701 amplifier (Bertec Corporation, Columbus, Ohio, USA), with a sampling rate of 100 Hz. Each subject was tested under eight experimental conditions. These conditions included standing on (1) rigid surface with open eyes (RO) without performing cognitive task; (2) RO while performing cognitive task; (3) rigid surface with closed eyes (RC) without performing cognitive task; (4) RC while performing cognitive task; (5) foam surface with open eyes (FO) without performing cognitive task; (6) FO while performing cognitive task; (7) foam surface with closed eyes (FC) without performing cognitive task; and (8) FC while performing cognitive task. During closed eye conditions, participants wore a blindfold to eliminate visual input and during foam surface conditions, the subjects stood on a foam placed on the top of the force platform. During single-task conditions, the subjects were asked to maintain a quiet stance barefoot on the force platform while the feet pressed together, arms comfortable at their sides with the instruction to breathe normally and relaxed. During dual-task conditions, subjects were instructed to stand as steady as possible while they simultaneously perform the cognitive task as accurately as possible. The cognitive task used in this study was silent backward counting in steps of three, beginning from a random number between 200 and 500. To familiarize each participant with experimental conditions, they performed a training trial prior to the actual tests.

Each recording lasted for 60 s producing 6000 data points in both anteroposterior (AP) and mediolateral (ML) directions. A five-minute rest time was considered between conditions to minimize fatigue. Moreover, the conditions were randomly assigned to subjects to minimize learning effects. Subjects performed three trials of each condition.

### 2.3. Data analysis

RQA is based on the construction of a recurrence plot in which some variables quantifying different aspects of the underlying dynamics of the COP data were extracted (Riley et al., 1999). For this purpose, the local recurrence of data points in the reconstructed phase space is determined (Ferrufino et al., 2011). Using the False Nearest Neighbors (FNN) method, the embedding dimension of 5 was found to be suitable for all cases (Negahban et al., 2013). Time delay parameter was calculated for each time series using auto-mutual information (Parlitz, 1998). At least three consecutive points in a recurrence plot were assumed a line pattern (Hasson et al., 2008; Negahban et al., 2013). Ten percent of the maximum phase space diameter using the Euclidean norm was used as the recurrency threshold in the construction of recurrence plots (Negahban et al., 2010; Negahban et al., 2013; Riley et al., 1999). No filtering was used prior to RQA analysis. In the present study, we used the %DET to measure complexity in both AP and ML time series. This parameter proved as the most reliable measure in our previous research (Mazaheri et al., 2010). The %DET is a measure of the predictability of the sway dynamics. It is calculated as the percentage of recurrent points which form diagonal lines to all recurrence points in the recurrence plot (Riley et al., 1999). Diagonal lines are defined by two or more adjacent points. For a random time series, no or very short diagonal lines will be observed and %DET will be close to 0% while long diagonal lines will be seen for a purely deterministic system in which %DET will be close to 100% (Ramdani et al., 2013; Tallon et al., 2013). Riley et al. studies (Riley