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Non-linear dynamical features of center of pressure extracted by recurrence quantification analysis in people with unilateral anterior cruciate ligament injury

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ABSTRACT

Knowledge about the non-linear dynamical pattern of postural sway may provide important insights into the adaptability (flexibility) of human postural control in response to everyday stresses imposed on the body. A commonly used non-linear tool, i.e. recurrence quantification analysis, was chosen to investigate the effect of prior anterior cruciate ligament injury on the deterministic pattern of postural sway under different conditions of postural and cognitive difficulty. In double leg stance, as postural difficulty increased from open-eyes to closed-eyes and rigid-surface to foam-surface, the centre of pressure regularity (%determinism) increased as well. In comparison to healthy counterparts, subjects with prior anterior cruciate ligament injury produced more regularity when maintaining balance on their injured leg. Also, for both the double and single leg stance balance conditions, the performance of a secondary cognitive task (a backward digit span task) caused less center of pressure regularity than the single postural task, which suggests that both study populations required the same amount of cognitive involvement for maintaining balance. Center of pressure dynamic patterns exhibited by the anterior cruciate ligament deficient patients were more regular than those of the healthy controls indicating "complexity loss" and may be indicative of the reduced adaptability (flexibility) of a balance system to sudden perturbations.

1. Introduction

Linear and non-linear measures of postural sway encompass two different approaches for evaluating postural performance during quiet standing on a force platform [1,2]. Traditional linear measures, such as mean and standard deviation of sway amplitude/velocity, have extensively been used in postural control investigations of patients with anterior cruciate ligament deficient (ACLD) knees [3–5]. Briefly, the results show that adults with anterior cruciate ligament (ACL) injuries have disturbed postural control on the injured leg as compared with the matched leg of a healthy group [3,4]. To our knowledge, however, very little is known about the non-linear dynamical features of postural sway in this specific population.

From a biomechanical perspective of postural stability, optimal postural control in quiet standing is characterized by lesser variability of center of pressure (COP) oscillations [1]. Thus, increased sway variability of ACLD patients relative to healthy control participants is considered an undesirable outcome leading to decreased balance control in this specific population. Contrary to this traditional view, however, it is well known that COP oscillations are intrinsically variable [6] and this property can provide the neuromuscular system with flexible adaptation to unpredictable perturbations [7].

Recently, the use of traditional linear measures to investigate postural variability has been questioned by some researchers [1,8]. The averaging procedure used to quantify traditional linear measures can mask the temporal structure of sway variability, while non-linear measures focus on determining how sway changes over time [1,2,7]. One of the non-linear tools developed

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to capture dynamical features of COP oscillations is recurrence quantification analysis (RQA) [9]. In recent years, RQA sensitivity to detect sway changes following sensory deprivation conditions [10], cognitive dual-tasking [10,11] and balance impairment [12] has been well established.

From a clinical viewpoint, characterizing the dynamical pattern of the COP time series would provide important information about the variability and the complexity of the human postural system. In addition, high predictive validity of non-linear measures has been established for other physiological systems such as the cardiovascular system [13].

Assessing the deterministic pattern of sway variability using RQA is a novel method to measure system complexity so that low (high) regularity values indicate more (less) complexity [12,14,15]. Complexity is defined as the number of system components and coupling function (interaction) among them [15]. Either a reduction in the number of system elements or a change in their coupling function could produce a "complexity loss" [13,15]. Loss of complexity, which is associated with more regularity in COP time series, has been confirmed in some balance impaired subjects (e.g. Parkinson [12] and elderly [14] participants) by using RQA variables.

While the effects of ACL injury on stride-to-stride gait variability have been investigated by non-linear tools such as the Lyapunov exponent [7] and approximate entropy [8], no study has yet reported the non-linear dynamical pattern of sway variability in ACLD patients. Therefore, the primary aim of this study was to investigate the non-linear dynamical structure of the COP time series in a population with ACLD knees. It was hypothesized that patients compared to controls would exhibit a more deterministic pattern of postural sway, indicating complexity loss.

Moreover, while several studies have investigated postural control of ACLD patients [3,4,16], little is known for the effect of cognitive tasks on their postural performance [5]. Some observations support impaired cognitive processing in ACLD patients [17] and other musculoskeletal injuries (e.g. low back pain [18]). Thus, the secondary aim of this study was to investigate the effects of cognitive loading on non-linear dynamical features of postural sway for the ACLD patients compared to healthy controls.

2. Materials and methods

2.1. Participants

All participants signed an informed consent form which had been approved by the local Ethics Committee (No. 260-310). Twenty-seven male ACLD patients were investigated. They were recruited from the Department of Orthopedics at Moayeri Hospital and Milad Hospital, Tehran, Iran, via referral by an orthopedic surgeon. Inclusion criteria were: (1) non-operated, non-acute, complete ACL rupture with and without meniscal injury as confirmed by magnetic resonance imaging and clinical knee stability testing; (2) pain no more than grade 2 according to a Visual Analogue Scale at the time of assessment (since focused attention toward pain stimuli can temporarily reduce attentional capacity [19], it was considered a factor that might confound the posture-cognition interaction); (3) absence of injuries involving the contra-lateral leg, neck or back; and (4) no history of ankle sprain on the ACLD side.

The Knee Injury and Osteoarthritis Outcome Score (KOOS) [20] were used to evaluate knee function in potentially stressful knee movements over the week prior to testing. The KOOS includes five subscales with a scoring range of 0–100. Higher scores represent lesser knee problems (0 = severe disability, 100 = no disability). The Persian-version of KOOS is a reliable and valid outcome measure used for ACLD patients [20]. The Tegner activity scale [21] was used to compare the activity level of the two groups prior to injury. This scale is based on activity levels for sport (recreational or competitive football, volleyball, etc.) and occupational activities involving light or heavy labor. It has 10 items with a scoring range of 0–10 for which higher scores represent higher levels of physical activity. The Tegner activity scale has acceptable psychometric properties for patients with knee injuries [21]. Most patients in the study had injured their ACL during football.

The control group consisted of 27 male participants recruited from uninjured teammates via invitation and through telephone contact. They were matched with the ACLD patients according to age, height, body mass index, activity level and sports background (Table 1). Both ACLD patients and healthy participants were excluded if they had a history of known visual, vestibular or neurological disorder, auditory or cognitive (memory) deficit, diabetes or use of any medicine that could affect their balance.

2.2. Postural and cognitive tasks

Although double leg stance (DLS) may be maintained by an ankle/hip strategy, altered characteristics demonstrated in the muscles of the ACLD leg [22] have the potential to affect balance in this position. Therefore, postural stability measurements were obtained in both DLS and single leg stance (SLS).

In DLS, participants were instructed to stand with their feet together on the central region of the force platform. Three levels of postural difficulty were investigated: (1) DLS on a rigid surface (force platform) with eyes open (RO); (2) on a rigid surface with eyes closed (RC); and (3) on foam (10.5 cm thickness) with eyes closed (FC).

In SLS, participants were asked to stand with open eyes on the injured or non-injured leg. The injured leg of the ACLD group was matched by leg dominance to a leg in the control group. Leg dominance was defined as the preferred kicking leg. The knee of the unsupported leg was held in slight flexion (30°) and the arms were open (30° abduction).

Center of pressure data were collected by using a strain gauge Bertec 9090-15 force platform and Bertec AM-6701 amplifier (Bertec Corporation, Columbus, OH, USA). Anteroposterior (AP) and mediolateral (ML) displacements of COP were measured along the *y*-axis and *x*-axis of the force platform, respectively.

A backward digit span task was selected as the cognitive task, which required participants to hold a string of random digits in mind while rehearsing it in reverse order [10,19]. Maximum digit span was determined by administering a backward digit test of the Wechsler Intelligence Scale [19]. The maximum number of digits recalled plus one constituted the number of digits presented in dual-task conditions.

Table 1
Demographic and functional characteristics of ACLD and healthy groups.

	ACLD group ($n = 27$) Mean (SD)	Healthy group ($n = 27$) Mean (SD)	*P* value (Mean differences)
Demographic data			
Age (year)	26.74 (5.84)	26.29 (5.07)	0.76
Height (m)	1.77 (0.64)	1.79 (0.55)	0.16
Body mass index (kg/m^2)	23.69 (2.42)	22.84 (2.38)	0.20
Duration of injury (year)	1.80 (2.23)	N/A	N/A
Tegner Scale[a]	6.30 (0.77)	6.04 (0.85)	0.24
KOOS[b]			
Pain	67.14 (21.89)	N/A	N/A
Symptom	56.77 (11.84)	N/A	N/A
Activity daily living	71.88 (22.38)	N/A	N/A
Sport and recreation	32.96 (27.57)	N/A	N/A
Quality of life	32.51 (24.20)	N/A	N/A

ACLD: anterior cruciate ligament deficient; N/A: not applicable.

[a] Range of scores is from 0 to 10.

[b] Range of scores is from 0 to 100.

2.3. Procedure

Each participant was exposed to 10 randomly ordered experimental conditions: (1) isolated DLS in RO condition; (2) DLS in RO condition while performing cognitive task; (3) isolated DLS in RC condition; (4) DLS in RC condition while performing cognitive task; (5) isolated DLS in FC condition; (6) DLS in FC condition while performing cognitive task; (7) isolated SLS on the injured leg; (8) SLS on the injured leg while performing cognitive task; (9) isolated SLS on the non-injured leg; and (10) SLS on the non-injured leg while performing cognitive task.

For the condition where there was no cognitive task, i.e. single task, participants were instructed to stand barefoot on the force platform. For the dual task conditions, participants were instructed to listen carefully to a random digit string repeated twice before beginning data collection. During the data collection period (30 s for DLS and 20 s for SLS), participants were instructed to mentally rehearse the string of numbers in reverse order and to focus on accuracy with each repetition. Immediately after data collection, participants were requested to recall the reversed digits. Three different types of cognitive error were documented; intrusion (a wrong number), order error, or omission (a number missing) [10]. Center of pressure data is computed from collected force and position data which were collected with a sampling frequency of 200 Hz. The whole experiment lasted approximately 90 min for each participant.

2.4. Data analysis

False nearest neighbors [23] and average mutual information [24] were used to determine embedding dimension and time delay parameters, respectively. The embedding dimension was assumed to be five for all cases while the time delay parameter was calculated for each case using the average displacement method [25] which is less sensitive to noise. The radius of the hyper-sphere used to regard points as recurrent neighbors was 10% of the maximum diameter of the reconstructed attractor [9]. A minimum number of three points was employed to detect diagonal lines. With these input parameters, distance matrixes and recurrence plots were computed from which the four RQA measures were extracted. According to the recurrence plots provided in Fig. 2, the presence of deterministic patterns commonly seen in non-linear COP time series (e.g. [9,10]) shows non-linear origin and absence of randomness of the COP time series. Moreover, data shuffling in a pilot study ensured the deterministic nature of the data.

Due to their acceptable reliability, only %determinism and Shannon entropy in the AP and ML directions were chosen for the present study. In a pilot study performed by our research group, the test–retest reliability of the RQA measures was estimated in a random sample of 12 ACLD patients. The results showed an intraclass correlation coefficient (ICC) range of 0.04–0.15, 0.54–0.69, 0.56–0.62 and −0.42 to 0.50 for %recurrence, %determinism, Shannon entropy and trend in ML direction, respectively. In addition, an ICC range of −0.41 to 0.26, 0.51–0.70, 0.53–0.69 and −0.09 to 0.24 was obtained for %recurrence, %determinism, Shannon entropy and trend in AP direction, respectively, in different conditions of postural difficulty. Haddad et al. [11] and Schmit et al. [12] also used %determinism and Shannon entropy in their study due to their satisfactory sensitivity for assessing the patterns of postural dynamics under various conditions.

%Determinism is the degree to which recurrent points constitute a regular (periodic) pattern of behavior. A system with a more deterministic pattern has more predictable behavior [12,14,15]. Shannon entropy is a measure of the extent of complexity of deterministic structure in a time series [9]. Since Shannon entropy is computed with respect to those recurrent points that constitute a pattern in the deterministic structure, it quantifies complexity of deterministic structure [9] and not complexity of the whole system.

2.5. Statistical analysis

The average values of RQA variables for three trials of each experimental condition were used for statistical analysis. Since all dependent variables were normally distributed, the authors used parametric statistical tests [26].

A separate 2 × 2 × 3 (2 groups; 2 levels of cognitive difficulty; 3 levels of postural difficulty) repeated measures analysis of variance (ANOVA) was used to determine possible main effects and interactions of factors for each of the RQA variables in DLS. For multiple comparisons, the Bonferroni adjustment method was used [26].

A separate 2 × 2 (2 groups; 2 levels of cognitive difficulty) repeated measures ANOVA was used for SLS on the injured leg and non-injured leg (and their matched leg in the control group). Alpha was set at 0.05 for all statistical analyses. A paired t-test was used to determine any significant difference between injured and non-injured legs.

3. Results

3.1. Postural performance for double stance conditions

Table 2 shows the mean and standard deviation (SD) of RQA variables for the different conditions of postural and cognitive difficulties for both groups.

For the double leg stance condition, %determinism and Shannon entropy in both the AP and ML directions were higher in the ACLD patients compared to the healthy participants (Table 3). When postural difficulty was increased for the double leg stance condition, %determinism and Shannon entropy significantly increased while when cognitive difficulty was increased (single

Table 2
Mean (SD) of RQA variables in different conditions of postural and cognitive difficulty for both ACLD and healthy groups in double leg stance.

Levels of postural difficulty	Levels of cognitive difficulty			
	No-task		Dual-task	
	ACLD	Healthy	ACLD	Healthy
Rigid surface—eyes open				
%Determinism				
AP	92.06 (2.99)	90.40 (5.45)	89.08 (4.52)	86.19 (7.92)
ML	93.65 (2.21)	91.52 (2.60)	91.96 (2.81)	89.85 (3.18)
Shannon entropy				
AP	4.72 (0.40)	4.55 (0.55)	4.40 (0.49)	4.13 (0.53)
ML	4.98 (0.42)	4.65 (0.34)	4.73 (0.41)	4.46 (0.39)
Rigid surface—eyes closed				
%Determinism				
AP	94.63 (2.13)	92.80 (2.39)	93.13 (3.06)	90.66 (4.74)
ML	95.44 (1.88)	94.82 (2.32)	94.31 (2.30)	92.90 (2.81)
Shannon entropy				
AP	5.22 (0.41)	4.83 (0.39)	4.98 (0.49)	4.58 (0.54)
ML	5.46 (0.46)	5.35 (0.50)	5.21 (0.45)	4.93 (0.49)
Foam surface—eyes closed				
%Determinism				
AP	97.86 (0.83)	97.19 (0.95)	96.51 (1.93)	95.92 (1.32)
ML	97.62 (0.67)	97.30 (0.75)	96.97 (0.82)	96.14 (1.17)
Shannon entropy				
AP	6.06 (0.38)	5.81 (0.38)	5.63 (0.40)	5.39 (0.34)
ML	5.90 (0.26)	5.86 (0.32)	5.69 (0.33)	5.48 (0.35)

RQA: recurrence quantification analysis; ACLD: anterior cruciate ligament deficient; SD: standard deviation; AP: anteroposterior; ML: mediolateral.

Table 3
Summary of analysis of variance for RQA variables in double leg stance: *F* ratios and *P* values by variable.

Independent variable	%Determinism				Shannon entropy			
	AP		ML		AP		ML	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Main effects								
Group	5.53	**0.02**	8.30	<**0.01**	9.55	<**0.01**	6.55	**0.02**
Postural difficulty	107	<**0.01**	203.1	<**0.01**	327.7	<**0.01**	227.1	<**0.01**
Cognitive difficulty	65	<**0.01**	73.25	<**0.01**	102.8	<**0.01**	92	<**0.01**
Interactions								
Group × postural difficulty	1.61	0.20	4.67	**0.03**	1.74	0.18	1.68	0.19
Group × cognitive difficulty	1.15	0.28	1.80	0.18	0.16	0.68	2.57	0.11
Postural × cognitive difficulty	7.88	<**0.01**	2.90	0.09	2.76	0.07	1.28	0.28
Group × postural × cognitive difficulty	0.58	0.55	0.73	0.43	0.30	0.73	2.08	0.13

RQA: recurrence quantification analysis.
Significant differences ($P < 0.05$) are in bold.

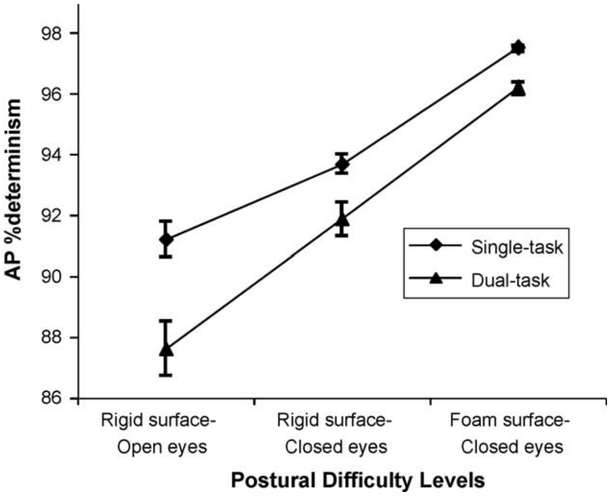

Fig. 1. Interaction plot showing AP %determinism as a function of postural and cognitive difficulty. Error bars represent standard error of mean. Two levels of cognitive difficulty were significantly different pairwisely in all of postural difficulty conditions.

to dual task conditions), %determinism and Shannon entropy significantly decreased (Table 3). Further sub-analysis performed using a paired *t*-test revealed that for all 3 levels of postural difficulty; AP %determinism and Shannon entropy in dual task were significantly lower than single task condition (see Fig. 1 for AP %determinism as an example).

3.2. Postural performance for single stance conditions

For the single leg stance condition, %determinism in the AP and ML directions and Shannon entropy in the ML direction were significantly higher for both the injured and non-injured leg in the ACLD patients when compared to the healthy participants (Table 4). When cognitive difficulty was increased (single to dual task conditions) for the single leg stance condition, %determinism and Shannon entropy significantly decreased (Table 4). The results of paired *t*-tests showed that there was no significant difference between injured and non-injured legs of ACLD patients for any of RQA variables ($P > 0.05$).

4. Discussion

The results of our study indicated that in both DLS and SLS, ACLD patients showed an increase in %determinism and Shannon entropy of the deterministic structure of COP time series. Regularity of COP time series can be quantified by other non-linear tools such as sample entropy [6] and approximate entropy [8]. These entropy measures are conceptually and computationally dissimilar to Shannon entropy [14]. As stated by Seigle et al. [14], sample entropy and Shannon entropy do not necessarily provide the same information about the complexity of COP time series. Perhaps due to

Table 4
Summary of analysis of variance for RQA variables in single leg stance: *F* ratios and *P* values by variable.

Independent variable	%Determinism				Shannon entropy			
	AP		ML		AP		ML	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Single leg stance on the injured leg (and its matched leg in the control group)								
Main effects								
Group	4.65	**0.03**	13.73	<**0.01**	3.16	0.08	10.51	<**0.01**
Cognitive difficulty	12.36	<**0.01**	12.03	<**0.01**	12.79	<**0.01**	4.21	<**0.01**
Interactions								
Group × cognitive difficulty	0.28	0.59	0.00	0.97	0.26	0.60	0.01	0.89
Single leg stance on the non-injured leg (and its matched leg in the control group)								
Main effects								
Group	13.91	<**0.01**	10.56	<**0.01**	12.77	<**0.01**	8.10	<**0.01**
Cognitive difficulty	25.46	<**0.01**	10.69	<**0.01**	27.45	<**0.01**	8.51	<**0.01**
Interactions								
Group × cognitive difficulty	0.82	0.36	0.04	0.83	0.00	0.92	0.33	0.58

RQA: recurrence quantification analysis.
Significant differences ($P < 0.05$) are in bold.

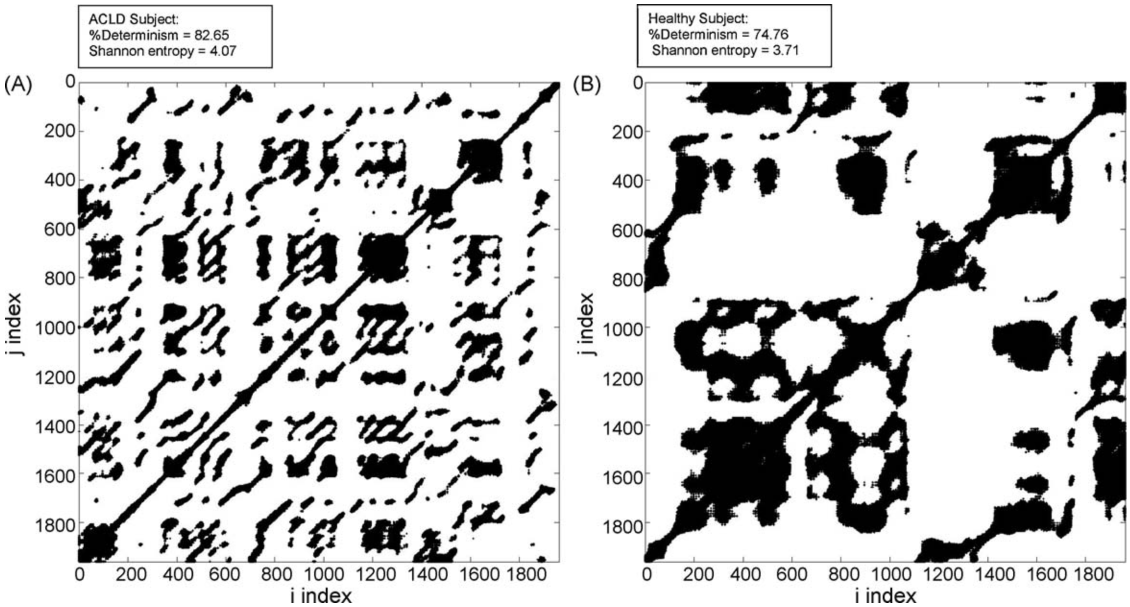

Fig. 2. Recurrence plots generated for the AP time series during standing on the injured leg (and its matched leg of healthy control) from a typical anterior cruciate ligament deficient (A) and healthy (B) subject. The RQA parameters are shown for performance.

this conceptual conflict, Schmit et al. [12] has cautioned against the use of Shannon entropy for evaluating the loss of complexity hypothesis and acknowledged that no prediction can be made for the effect of a given pathology on this parameter.

There are two explanations for the increased COP regularity in the ACLD patients compared to healthy controls. First, increased COP regularity in patients may indicate that ACL injury is associated with a tendency of sway dynamics for decreased complexity [12,14]. It is well established that under unperturbed conditions, most healthy systems exhibit highly irregular complex dynamics due to interactions between multiple elements over multiple time scales [13]. Given the adaptability of complex systems to internal and external perturbations [13,15], loss of complexity observed in this study would reduce the range of adaptive responses to sudden perturbations [7] and could increase the risk of other knee injuries (e.g. meniscal tear and articular cartilage degeneration), which are commonly seen in ACLD patients. However, this possibility must be evaluated in a longitudinal study where loss of complexity is considered in conjunction with other valid clinical and radiological findings [7]. Our results are in agreement with two recent studies conducted by Moraiti et al. [7] and Georgoulis et al. [8] who investigated the effects of ACLD on stride-to-stride variability as measured by the Lyapunov exponent and approximate entropy, respectively. They reported increased regularity (decreased complexity) in the structure of gait variability of ACLD patients. This was attributed to the disruption of sensory feedback and consequent change in muscle activation patterns involved in postural synergies caused by tear of the ACL [7].

Second, increased COP regularity can be interpreted as a reflection of higher cognitive processing (attention demanding) in maintaining balance [6]. The results of this study, however, revealed that ACLD patients reduced their COP regularity with increasing cognitive difficulty to the same extent as compared to healthy subjects, as evident from absence of interaction of group by cognitive task. Therefore, it seems that the amount of attention demands allocated to standing balance is the same for both study groups. We suggest selecting ACLD patients with more severe disability and exposing them to more demanding dynamic balance conditions to further explore dual-tasking effects in future studies.

The results revealed that as postural difficulty increased, COP regularity increased as well. In addition, performing a cognitive task caused decreased COP regularity when compared to a single task. The importance of these results could be highlighted when contrasted with those of Negahban et al. [5] who investigated the effect of postural and cognitive loading on the same data by traditional linear measures of variability (i.e. mean velocity, phase plane portrait and SD of velocity). Their important observations include: (1) increased sway variability in the ACLD group relative to the healthy group in all but one condition: standing on the injured leg with open-eyes; (2) increased sway variability with more challenging postural tasks and (3) decreased sway variability with more challenging cognitive tasks. Comparing these results to those of the current study, it is apparent that an increase in variability is accompanied by a decrease in randomness (i.e. by an increase in determinism) and vice versa. Numerous studies support this finding. In a recent study, Schmit et al. [12] found that the higher level of postural variability in individuals with Parkinson's disease compared with a matched control group was accompanied by greater determinism. Furthermore, Riley and Clark [27] reported that when sensory organization test conditions became more difficult, COP variability increased while degree of randomness decreased. In another study, Riley et al. [10] observed similar findings in their investigation which studied the effect of vision, surface and cognitive loading on both linear and RQA measures of COP. They found increased variability and determinism when participants' eyes were closed (relative to eyes open) and when standing on a foam surface (relative to a rigid surface). Inversely, postural variability and determinism decreased when subjects rehearsed a difficult cognitive task (relative to no-task). An overview of these data indicates that variability is dominated by a deterministic structure and should not be equated with randomness, which contrasts with the traditional perspective that regards variability as randomness [1].

In conclusion, results showed increased regularity of COP time series of ACLD patients compared to healthy controls. These changes may compromise behavioral flexibility of these patients when encountering a constantly changing environment. Additionally, the findings confirm the effects of a concurrent digit span memory task on COP regularity. Finally, the response to cognitive loading was found to be similar for the two groups.

Conflict of interest

None of the authors have any financial or other interests relating to the manuscript to be submitted for publication in Gait and Posture.

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