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Differences in postural control between healthy and subjects with chronic ankle instability

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A B S T R A C T

Introduction: Chronic ankle instability (CAI) is characterized by the occurrence of repetitive inversion mechanism of the ankle, resulting in numerous ankle sprains. CAI occurs in approximately 70% of patients with a history of a lateral ankle sprain. Many causes of functional ankle instability have been postulated and include deficits in proprioception, impaired neuromuscular-firing patterns, disturbed balance and postural control.
Objective: The purpose of this study was to compare postural control behaviour in subjects with chronic ankle instability and healthy subjects, using the traditional linear and nonlinear variables for the centre of pressure (CoP) displacement, during one-leg stance on stable and unstable surfaces.
Methods: 16 CAI subjects and 20 healthy subjects were evaluated with the single leg stance on a stable surface and an unstable surface, for 60 s with a force plate. The traditional linear variables like CoP displacement, CoP amplitude and CoP velocity were calculated. Variability of CoP displacement was also submitted to nonlinear analysis and the approximated entropy, sample entropy, correlation dimension and Lyapunov exponent were calculated.
Results: On the stable surface, no differences between groups for all the traditional variables were found but the correlation dimension of CoP mediolateral displacement had lower values on the CAI group with statistical significance ($p < 0.05$). On the unstable surface, no differences were found neither with linear variable neither with variability nonlinear analysis.
Conclusion: Correlated dimension of CoP displacement during one-leg stance on a stable surface was the only variable that show significant differences between the two groups. The lower values of this variable in the CAI subjects may implicate a balance control system with more difficulties to adapt to the environment and the task demands. More studies are needed to better understand CAI subjects balance control.

1. Introduction

The knee and ankle are the most common injured joints in the lower extremity of athletic people (Hootman, Dick, & Agel, 2007; Joseph et al., 2013; Viljoen et al., 2021). These joints are forced to rely on their dynamic characteristics to maintain postural control and joint stability, due to the lack of bone congruence and the inability to handle different forces generated during functional tasks. Several parameters (proprioception, postural control, neuromuscular activation and coordination, kinetics/kinematics variables, dynamic stability) have been measured to better understand how the body maintains joint stability during static and/or dynamic activities (Wikstrom, Tillman, Chmielewski, & Borsa, 2006).

Lateral ankle sprains (LAS) are the most common injuries in

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sports activities (Garrick, 1977) and the most prevalent musculoskeletal injury in physically active populations (Gribble et al., 2016a). LAS correspond to 11.5%–22% of sports injuries in the United Kingdom (MacAuley, 1999). An injury surveillance data study for 15 sports during 16 years performed by the National Collegiate Athletic Association, reported that LAS correspond to 14.8% of all injuries reported (Hootman et al., 2007). In the active-duty US Army soldiers, the incidence rate for ankle sprains was 45.14 per 1000 person-years (Bulathsinhala, Hill, Scofield, Haley, & Kardouni, 2015). Trauma in inversion with plantar flexion is the most frequent injury mechanism, being the cause of about 85% of all ankle sprains (Robbins & Waked, 1998). After an ankle sprain, 32%–74% of individuals may have residual and chronic symptoms, recurrent ankle sprains and/or perceived instability (Anandacoomarasamy & Barnsley, 2005; Konradsen, Bech, Ehrenbjerg, & Nickelsen, 2002). Approximately 70% of patients with a history of LAS develop chronic instability of the ankle joint (Gribble et al., 2016b).

Chronic ankle instability (CAI) is characterized by the occurrence of repetitive inversion mechanism of the ankle, resulting in numerous ankle sprains (Hertel, 2002). The prevalence of residual symptoms (pain and swelling) and disability (*"giving-way"* and weakness) after an initial ankle sprain is common. CAI is a common problem after an acute lateral ankle sprain, manifested by recurring injuries that often limit sports participation (Hubbard, Kaminski, Vander Griend, & Kovaleski, 2004).

Hertel (2002) described a model with two possible causes for CAI: mechanical instability and functional instability. He referred that these two causes do not explain the etiologic process individually but they are interrelated and *"form a continuum of pathologic contributions to CAI"*. The mechanical ankle instability occurs as a result of anatomical structures changes after an ankle sprain, like pathologic capsule and ligament laxity, impaired arthrokinematics, synovial changes and degenerative joint pathology, leading to further episodes of instability (Hertel, 2002).

Functional ankle instability is characterized by a history of instability and "*giving-way*" of the ankle during activity. It arises from a dysfunction to the neuromuscular control system failing the dynamic mechanism of ankle protection (Hertel, 2002). Many causes of functional ankle instability have been postulated and include deficits in proprioception and cutaneous sensation, impaired neuromuscular recruitment patterns, reduced postural control and muscle weakness (Hertel, 2002).

Postural control is defined as the capacity to maintain stability on a base of support (Tropp & Odenrick, 1988). The postural control is reflected on postural sway and it can be quantified with a force plate by measuring the displacement of the centre of pressure (CoP) on the base of support during the standing position (Howe, Rochester, Neil, Skelton, & Ballinger, 2011; Winter, Patla, Ishac, & Gage, 2003). The use of postural control to study the motor behaviour of subjects with CAI was firstly proposed by Freeman and colleagues (Freeman, 1965). Several systematic reviews have shown that for more than 30 years researchers have evaluated static balance with a force plate measuring the CoP displacement variables on subjects with CAI (Arnold, De La Motte, Linens, & Ross, 2009; Hiller et al., 2011; McKeon & Hertel, 2008; Munn, Sullivan, & Schneiders, 2010; Thompson et al., 2018; Wikstrom, Naik, Lodha, & Cauraugh, 2009). These systematic reviews have shown conflicting conclusions, some pointing out that CAI is associated with static balance impairments (Arnold et al., 2009; Munn et al., 2010; Wikstrom et al., 2009), others stating that association of CAI with this factor is not consistent (Hiller et al., 2011; McKeon & Hertel, 2008; Thompson et al., 2018). Several conditions have been used like single and double-limb stance, static and dynamic tasks (e.g. Star Excursion Balance Test or step laterally to force plate), but few studies were found using an unstable surface and only one study (Nakagawa & Hoffman, 2004) was found using a foam pad over the force plate, to increase the instability condition during the one-leg stance.

The variability of human movement refers to the normal variations that occur in motor performance through multiple repetitions of a task over time (Stergiou, Harbourne, & Cavanaugh, 2006). Maintaining balance on one leg stance implies a postural sway around a central equilibrium point without ever remaining exactly still (Harbourne & Stergiou, 2009). The motor control system never stabilizes in a steady-state and the continuous fluctuations characterize the healthy variability that allows adaptation to the environment (Harbourne & Stergiou, 2009). This variability is inherent to all biological systems (Stergiou & Decker, 2011) and it is a positive adaptation characteristic of functional movement (Harbourne & Stergiou, 2009). Some authors suggest that movement variability is not entirely random and may estimate the flexibility of the motor control system to adapt to the environment and the task requirements (Stergiou et al., 2006). The study of the variability of human movement during motor tasks can be developed based on dynamic theories of motor control using nonlinear variables (e.g. sample entropy, approximate entropy, correlation dimension, Lyapunov exponent, etc.) on its analysis (Harbourne & Stergiou, 2009; Stergiou & Decker, 2011; Stergiou et al., 2006). Nonlinear analysis helps to understand whether the variability of movement or of biological process is favourable or harmful for the control system (Harbourne & Stergiou, 2009). The use of nonlinear variables to analyse movement variability in subjects with unstable ankles may provide additional information that may help to clarify motor behaviour and its control mechanisms in the CAI population. A study that investigated stride-to-stride variability during walking found alterations in individuals with chronic ankle instability (Terada et al., 2015). The nonlinear analysis of the variability of the displacement of CoP during the stance position can also be used to study CAI related to balance control. Several studies have shown that subjects with CAI present results in nonlinear variables that may signify a motor behaviour with less ability to adapt to the demands related to the task and environmental changes in balance control (Terada, Johnson, Kosik, & Gribble, 2019; Terada, Kosik, Johnson, & Gribble, 2018). In another study, Terada and colleagues did not found any difference between CAI subjects and healthy controls on sample entropy of CoP displacement (Terada, Beard, et al., 2019).

The purpose of this observational study was to compare postural control behaviour in subjects with chronic ankle instability and healthy subjects, using the traditional linear and nonlinear analysis for CoP displacement, during one-leg stance on stable and unstable surfaces. Based on the effect of the disturbance promoted by the unstable surface, which is supposed to increase the intensity of postural control actions, it was hypothesized the results from this task show more differences between subjects with chronic ankle instability and healthy subjects. The use of an unstable surface on the force plate and the nonlinear analysis of the variability of movement in the study of the CAI subjects when compared to the healthy subjects can contribute to a better understanding of this condition.

2. Materials and methods

2.1. Participants

Sixteen young adults with CAI (CAI group) and 20 healthy subjects (Healthy group), volunteered to participate. The CAI group selection followed the criteria of the International Ankle Consortium (Gribble et al., 2013) and the self-reported ankle instability questionnaire used was the IdFAI - Identification of Functional Ankle Instability (Simon, Donahue, & Docherty, 2012). The healthy subjects never had an ankle sprain. Both groups didn't have a history of previous surgery, fracture or other symptom/sign in the lower limbs, nor dysfunction of the nervous system.

Both groups were similar for sex, limb dominance, age, height and weight and no significant differences were found ($p > 0.05$) in demographic and anthropometric data (Table 1).

Subjects were instructed about the study purpose and procedures and signed informed consent. The ethical committee of the Escola Superior de Saúde do Alcoitão approved the study (PARECER nº2-2017).

2.2. Instrumentation and variables

To measure posturography it was used a force plate Bertec model 4060-08 with an AM6501 amplifier (Bertec Corporation, Columbus, Ohio, United States). The centre of pressure (CoP) traditional linear variables were selected according to Duarte and Freitas (2010): CoP total displacement (Displ_Total) – the total length of the CoP trajectory; CoP total displacement area (area) – the CoP ellipse area with 95% confidence; CoP total displacement velocity (Vel_Total) – the CoP total displacement average velocity; CoP mediolateral displacement (Displ_ML) – the CoP displacement on the mediolateral direction; CoP anteroposterior displacement (Displ_AP) – the CoP displacement on the anteroposterior direction; CoP mediolateral amplitude (Ampl_ML) – the distance between the maximum and the minimum value of the CoP displacement on the mediolateral direction; CoP anteroposterior amplitude (Ampl_AP) – the distance between the maximum and the minimum value of the CoP displacement on the anteroposterior direction; CoP velocity mediolateral (Vel_ML) – the CoP mediolateral average velocity; and CoP velocity anteroposterior (Vel_AP) – the CoP anteroposterior average velocity.

The nonlinear variables, according to Stergiou (2016a), calculated for the anteroposterior and mediolateral CoP displacement are approximate entropy of mediolateral (ApEn_ML) and anteroposterior (ApEn_AP); sample entropy of mediolateral (SamEn_ML) and anteroposterior (SamEn_AP); correlation dimension of mediolateral (CoDim_ML) and anteroposterior (CoDim _AP); Lyapunov exponent of mediolateral (LyE_ML) and anteroposterior (LyE_AP).

2.3. Procedures

Subjects were height and weight measured. The lower limb dominance was determined with two functional tests: step-up and recovery of balance after a push on the back of the trunk (Schneiders et al., 2010). All the measurements were performed with the subjects barefoot.

Single leg stance was maintained for 60 s, with the affected side (CAI group) or the dominant side (Healthy group), with the foot on the centre of the force plate, hands on the waist and looking to a previously defined point. The measurement was randomly performed directly on the force place (stable surface) and a foam pad (Balance-pad Airex®, Airex AG, Sins, Switzerland) placed over the force plate (unstable surface) (Mademli et al., 2021; Sozzi, Nardone, & Schieppati, 2021). Each condition was repeated three times. In case of failure, the task was repeated until three complete measurements were obtained.

Table 1
Participants' demographics and anthropometrics.

	CAI group n = 16	Control group n = 20
sex	female - 8	female - 9
	male - 8	male - 11
limb dominance	left - 1	left - 2
	right - 15	right - 18
age, years - mean (SD)	20.9 (2.5)	23.2 (4.9)
height, m - mean (SD)	1.69 (0.08)	1.71 (0.10)
weight, kg - mean (SD)	67.5 (7.9)	65.2 (11.9)
BMI - mean (SD)	23.3 (2.3)	21.9 (2.1)

SD = standard deviation; BMI = body mass index.

2.4. Data analysis

The data were collected with a 1000 Hz sample rate and downsampled to 100 Hz. The signal was filtered with a Butterworth, 2nd order, 10 Hz low pass filter. Matlab software (MatLab® R2015a, The MathWorks, Inc., Natick, Massachusetts, United States) was used to process, according to Duarte and Freitas (2010).

The nonlinear variables required a previous behaviour and series type analysis. Nick Stergiou's Matlab routines (Stergiou, 2016b) were used. According to the power spectral density analysis (PSD), more than 99% of the data signal strength was preserved. The time delay between two signals (τ - tau) was calculated using the average mutual information (AMI) method, for the perfect construction of the appropriate phase space in dimension (dim - embedding dimension). The LyE is very sensitive to the values of tau and dim because these parameters can introduce error since the nonlinear systems are very sensitive to the initial conditions. The determination of this variable was obtained from mathematical procedures based on the Wolf et al. algorithm (Wolf et al., 1985; Wurdeman, 2016).

2.5. Statistical analysis

The average of the three repetitions was calculated. Since no normality was determined by the Shapiro-Wilk test, the Mann-Whitney *U* test was chosen to compare groups. Statistical significance was set at an alpha level of $p \leq 0.05$. The Bonferroni correction was used to adjust p values, according to the family-wise error rate (Mademli et al., 2021). The SPSS 24 software (IBM SPSS Statistics for Windows, Version 24.0., IBM Corp., Armonk, New York, United States) was used.

3. Results

The results of the linear variables for the CoP displacement collected on a stable surface are presented in Table 2. No statistically significant differences were found between both groups ($p > 0.05$), but there is a tendency for higher values of mean and median in the Healthy group for most of the variables.

For the same data, the nonlinear variables are presented in Table 3. The CoDim_ML was higher in the Healthy subjects with statistical significance ($p < 0.05$). No other statistically significant differences were found. Except for the SamEn_ML, the other variables presented higher values in the Healthy group.

In Table 4 the results of traditional variables of CoP displacement on the unstable surface are presented. No statistically significant differences were found between groups. However, healthy subjects tend to have higher values.

Table 5 shows the nonlinear variables on the unstable surface. There were no statistically significant differences between groups ($p > 0.05$). Healthy subjects tend to show lower values in ML variables, except for SamEn_ML, and higher values in AP variables, except for SamEn_AP.

Table 2
Posturographic traditional variables - Stable surface.

	CAI					Healthy					
	$\overline{X}$	SD	Median	Min	Max	$\overline{X}$	SD	Median	Min	Max	P
Displ_AP (mm)	1086.85	343.09	993.02	654.99	2149.54	1061.59	226.21	1019.54	818.46	1782.84	0.95
Ampl_AP (mm)	42.10	15.58	38.50	23.76	88.45	45.43	18.58	40.59	25.76	102.22	0.66
Vel_AP (mm/s)	18.11	5.72	16.55	10.91	35.82	17.69	3.77	16.99	13.64	29.71	0.95
Displ_ML (mm)	1118.80	196.99	1075.88	757.43	1578.06	1172.20	289.33	1089.96	935.11	2080.26	0.98
Ampl_ML (mm)	30.17	3.57	30.26	24.48	35.20	30.91	5.82	29.53	23.62	47.80	0.98
Vel_ML (mm/s)	18.64	3.28	17.93	12.62	26.30	19.53	4.82	18.16	15.58	34.67	0.98
Displ_Total (mm)	1735.35	418.24	1583.31	1109.88	2860.76	1749.21	382.84	1628.66	1409.90	3020.41	0.98
Area (mm^2)	708.77	277.14	651.07	342.26	1530.05	772.91	418.58	655.91	393.21	2285.13	0.77
Vel_Total (mm/s)	28.92	6.97	26.38	18.49	47.67	29.15	6.38	27.14	23.49	50.33	0.98

Displ_AP: anteroposterior displacement of CoP; Ampl_AP: amplitude of anteroposterior displacement of the CoP; Vel_AP: velocity of anteroposterior displacement of the CoP; Displ_ML: mediolateral displacement of the CoP; Ampl_ML: amplitude of mediolateral displacement of the CoP; Vel_ML: velocity of mediolateral displacement of the CoP; Displ_Total: total displacement of the CoP; Area: area of total displacement of the CoP; Vel_Total: velocity of total displacement of the CoP; $\overline{X}$: mean; SD: standard deviation; Min: minimum; Max: maximum; p: p-value of Mann-Whitney *U* test.

Table 3
Posturographic nonlinear variables - Stable surface.

	CAI					Healthy					
	$\overline{X}$	SD	Median	Min	Max	$\overline{X}$	SD	Median	Min	Max	p
ApEn_ML	0.49	0.04	0.48	0.42	0.56	0.52	0.08	0.52	0.30	0.68	0.18
ApEn_AP	0.39	0.05	0.40	0.26	0.50	0.40	0.08	0.40	0.22	0.55	0.80
SamEn_ML	0.10	0.02	0.10	0.05	0.15	0.10	0.04	0.10	0.04	0.19	0.98
SamEn_AP	0.16	0.03	0.15	0.12	0.21	0.17	0.04	0.17	0.06	0.25	0.28
CoDim_ML	**2.47**	**0.05**	**2.48**	**2.36**	**2.54**	**2.51**	**0.09**	**2.53**	**2.29**	**2.64**	**0.01***
CoDim_AP	2.44	0.05	2.44	2.36	2.55	2.46	0.10	2.45	2.25	2.64	0.43
LyE_ML	59.62	11.50	62.14	39.92	75.84	63.90	18.64	64.50	23.94	104.33	0.52
LyE_AP	33.68	11.44	34.98	13.03	60.39	35.50	17.28	35.59	7.24	64.43	0.70

ApEn_ML: approximate entropy of mediolateral displacement of the CoP; ApEn_AP: approximate entropy of anteroposterior displacement of the CoP; SamEn_ML: sample entropy of mediolateral displacement of the CoP; SamEn_AP: sample entropy anteroposterior displacement of the CoP; CoDim_ML: correlation dimension of mediolateral displacement of the CoP; CoDim _AP: correlation dimension of anteroposterior displacement of the CoP; LyE_ML: Lyapunov exponent of mediolateral displacement of the CoP; LyE_AP: Lyapunov exponent anteroposterior displacement of the CoP; $\overline{X}$: mean; SD: standard deviation; Min: minimum; Max: maximum; p: p-value of Mann-Whitney *U* test.

Table 4
Posturographic traditional variables - Unstable surface.

	CAI					Healthy					
	$\overline{X}$	SD	Median	Min	Max	$\overline{X}$	SD	Median	Min	Max	P
Displ_AP (mm)	1432.84	1484.06	351.30	798.85	2166.41	1680.05	1501.88	591.74	1017.52	2941.80	0.51
Ampl_AP (mm)	55.79	51.86	10.92	42.05	78.38	64.95	56.05	26.42	40.95	145.80	0.67
Vel_AP (mm/s)	23.88	24.73	5.85	13.31	36.10	28.00	25.03	9.86	16.96	49.02	0.51
Displ_ML (mm)	1355.16	1374.06	238.16	787.23	1799.66	1470.76	1427.28	377.16	925.51	2250.98	0.72
Ampl_ML (mm)	31.39	30.98	3.26	24.20	36.52	44.16	33.29	26.97	27.10	123.11	0.12
Vel_ML (mm/s)	22.58	22.90	3.97	13.12	29.99	24.51	23.78	6.28	15.42	37.51	0.72
Displ_Total (mm)	2189.05	2230.58	439.65	1249.39	3112.54	2475.47	2280.33	759.71	1617.10	4065.66	0.60
Area (mm^2)	1005.93	1046.38	223.48	603.44	1366.91	1291.78	1107.47	778.77	641.71	3928.88	0.57
Vel_Total (mm/s)	36.48	37.17	7.33	20.82	51.87	41.25	38.00	12.66	26.95	67.75	0.60

Displ_AP: anteroposterior displacement of CoP; Ampl_AP: amplitude of anteroposterior displacement of the CoP; Vel_AP: velocity of anteroposterior displacement of the CoP; Displ_ML: mediolateral displacement of the CoP; Ampl_ML: amplitude of mediolateral displacement of the CoP; Vel_ML: velocity of mediolateral displacement of the CoP; Displ_Total: total displacement of the CoP; Area: area of total displacement of the CoP; Vel_Total: velocity of total displacement of the CoP; $\overline{X}$: mean; SD: standard deviation; Min: minimum; Max: maximum; p: p value of Mann-Whitney *U* test.

4. Discussion

Most of the studies that investigate the postural control in CAI subjects use the posturography during the leg stance on a stable surface. In this study was added a new demand using an unstable surface. The main aim of this study was to compare postural control behaviour between subjects with chronic ankle instability and healthy subjects, during one-leg stance on a stable surface and on an unstable surface, using the traditional linear and nonlinear variables for CoP displacement.

Some studies with static balance tests with posturography report differences between CAI and healthy subjects (Arnold et al., 2009; Hadadi et al., 2017; Hiller et al., 2011; Linens, Ross, Arnold, Gayle, & Pidcoe, 2014; Munn et al., 2010; Tropp, 1986; Tropp & Odenrick, 1988; Tropp, Odenrick, & Gillquist, 1985). Others did not find differences between groups (Bernier, Perrin, & Rijke, 1997; P.; McKeon & Hertel, 2008; Thompson et al., 2018; Toyooka et al., 2018; Tropp, Ekstrand, & Gillquist, 1984).

In the present study, when comparing the CAI group and the Healthy group, during single-leg stance on the stable surface, no statistically significant differences were found for all the traditional linear variables of the CoP displacement. Arnold et al. (2009) computed a mixed-effects analysis to compare the linear variables of CoP displacement and found significant differences indicating impaired balance in unstable ankles measured by static balance. Wikstrom et al. (2009) also found a medium significant

Table 5
Posturographic nonlinear variables - Unstable surface.

	CAI					Healthy					
	$\overline{X}$	SD	Median	Min	Max	$\overline{X}$	SD	Median	Min	Max	P
ApEn_ML	0.54	0.06	0.53	0.43	0.65	0.52	0.08	0.52	0.36	0.69	0.92
ApEn_AP	0.42	0.05	0.42	0.34	0.51	0.46	0.09	0.46	0.30	0.67	0.14
SamEn_ML	0.11	0.02	0.11	0.07	0.15	0.13	0.04	0.12	0.06	0.23	0.21
SamEn_AP	0.18	0.03	0.17	0.12	0.23	0.17	0.03	0.17	0.10	0.24	0.92
CoDim_ML	2.54	0.06	2.57	2.41	2.63	2.53	0.10	2.53	2.30	2.74	0.87
CoDim_AP	2.51	0.06	2.50	2.38	2.62	2.53	0.09	2.53	2.31	2.68	0.23
LyE_ML	67.45	16.41	61.27	47.96	100.41	63.24	17.38	63.68	35.50	97.25	0.79
LyE_AP	36.89	8.38	35.73	22.75	54.82	41.53	17.70	41.21	11.73	88.73	0.28

ApEn_ML: approximate entropy of mediolateral displacement of the CoP; ApEn_AP: approximate entropy of anteroposterior displacement of the CoP; SamEn_ML: sample entropy of mediolateral displacement of the CoP; SamEn_AP: sample entropy anteroposterior displacement of the CoP; CoDim_ML: correlation dimension of mediolateral displacement of the CoP; CoDim _AP: correlation dimension of anteroposterior displacement of the CoP; LyE_ML: Lyapunov exponent of mediolateral displacement of the CoP; LyE_AP: Lyapunov exponent anteroposterior displacement of the CoP; $\overline{X}$: mean; SD: standard deviation; Min: minimum; Max: maximum; p: p-value of Mann-Whitney *U* test.

mean effect size that indicates a postural control deficit in individuals with CAI. Munn et al. (2010) found that postural sway displacement on flat foot standing was greater in subjects with CAI compared to healthy control subjects. These results are different from the present research, but as they come from meta-analyses, the methodologies and samples of the analysed studies may differ from this study.

In a former study by Tropp et al. (1984) the authors did not find increased postural sway in players with a history of previous ankle joint injury. Also, Bernier et al. (1997) found no significant difference in postural sway between functionally unstable and non-injured subjects. In a more recent study, Toyooka et al. (2018) investigated the CoP displacement during the single-limb stance and its relationship with instability and ankle function in physical activity for athletes. They did not find a correlation between CoP variables and ankle instability. These results are similar to those found in the present study. The unipedal stand is a key position during the mid-stance phase in gait, which demands functional adaptations, even for young and active subjects with ankle instability, what might explain the results of the present study, showing few changes in the postural control in a static position.

To increase the instability condition during one-leg stance, a foam pad was placed over the force plate, although no statistically significant differences for all the traditional variables of CoP displacement were found. Nakagawa and Hoffman (2004) found that the recurrent ankle sprain group had a significantly greater total excursion of the CoP during dynamic tests with a single leg stance on foam over the force plate. Although, a different task was evaluated as they required subjects to step laterally onto a foam pad and maintained a single-leg stance for 4 s. The anticipatory adjustments of CAI subjects might compensate for the demand of the static task, leading to no differences between groups on CoP traditional variables. It could be possible that the used assessment approach does not reveal yet all the information related to the posture control system in CAI subjects. These results suggest there could be still a lack of understanding of all the factors involved in the process of postural control in this clinical condition.

In the CoP displacement variability analysis in the one-leg stance test on a stable surface, no differences were found between groups in most of the nonlinear variables with exception of CoDim_ML. The CAI group showed a significantly lower value of CoDim_ML ($p < 0.05$) which may indicate a system with fewer degrees of freedom and a slower tendency to change (Hunt, 2016), i.e., a balance control system with more difficulties to adapt to the environment and the task requirements. Also, all the nonlinear variables tended to lower values in the CAI group but with no statistical significance. Terada, Johnson, Kosik, and Gribble (2019) studied the time-to-boundary and sample entropy during a single-leg balance task between individuals with CAI, lateral ankle sprain copers and healthy controls. Regarding the sample entropy CoP mediolateral and anteroposterior displacement, they did not find significant differences between groups. Besides the duration of the test (20 s), which was shorter, the anthropometric characteristics of the participants were similar to those of the present study (Terada, Beard, et al., 2019). In another study, Terada, Beard, et al. (2019) investigated postural control performance during a single-leg balance task in elderly individuals with and without a previous history of lateral ankle sprain and also found no differences in traditional variables but found differences in postural sway variability. They found lower sample entropy values on anteroposterior and mediolateral CoP sway in subjects with a previous history of lateral ankle sprain, indicating a more rigid postural control pattern which can mean a protective mechanism to avoid excessive motion but less capacity to adapt to more demanding changes on task (Terada et al., 2018). In any case, the sample of the referred study consisted of elderly subjects who had an ageing-altered motor behaviour that is different from the young subjects who participated in the present study.

On the analysis of the one-leg stance over an unstable surface no differences, nor a tendency of values, were found in the variability of postural sway. With this more challenging task, it was expected that the values of nonlinear variables would show that healthy subjects had greater variability in motor patterns, which would demonstrate a better ability to adapt to the context. However, this challenge also increases motor awareness in both CAI and healthy subjects, which can lead to a more rigid anticipatory behaviour, similar in both groups.

On the other hand, the participation of other factors that contribute to postural control, such as the visual or vestibular systems, is not known. Further studies should be developed to clarify this issue.

The present study has some limitations that may be overcome in future studies. The sample should be larger to have more explicit results with a closer to normal distribution. Static balance tests were performed only with eyes open, so they may be more accurate in terms of balance control if performed with eyes closed. As in other studies, it has also been found that static balance testing alone is not enough demanding, even on unstable surfaces, to show differences between healthy and CAI subjects. Dynamic balance tests like the Star Excursion Balance Test or Y Balance Test, or others, may be performed, preferably on unstable surfaces where demands are higher.

5. Conclusion

Among most of the linear and nonlinear variables of CoP displacement on a stable or an unstable surface, no differences were found between healthy and CAI subjects. However, participants with CAI had lower values in the correlated dimension of CoP displacement during one-leg stance on a stable surface, which could mean less variability in movement that may implicate a balance control system with more difficulties to adapt to the environment and the task demands. More investigation is needed to make clear the knowledge about the motor behaviour of subjects with CAI.

Ethical statement

The study was approved by Ethics Committee of the Escola Superior de Saúde do Alcoitão, where it was performed (PARECER nº 2/2017). All subjects participated voluntarily of their own free will and gave written informed consent to the work.

Declaration of competing interest

None. All the authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article.

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References

Anandacoomarasamy, A., & Barnsley, L. (2005). Long term outcomes of inversion ankle injuries. *British Journal of Sports Medicine, 39*(3), e14.
Arnold, B. L., De La Motte, S., Linens, S., & Ross, S. E. (2009). Ankle instability is associated with balance impairments: A meta-analysis. *Medicine & Science in Sports & Exercise, 41*(5), 1048–1062.
Bernier, J. N., Perrin, D. H., & Rijke, A. (1997). Effect of unilateral functional instability of the ankle on postural sway and inversion and eversion strength. *Journal of Athletic Training, 32*(3), 226–232.
Bulathsinhala, L., Hill, O. T., Scofield, D. E., Haley, T. F., & Kardouni, J. R. (2015). Epidemiology of ankle sprains and the risk of separation from service in US Army soldiers. *Journal of Orthopaedic & Sports Physical Therapy, 45*(6), 477–484.
Duarte, M., & Freitas, S. M. (2010). Revision of posturography based on force plate for balance evaluation. *Revista Brasileira de Fisioterapia, 14*(3), 183–192.
Freeman, M. A. (1965). Instability of the foot after injuries to the lateral ligament of the ankle. *The Journal of Bone and Joint Surgery British, 47*(4), 669–677. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/5846766.
Garrick, J. G. (1977). The frequency of injury, mechanism of injury, and epidemiology of ankle sprains. *The American Journal of Sports Medicine, 5*(6), 241–242.
Gribble, P. A., Bleakley, C. M., Caulfield, B. M., Docherty, C. L., Fourchet, F., Fong, D. T.-P., et al. (2016a). 2016 consensus statement of the International Ankle Consortium: Prevalence, impact and long-term consequences of lateral ankle sprains. *British Journal of Sports Medicine, 50*(24), 1493–1495.
Gribble, P. A., Bleakley, C. M., Caulfield, B. M., Docherty, C. L., Fourchet, F., Fong, D. T. P., et al. (2016b). Evidence review for the 2016 International Ankle Consortium consensus statement on the prevalence, impact and long-term consequences of lateral ankle sprains. *British Journal of Sports Medicine, 50*(24), 1496–1505.
Gribble, P. A., Delahunt, E., Bleakley, C., Caulfield, B., Docherty, C. L., Fourchet, F., et al. (2013). Selection criteria for patients with chronic ankle instability in controlled research: A position statement of the International Ankle Consortium. *Journal of Orthopaedic & Sports Physical Therapy, 43*(8), 585–591.
Hadadi, M., Ebrahimi, I., Mousavi, M. E., Aminian, G., Esteki, A., & Rahgozar, M. (2017). The effect of combined mechanism ankle support on postural control of patients with chronic ankle instability. *Prosthetics and Orthotics International, 41*(1), 58–64.
Harbourne, R. T., & Stergiou, N. (2009). Movement variability and the use of nonlinear tools: Principles to guide physical therapist practice. *Physical Therapy, 89*(3), 267–282.
Hertel, J. (2002). Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. *Journal of Athletic Training, 37*(4), 364–375. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=164367&tool=pmcentrez&rendertype=abstract.
Hiller, C. E., Nightingale, E. J., Lin, C.-W. C., Coughlan, G. F., Caulfield, B., & Delahunt, E. (2011). Characteristics of people with recurrent ankle sprains: A systematic review with meta-analysis. *British Journal of Sports Medicine, 45*, 660–672.
Hootman, J. M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training, 42*(2), 311–319.
Howe, T., Rochester, L., Neil, F., Skelton, D., & Ballinger, C. (2011). Exercise for improving balance in older people (review). *Coharane Database of Systematic Reviews*, (11), 0–308.
Hubbard, T. J., Kaminski, T. W., Vander Griend, R.a., & Kovaleski, J. E. (2004). Quantitative assessment of mechanical laxity in the functionally unstable Ankle. *Medicine & Science in Sports & Exercise, 36*(5), 760–766.
Hunt, N. H. (2016). Autocorrelation function, mutual information, and correlation dimension. In N. Stergiou (Ed.), *Nonlinear analysis for human movement variability* (pp. 301–341). Boca Raton, FL, USA: CRC Press.
Joseph, A. M., Collins, C. L., Henke, N. M., Yard, E. E., Fields, S. K., & Comstock, R. D. (2013). A multisport epidemiologic comparison of anterior cruciate ligament injuries in high school athletics. *Journal of Athletic Training, 48*(6), 810–817.
Konradsen, L., Bech, L., Ehrenbjerg, M., & Nickelsen, T. (2002). Seven years follow-up after ankle inversion trauma. *Scandinavian Journal of Medicine & Science in Sports, 12*, 129–135.
Linens, S. W., Ross, S. E., Arnold, B. L., Gayle, R., & Pidcoe, P. (2014). Postural-stability tests that identify individuals with chronic ankle instability. *Journal of Athletic Training, 49*(1), 15–23.
MacAuley, D. (1999). Ankle injuries: Same joint different sports. *Medicine & Science in Sports & Exercise, 31*, S409–S411, 7 (Suppl).
Mademli, L., Mavridi, D., Bohm, S., Patikas, D. A., Santuz, A., & Arampatzis, A. (2021). Standing on unstable surface challenges postural control of tracking tasks and modulates neuromuscular adjustments specific to task complexity. *Scientific Reports, 11*(1), 1–11.
McKeon, P., & Hertel, J. (2008). Systematic review of postural control and lateral ankle instability, part I: Can deficits be detected with instrumented testing. *Journal of Athletic Training, 43*(3), 293–304. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2386423/.
McKeon, P. O., & Hertel, J. (2008). Spatiotemporal postural control deficits are present in those with chronic ankle instability. *BMC Musculoskeletal Disorders, 9*(76), 1–6.
Munn, J., Sullivan, S. J., & Schneiders, A. G. (2010). Evidence of sensorimotor deficits in functional ankle instability: A systematic review with meta-analysis. *Journal of Science and Medicine in Sport, 13*, 2–12.
Nakagawa, L., & Hoffman, M. (2004). Performance in static, dynamic, and clinical tests of postural control in individuals with recurrent ankle sprains. *Journal of Sport Rehabilitation, 13*(3), 255–268.
Robbins, S., & Waked, E. (1998). Factors associated with ankle injuries. Preventive measures. *Sports Medicine, 25*(1), 63–72.
Schneiders, A. G., Sullivan, S. J., O'Malley, K. J., Clarke, S. V., Knappstein, S. A., & Taylor, L. J. (2010). A valid and reliable clinical determination of footedness. *Philosophy and Medicine R, 2*(9), 835–841.
Simon, J., Donahue, M., & Docherty, C. (2012). Development of the Identification of Functional Ankle Instability (IdFAI). *Foot & Ankle International, 33*, 755–763.
Sozzi, S., Nardone, A., & Schieppati, M. (2021). Specific posture-stabilising effects of vision and touch are revealed by distinct changes of body oscillation frequencies. *Frontiers in Neurology, 12*(November).
Stergiou, N. (2016a). *Nonlinear analysis for human movement variability*. Boca Raton, FL, USA: CRC Press.
Stergiou, N. (2016b). Variability workshop handouts. In *ENAW - European nonlinear analysis workshop*. Lisbon: Human Kinetics Faculty - University of Lisbon.
Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Human Movement Science, 30*(5), 869–888.
Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. (2006). Optimal movement variability: A new theoretical perspective for neurologic physical therapy. *Journal of Neurologic Physical Therapy, 30*(3), 120–129.
Terada, M., Beard, M., Carey, S., Pfile, K., Pietrosimone, B., Rullestad, E., et al. (2019). Nonlinear dynamic measures for evaluating postural control in individuals with and without chronic ankle instability. *Motor Control, 23*(2), 243–261.
Terada, M., Bowker, S., Thomas, A. C., Pietrosimone, B., Hiller, C. E., Rice, M. S., et al. (2015). Alterations in stride-to-stride variability during walking in individuals with chronic ankle instability. *Human Movement Science, 40*, 154–162.
Terada, M., Johnson, N., Kosik, K., & Gribble, P. (2019). Quantifying brain white matter microstructure of people with lateral ankle sprain. *Medicine & Science in Sports & Exercise, 51*(4), 640–646.
Terada, M., Kosik, K., Johnson, N., & Gribble, P. (2018). Altered postural control variability in older-aged individuals with a history of lateral ankle sprain. *Gait & Posture, 60*(April 2017), 88–92.
Thompson, C., Schabrun, S., Romero, R., Bialocerkowski, A., van Dieen, J., & Marshall, P. (2018). Factors contributing to chronic ankle instability: A systematic review and meta-analysis of systematic reviews. *Sports Medicine, 48*(1), 189–205.
Toyooka, T., Urabe, Y., Sugiura, S., Takata, A., Shinozaki, M., Takata, Y., et al. (2018). Does the single-limb stance reflect chronic ankle instability in an athlete? *Gait*

& Posture, 66(August), 242–246.
Tropp, H. (1986). Pronator muscle weakness in functional instability of the ankle joint. *International Journal of Sports Medicine, 7*(5), 291–294.
Tropp, H., Ekstrand, J., & Gillquist, J. (1984). Stabilometry in functional instability of the ankle and its value in predicting injury. *Medicine & Science in Sports & Exercise, 16*(1), 64–66. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/6708781.
Tropp, H., & Odenrick, P. (1988). Postural control in single-limb stance. *Journal of Orthopaedic Research, 6*(6), 833–839.
Tropp, H., Odenrick, P., & Gillquist, J. (1985). Stabilometry recordings in functional and mechanical instability of the ankle joint. *International Journal of Sports Medicine, 6*(3), 180–182.
Viljoen, C. T., Janse van Rensburg, D. C. C., Jansen van Rensburg, A., Booysen, E., Chauke, S., Coetzee, P., et al. (2021). One in four trail running race entrants sustained an injury in the 12 months training preceding the 2019 SkyRun race. *Physical Therapy in Sport, 47*, 120–126.
Wikstrom, E. A., Naik, S., Lodha, N., & Cauraugh, J. H. (2009). Balance capabilities after lateral ankle trauma and intervention: A meta-analysis. *Medicine & Science in Sports & Exercise, 41*(6), 1287–1295.
Wikstrom, E. A., Tillman, M. D., Chmielewski, T. L., & Borsa, P. A. (2006). Measurement and evaluation of dynamic joint stability of the knee and ankle after injury. *Sports Medicine, 36*(5), 393–410. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16646628.
Winter, D. A., Patla, A. E., Ishac, M., & Gage, W. H. (2003). Motor mechanisms of balance during quiet standing. *Journal of Electromyography and Kinesiology, 13*(1), 49–56.
Wolf, A., Swift, J., Swinney, H. L., Vastano, J., Wolf, A., Swift, J., et al. (1985). Determining Lyapunov exponents from a time series. *Physica D: Nonlinear Phenomena, 16*(3), 285–317.
Wurdeman, S. R. (2016). Lyapunov exponent. In N. Stergiou (Ed.), *Nonlinear analysis for human movement variability* (pp. 83–110). Boca Raton, FL, USA: CRC Press.