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Postural control is altered in females with excessive medial knee displacement

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ABSTRACT

Knee valgus motion observed during landing tasks has been proposed as a predictor of future knee injury. It mainly involves excess motion in the frontal plane and is known to be greater in individuals with excessive medial knee displacement (MKD). This affects postural control during sports manoeuvres. Previous sports medicine-related research suggests that the nature of these fluctuations provide rich and more sensitive information to identify risk of (re)injury. We aimed to investigate the fluctuations of the centre of pressure (CoP) in individuals with and without excessive MKD. Twenty females (12 controls; 8 excessive MKD) were instructed to perform single-leg landing tasks from three different directions. The participants landed on a force plate and stayed still for 20 seconds. The fluctuations of the anterior-posterior and medial-lateral directions of the CoP were determined through the calculation of Sample Entropy. Mixed-model ANOVAs (3 [Landing Direction] x 2 [Group]) were used. We have found that only the entropy of the medial-lateral direction was different between groups. Individuals with excessive MKD exhibited an increase in entropy values, indicating greater randomness in CoP fluctuations. This suggests a decreased ability to adapt to environmental demands that likely result in an increased risk of injury.

KEYWORDS

Sports Medicine, valgus, balance, variability, entropy

Introduction

Lower extremity injuries are common in sports activities, especially the anterior cruciate ligament (ACL) tear (Arendt & Dick, 1995; Bollen, 2000). ACL injuries occur even more often in team sports such as handball, basketball, volleyball and soccer (Ferretti et al., 1992; Olsen et al., 2004; Renstrom et al., 2008). These injuries are often related to specific lower limb manoeuvres such as cutting, stopping and landing movements (Alentorn-Geli et al., 2009; Ireland, 2002). Females have also been found to be more prone to ACL injuries as compared to males (Arendt et al., 1999; Arendt & Dick, 1995; Hewett, Myer, et al., 2006; Oliphant & Drawbert, 1996). However, an explanation for this sex discrepancy is not straightforward due to its multifactorial nature.

Although the cause of ACL injury is known to be multifactorial (Arendt & Dick, 1995; Hewett, Myer, et al., 2006; Ireland, 2002), some intrinsic risk factors can be targeted for intervention (e.g., neuromuscular control deficits) (Hewett, Ford, et al., 2006). In other words, it is possible that injury prevention programmes can reduce the risk of injury (Hewett, Ford, et al., 2006; Staynor et al., 2017). Regarding sex, it is believed that lower extremity malalignment is a major intrinsic risk factor in females (Hughes et al., 2008; Zazulak et al., 2007). Although it is not possible to change the structural or morphological characteristics (e.g., pelvis, femur or tibia orientation), a possible female lower extremity malalignment could be related to, or even exacerbated by, motor control deficits (Ireland, 2002). Indeed, in certain situations females have been found to exhibit altered neuromuscular control of the medial-lateral knee motion, resulting in higher knee valgus angle (Hewett et al., 2002); the so-called dynamic knee valgus (Hewett, Ford, et al., 2006; Krosshaug et al., 2007). Importantly, a greater knee valgus angle observed during landing tasks has been proposed as a predictor of future injury, particularly for non-contact ACL injuries (Hewett et al., 2005; Laprade & Wijdicks, 2012). There are, however, other studies that reported no predictive value (Krosshaug et al., 2016). Greater knee valgus is likely the consequence of neuromuscular control and not the problem itself. Indeed, greater knee valgus can have different origins from a motor control standpoint (e.g., foot pronation; hip abductors/external rotators strength; trunk stability, etc.). The dynamic knee valgus, which mainly involves excess motion in the frontal plane, is greater in individuals with excessive medial knee displacement (Hollman et al., 2014; Padua et al., 2012). It also affects the control of the centre of pressure (CoP), particularly in the medial-lateral component, which could possibly alter the global dynamics of postural control and overall balance (Carvalho-e-Silva et al., 2016; Lee et al., 2012; Powers, 2010). Regardless of the inconsistencies in terms of its predictive value, the excessive knee displacement likely reflects poorer motor control.

The importance of postural control assessment in sports has been stressed from an injury prevention and return-to-play decision perspective (Knapp et al., 2011; McKeon & Hertel, 2008; Noronha et al., 2006; Trojian & McKeag, 2006; Wang et al., 2006).

However, a critical question regarding such an assessment deals with the methodological approach at the data processing level in order to unveil underlying deficiencies. Specifically, nonlinear analysis enables richer and hidden characteristics of the time series that traditional linear methods disregard or are unable to detect (Harbourne & Stergiou, 2009; Stergiou & Decker, 2011). For example, it was generally accepted that individuals evidencing less movement of the CoP in a balance task present better postural control and, therefore, expected to be at a lower injury risk level (McGuine et al., 2000; Oshima et al., 2015; Willems, Witvrouw, Delbaere, Mahieu, et al., 2005; Willems, Witvrouw, Delbaere, Philippaerts, et al., 2005). However, Cavanaugh and colleagues that investigated the temporal structure of the CoP oscillations (Cavanaugh, Guskiewicz & Sergiou, 2005) argued that this assumption might be flawed. This has also been supported by several other studies (Cavanaugh et al., 2005; Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh et al., 2006; Dusing et al., 2009; Fewster et al., 2020; Ko et al., 2017; Schmit et al., 2005). Such an approach allows the study of control mechanisms that cannot be detected by simply evaluating the amount of CoP oscillations. By also exploring the temporal structure of the CoP oscillations, in other words, the temporal structure of the variability present in the CoP time series, new information can be found (Harbourne & Stergiou, 2009; Stergiou & Decker, 2011). This approach and the related experimental results that have been gathered has allowed the development of a theoretical perspective regarding health and variability. Specifically, Stergiou and colleagues (Stergiou et al., 2006) have proposed that a healthy system present an optimal state of variability. Thus, values above or beneath would represent unhealthy states: more noisy or more rigid, respectively. In both unhealthy states, a system has lower adaptive capacity and is more vulnerable to injury. For example, Cavanaugh and colleagues (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh et al., 2006) have shown that after a cerebral concussion, the temporal structure of CoP oscillations exhibits a more rigid state during a balance task. This result highlights the potential utility of the temporal structure of CoP oscillations in clinical research. It can also serve as a tool to support the return to play decision. Specifically, Cavanaugh and colleagues showed that measures of the temporal structure of the CoP oscillations are more sensitive than traditional measures (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh et al., 2006) of the amount of CoP oscillations, to assess the athlete’s health with respect to postural control. These studies showed a significant discrepancy (3 to 4 days) regarding optimal recovery of postural control after a cerebral concussion. Based on the above presented theoretical framework and several related studies on ACL injury and reconstruction (Decker et al., 2011; Moraiti et al., 2009, 2010), Decker and colleagues (Decker et al., 2011) proposed that an injury state (e.g., ACL-deficient knee) may result in a ‘careful’ feeling state from the individuals that will try to avoid extra motion, i.e., the individual will exhibit a rigid behaviour. An ACL-reconstructed knee, on the other hand, may result in a 'secured' feeling state, which could incorrectly allow excess motion and a more random behaviour. This could also be due to the fact that an ACL-reconstructed knee is associated with loss of knee proprioception usually provided by the original ACL (Solomonow & Krogsgaard, 2001).

The Decker et al. (2011) proposition also suggests that the presence of an increased injury risk factor (e.g., excessive medial knee displacement) should alter the temporal structure of the CoP oscillations resulting in a more random state. This is because an individual might not be aware of the presence of such risk factor which could also result in incorrectly allowing excess motion. In the present study, we sought to investigate this proposition. Therefore, we explored the temporal structure of CoP oscillations in females with and without excessive medial knee displacement. We hypothesised that females with excessive medial knee displacement would exhibit an altered temporal structure that will be noisier and this behaviour will be characterised with more randomness in the temporal structure. To explore this hypothesis and to further understand the mechanisms underlining potential lower extremity injuries, we devised an experiment where the participants performed single-leg landings and asked to remain in a single-leg stance position while CoP oscillations during this stance position were assessed.

Methods

Participants and screening

Twenty recreationally active females participated in this study. Recreationally active was defined here as exercising a minimum 90-min of vigorous or 150-min of moderate exercise per week. The group assignment was determined through the overhead squat test (Post et al., 2017). Participants were instructed to place their feet interspaced by the shoulder. Those who showed an inward movement of the patella over the first metatarsophalangeal joint were assigned to excessive medial knee displacement group (MKD) (Bell et al., 2008; Stiffler et al., 2015), while others were assigned as controls (CON). This was assessed through video analysis in the frontal plane by marking a vertical line from the patella to the floor. This screening, conducted by a certified physical therapist, resulted in 12 participants in the CON group (age 21.22 ± 2.17 yrs; height 1.61 ± 0.06 m; body mass 56.15 ± 6.95 kg; BMI 21.61 ± 2.00) and 8 in the MKD (age 20.09 ± 1.32 yrs; height 1.61 ± 0.08 m; body mass 59.11 ± 8.84 kg; BMI 22.62 ± 1.85). All participants were healthy, free of lower limb injury within the past 6 months and with no history of an ACL injury, chronic lower limb pathologies, and balance disorders. The Ethics Committee of the Faculty of Human Kinetics—University of Lisbon approved the experiment and all procedures adhered to the Declaration of Helsinki.

Experimental protocol

All testing was conducted in one session. First, the dominant limb was determined as the limb kept on the floor during a ball kicking action. For the jump-landing task, participants were instructed to jump from a single-leg stance position and land in their contralateral lower limb after jumping from an approximately 70 cm distance from the centre of the force plate (Azevedo et al., 2019; Webster & Gribble, 2010; Wikstrom et al., 2008). They jumped from three different directions: frontal, lateral and diagonal. The three directions were used to mimic biomechanical demands in various directions that would challenge medial-lateral and anterior-posterior differently. Previous investigations in knee and ankle instability have shown that assessing single-leg landing in one direction only, is not sufficient to identify individuals at risk of injury (Patterson & Delahunt, 2013; Wikstrom et al., 2006). For the diagonal jump, an angle of roughly 45º was used. A successful trial consisted in a single-leg landing followed by a 20 seconds balance period while holding the hands on the hips and looking straight ahead. If a participant lost her balance or touched the floor with the contralateral limb, the trial was discarded. If an additional short hop occurred upon landing or if excessive swaying of the contralateral limb, arms, and/or trunk occurred, the trial was also discarded. Three successful trials were collected from each direction in a randomised order.

Data analysis

Ground reaction forces were measured using a tri-axial force platform (Bertec Corporation, Columbus, Ohio) at 1000 Hz to allow a more reliable timing of the landing. CoP data were identified from the ground reaction forces. Then, the vertical time to stabilisation (TTS) was determined as a measure of postural stability and to set the starting point for the CoP oscillations analysis. Similarly, to other studies, TTS was defined as the time that the vertical component of ground reaction force remained within ±5% of the participant's body weight (DuPrey et al., 2016; Liu et al., 2016). For the TTS calculation, the signal was low pass filtered (12 Hz Butterworth, 4^{th} order). The CoP signals were cropped for further analysis from the TTS event to 20 sec after the TTS event. Then, we downsampled the CoP data to 50 Hz after visual inspecting the signals. We found that 50 Hz to be the appropriate sampling frequency to contain all the relevant information, accounting for the Nyquist theorem. This was conducted by analysing the power spectrum density.

We used Sample Entropy (SampEn) (Richman & Moorman, 2000) to determine the temporal structure of the CoP oscillations, for both the anterior-posterior (AP) and the medial-lateral (ML) component. SampEn determines the probability that short sequences of data points are repeated throughout a temporal sequence of points. For a given time series of length N, $X_N = [x_1, x_2, \ldots, x_N]$, subseries (i.e. vectors) of length m are constructed and defined as $X_{m,i} = (x_i, x_{i+1}, \ldots, x_{i+m-1})$. Then, the probability that any of the vectors will be similar to X_m, is calculated:

$$C_i(m,r) = \frac{n_i(m,r)}{N-m+1} \tag{1}$$

where n_i (m,r) represents the number of vectors $X_{m,j}$ that are similar to $X_{m,i}$ with a constraint

$$d(X_{m,i}, X_{m,j}) \leq r \tag{2}$$

in which $d(X_{m,i},X_{m,j})$ is the maximal difference between vectors $X_{m,i}$ and $X_{m,j}$ in their respective scalar components. Subsequently, the average probability is computed:

$$\Phi(m,r) = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} C_i(m,r) \tag{3}$$

The same process is repeated for the subseries of length $m + 1$ to calculate $\Phi(m + 1,r)$. Lastly, the sample entropy is calculated:

$$SampEn(X_N, m, r) = -ln \frac{\Phi(\mathrm{m+1,r})}{\Phi(\mathrm{m,r})} \tag{4}$$

where *ln* is the natural logarithm. The value of the sample entropy is always greater than or equal to zero. A time series with similar distances between data points would result in a lower SampEn value, while large differences would result in higher SampEn values. A perfectly repeatable time series thus has a SampEn value equal to zero and a perfectly random time series has a SampEn value converging towards infinity. In the current study, a pattern length (m) of 2, error tolerance (r) of 0.3 and data length (N) of 1000 data points (i.e. 50 Hz x 20 sec) were selected and used in the determination of SampEn values (Yentes et al., 2013). The reliability of entropy measures was shown to be optimal when these input values are identical for all participants (Pincus, 1991; Cavanaugh et al., 2006). All the calculations were performed on each trial and averaged across trials for further analysis.

For comparison purposes, we also calculated typical linear measures of the amount of variation within the CoP oscillations: root-mean-square (RMS), range (maximum minus minimum) and sway path. RMS and range were determined, individually, for both the anterior-posterior (AP) and the medial-lateral (ML) component. These parameters were also obtained from the time series used for the calculation of SampEn.

Statistical analysis

Mixed-model ANOVAs (3 [Landing Direction] x 2 [Group]) were performed to determine statistical significance for TTS and for the CoP dependent variables: SampEn, and Sway Path, RMS, Range, for both the AP and ML directions. When significant main effects were determined, post hoc comparisons were performed using Tukey's method. Mauchly's test was implemented to test sphericity and Greenhouse-Geisser correction was used when not verified. The Shapiro–Wilk Normality Test was used to test the normality of each dependent variable, with the alpha significance level set at 0.05.

Results

Nonlinear measures of postural control

For SampEn, no main effect was found for direction in the anterior-posterior ($F_{(2,36)} = 2.460$; $p = 0.100$; ηp2 = 0.120) nor in the medial-lateral ($F_{(2,36)} = 0.739$; $p = 0.485$; ηp2 = 0.039) CoP components. No main effect for group was observed in the anterior-posterior component ($F_{(1,18)} = 2.171$; $p = 0.158$; ηp2 = 0.158). However, in the medial-lateral component, a main effect was observed for group ($F_{(1,18)} = 17.818$, $p < 0.001$, ηp2 = 0.497; 0.21 ± 0.01 and 0.27 ± 0.01, for CON and MKD, respectively). Additional independent samples t-test were used to reveal that SampEn was greater in MKD group in all three directions (frontal: $p = 0.002$; lateral: $p = 0.005$; diagonal: $p = 0.004$)—Figure 1.

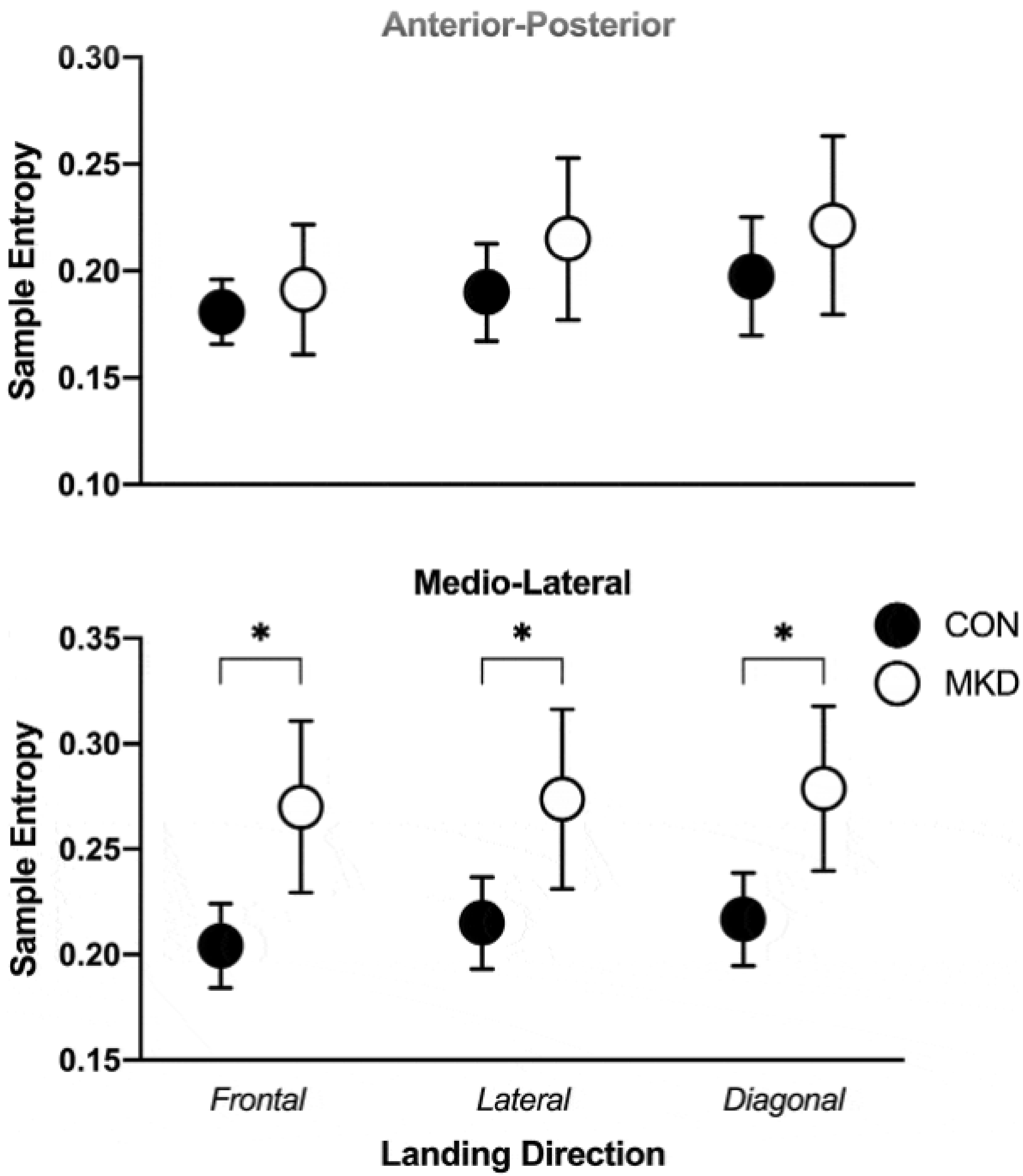

Figure 1. Sample entropy for anterior-posterior (upper panel) and medio-lateral (lower panel) centre of pressure components in healthy controls (CON) and females with excessive medial knee displacement (MKD). Data is presented as mean and confidence intervals. * indicate differences between groups ($p < 0.01$).

Linear measures of postural control

For the TTS, no main effect was found for direction ($F_{(2,36)} = 0.561$; $p = 0.575$, $\eta p2 = 0.030$), and no differences between groups were observed ($F_{(1,18)} = 0.340$; $p = 0.567$; ηp2 = 0.019). No interaction was observed ($F_{(2,36)} = 0.445$; $p = 0.645$; ηp2 = 0.024).

For the Sway Path, a main effect was found for direction ($F_{(2,36)} = 5.180$; $p = 0.011$; ηp2 = 0.223) but not for group ($F_{(1,18)} = 0.456$; $p = 0.504$; ηp2 = 0.025). Pairwise comparisons showed that frontal direction produced significantly higher Sway Path values than the lateral ($p = 0.010$). No interaction was observed ($F_{(2,36)} = 0.578$; $p = 0.566$; ηp2 = 0.031).

For the Anterior-Posterior CoP component, an effect of direction was found for RMS ($F_{(2,36)} = 16.587$; $p < 0.001$; ηp2 = 0.480) and Range ($F_{(1.217,21.899)} = 4.564$; $p = 0.038$; ηp2 = 0.202), Pairwise comparisons showed that RMS was significantly lower in the lateral direction compared to the frontal ($p < 0.001$) and the diagonal ($p = 0.016$). Conversely, Range was significantly higher in the lateral compared to frontal ($p = 0.049$). There were no differences between groups for RMS ($F_{(1,18)} = 1.066$; $p = 0.316$, ηp2 = 0.056) nor Range ($F_{(1,18)} = 0.624$; $p = 0.316$, ηp2 = 0.014) (Table 1). No interaction was observed for either RMS ($F_{(2,36)} = 0.386$; $p = 0.683$; ηp2 = 0.021) nor Range ($F_{(1.217,21.899)} = 3.294$; $p = 0.076$; ηp2 = 0.155).

Table 1. Centre of pressure studied parameters for each group and landing direction. CON—control group; MKD—excessive medial knee displacement group. * indicate significant differences. TTS—Time to Stabilisation; RMS—Root Mean Square. (Table view)

	Frontal		Lateral		Diagonal		
	CON	MKD	CON	MKD	CON	MKD	Landi Directi
TTS (s)	1.12 ± 0.42	1.18 ± 0.35	1.34 ± 0.45	1.27 ± 0.44	1.41 ± 0.77	1.17 ± 0.35	0.57
Sway Path (cm)	233.87 ± 71.96	207.85 ± 73.31	176.52 ± 49.27	151.89 ± 46.31	170.45 ± 82.23	179.88 ± 49.55	0.011
Anterior-Posterior							
RMS (cm)	8.66 ± 3.06	7.47 ± 3.09	3.95 ± 1.93	2.73 ± 1.12	6.01 ± 3.52	6.05 ± 2.05	< 0.0 *
Range (cm)	4.50 ± 0.84	4.69 ± 0.83	6.80 ± 2.49	5.16 ± 1.53	4.25 ± 0.68	5.14 ± 1.86	0.038
Medial-Lateral							
RMS (cm)	3.34 ± 1.03	3.27 ± 2.11	5.32 ± 2.66	5.31 ± 1.75	2.93 ± 1.06	3.32 ± 2.12	0.001
Range (cm)	6.65 ± 2.04	6.11 ± 3.86	4.11 ± 1.98	5.69 ± 3.76	3.89 ± 1.54	4.57 ± 2.35	0.05

Discussion and implications

The aim of the present study was to investigate the temporal structure of CoP oscillations in females with and without excessive medial knee displacement. In accordance to our hypothesis, we observed that females with excessive medial knee displacement exhibited a more random temporal structure in their CoP oscillations, particularly in the medial-lateral direction. Additionally, we analysed commonly used linear parameters of CoP and we verified that those were not significantly different between groups, suggesting that measures of the temporal structure are likely to contain more relevant and unique information to the study of risk of injury.

Importantly, our results showed that SampEn in the medial-lateral direction of CoP was the only studied variable that exhibited differences between groups. Although the sample size is relatively small, our results are supported by the large effect size observed (Cohen, 2013). We observed greater randomness in the temporal structure of CoP oscillation in the medial lateral direction for the females with excessive medial knee displacement. On the other hand, no differences were observed in the anterior-posterior direction. This was somewhat expected due to the balance demanding in single-leg stance. In a single-leg stance position, the base of support in the medial-lateral direction is reduced which requires an increased control of the centre of mass oscillations in this direction. Our results suggest that SampEn is a particularly sensitive measure to identify individuals at risk of injury during multidirectional jump-landing tasks. Prior research in postural control revealed measures of temporal structure, such as entropy analysis, to contain rich and unique information (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh et al., 2006).

Regarding the effect of jump-landing direction, we observed that the anterior-posterior direction of the CoP, RMS and Range were lower in the lateral jump direction compared to both frontal and diagonal. In the medial-lateral CoP direction, the RMS showed to be higher in the lateral compared to frontal and diagonal landing directions. From a biomechanical standpoint, these results were anticipated. During the lateral landing, the greater peak knee valgus angle created at the frontal plane, challenges more the medial-lateral balance (Sinsurin et al., 2013) and, therefore, resulting in an increase of CoP displacement compared to forward landing. Conversely, anterior-posterior control is more challenged during a forward landing, resulting in an increased CoP displacement, compared to the lateral landing. In the present study, the diagonal direction of landing seems to present a similar demand in the postural control system. In order to better assess the landing behaviour, the use of different directions has been proposed since ACL injury mechanisms are more likely to include a medial-lateral direction of landing, which the forward landing seems not to challenge (Patterson & Delahunt, 2013; Wikstrom et al., 2008). This is in agreement with recent research which suggests that ACL injury is more likely the result from multiplanar neuromuscular control deficits (Koga et al., 2010). The present study, however, does not fully support the need of assessing landings from different directions. Our results indicate that to distinguish individuals with excessive medial knee displacement, the direction of the landing is not relevant. One should note, however, that this is the case for the assessment of postural control. Most of the previously mentioned studies aimed to study the effects of the landing direction at the biomechanical level. Future research should investigate how the biomechanics of landing may affect postural control. Although this can be seen as a limitation of the present study, we consider that kinematics of landing may provide more information regarding the effects found in the linear parameters, but not in sample entropy results. This suggests that the findings in sample entropy are likely to be independent of kinematics and are most likely related to motor control mechanisms. Here, we propose that we should be looking to the hidden characteristics of control of movement, i.e. postural control. Our results suggest that in such case there might be no added value to analyse the different landing directions. In fact, the present study suggests that female individuals with excessive medial knee displacement present sensorimotor deficits evidenced through the CoP fluctuations. Other than the cerebral concussion-related research mentioned earlier, a recent study showed that sample entropy of postural control in individuals with history of ankle injury was also altered (Terada et al., 2019). More importantly, the authors showed lower brain's white matter microstructure in those individuals. They further suggested that brain's white matter microstructure may be a potential biomarker of postural control performance. Although a cause–effect relationship cannot be made at the moment, entropy measures of postural control appear to reflect the central nervous system functioning.

Overall, our results can be interpreted through the *optimal state of movement variability model* (Stergiou et al., 2006). According to this theory, there is an optimal level of variability that characterises a healthy system. Whichever the deviation, either more rigid (more stable) or more random (more unstable), it represents a loss of adaptability to perturbations and environmental demands. The present study results showed an increased SampEn values in the MKD group, which could indicate lack of control of the CoP and decreased adaptability during single-leg jumping-landing tasks. From a motor control standpoint, the increased SampEn indicates that the fluctuations in the CoP were more irregular, possibly suggesting reduced proprioception within the system and hence, greater likelihood to injury. Importantly, these findings recommend future experimental work with MKD individuals to validate these propositions. For example, perturbing the balance by creating oscillations in the different directions while standing in one-leg would possibly show the control of the CoP in these and healthy individuals, potentially indicating signs of adaptability to environmental constraints.

As already mentioned early on, the contributions of nonlinear dynamics to sports medicine has emerged with ACL-related studies. Decker and colleagues (Decker et al., 2011) have proposed that injury creates a 'careful' state that will result in a more regular pattern. On the other hand, the unawareness of increase risk of injury can place the individuals at a 'secure' state, that results in more irregular patterns, as is likely the case of our findings. In the present study, we found that excessive medial knee displacement alters the control of movement towards a more unstable state that potentially increases the risk of injury. This irregularity in the CoP patterns can also result in an undesirable loading of some anatomical structures in the knee, particularly in the medial compartment (e.g., collateral medial ligament). For example, excessive medial knee displacement is a well-established injury risk factor for knee osteoarthritis (Sharma et al., 2001), patellofemoral pain syndrome (Nakagawa et al., 2012) and ACL tear (Hewett et al., 2005).

The calculation of SampEn values in CoP time series for the single-leg jump-landing tasks appears to have a great potential as a robust measure of injury risk. The use of a force plate in a clinical setting is common and all modern gait analysis laboratories in orthopaedic hospitals have such instrumentation. As a measure, it can also help to make decisions regarding return to practice after rehabilitation process or injury risk screening. However, more research work is needed to explore how Sample Entropy changes through rehabilitation and to identify the healthy cut-off levels of this parameter; and how reliable Sample Entropy is across days. The understanding of how controlled of movement is altered in injured or exposure to risk individuals in different clinical tests (e.g., double-leg overhead squat, single-leg squat, drop-jump, etc.) may also provide important clinical information to the clinical test selection.

Conclusion

The present study showed that the centre of pressure oscillations patterns are more irregular in females with excessive medial knee displacement during single-leg landing, indicating a possible loss of adaptability of the system to adapt to external constraints with those who have excessive knee displacement. This likely contributes to increased likelihood of injury in such individuals. More interestingly, we observed that common traditional measures used frequently in the study of postural control (e.g., time to stabilisation, sway path) were unable to distinguish between individuals with and without excessive medial knee displacement. This suggests that alternative methods that explore not only the amount of movement variability but also the temporal structure and organisation of movement are highly relevant in sports medicine. Future research should further explore the potential of measures of temporal organisation and their meaning, particularly related to postural control. Retrospective studies are also needed to further investigate if there is a correlation between the likelihood of injury and the temporal organisation of postural control.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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