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Changes in postural stability induced by a ball-and-board game designed from a systems perspective

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Abstract

Background Postural behavior can be understood from a systems perspective, emerging from complex interactions within the agent's body system and the agent-environment system, where inherent variability enables adaptive and functional solutions to balance perturbations. Recent studies have recommended that lower limbs rehabilitation programs should be addressed from a systems perspective for both clinical assessment and intervention. In this context, we designed a ball-and-board game that fosters interactions between the lower limbs and between the agents through informational and mechanical couplings. The present paper aims to investigate whether such a game – designed from a systems perspective – has an impact on an agent's postural stability – using variability measures – also derived from a systems perspective.

Methods Twenty-four novice participants were randomly assigned to twelve dyads to perform our game, which consists in a joint-action task where two participants stand on an unstable surface (BOSU) while jointly manipulating a board on which a ball rolls along a circular target. Body and ball's three-dimensional movements were obtained using an 8-camera motion capture system. Postural stability was assessed using both linear and nonlinear measures, which respectively capture the amount and structure of variability in the center of mass' kinematics. Additional between-subject analyses were conducted to study relationships between postural stability and task performance.

Results Despite the heterogeneous postural pathway of the participants, significant postural changes occurred with practice (i.e., decreased standard deviation and increased sample entropy of postural oscillation variability) in the anteroposterior plane, which is also the plane of motion where the knee joint is predominantly engaged through flexion-extension movements. Participants with higher performance were characterized by a greater complexity in their postural oscillations (i.e., greater sample entropy), allowing an increased ability to resist to perturbations that threaten postural stability.

Conclusions The amount of variability in postural oscillations evolved heterogeneously across participants, which suggests a broad exploration of different postural solutions and therefore an enhanced adaptability to balance perturbations. This adaptability was particularly evident in participants with higher performance, whose postural

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oscillations exhibited a less periodic, and thus more complex, variability structure. In conclusion, our game led to a postural reorganization that encourages us to test it in clinical settings.

Key points

• From the existing literature on lower limb injuries, we identified the need to incorporate a systems perspective into the design of an original game that challenges postural stability.
• The amount of variability in postural oscillations evolved heterogeneously across participants with practice, which may indicate an exploratory behaviour towards the development of a new motor skill.
• Better performance was characterized by postural oscillations with a less periodic – more complex – variability structure, enhancing adaptability to balance perturbations.

Keywords Postural control, Balance training, Body sway, Coordination, Joint action, Motor exploration, Degrees of freedom, Variability, Nonlinear analysis, Sample entropy

Background

Recovering functional levels of postural stability could be a major concern for patients that suffered from lower limb injuries, such as an anterior cruciate ligament (ACL) injury. The ACL is a key structure in the knee joint as it contributes about 85% to restricting anterior translation of the tibia over the femur and as it also limits the medial and lateral rotation of the tibia [1–3]. The ACL is damaged in nearly 50% of knee injuries, with over two million of ACL injuries occurring worldwide annually [4, 5]. Such a report is concerning since ACL injuries lead to postural stability deficits due to alterations in perception-action couplings [6–8].

The role of ACL in knee stability was first studied in the period of 460 – 370 BC and its deficiency has been a major focus of research over the last five decades, especially with the development of surgery, technology, and biology [9–11]. Yet, the current rehabilitation techniques are still controversial or present a very little scientific evidence for their validity [12–15]. Moreover, re-injury often occurs, in half the cases in the contralateral limb because of non-contact mechanisms [16]. This observation may likely be the consequence of reducing the complex phenomenon of ACL injury into a sum of damaged structural elements and isolated risk factors [17–19].

Lately, few authors proposed a paradigm shift in sport injury research by substituting the philosophy mostly used in ACL prevention and rehabilitation for a systems perspective. Bittencourt and colleagues (2016) provided a model of sport injury, using ACL injury as an example of an emerging pattern arising from complex interactions among multiple context-specific factors [17]. Tools dealing with nonlinearity inherent to complex systems have lately been suggested to help assess return-to-sport [20]. Recent studies also encouraged clinicians to consider ACL injury as a whole-body problem when designing rehabilitation programmes [18, 21–23].

In this context, we identified a need of designing and assessing an original ball-and-board game based on a systems perspective, where the elements of the postural system jointly relearn how to move. Our game consists in a joint-action task where two participants stand on an unstable surface while jointly manipulating a board on which a ball rolls along a circular target. This game was born out of a systems perspective through the informational and mechanical couplings it involves between lower limbs and between agents. Based on Bernstein's hypothesis (1967) [24], such couplings should foster a reorganization of the degrees of freedom (DoF) involved and eventually a formation of synergies. As synergies must be viewed as low-dimensional units, it can be hypothesized that the system's elements should compensate each other's variability during joint action. In other words, limbs' reciprocal adjustments should stabilize postural stability, and participants' actions should be compensated and lead to postural reorganization. Therefore, we hypothesized that the incorporation of a systems perspective into our game would lead to improvements in participants' postural stability.

Postural stability is ensured if the centre of mass (CoM)'s projection is maintained within the base of support. In the literature, postural stability has been widely assessed using linear tools measuring the CoM – or centre of pressure (CoP), excursions relatively to a mean point or a total range of movement (e.g., standard deviations, mean velocity, sway path length and area) [25–27]. However, it has been shown that linear tools could not fully capture the postural changes that occur when performing on a new balance task or when dealing with new body constraints (e.g., due to development, injury, disease, or aging) [28].

To fill this gap, nonlinear tools have been shown to be more appropriate to study human behaviour which emerges from nonlinear dynamical systems. Whereas linear analyses can be useful in quantifying the magnitude/amount of sway variability, nonlinear tools reveal a complexity index of postural control based on the structure/organization of sway variability. Embracing the field of nonlinear dynamics, the concept of "complexity" can notably refer to the presence of chaotic temporal variations that are inherent to healthy biological systems, functional in the sense that they are able to adapt to changing constraints [29]. More specifically, the CoM fluctuations convey rich information for postural stability and nonlinear measures (e.g., entropy measures, the largest Lyapunov exponent, fractals, dimensional analysis and detrended fluctuation analysis) can unmask the *"subtle, hidden temporal structure"* of biological signals' variability [30]. Thirty years ago, Newell and colleagues (1993) [31] already showed through an experiment conducted on patients with postural disorders and healthy controls that postural stability assessment can be greatly enriched if considering the variability structure in the pattern of postural oscillations.

Practically, the selection of assessment measures can lead to different clinical interventions, that might be inadequate if neglecting some important aspects of sway variability. For example, Cavanaugh and colleagues (2005, 2005b, 2007) demonstrated that the structure of postural oscillations was not fully restored in athletes after concussion, as healthy controls exhibited less periodicity in their postural oscillation patterns [32–34]. Yet, similar sway amplitudes and acceptable equilibrium scores encouraged return-to-sport, disregarding the abnormal rigid behaviour in athletes. Thus, the authors recommended that the use of linear measures of postural stability should be combined with entropy analyses to better identify structural changes after injury, to better design a rehabilitation plan targeting functional recovery, and therefore avoid reinjury due to a premature resumption of sport and physical activities.

Assessing postural stability should consider both variability and determinism components, as preconised earlier by Riley and Turvey (2002) [35]. The authors added that improving postural stability does not equate to reducing sway amplitude and removing postural noise, as more variable and more random are not necessarily synonymous with less controllable. Instead, an optimal level of variability and complexity ensures healthy, functional, and adaptable postural mechanisms, allowing the body to resist to perturbations that might drive the CoM out of the base of support [28]. Nevertheless, analysing the evolution of variability magnitude in the CoM fluctuations with linear measurements can still be useful in revealing how a performer initiates themselves to a new postural task, as it can reflect how the DoF in the postural system (i.e., multitude of joints and muscles) can be freezed and/or freed during task exploration [36]. To sum up, the linear measures of CoM variability can provide insight into the evolution of a performer along the practice of a new (supra-)postural task in terms of DoF organization; however, it is highly recommended to combine them with nonlinear measures that can capture the structure of CoM variability, allowing for a more accurate assessment of postural stability.

Following the recommendations outlined above, the present study aims to investigate whether our game designed from a systems perspective has an impact on a performer's postural stability. As a first experimental step, the study focused on evaluating its effects within a healthy population. Importantly, both analysis and task design were guided by a systems perspective, with the concept of "complexity" at its core. First, the use of nonlinear measures acknowledges the importance of considering the variability structure of the CoM when assessing postural stability, as complex fluctuations are a key feature of healthy, functional biological systems. The complementary use of linear measures was interpreted in terms of DoF organization – that is, how the amount of CoM variability evolved while the postural system explored how to cope with its physiological complexity. Second, the design of our joint-action task (i.e., jointly controlling a ball trajectory while maintaining balance on an unstable surface) incorporated a systems perspective by introducing informational and mechanical couplings between limbs and between agents, thereby fostering complexity through enriched interactions among system elements.

Given that all participants were novice at performing this joint-action and balance-challenging game, both task performance and postural stability were expected to improve over practice. More specifically, it was hypothesized that the participants would first "map" a vast spectrum of postural solutions as they aim to maintain balance while performing the task, and that they would later adopt a more selective behaviour as they adapt to task constraints. This postural progression would be described by an initial high amount of variability in CoM oscillations that should decrease over practice. We also hypothesized that participants with higher performance could exhibit an increased amount of CoM variability at the end of practice, revealing a better ability of mastering DoF to adapt to perturbations. More adaptable and functional postural behaviour should also be reflected through greater complexity in the structure of CoM variability. If we assume that the abilities of controlling the ball trajectory and controlling balance are intrinsically linked in our game, we can finally suppose that participants with higher performance would display less periodicity (i.e., more complexity) in their CoM signals, compared to participants with lower performance. These hypotheses formulated at the task (performance) level and at the effector (behavioural) level were tested and discussed below in the present paper.

Methods

Participants

Twenty-four university level students (ten men and fourteen women; mean age: 21.83 +/- 2.12) participated in this study. The participants were randomly assigned into twelve dyads. The sample size was estimated using F-tests (ANOVA, Repeated Measures, Within Factors) for a group and 2 measurements, with a large effect size of 0.40, an alpha error probability of 0.05, a beta error probability of 0.20 (i.e., a power of 0.80), and a correlation among measures of 0.50. This procedure was performed using the G*Power software (Universität Düsseldorf, Germany). All participants declared not having any lower limb injury/surgery history or any disorder affecting postural stability. They all provided free and informed consent before starting the experiment. The study was approved by the Ethics Committee CEIFMH (Conselho de Ética para a Investigação da Faculdade de Motricidade Humana; N° 28/2022).

Game device

The device used in our ball-and-board game (mass: 2.5 kg; dimensions: $114 \times 114 \times 8$ cm) was composed by a hexagonal board (long diagonal: 96 cm) made of polyurethane. The board was connected to a ring handle (i.e., 25-mm polyethylene pipe) that the participants could easily hold. The board-handle connectors were six rigid PVC pipes. Six polystyrene rods were tapped to the edges of the board as a ball-stop system. The main criteria used for material selection were lightness and rigidity of a relatively large device, as well as affordability to ensure practical applicability in clinical settings.

A 10-cm-wide target path defined by two circles (inner circle radius: 20 cm; outer circle radius: 30 cm) was drawn on the board. The midline of the target path was drawn as a landmark, in the same manner as for road markings. Four equidistant doors marked with paper pins were added along the target, two of them being the nearest and the furthest target points from the participants. The ball that rolls on the board was a reflective marker (diameter: 12.7 mm). Another reflective marker was attached to the board centre.

The unstable surface on which participants stood was a BOSU ball, which is an inflated rubber hemisphere attached to a rigid board. To challenge even more postural stability, the half-ball side was in contact with the ground and the participants' feet were on the rigid side of the BOSU.

Game rules

Both participants of each dyad were instructed to stand barefoot on the BOSU, facing each other while jointly manipulating a board over which was placed a ball. In each trial, dyads were asked to use a supination grip to hold the board and to manipulate it in such a manner that the ball completes as many circles as possible within the target path in 60 s (Fig. 1).

Each performance was quantified in real-time by the dyads, where one participant counted the number of crossed doors (1 point was gained every time the ball rolled across one door) and the other one counted the number of penalties (1 point was deducted every time the ball touched the board's edge). All along the experiment, the current best score (i.e., number of crossings – number of penalties) was reminded to the dyads to keep them engaged into the game. Counting points was only prescribed for motivational purposes (i.e., actual points were rather obtained by the experimenter using objective measures, as described further below).

Experimental design

Participants attended one experimental session of 30 trials. Trials where the ball or one participant fell were performed again. The session was divided into two 15-trial sets (i.e., Set 1 and Set 2) to better investigate the practice effects of our game on postural variables. To avoid any fatigue effects, a 5-minute break was imposed between the two sets, as recommended by the participants recruited in pilot tests. Before the session starts, the participants played freely for a few minutes (i.e., less than 3 min) to ensure that the task goal was clearly understood and that data collection was ready to be launched. No verbal communication about game strategies were allowed during the experiment.

Data acquisition

Data were recorded with the 8-camera motion capture system OptiTrack (NaturalPoint, Corvallis, Oregon) operating at 60 Hz. Reflective markers were used to obtain the movements of the ball, the board centre and extremities (i.e., using the distal wrist crease, as the participants' hands were fixed on the board handle). Sacrum position (second sacral vertebra) was tracked in one participant to investigate postural changes. By focusing on one participant, we ensured that the study setup remained adequate to address our research question while also preparing the groundwork for further research involving pathological participants.

Data processing and analysis

Three-dimensional movement data were tracked and labelled using the software Motive: Body 2.1.1., exported at 28 Hz in Excel and later processed in MATLAB (version R2022b, MathWorks Inc., USA). This sampling frequency was selected based on recommendations from studies using kinematic measures in a supra-postural task or a joint-action task performed on an unstable surface [37, 38]. The ball itself was a marker of which the

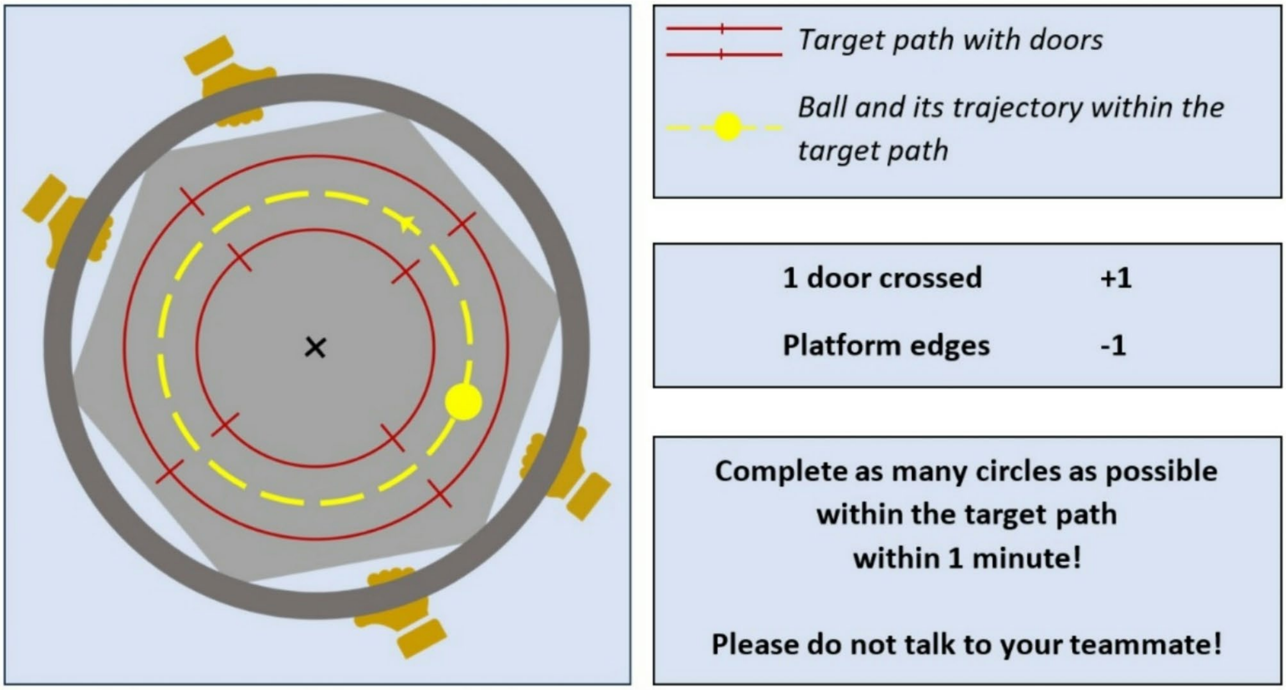

Fig. 1 Instructions given to the participants before the ball-and-board game starts. For each dyad, one participant counted the number of times the ball rolled through a door (i.e., number of crossings), while the other participant counted the number of times the ball bumped into the board edges (i.e., number of penalties)

trajectory was analysed. As the participants' hand position relatively to the ring handle remains the same during the game, the wrist markers were used with the marker defining the board centre to obtain the board 3D rotations and, therefore, the ball 2D trajectory relatively to the board and its doors. Due to important and inconsistent missing data (mainly markers hidden by the board held by the participants), the usage of the CoM based on a thirteen-marker model [39] was compromised and therefore the approximate centre of mass (ApCoM) provided by the sacral back marker [40] was used in the present study. Given our focus on changes in the CoM position over practice, the inherent inaccuracy in precisely defining the absolute CoM was not deemed to be an issue for our purposes.

All time series were filtered with a low-pass 4-order Butterworth filter with a cut-off frequency of 6 Hz. In each trial, the first 3.5 s were removed to account for the ball's initial motion lag, allowing for a smooth 60-second trajectory consisting of 1680 data points. At the task level, the number of crossed doors completed by the ball within 60 s were analysed to assess the participants' performance. At the effector level, postural stability was assessed through both linear and nonlinear tools, respectively measuring the amount and the structure of ApCoM variability. Linear tools included standard deviation (STD), mean velocity (VEL), range and sway path of ApCoM. Sample entropy (SampEn) was employed as a nonlinear measure to investigate the degree of complexity in the ApCoM structure. It was found that this metric was particularly effective to assess postural stability in healthy adults during bipedal stance on an unstable surface [41]. Entropy quantifies the regularity of a time series [42] as it determines the probability that the m-length pattern repeats itself within the subsequent $m+1$ datapoints, considering a r tolerance. This algorithm is conducted as a moving window technique across an entire time series of length N, where $N > 200$ and as large as possible, accounting for factors like fatigue and specificities of the population investigated [43]. In our study, these parameters were determined as $m = 2$ and $r = .2$*standard deviation, as these values were found to be predominant in comparable studies, according to a recent systematic review on the use of nonlinear tools to assess upright postural stability [44]. The function used to compute SampEn values in Matlab was obtained from the Physionet research resource providing tools for analysing complex biological signals [45, 46], using the following Eq. (1):

$$\mathbf{SampEn}\left(m,\ r,\ N\right) = -\ \mathbf{ln}\left(\frac{\mathbf{A}^{m}\left(r\right)}{\mathbf{B}^{m+1}\left(r\right)}\right) \quad (1)$$

where B represents the total number of identical patterns for m points, and A represents the subset of B that also shows identical patterns for $m+1$ points. Lower SampEn values indicate that a signal is more regular and predictable, which also reveals less complexity in the signal structure (41). All ApCoM measures were selected in line with previous studies that combine both linear and nonlinear analyses to assess postural stability in similar contexts (i.e., postural changes in a supra-postural task [47]; learning upright stance on the reversed rigid side of the BOSU [48]; postural stability in individuals inclined to ACL injury [49]). Entropy computations were the only analyses done on raw data, not to lose precious information related to stochastic dynamics (while external noise was already reduced when diminishing the sampling frequency from 60 Hz to 28 Hz) [50].

Statistical analysis

In the following paragraphs, the terms *"dyads"* and *"participants"* can be permuted, as task performance resulted from the dyads' behaviour while ApCoM measures were extracted from only one participant of the dyad. Due to back missing data, 5 and 4 trials respectively performed by Participant 2 and Participant 4 at the first set of the experiment were removed in analyses involving ApCoM measures. Participant 7 was excluded from postural analyses due to back marker missing. As Dyad 10's hands markers were unavailable, board rotations and consecutively scores were not obtained for this dyad. Despite those dyad-specific missing marker issues, the data collected for this study were sufficient to support statistical analyses. Before running analyses, data were tested for normality and homoscedasticity with Kolmogorov-Smirnov's and Levene's tests, respectively. Significant values were considered when $p < \alpha$, where $\alpha = 0.05$.

Performance analyses

All scores obtained (i.e., number of crossed doors) were organized into a matrix of 11 dyads x 30 trials. For each dyad, scores were averaged in each of the two 15-trial sets. Paired T-tests were run to investigate the evolution of performance over practice (i.e., from Set 1 to Set 2).

Postural analyses

For each of the 15 measures of the ApCoM variable (i.e., 5 ApCoM measures in all 3 planes of motion), a matrix of 11 participants x 30 trials was built. In the same manner as for performance analyses, averages across trials in each set were computed for each participant and statistical comparisons between the first and second sets were made using paired T-tests to get an overview of the effects of our joint-action game on postural stability in healthy individuals.

Relationships between the performance and postural levels

For additional insights, dyads were divided into two groups, namely "*Low Performance*" and "*High Performance*" where the criterion of *low* versus *high* was based on the median scores obtained by all dyads at the first and second sets of the experiment and along the whole session. Averages across trials in each set were computed for each ApCoM measure in each performance group. Because the data distribution could not be accurately determined due to the small sample size in each group (i.e., $N = 5$), nonparametric statistical tests were selected accordingly [51]. Mann-Whitney U tests were performed to compare the body data from the low- and high-performance groups. In each group, comparisons between sets were also made using Wilcoxon tests.

Results

The present section addresses an overview of our game based on a systems perspective in terms of: (i) performance, (ii) effects on the magnitude and structure of ApCoM oscillations, and (iii) a comparison of the postural outcomes found in low- and high-performance groups.

Evolution of performance

Overall, the average performance across dyads significantly increased from Set 1 (29.024 ± 6.958) to Set 2 (31.678 ± 6.675) ($t = -2.3977$; $p < .05$). Figure 2 shows how performance evolved from the first set to the second set of the experiment in eleven dyads. Whereas the number of crossed doors tended to get higher in the second set of the experiment, task performance was not homogeneous across dyads. For each set, the highest score obtained was approximatively twice as high as the lowest score recorded (i.e., score range in Set 1: 19.53; Set 2: 18.07).

Evolution of postural stability

Averages across dyads were also computed for ApCoM on the three planes of motion in both sets of the session to provide an overview of the influence of our game on postural stability in healthy individuals. Means and standard deviations of linear and nonlinear measurements, capturing the amount and structure of ApCoM variability respectively, were calculated in the mediolateral (ML), anteroposterior (AP) and vertical (VT) planes and presented in Fig. 3.

Significant changes were only found in the AP plane: one linear measure showed a decrease in ApCoM variability (STD(y): $t = 2.5276$, $p < .05$) and the sample entropy (nonlinear) measure revealed a decrease periodicity in the ApCoM signal ($t = -2.3329$, $p < .05$). Although the ApCoM fluctuations got more irregular in that plane over practice, the sample entropy values remained relatively low (i.e., nearby zero) and thus revealed a postural behaviour highly periodic. Additionally, the decrease of SWAY(z) from Set 1 to Set 2 was marginally significant

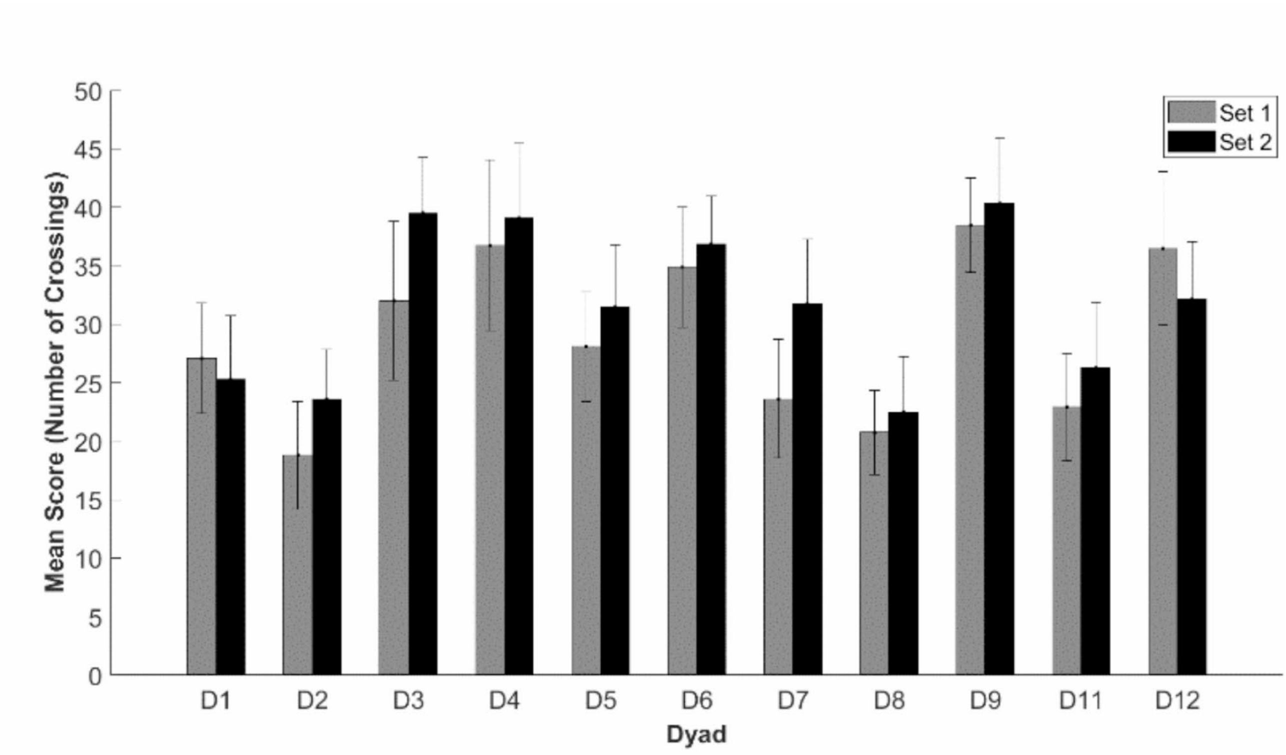

Fig. 2 Evolution of the number of crossings in all dyads from Set 1 to Set 2. The set average number of doors crossed by the ball within a 60-second trial for each dyad (but Dyad 10) and each set is presented

[52] (p =.056), as well as the decrease of RANGE(y) (p =.07).

Postural changes relatively to performance

As heterogeneous performance results were obtained across dyads, further analyses were conducted to inspect whether score differences could reflect different ways of moving the body to perform the ball-and-board task while maintaining balance. For that purpose, dyads were divided into two performance groups, as described earlier in the methodology section. In the *Low-Performance* group, no dyad obtained a score higher than the respective set's median score (i.e., Set 1: 28.07 and Set 2: 31.73) and no total score (i.e., sum of the points obtained in Set 1 and Set 2) superior to the median total score (i.e., 59.8) was recorded. Inversely, *High-Performance* dyads showed scores above medians in both sets and all along the session. A gap of 9 points separated the low group from the high one. Moreover, a Mann-Whitney U-test confirmed the relevance of the mentioned group assignment, as significant differences were found between the two groups in terms of performance (i.e., p <.01 in both sets comparison; p <.001 when comparing the groups all along the session) (Table 1).

Mann-Whitney U-tests reported significant between-group differences. Means and standard deviations of the ApCoM measures are presented in both performance groups in Table 1. Sample entropy of ApCoM in the vertical plane was found to be a relevant performance determinant as *High-Performance* participants showed significantly higher values in both sets of the experiment (i.e., p <.01) and all along the session (i.e., p <.001), compared to the *Low-Performance* group. In the two other planes of motion, they also demonstrated higher sample entropy values compared to the *Low-Performance* group over the whole session, and these results were found to be significant or marginally significant (i.e., p <.05 in the mediolateral plane; p =.05 in the anteroposterior plane). In contrast, the two performance groups could not be distinguished based on any linear measure (i.e., for all linear measures, in all sets and planes of motion: p >.05).

In each group, Wilcoxon's tests revealed no statistical differences between sets for any dependent variable (p >.05). However, increase in ApCoM ML sample entropy in the *Low-Performance* group from Set 1 to Set 2 was marginally significant (p =.06). Decrease in ApCoM VT range revealed a marginal significance in the *High-Performance* group (p =.06), which also exhibited an overall tendency to decrease in the other linear variables from Set 1 to Set 2. This tendency to decrease was less observable in the *Low-Performance* group, especially in the ML plane.

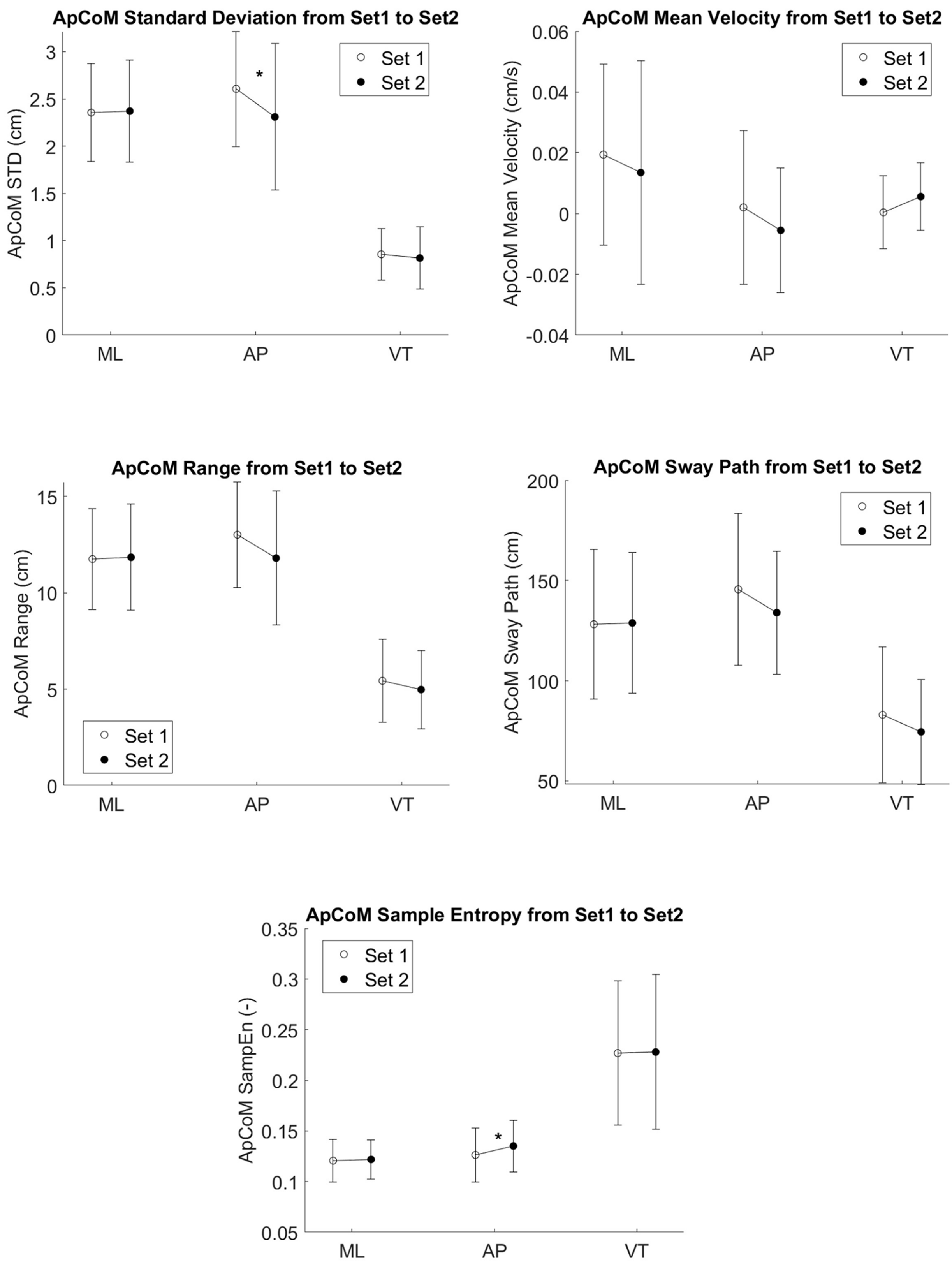

Fig. 3 Average evolution of ApCoM measures across dyads and trials from Set 1 to Set 2. Standard deviation, mean velocity, range, sway path and sample entropy values are presented for all three planes of motion. (p<.05*)

Table 1 Performance and ApCoM measures in *Low-* and *High-Performance* groups in set 1 and set 2

	Mean ± SD Set 1		Mean ± SD Set 2		Set 1 (*p*)	Set 2 (*p*)	Session (*p*)
	LOWPERF	**HIGHPERF**	**LOWPERF**	**HIGHPERF**	**LOW vs. HIGH**	**LOW vs. HIGH**	**LOW vs. HIGH**
Score	23.520 ± 3.991	35.708 ± 2.434	25.816 ± 3.485	37.640 ± 3.350	**0.0079****	**0.0079****	**1.83e-04*****
ML plane							
STD(x)	2.417 ± 0.579	2.356 ± 0.561	2.653 ± 0.585	2.189 ± 0.431	0.6905	0.3095	0.2413
VEL(x)	0.019 ± 0.038	0.025 ± 0.024	0.036 ± 0.043	− 0.003 ± 0.018	1	0.2222	0.3075
RANGE(x)	11.990 ± 2.743	11.800 ± 2.999	13.117 ± 3.276	10.986 ± 2.036	1	0.4206	0.3847
SWAY(x)	119.826 ± 31.423	138.666 ± 47.362	133.661 ± 43.111	125.386 ± 33.490	0.8413	0.8413	0.9097
SampEn(x)	0.108 ± 0.017	0.132 ± 0.021	0.112 ± 0.013	0.127 ± 0.023	0.0952	0.3095	**0.0257***
AP plane							
STD(y)	2.706 ± 0.534	2.659 ± 0.695	2.449 ± 0.370	2.320 ± 1.097	1	0.4206	0.5205
VEL(y)	− 0.002 ± 0.018	0.002 ± 0.035	0.006 ± 0.024	− 0.013 ± 0.013	0.5476	0.3095	0.8501
RANGE(y)	13.463 ± 2.370	13.296 ± 3.076	12.670 ± 2.149	11.644 ± 4.631	1	0.4206	0.5205
SWAY(y)	137.255 ± 27.731	159.141 ± 48.583	134.316 ± 19.169	137.840 ± 43.111	0.5476	1	0.6232
SampEn(y)	0.110 ± 0.007	0.137 ± 0.031	0.124 ± 0.018	0.140 ± 0.030	*0.0556*	0.4206	*0.0539*
VT plane							
STD(z)	0.876 ± 0.237	0.874 ± 0.350	0.952 ± 0.390	0.768 ± 0.280	1	0.5476	0.5708
VEL(z)	0.003 ± 0.008	0.004 ± 0.010	0.012 ± 0.009	0.003 ± 0.010	0.6905	0.2222	0.2413
RANGE(z)	6.109 ± 2.464	5.072 ± 2.053	5.999 ± 2.241	4.359 ± 1.1556	0.6905	0.0952	0.1041
SWAY(z)	69.180 ± 27.790	94.987 ± 40.984	67.988 ± 26.397	80.586 ± 30.124	0.4206	0.3095	0.1620
SampEn(z)	0.170 ± 0.037	0.258 ± 0.045	0.172 ± 0.057	0.252 ± 0.021	**0.0079****	**0.0079****	**4.40e-04*****

Mean and standard deviation (SD) values of ApCoM measures – namely standard deviation (cm), mean velocity (cm/s), range (cm), sway path (cm) and sample entropy (–), are presented for all three planes of motion. Significant results are highlighted in bold ($p < .05$*; < 0.01**; < 0.001***)

Discussion

In agreement with the hypothesis formulated at the task level, the overall performance increased from the first set to the second set of the experiment. However, performance improvement was not observed for all participants. This observation could be interpreted as a ceiling effect in the case of becoming an expert in the game. However, all participants were unexperienced in achieving a new task that was relatively complex and unconstrained – i.e., involving multiple degrees of freedom at both inter-limb and inter-agent coordination scales, and requiring both precision and balance abilities. Therefore, the dyads who did not obtain better scores at the end of the session were more likely still exploring different game strategies. Exploration is inherent to motor learning and can also be observed at the effector level. Overall, no significant changes were observed from the beginning to the end of the experiment in the linear measures reflecting the amount of ApCoM variability, except from a decreased STD(y) (in the AP plane of motion). This absence of significant changes was also reported in both performance groups separately. These findings may reflect that no standardized behaviour pathway emerged from playing the game. Instead, they are more likely to point out that the participants have explored differently the mosaic of postural solutions possible to perform a game where they were novice. This variability observed across individuals at both task and effector levels is not surprising as it can be viewed as a signature of exploratory behaviour towards the development of a new motor skill [53].

In participants with higher performance, however, the amount of ApCoM variability (assessed with linear measures) tended to decrease from the first set to the second set of the session. In their renowned ski apparatus-based experiment, Vereijken and colleagues (1997) also explored the evolution of the amount of ApCoM variability with practice [36]. They portrayed the postural organization of novice, advanced and expert participants through three different pendulum systems. At the beginning of practice, the body postural configuration was compared to an unstable upright, balancing pendulum system with highly-variable ApCoM oscillations. A postural shift to a more stable hanging pendulum, characterized by a decrease of the amount of variability in ApCoM fluctuations, was observed as the participants got more skilled. At the expert stage finally, the body behaved like a less simple hanging pendulum, where the increase of ApCoM variability was introduced by new knee joint coordinative structures.

Even though the objective of our game implies a cyclical ball motion at the task level, a comparison of body configurations with diverse pendulum systems might be less relevant in our study. However, similar interpretations can be formulated regarding of how the amount of ApCoM variability evolved with practice, based on the Bernstein's theory of motor learning. The overall tendency to decrease in the amount of ApCoM variability in *High-Performance* participants can be compared to the postural shift from novice to advanced players described in Vereijken and colleagues' study [36]: first, these participants explored a wide array of solutions to postural control, implying an initial high amount of ApCoM variability; then, they freezed some degrees of freedom, reducing ApCoM sway amplitude, to have fewer parameters to control. In our study, results obtained at both performance and postural levels therefore suggest that participants did not reach expertise at the end of the experiment. Additional training sessions – including a retention session, could provide more insights into the postural learning process in our task. We suggest leaving this as an issue for further research. As we aim to translate knowledge from Motor Learning to ACL rehabilitation, it would also be interesting to investigate whether a longer practice could lead to a final increase in the amount of ApCoM variability and, more importantly, foster the emergence of new knee joint coordination structures – or synergies, as reported by the authors in their own experiment.

Extending the duration of practice could also clarify whether the observed tendency of ApCoM entropy to increase from Set 1 to Set 2 in the *Low-Performance* group becomes more pronounced as participants undergo additional training. As we mentioned previously, the amount of ApCoM variability (assessed with linear measures) is not the only property to be analysed; its structure (assessed with nonlinear measures) is highly relevant in the context of postural stability analysis. For instance, Wayne and colleagues (2014) stressed that the effects of Tai Chi – another balance training based on a systems approach, on postural control were not well-captured by the traditional linear measures, as both increase and decrease tendencies were reported in the literature [54]. In contrast, entropy analyses appeared to be more sensitive to detect differences in postural stability between healthy controls and populations with specific balance abilities [54, 55]. Young obese individuals exhibited a CoP signal relatively periodic (i.e., low entropy values) [55], while a greater complexity of sway was found in Tai Chi experts (i.e., higher entropy values) [54]. These findings were comparable with our results: whereas the two performance groups could not be differentiated on the basis of any ApCoM linear measure, entropy analyses revealed that the *High-Performance* group was characterized by a more complex ApCoM signal in its structure, with less predictable sway fluctuations, compared to the *Low-Performance* group. The irregularity in the sway oscillations can be related to a more exploratory and flexible behaviour, facilitating adaptations to perturbations while maintaining balance [56].

Consistent results were found in a study led by Menayo and colleagues (2014) that shows tight similarities with our theoretical framework, research question and methodology [57]. Using a nonlinear approach, the authors also used sample entropy analyses to assess an original balance training aiming to improve postural stability. Their balance training included various tasks, also using the BOSU as an unstable surface, where healthy participants were invited to explore a wide range of motion in diverse situations that imply inter-limb coordination in the three-dimensional space. Moreover, some tasks invited the participants to play as a dyad on the BOSU (e.g., ball throwing; feet and hands wrestling). While our task design uses the intrinsic properties of *Joint Action* to promote both intra- and interpersonal coordination through informational and mechanical couplings, Menayo and colleagues' setup is based on a *Differential Training* which implements random variability to the practice environment. By enriching the interactions between the system elements or by amplifying the inherent chaotic fluctuations of this system, both *Joint Action* and *Differential Training* approaches embrace the concept of complexity to encourage the exploration of new movement solutions and, therefore, enhance the body's ability to adapt to perturbations that threaten postural stability. Other common methodological choices (e.g., same m and r parameters values in SampEn computations; similar session durations) strengthen the relevance of the comparisons of our respective findings. Both of our complexity-promoting tasks led to an overall increase of SampEn in at least one plane, and such an increase was found to be functional in terms of task performance.

Moreover, the observation of a SampEn increase in one plane of motion did not necessarily concur with a similar evolution in the two other planes. In their study evaluating the learning process of standing on a BOSU, Valle and colleagues (2015) also reported an anisotropic stability between AP and ML directions [48]. We agreed with Menayo and colleagues' explanation [57], suggesting that the participants might have compensated the irregularity of the sway fluctuations in one plane with a more periodic behaviour in the other plane. In a review assessing the CoM-CoP relative phase as a collective variable of the postural system, oscillations between periodic and chaotic strategies were also reported in maintaining upright balance [58]. These compensatory interactions between the postural system's elements across planes of motion have also been evidenced at the joint level to ensure postural stability [59]. So far, the present results revealing changes in postural stability with practice encourage us to test our game in ACL patients.

Another remarkable observation was that the postural changes that were statistically significant over practice – namely, a decrease of ApCoM standard deviation and an increase of ApCoM sample entropy, both occurred in the AP plane of motion. In their archery-inspired experiment, Balasubramaniam and colleagues (2000) also reported that both the magnitude and patterning of sway fluctuations differed across planes of motion [60]. Besides the *compensation explanation* detailed above which was also used to interpret their findings, the authors added that the contribution of postural activity in each of ML and AP direction was task-specific. By manipulating the orientation of the body relatively to the target plane, they evidenced that ML and AP fluctuations shared distinct and mutual responsibilities in ensuring precision and postural stability functions.

In the present study, the participants faced each other in the AP plane of motion. This dyadic configuration can lead to destabilizing movements such as pushing and pulling each other, which would better be restricted to better perform our supra-postural task. We can speculate that (i) minimizing the sway magnitude and increasing the complexity in the sway structure were particularly functional in the AP plane of motion, and/or (ii) the significant postural changes observed in the AP direction reflect the exploration of diverse interpersonal coordination strategies over practice to better cope with AP instability. Further analyses on board motion are needed to test this hypothesis relating these postural differences across planes of motion with task specificities. From a clinical perspective, the postural reorganization evidenced in the AP plane of motion may provide an added value to our game as the knee joint kinematics can also be mainly described in this specific plane by a one-degree-of-freedom model (i.e., flexion-extension). In other words, the fact that our game led to postural changes in the plane of motion where the knee joint is active might be clinically relevant for ACL rehabilitation.

Aside from missing data, a primary limitation of our study lies in the protocol duration, which was found to be too short to fully understand the postural changes occurring during practice. This might explain why the increase of SampEn(y) found in the general population was not significant when inspected in both performance groups. In their study extending Cavanaugh and colleagues' work on athletes with cerebral concussion (2005, 2005b, 2007) [32–34] onto the long-term period, Purkayastha and colleagues (2019) demonstrated that, even though the amount of sway variability (defined as the AP range and standard deviation of CoP) was restored one month after the concussion, a 3-month postinjury period was not sufficient to the athletes to exhibit a postural sway as complex as healthy controls [61]. Because our multi-joint dyadic supra-postural task encompasses a high level of difficulty, we speculate that both task performance and sway complexity would have increased in all dyads within a longer period of practice.

Another limitation of our study is the estimation of ApCoM. While methods that estimate CoM position based solely on back movement have been validated in balance perturbation tasks [38, 40], comparisons with studies using multi-segment models should be made with caution. However, because our protocol focuses on comparisons across sets and groups, these significant differences can still be interpreted meaningfully, even without highly precise CoM values. Finally, as our game has been designed to help improve participants' postural stability, a next research question that instinctively arises is whether its use could lead to a postural reorganization that overcome the deficiencies caused by a knee injury. How to analyse postural stability is a key issue to assess the efficacy of a rehabilitation program. In the last decade, nonlinear metrics have been employed in a few studies assessing kinematics in ACL patients [62]. More specifically, entropy measures unveiled an excessively rigid behaviour of ACL patients in gait (i.e., greater regularity in stride-to-stride variability compared to healthy controls [63–65] and in quiet stance (i.e., greater regularity in CoP fluctuations than healthy controls [66]. Since the magnitude and the structure of variability can provide complementary information, the use of linear along with nonlinear measures could be relevant to assess the applicability of our game into ACL rehabilitation. To provide some direction for future research, further investigations are necessary to examine whether improvement in postural stability is accompanied by the emergence of new inter-limb and inter-agent coordination patterns. After testing this game in healthy participants and inspired by our results, we may suggest testing our joint-action game within the ACL population to offer valuable insights for guiding its implementation into clinical settings.

Conclusions

The present study provides evidence that experiencing our game designed from a systems perspective can be viewed as a way of challenging the participants' balance, encouraging them to explore different postural solutions. With practice, and in the anteroposterior plane of motion only, ApCoM variability decreased in terms of magnitude whereas the complexity of its structure increased. Higher performance was characterized by less periodicity, and thus more complexity, in the structure of ApCoM variability. This enhanced complexity in the ApCoM oscillations is functional as it leads to a greater ability to resist to perturbations that may compromise balance. Our game leads to a postural reorganization that encourages us to test it as an ACL rehabilitation device.

Abbreviations

ACL	Anterior Cruciate Ligament
AP	Anteroposterior
ApCoM	Approximate Centre of Mass
CoM	Centre of Mass
CoP	Centre of Pressure
DoF	Degrees of Freedom
ML	Mediolateral

SampEn	Sample Entropy
STD	Standard Deviation
VEL	Mean Velocity
VT	Vertical

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Author contributions
AC: Conceptualization, Device fabrication, Study design, Data Collection, Data Processing, Data Analysis, Investigation, Writing, Editing. JM: Study design, Data Analysis, Reviewing. PP: Project administration, Supervision, Funding acquisition, Conceptualization, Study design, Investigation, Reviewing, Validation. All authors have read and approved the final manuscript.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
All participants involved in the present study provided free and informed consent before starting the experiment. The study was approved by the ethics committee CEIFMH (Conselho de ética para a Investigação da Faculdade de Motricidade Humana), N° 28/2022. The present study adheres to the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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