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Coordination and coordination variability during single-leg drop jump landing in children

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ABSTRACT

Coordinative patterns require experience and learning to be acquired, producing movements that offer efficient solutions to various situations and involving certain degree of variability. This coordination variability implies functionality in movement, but it can be impacted by the type of sport practice from early years. The purpose of this work is to analyze the coordination variability and coordination patterns in a specific action such as single-leg landing in children practicing gymnastics, volleyball and non-sporting children.

Thirty children (15 girls) performed 10 successful trials of single-leg landing from a height of 25 cm. A motion capture system (9 cameras) was used to capture 3D thigh and shank kinematics. To identify the significant effect of children's groups on coordination and coordination variability during single-leg landing, one-dimensional Statistical Parametric Mapping (SPM) was used.

Regarding the coordination patterns, in the frontal plane, during the attenuation phase of single-leg landing, the control group exhibited a higher frequency of Anti-Phase with proximal dominancy compared to the sport groups (i.e., gymnastics, and volleyball). In addition, in the sagittal plane during the second peak phase, volleyball players exhibited a higher coordination variability than the gymnastics.

The children in the control group showed a greater frequency of antiphasic movements, which indicates the influence of training at an early age, being a determining factor in the increase or not of variability.

1. Introduction

Coordination refers to the process by which mastery of the redundant biomechanical degrees of freedom of a moving body is achieved (Bernstein, 1967). Coordination arises from the constraints imposed on the system's degrees of freedom associated with the task and the dynamics of the environment (Newell, 1986). According to dynamical systems theory (Smith & Thelen, 2003; Thelen, 2005; Thelen & Smith, 1994), humans are considered to select their movement coordination patterns through a process of self-organization to find a solution within the context of these constraints.

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Coordinative patterns require experience and learning to be acquired, producing movements that offer efficient solutions to various situations (Wilson et al., 2008). The importance of finding suitable attractors (relatively stable coordination patterns) to achieve a particular goal lies in the fact that these allow individuals to successfully face encountered situations, such as common motor tasks like vertical jumping and subsequent successful landing. However, even when faced with similar or identical situations, the coordination of movements is not always the same; there is a certain degree of variability. This variability in movement is defined as the normal variations that occur in motor execution over multiple repetitions of a task (Stergiou & Decker, 2011), implying functionality in movement because each repetition involves unique, non-repetitive neural and motor patterns (Bernstein, 1967).

As a result, coordination variability is particularly important in many motor skills where adaptability of motor patterns to the environment is required (Button et al., 2006). In well-learned movements, high accuracy associated with consistent performance was found to be related to high coordination variability (Wilson et al., 2008). In fact, the same authors suggested the existence of a U-shaped pattern in expert performers' coordination variability as skill competence increases. From a dynamical systems perspective, it is purported that coordination variability in a system provides the required flexibility to adapt to perturbations (Hamill et al., 1999), explaining the higher coordination variability in high skill competence participants. This finding suggests that coordination variability may provide flexibility that helps search for the optimal solution depending on the task and context (Wilson et al., 2008).

A specific common task in many sports is landing in its different forms, such as single-leg landing (Briem et al., 2017; Fransz et al., 2013; Keiner et al., 2013; Lazaridis et al., 2010; Liederbach et al., 2008). Such an action is frequently used as a motor task during physical activity and is often used to study motor pattern development, in addition to dynamic postural stability and injury prevention. Landing, an integral part of sports (Dickin et al., 2015), is a discrete task with a different beginning and end, without a continuous cyclic pattern (Raffalt et al., 2016).

In addition to this motor task, another constraint to keep in mind that impacts coordination variability is the context (Hamill et al., 2012). Indeed, individuals' characteristics, such as age, and the type of sport practiced, are two main factors to be analyzed (DiCesare et al., 2019; Hafer & Boyer, 2018). The impact of age on the mechanics of movement (including inter-joint coordination variability) exhibited a non-equivalent aging process for adults' running (Boyer et al., 2017). Regarding research focused on measuring healthy children's coordination variability, Busquets et al. (2016) studied children and adolescent gymnasts between 8 and 20 years old, during the performance of longswings on the high bar. Some of the coordination variability measures taken throughout the movement were found to conform to an age-related U-shaped function, partially supporting the earlier findings of Wilson et al. (2008) regarding exploratory strategies among novices and adaptive functional variability among those with more experience.

Notwithstanding the influence of the type of sport practiced by children, it has been observed that unlike children who do not practice any sport in a structured and formal way, the practice of a specific jumping sport (e.g., volleyball and gymnastics) could influence the ability to adapt to this specific action (Estevan et al., 2020). In this line, specific environmental constraints, such as rules and norms in gymnastics or volleyball, could diversify experiences that enrich children's coordination ability not only to improve their performance but also to prevent injuries.

Considering the above, to our knowledge, no work has yet been done involving children analyzing coordination variability according to the specific sports practiced and those who do not practice sports. Understanding the relationship between the type of children's sport practice and segment coordination is important to determine whether the type of activity provides insight and might be considered for interventions (Hafer & Boyer, 2018). So, the aim of the present study was to analyze the coordination variability and coordination patterns in a specific action such as single-leg landing in children practicing gymnastics, volleyball, and non-sporting children.

2. Methods

2.1. Participants

Thirty children, 15 boys and 15 girls aged 8–12, were divided into three equal groups (gymnastics, volleyball, and a control group) and voluntarily participated in this study. Participants in the gymnastics and volleyball groups had been active players for at least one year and underwent training sessions at least twice a week. The control group did not engage in any organized physical activity. Before

Table 1
Sample description in each group.

	Gymnastic	Volleyball	Control
	(Mean ± SD)	(Mean ± SD)	(Mean ± SD)
Sex (boys/girls)	3/7	7/3	5/5
Age (years)	10.18 ± 1.39	10.10 ± 1.56	10.15 ± 1.64
Weight (kg)	28.10 ± 3.13	35.63 ± 13.69	36.67 ± 11.50
Height (m)	1.36 ± 6.76	1.39 ± 13.76	1.41 ± 9.81
BMI (kg/m^2)	15.20 ± 1.15	17.82 ± 3.34	19.08 ± 3.77
Fat (%)	8.79 ± 2.57	18.29 ± 9.35	18.62 ± 8.01
Laterality (right/left)	10/0	8/2	9/1
Activity time (years)	4.30 ± 1.74	2.75 ± 1.86	–

Note. BMI – Body mass index; Laterality was determined by observing the lower limb used to kick a ball for three times; SD – Standard deviation.

testing, participants had not experienced any injuries or musculoskeletal problems for six months. A more detailed description of the sample can be found in Table 1. As the participants were under the age of 18, their parents were informed about the research. By signing an informed consent form, parents agreed to involve their children in the study. The research was approved by the Ethics Committee of the University of Valencia (IRB number: H1446557620395). A previous study utilizing some data focused on the analysis of children's lower limb discrete joint angles from this same project was published (Estevan et al., 2020).

2.2. Protocol

Measurements were conducted for each participant in the Human Movement Biomechanics Laboratory at the University of Ostrava. At the beginning of the testing, participants underwent body composition measurements. Subsequently, a ball-kick test was performed to determine lower limb dominance (Estevan et al., 2020). Before measuring the single-leg drop jump landing barefoot, participants warmed up and performed a test jump landing on the dominant lower limb to the ground from a drop height of 25 cm. A standardized warm-up was conducted on a 17 m long runway, including hip, knee, and ankle joint mobility exercises, 5 sets of high amplitude knee flexion-extension, 10 sets of skipping, 5 sets of countermovement jumps, and individual warm-up and stretching as needed. After the warm-up, once reflective markers were placed on the participants' bodies, a standing calibration trial was measured. Subsequently, participants performed 10 successful jump landings from a height of 25 cm. A successful trial was defined by the following criteria: the foot of the dominant lower limb landed on the force plate, the knee flexion on the non-dominant lower limb was approximately 90° and it did not touch the floor, the elbows were flexed with hands located at the hip under the superior iliac crest, and after landing, the participant could stand and maintain balance in place for 10 s. The rest time between each trial was 1–2 min.

2.3. Experimental set-up

The single-leg drop jump landing was recorded using a 9-camera motion capture system (comprising 8× Oqus 100 and 1× Oqus 700+, Qualisys, Inc., Gothenburg, Sweden) with a recording frequency of 240 Hz. This system was positioned 2.5 m high around the force plate. Forty-seven reflective pearl markers, each 12 mm in size, were placed on anatomical parts of the body including the thorax, pelvis, and lower extremities. Specifically, reflective calibration and tracking markers were placed on the 7th cervical vertebra, the 10th thoracic vertebra, the sternum-xiphoid process, and bilaterally on the acromion, crests of the ilium, posterior superior iliac spines, and the anterior superior iliac spines. Furthermore, markers were placed bilaterally on the greater trochanter of the femur, medial and lateral femoral condyles, and medial and lateral malleolus. Lightweight rigid plates with four markers per plate were placed on the shanks and thighs. On the feet, markers were placed on the fifth and first heads of the metatarsus, and triad markers were placed on the heel.

Ground reaction force (GRF) data were collected using a force plate (Kistler 9281CA, Kistler Instruments AG, Winterthur, Switzerland) with a recording frequency of 1200 Hz. The structure was positioned 20 cm behind the force plate, and its take-off platform was located 5 cm from the rear side of the force plate. Mass and body composition were determined using bioelectric impedance measurement (InBody 770, South Korea). Height was measured using a wall-mounted height rod.

2.4. Data analysis

The raw data were processed using QTM software (Qualisys Track Manager; Qualisys, Sweden, Göteborg), where the markers were labeled. A skeletal model of the thighs, and shanks was created using Visual3D (C-Motion, USA, Germantown). The lower extremity segments were modeled as frusta of right circular cones.

Kinetic and kinematic data were filtered using a fourth-order Butterworth Low-pass filter with cutoff frequencies of 50 Hz and 12 Hz, respectively. Jump landing signals were determined based on a threshold vertical ground reaction force (VGRF) value of 15 N. The landing phase was divided into three parts: 1) from initial contact (IC) to the first passive peak VGRF (first peak phase), 2) from the first passive peak VGRF to the maximum VGRF (second peak phase), and 3) from the maximum VGRF to the maximum knee flexion on the dominant lower limb (attenuation phase) (Johnston et al., 2018; Kim & Jeon, 2016; Zahradnik et al., 2017). In each part, data were time normalized to 100% (101 points). For each part, angular data from the thigh and shank of the dominant lower limb (sagittal, frontal, and transverse planes) were exported to calculate coordination and coordination variability.

Segment coordination and coordination variability during jump landings with balance in the three planes were calculated for each participant and each trial for the thigh and shank using a modified vector coding technique (Chang, Van Emmerik, & Hamill, 2008). The coordination pattern specified by the coupling angle was classified as described by Needham, Naemi, and Chockalingam (2015). Each 45° interval of the coupling angle represented the coordination pattern between the distal segment (shank) and the proximal segment (thigh). Coupling angles were categorized into four phases: In-Phase with proximal dominancy, In-Phase with distal dominancy, Anti-Phase with distal dominancy, and Anti-Phase with proximal dominancy. To identify the dominant pattern, the frequency of each specific pattern was calculated for each part of the monitored movement. Coordination variability was calculated as the standard deviation of the coupling angles across all trials.

2.5. Statistical analysis

To identify the significant effect of children's groups on coordination variability during single-leg landing, one-dimensional Statistical Parametric Mapping (SPM) was utilized [29]. At each point of the monitored movement, scalar output SPM t-statistic curves were calculated, forming a statistical parametric map. One-way ANOVA using SPM and subsequent independent *t*-tests with SPM were performed to determine the differences between groups. Significance in children's groups was established when the statistic test value exceeded the threshold.

Furthermore, to assess differences in coordination pattern frequencies during jump landings with balance, a normality test was conducted using the Shapiro-Wilk test. Differences among groups of children were evaluated using the Kruskal-Wallis test in the IBM SPSS Statistics software (version 24, IBM SPSS Inc., Chicago, Illinois, USA). The significance level was set at a *p*-value <0.05.

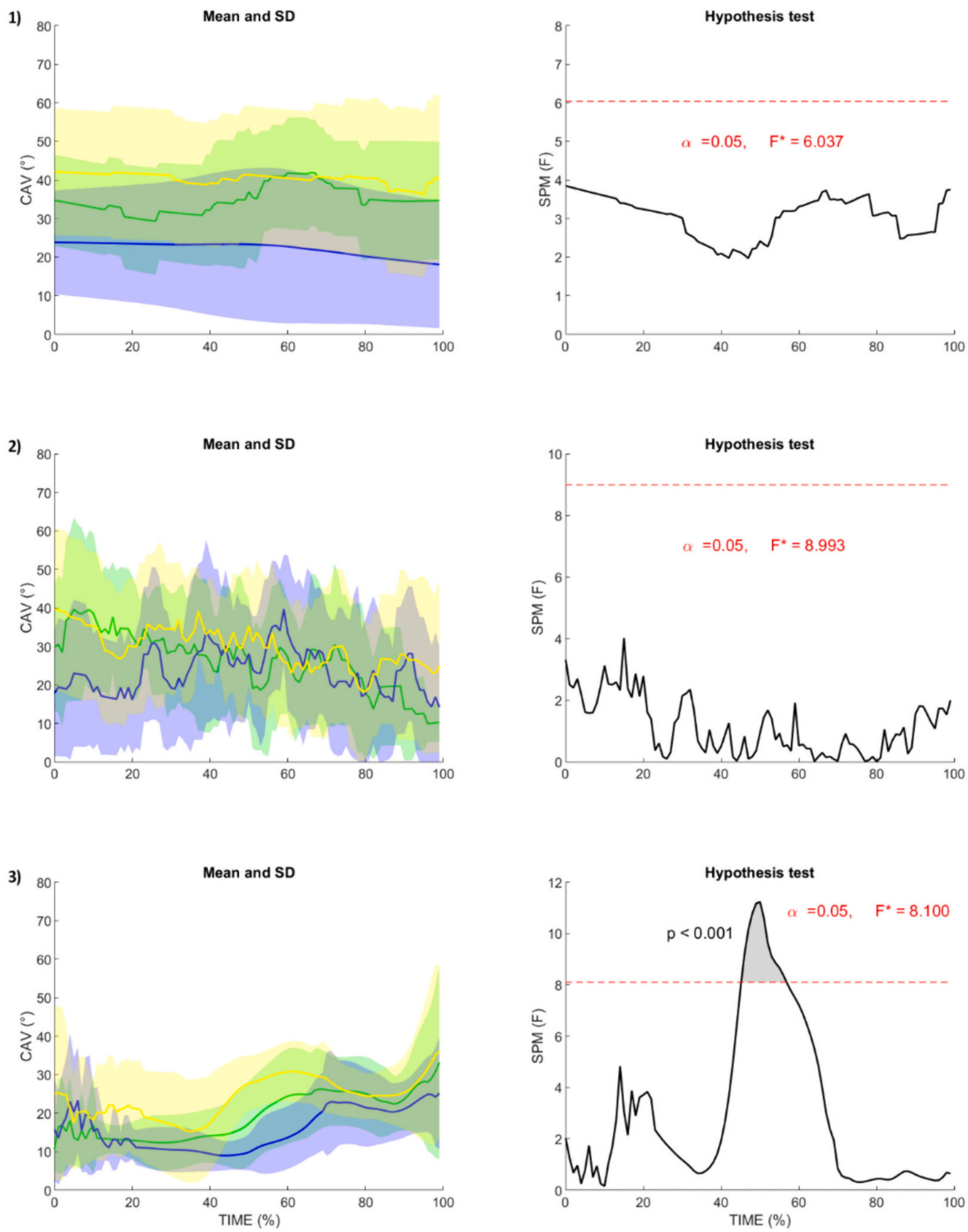

Fig. 1. Coordination variability between thigh and shank in sagittal plane for jump landing.
Note. CAV *means coupling-angle variability (°). SPM means statistical parametric mapping. 1) First peak phase from IC to first passive peak VGRF, 2) Second peak phase from first passive peak VGRF to maximum VGRF, 3) Attenuation phase from maximum VGRF to maximum knee flexion on dominant lower limb (green – control group, blue – gymnastics, yellow – volleyball players). Statistical parametric map for coordination variability data.*

3. Results

Coordination variability between the thigh and shank, as well as the frequency of coordination patterns during single-leg landing in the sagittal, frontal, and transverse planes, were analyzed within each group of children. In the sagittal plane, during the attenuation phase (from the maximum vertical ground reaction force to the maximum knee flexion on the dominant lower limb), an effect of the group type on coordination variability was observed, ranging from 45.15% to 56.82% ($p < 0.001$). According to the SPM independent

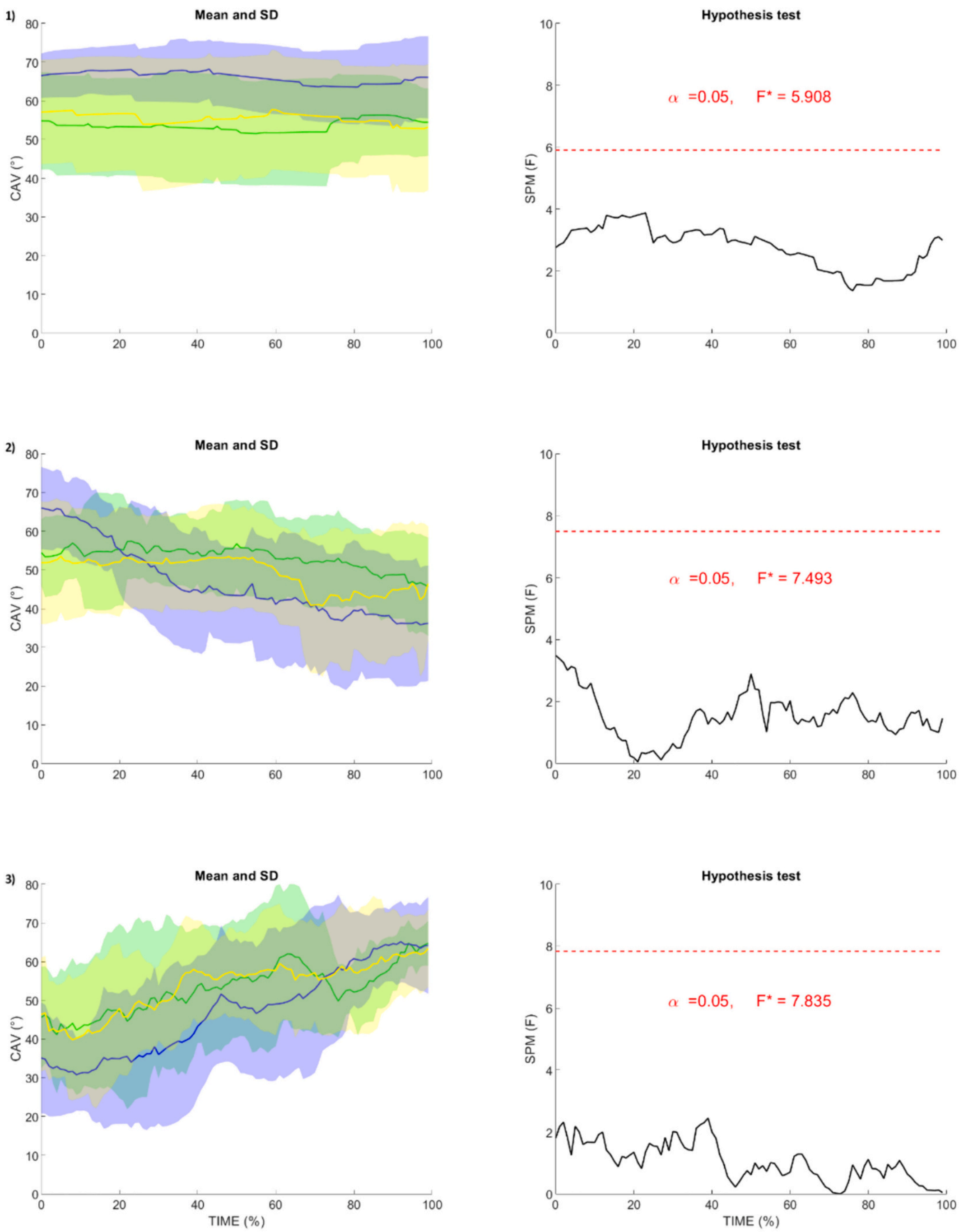

Fig. 2. Coordination variability (CAV) between thigh and shank in frontal plane for jump landing.
Note. CAV *means coupling-angle variability (°). SPM means statistical parametric mapping. 1) First peak phase from IC to first passive peak VGRF, 2) Second peak phase from first passive peak VGRF to maximum VGRF, 3) Attenuation phase from maximum VGRF to maximum knee flexion on dominant lower limb (green – control group, blue – gymnastics, yellow – volleyball players). Statistical parametric map for coordination variability data.*

t-test, higher thigh-shank coordination variability was observed, ranging from 44.3% to 63.9%, in the volleyball group compared to the gymnastics group (Fig. 1.3). There were no differences in the preceding two phases (Figs. 1.1 and 1.2).

No significant difference in coordination variability between thigh-shank among children in gymnastics, volleyball, and the control group was found in the frontal plane in any of the three phases (Fig. 2).

In the transverse plane, also in the attenuation phase, an effect of the type of group in coordination variability from 2.9 to 3.1% ($p < 0.001$) was found (Fig. 3). However, based on the SPM independent t-test, no differences were found between the groups. There was

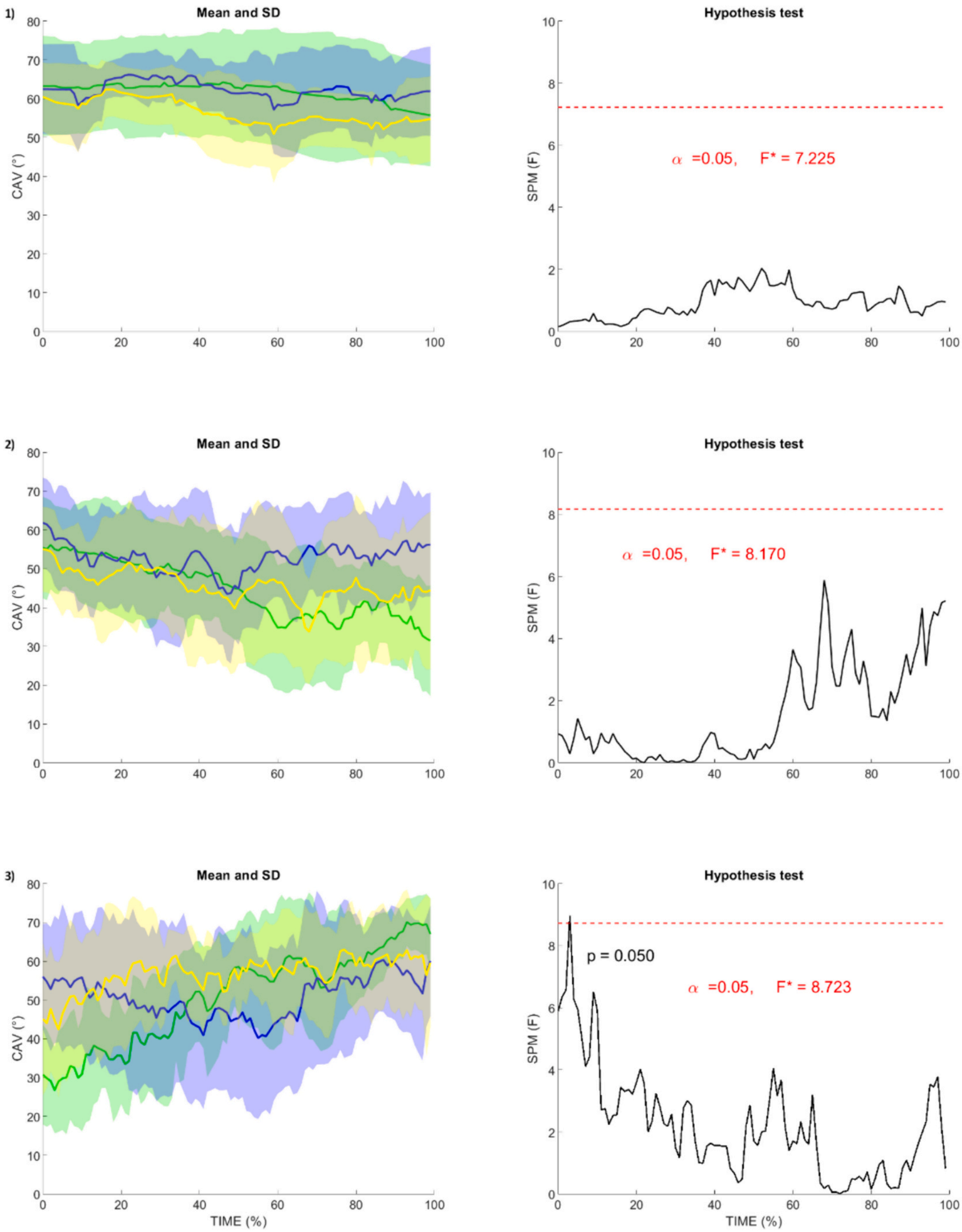

Fig. 3. Coordination variability (CAV) between thigh and shank in transversal plane for jump landing.
Note. CAV *means coupling-angle variability (°). SPM means statistical parametric mapping. 1) First peak phase from IC to first passive peak VGRF, 2) Second peak phase from first passive peak VGRF to maximum VGRF, 3) Attenuation phase from maximum VGRF to maximum knee flexion on dominant lower limb (green – control group, blue – gymnastics, yellow – volleyball players). Statistical parametric map for coordination variability data.*

not any difference in the previous two phases.

Furthermore, concerning the frequency of thigh-shank coordination patterns during single-leg landing, no significant effect was found for the type of group in the sagittal and transverse planes in any phase. In other words, children in the gymnastics, volleyball, and control groups displayed a similar number of coordination types (i.e., In-Phase with proximal dominancy, In-Phase with distal dominancy, Anti-Phase with distal dominancy, and Anti-Phase with proximal dominancy) in all three landing phases. In the frontal plane, during the attenuation phase of single-leg landing, the control group exhibited a higher frequency of Anti-Phase with proximal dominancy compared to the sport groups (i.e., gymnastics, and volleyball) (Fig. 4).

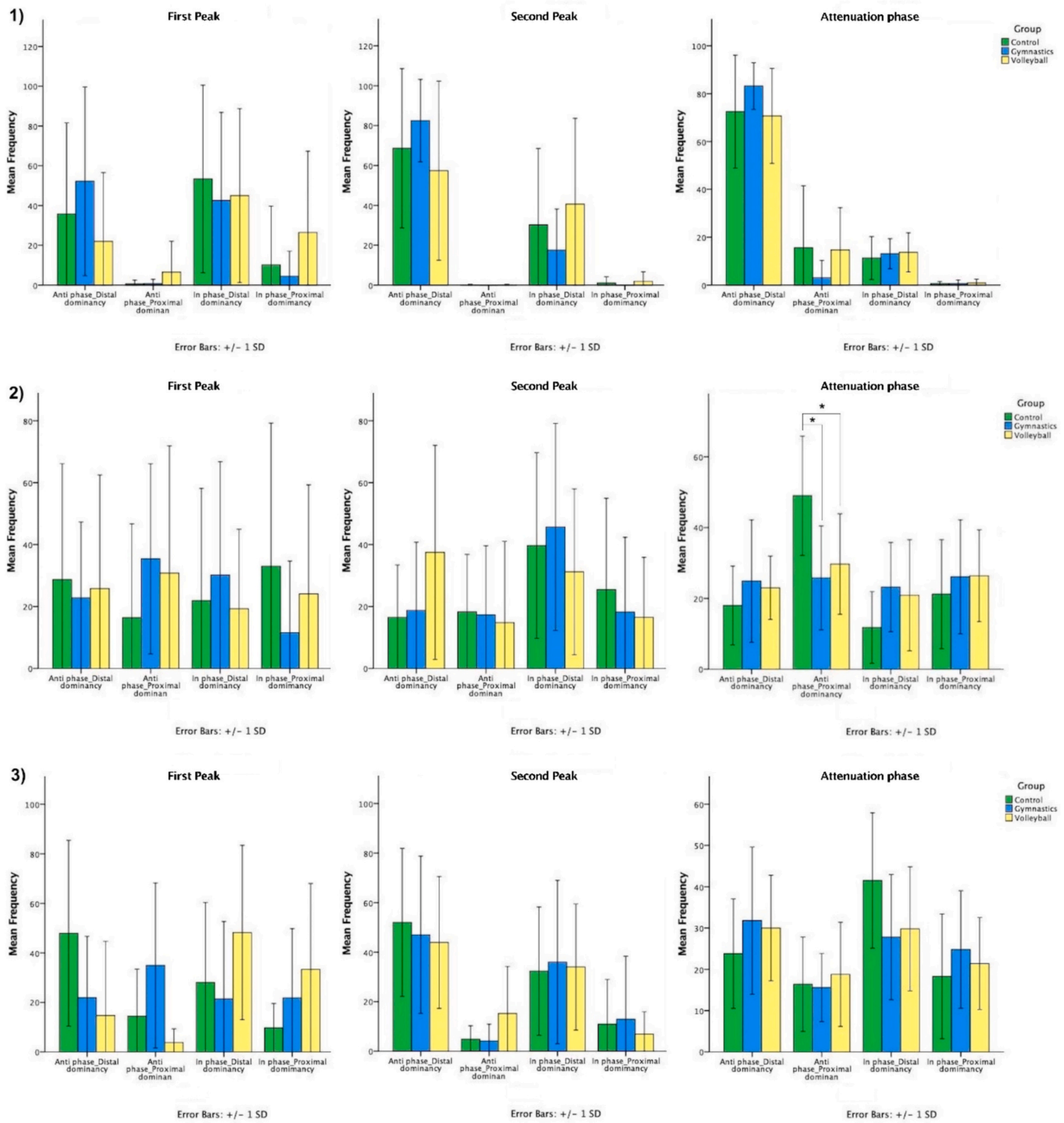

Fig. 4. Histograms of coordination pattern frequency (mean and SD) for thigh and shank in the first peak, second peak and attenuation phases. Note. 1) Sagittal plane during every of the three phases; 2) Frontal plane during every of the three phases; 3) Transversal plane during every of the three phases. *Statistically significant difference between groups (p-value<0.05).

4. Discussion

The analysis of single-leg landing in children who participate in different sports can aid in understanding the underlying mechanisms that influence children's movement execution in terms of injury prevention, motor performance, and their overall health (Estevan et al., 2020; Hulteen et al., 2018; Keiner et al., 2013). The objective of the present study was to analyze coordination variability and patterns during single-leg landing in children engaged in gymnastics, volleyball, and non-sporting activities (control group). To achieve this goal and in alignment with previous studies analyzing coordination variability (Estevan et al., 2016; Zahradnik et al., 2015), single-leg landing was divided into three phases to enable meaningful comparisons between the groups (Johnston et al., 2018; Kim & Jeon, 2016; Zahradnik et al., 2017).

Concerning coordination variability, no differences were found in the sagittal plane during the first peak and second peak phases of the movement. However, in contrast to the initial phases, in the attenuation phase a higher coordination variability in volleyball athletes compared to gymnasts was revealed. These results support those reported by DiCesare et al. (2019) who showed that athletes who exclusively practice volleyball exhibited a higher coordination variability compared to those non-specialized athletes. Our results may be due to the nature of sport and the components training. Whereas volleyball is a collective and opposing sport wherein athletes must react to many stimuli, in gymnastics there is not as much uncertainty as in volleyball; athletes must land as still as possible. As a result, this could impact volleyball players coordination variability. Nonetheless, in the frontal plane, the results were similar across all three groups, showing no differences in any phase of the movement. In the transverse plane, differences among the groups were more apparent than in the frontal plane, although no significant distinctions were observed in any of the three phases. So, the slightly differences found in coordination variability between volleyball players and gymnasts might reflect that the nature and internal logic (constraints) of each sport impact athletes underlaying mechanisms even from early ages.

The interpretation of these findings suggests that the elevated coordination variability in the sagittal plane among volleyball players could stem from the specific movements trained in volleyball compared to those typically performed in gymnastics and among non-trained children. Another potential explanation could be the level of training and experience with landings. Considering the age of the children, gymnasts are exposed to fewer landings compared to volleyball players. From this perspective, it is reasonable to assume that children engaged in volleyball have more landing experience than their counterparts. Previous studies have indicated that experienced athletes exhibit higher coordination variability compared to novices (Hamill et al., 2012). Volleyball training emphasizes movements that are less predetermined and more open to modification and variability (DiCesare et al., 2019; Keiner et al., 2013). Moreover, the variety of landing techniques in volleyball, such as landing on a single lower limb and seamlessly transitioning into the next movement (Zahradnik et al., 2017), might contribute to the differences observed. Thus, our findings support previous research emphasizing the importance of considering limb dominance during block jump-landings in volleyball (Mercado-Palomino et al., 2021).

Coordination variability was further analyzed in relation to the coupling between lower limb segments, reflecting coordination patterns. The frequency of these coordination patterns indicated the prevalence of each type of coupling during single-leg landing based on the practiced sport. Our findings demonstrated similar frequencies of coordination patterns in the sagittal and transverse planes among the four patterns. However, in the frontal plane, the control group exhibited a higher frequency of anti-phase movements with proximal dominancy compared to both sport groups (gymnastics and volleyball). Anti-phase coupling has been considered a potential mechanical dysfunction associated with injury risk, as it stresses and twists joints in a manner conducive to injury (Langley et al., 2020; Lopes et al., 2012). Additionally, uncontrolled knee motion in the frontal plane during landing has been linked to injuries such as anterior cruciate ligament injuries (Chappell et al., 2002; Hewett et al., 2005; Krajewski et al., 2020; McLean et al., 2005).

However, it is important to acknowledge the limitations of this study. One major limitation is the lack of information regarding the number of training sessions per week for the children. Consequently, we can only speculate about potential differences in experience among those who practice specific sports, limiting the depth of our insights. Additionally, due to the limited sample size, age group comparisons could not be established, which could have provided valuable insights into the influence of practiced sports on coordination patterns and variability at different ages.

Another limitation is that the condition in which the study was conducted was with barefoot subjects which in turn it is only a common condition for the gymnastics group who usually train barefoot. Neither the volleyball group nor the control group train in such condition. Although this decision was made to gain uniformity and consistency during the protocol, we are aware that it is not completely faithful to reality, and that the results should be taken as a starting point towards more specific studies. Hence, future studies aiming to analyze the impact of specific jumping sport practice according to the type and amount of training in children's coordination variability should consider to establish a procedure of assessment which is not potentially affected by the nature of the sports analyzed (e.g., using common techniques such as plyometric jumping).

On the positive side, the study's strengths include the comprehensive analysis in all three planes: sagittal, frontal, and transverse. While many studies have traditionally focused on two-dimensional analyses in the sagittal plane (Bart, 2014; Holden et al., 2017; Munro et al., 2017), our three-dimensional modeling allowed us to observe variability differences across all axes, particularly in movements involving knee flexion and extension. Moreover, the study compared sports with similar jumping frequencies and types of jumps, revealing significant differences. This finding is noteworthy as it suggests that even in sports with comparable movements and among participants with limited experience, the specific sport modality remains an influential factor.

In conclusion, this study offers emerging evidence of the connection between the type of sports practiced and its impact on coordination and coordination variability in childhood. Engaging in jumping-related sports during childhood might influence movement capabilities and encourage diverse motor skills, leading to distinct ways of performing similar motor tasks.

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CRediT authorship contribution statement

Gonzalo Monfort-Torres: Writing – review & editing, Writing – original draft, Validation, Investigation. **Xavier García-Massó:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Jiří Skýpala:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Denisa Blaschová:** Writing – original draft, Supervision, Methodology, Conceptualization. **Isaac Estevan:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

No artificial intelligence tools were used.

Declaration of competing interest

There is no conflict of any author.

Data availability

Data will be made available on request.

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