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Individual differences in children's movement variability in a virtual reality playground task

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ABSTRACT

Children's movements are highly complex, and thus require measurements that capture various gross motor strategies. This study examined whether aspects of individual differences in children's gross motor movement patterns could be captured in virtual reality (VR) and how motor movements could be conceptualized through freezing-freeing patterns of degrees of freedom. To this end, a three-minute VR scenario was developed for children to freely explore, play, and move around without further instructions, and their movement strategies were simultaneously captured by a non-invasive inertial motion capture system. Sixty-four children aged 7–10 (boys: $n = 37$, girls: $n = 27$) participated. The results of correlational and principal component analysis (PCA) on measures of variability of upper extremities indicated significant relationships between nearly all measures ($r = 0.31$–0.69, $p < 0.05$). Similarly, a PCA on variability from joint movements in the lower extremities indicated relatively high intercorrelations ($r = 0.31$–0.71, $p < 0.01$). A pattern of four different variability profiles was indicated in the interrelationship between the upper and lower body. These findings emphasize the value of using innovative measurements and whole-body motion capture to disentangle individual differences in children's movement variability in product- and process-oriented assessments of gross motor competence.

1. Introduction

Gross motor competence can be defined as an individual's ability to perform various movements of several large muscle groups to engage in activities of daily living and physically demanding activities across the lifespan (Barnett et al., 2016; Goodway, Ozmun, & Gallahue, 2019). The term represents the degree to which children can execute fundamental motor skills with task-appropriate co-ordination and quality (Robinson et al., 2015). Globally, it is operationalized through three interrelated concepts: *locomotor* (e.g., run, hop, jump, and slide), *object control* (e.g., kick, throw, and catch) and *stability* (i.e., maintaining balance). Gross motor competence has been systematically linked to many positive health and developmental benefits in children and adolescents (Lubans, Morgan, Cliff, Barnett, & Okely, 2010), including preventing obesity and negative influences on future gross motor coordination (D'Hondt et al., 2014; Niemistö, Finni, Cantell, Korhonen, & Sääkslahti, 2020). Gross motor competence is also found to be important for maintaining an active lifestyle across the lifespan (Barnett et al., 2021; Lubans et al., 2010).

Many decades of work have been devoted to attempting to develop instruments that capture individual differences in children's

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gross motor competence. This work can be broadly classified into two main approaches: The first approach comprises *product-oriented* assessments that focus mainly on quantitative outcomes such as time, distance, or successful attempts (Burton & Miller, 1998; Hulteen et al., 2022). Prominent examples and widely used assessment batteries within this approach are *the Movement Assessment Battery for Children* (MABC) (Henderson & Sugden, 1992), *Bruininks-Oseretsky test of motor proficiency* (BOT) (Bruininks & Bruininks, 1978), and the Körperkoordinationstest für Kinder (KTK) (Kiphard, 1974; Kiphard, 2007). The second approach encompasses *process-oriented* assessments that more closely describe the qualitative characteristics of movement patterns (i.e., how a movement is performed). The *Test of Gross Motor Development* (TGMD) (Ulrich & Sanford, 1985) and *Get Skilled; Get Active* (New South Wales Department of Education and Training, 2000) are well-known tests within this approach, and the TGMD represents one of the most common assessment batteries for gross motor competence in children together with the MABC (Logan, Barnett, Goodway, & Stodden, 2017; Smits-Engelsman, Verbecque, Denysschen, & Coetzee, 2022).

Several integrated theoretical, methodological, and practical issues have been raised regarding the predominant approaches within the assessment of children's gross motor competence (Hulteen et al., 2022; Kennedy, Brown, & Stagnitti, 2013; Palmer, Stodden, Ulrich, & Robinson, 2021). The current and predominant approaches all share a focus on tasks with somewhat down-scaled complexity, detailed instructions, and highly specific assessment criteria, that can typically be performed in a gymnasium or some other specific test facility with isolated contextuality (e.g., static one-leg balance on a small surface). All these are necessary to ensure reliability and experimental control of potential systematic and random errors inherent in assessment procedures (Krippendorff, 1970). However, concerns about ecological validity have been raised regarding this general approach (Hulteen et al., 2022). The motor behavior (and corresponding motor competence level) displayed by children emerges because of the interacting and defining motor, perceptual, cognitive, and affective features inherent in the design of the gross motor assessment. Furthermore, many operational definitions exist to delineate the parameters of skilled/highly competent movements (Button, Seifert, Chow, Davids, & Araujo, 2020; Newell, 1991; Schmidt, 1975). Seen through the lens of an ecological dynamics approach, the interaction between environmental, individual, and task constraints contribute to the level of motor competence displayed by an individual child in gross motor assessment (Button et al., 2020; Handford, Davids, Bennett, & Button, 1997). In ecological dynamics, perception and action are intertwined processes between the individual and the environment (Davids, Araújo, Hristovski, Passos, & Chow, 2012). Thus, different environmental situations and children's perceptions of these environments can alter how they successfully achieve a gross motor task (Golding, Emmett, Iles-Caven, Steer, & Lingam, 2014).

To further discern the importance of ecological validity in the assessment of gross motor competence, the development of task design thus needs to consider how children alter their movements due to balancing individual, environmental, and task constraints. In real-world dynamic environments, children experience multiple requirements inherent to performing a skill; incorporating such features includes a greater emphasis on motor, perceptual, cognitive, and affective integration in a dynamic context. Following the concept of *representative design* conceived by Brunswik (1956), key variables should be sampled from children's everyday experiences to accurately represent environmental simulation incorporated in task designs. The phrase representative (test) design thus refers to the arrangement of conditions in a gross motor assessment, so they represent the motor behavioral setting to which the results are intended to apply. According to Brunswick (1956), children's motor behavior includes coping with multiple, noisy, and messy situations in their environment. By representing aspects of those irregular conditions to a child in motion, the level of competence in achieving a patterned relation with its environment (despite potential uncertainty) can be revealed (Araújo, Davids, & Passos, 2007; Pinder, Davids, Renshaw, & Araújo, 2011).

A second component in capturing ecologically valid assessments of gross motor competence concerns the level of task performance and the way it should be operationalized. Adopting more representative task designs can allow children to apply and adjust different coordination patterns to effectively satisfy the interacting and altering constraints to explore the task. This in turn, allows for the assessment of the child's capability to adapt, modify, and regulate gross movement patterns. Following the ecological dynamics framework, a developing child and the child's corresponding level of gross motor competence are conceptualized through the lens of a dynamical systems viewpoint. Here, skilled movement can be thought of as the control of the many different properties operating within human systems to accomplish the goal of a motor task with consistency (Kelso, 1995; Thelen & Smith, 1994). Indeed, it has long been recognized that human motor systems consist of an extraordinary number of independent biomechanical and neuroanatomical properties (bones, joints, muscles, neurons, etc.) or *degrees of freedom,* which have countless combinations of possibilities (Bernstein, 1967).

According to Bernstein (1967), controlled movements in a specific task can emerge through a strategy of reducing the many possibilities of skill performance to the minimum number required, and this strategy is denominated by *freezing* the degrees of freedom. Alternatively, the degrees of freedom can be released (gradually), a strategy depicted as *freeing* degrees of freedom. In terms of gross motor competence, the first strategy is indicative of simplifying control and less variability in the relationship between movements displayed, the potential goal of the task, and the intentions of the children. The latter strategy alternatively, signifies higher motor competence by having children explore a higher number of degrees of freedom combinations and displaying more variability in task achievement. The nature of children's freezing-freeing of movements as they try to satisfy the interacting constraints in gross motor assessments can therefore be applied to the analysis of whole-body movements to provide a more complete understanding of children's motor repertoire in a specific task. Especially important from a dynamical systems viewpoint, it also considers the inherit inter- and intra-individual variability in human movements (Hadders-Algra, 2010; Hossner & Zahno, 2022): Children might display similarities or differences in overall motor behavior when completing a task, in combination with either similar or different movement strategies (i.e., freezing or freeing of movements) in the same tasks. Adding to the complexity of interpreting the dynamics of children's gross motor movements, it has also been shown that consistency in meeting task goals might be achieved by freezing some degrees of freedom, and at the same time freeing other degrees of freedom (Latash, Scholz, & Schöner, 2002; Scholz & Schöner, 1999). This latter point demonstrates the need to consider the relationship between various features of whole-body movements in the assessment of children's motor repertoire.

The conceptualization of freezing-freeing degrees of freedom as a movement strategy has been systematically linked to various motor skill and task performance levels, as well as being an integrated feature of the motor learning process (Gray, 2020; Guimarães, Ugrinowitsch, Dascal, Porto, & Okazaki, 2020). Across studies and various learning tasks and paradigms, the pattern of freezing DFs in the initial learning phase (lower skill level) towards exploration and freeing DFs as learning progress towards higher skill level has been demonstrated in diverse motor skills such as handwriting (Newell & Van Emmerik, 1989), dart throwing (McDonald, Van Emmerik, & Newell, 1989), skiing on a simulator (Vereijken, Emmerik, Whiting, & Newell, 1992), football kicking (Anderson & Sidaway, 1994), racquetball serve (Smith, McCabe, & Wilkerson, 2001), volleyball serve (Temprado, Della-Grasta, Farrell, & Laurent, 1997), and walking (Sparrow & Irizarry-Lopez, 1987). However, the initial strategy of DF freezing because of lower skill level might not be unique or universal (Berthouze & Lungarella, 2004; Newell & Vaillancourt, 2001), as other patterns of reorganizing DFs as skill develops have also been observed (Chow, Davids, Button, & Koh, 2008; Ko, Challis, & Newell, 2003; Konczak, Vander Velden, & Jaeger, 2009). When applied to the understanding of gross motor competence development, there seems to be a paucity of studies that have examined whether consistent individual differences in children's movements can be captured by the postulated freezing-freeing pattern of degrees of freedom. A notable exception was a study by Palmer, Newell, et al. (2021), Palmer, Stodden, et al. (2021), which demonstrated that 6-year-old children demonstrated freezing of degrees of freedom in a standing overarm throwing task, i.e., smaller range of motion at the ankle and knee joints and greater range of motion at the hip and upper limb joints, compared to 10-year-old children and 14-year-old adolescents.

Assessment of gross motor competence can be depicted as being on opposite ends of a continuum, with static discrete tasks performed in a highly defined environmental context with specifically defined instructions and criteria on one end and the children's exploration of real-world, dynamic tasks performed in high-complexity environments on the other end of the continuum. Occupying a middle ground, however, is the alternative approach of applying *virtual reality* technology (VR). Although it is mostly known as a simulation of an environment used in gaming or movies, VR is increasingly used in health-related research towards rehabilitation and physical/psychological disabilities (Bortone et al., 2018; Ravi, Kumar, & Singhi, 2017; Snider, Majnemer, & Darsaklis, 2010). VR provides a possibility for creating environments in gross motor assessments that might feel realistic and contain features similar to those experienced by children in their daily circumstances. Indeed, VR has demonstrated its feasibility in evaluating learning and transfer of complex skills in e.g., sport science (Harris et al., 2020) and in work with assessment of children with specific motor impairments. In the latter example, movement strategies were found to be better assessed compared to traditional rating scales (Levac, Huber, & Sternad, 2019).

In the current study, a virtual playground scenario (see Figs. 2 and 3) was applied to situate the children in a novel and safe environment where they were allowed to explore without any specific instructions other than "don't fall off." The emergent motor behavior in the VR playground is spontaneous, unpredictable, and self-generated, and thus captures some of the dispositional characteristics of *play*. This is an important feature not previously considered in gross motor task designs for children, and as stated by Hulteen et al. (2022): "*Play is representative of the most ecological context where movement skills may be performed…*" (p. 38). The nature of play involves a potential for variety in exploring degrees of freedom within the boundaries of the task and represents a transaction/interaction between the child and the environment that is internally controlled and potentially free of many of the constraints inherent in other test designs.

Based on the presented considerations, the main aim of the current study was to explore whether consistent patterns of individual differences in children's gross movement variability, conceptualized through the potential freezing-freeing of degrees of freedom, emerges when children explore a virtual reality playground task. Virtual reality provides completely equal novelty in tasks and conditions for every child, in contrast to gathering data outside in a real playground where environmental constraints (weather, wind temperature etc.) especially contribute to different conditions. By situating the playground in a three-dimensional (multimodal) city environment with various task constraints (e.g., height of pillars, lengths/widths/connections of bars) and not providing any specific instructions to move in a particular way, children were expected to explore their individual degrees of freedom as they freely moved around in the playground and tried to satisfy the interacting constraints. As the virtual playground potentially allows for many types of locomotory behaviors and strategies for maintaining balance/stability, it was hypothesized that the emergent features of the whole-body movements would consist of distinct patterns of individual freeing or freezing degrees of freedom.

2. Materials and methods

This study is a part of the larger project, Virtual Risk Management (ViRMa), described in a separate protocol paper (Sandseter et al., 2023). In the present article, we focus on how to capture children's bodily movements in one of the VR scenarios developed in the ViRMa project: a virtual playground designed for children's free movement and exploration.

2.1. Participants

A total of $n = 64$ children from a Norwegian elementary school were recruited to participate in the study (37 boys and 27 girls). Two of the 64 children declined their consent, and two did not complete the test. Four files were missing data from the playground and were excluded in the analysis, giving a final sample of 58 participating children. There were 12 children from 2nd grade, 23 from 3rd grade, and 23 from 4th grade, with a mean age of 8.9 (SD = 0.8) years old. Before participating in the study, children's parents/caregivers signed and approved a digital informed consent and assent from the children. The children had the opportunity to withdraw from the study at any time without any consequences. During the tests, an adult walked close to the child to make the child feel safer and to give the participant the possibility to withdraw immediately. The participants were able to communicate with the researchers in case they felt some tasks were too difficult and wanted to skip to the next task. The study (ViRMa project) was approved by the Norwegian Social Science Data Services (NSD), with project number 324155.

2.1.1. Procedures

Numerous test subjects participated before the data collection to familiarize the researchers with the placement of the equipment. It took approximately 3–5 min to assemble all the equipment, which was transportable and brought to the school for data collection. One researcher went to the children's classrooms, and the children followed the researcher to the gym hall, where all the data was collected. The researcher talked to the child before applying the equipment, and the same researcher walked beside the participant during the VR scenarios. Before starting the task in virtual reality, the participants were instructed to do an N-pose and walk due to the Xsens calibration from the user manual (Xsens Technologies, n.d.). To familiarize the participants with VR, they all performed a practice trial where they walked around in a park with an environment similar to the scenarios before starting the tasks. The participants were instructed by a pre-recorded voice over the headphones giving each child the following command: "Let's start. When you are in the virtual world, the adult is able to hear you. So please tell them if you are feeling unwell, need help, or want to stop. Go to the red square, turn around, and look towards the text." All scenarios were completed in approximately 10–15 min. Following the completion of the VR tasks, a conversation with the child was held, where the children were asked questions about their VR experience and how authentic they perceived it to be.

2.1.2. Equipment [VR headset and Xsens]

The task was done in virtual reality using HTC Vive pro-VR goggles. Children also wore HTC Vive trackers (v3) to be able to see their feet in the VR environment. In the physical environment at the school, an area of 6.4 m × 5.4 m was measured and set up in the gym area with one HTC Vive base station 2.0 placed in each corner (a total of four). The participants were moving within the area that did not consist of any further equipment, as the participants get all the environmental senses in VR (Fig. 1). However, the participant is walking on a flat floor in an empty area in the gym hall, but the experience from VR creates a realistic feeling of different heights and sounds from traffic and birds that influences the child's perception. This also allows exploring challenging and risky situations that are accepted according to the ethical guidelines.

The Xsens Mtw Awinda system collected whole-body movement data from 17 motion trackers (IMUs) placed around the participant's body according to the Xsens user manual (Xsens Technologies, n.d.). The IMUs sample data at 60 Hz and provide 3D kinematics data from position, linear and angular acceleration, and velocity of 23 segments together with 3D joint angles from 22 joints (Xsens Technologies, n.d.). Three orthogonal axes are captured from the IMUs based on the Global reference system where X points to the local magnetic North, Y according to the west, and Z points up.

The trackers were strategically placed to measure the motions of each body segment (Xsens Technologies, n.d.). All participants wore an Xsens t-shirt where three (left and right shoulder and sternum) of the sensors were placed, one sensors on the pelvis, and a forehead sensor, which was placed on top of the VR headset. The other sensors were placed on the right and left side with Velcro straps on the following locations: Palmer side of the hand, lateral side of the upper arm, wrist, lateral side of lower and upper leg and foot. Required measurements of the participant's foot length and body height were gathered and put into the Xsens system before each execution. The Xsens Awinda system ensures highly accurate time-synchronized data and has been determined to be a more reliable tool for capturing human motion compared to a wired inertial system (Paulich, Schepers, Rudigkeit, & Bellusci, 2018). The Xsens Awinda system has been used successfully in sports, physical activity, and rehabilitation research (Al-Amri et al., 2018; Robert-Lachaine, Mecheri, Larue, & Plamondon, 2017).

Fig. 1. picture of the setup with four base stations, and an illustration of how the physical environment looks like.

2.1.3. Playground task in virtual reality

The playground is located in an urban environment; various pillars and planks are placed in a pattern where the participant can move around (see Figs. 2 and 3). The width of the planks at the balancing beam is 20 cm, and the smallest poles have a diameter of 30 cm. The task starts on flat ground with no height difference before the height increases to 80 cm in the first step, 145 cm from the ground and up to the balancing beam on the second step and 235 cm from the virtual ground to the balancing beam at the highest place (See Figs. 2 and 3). The participants get sounds from birds through the headset attached to the VR goggles to facilitate the VR experience and include an environmental constraint that might influence the children's balancing skills and movements. As the playground was located in a city environment with cars and bicycles passing by (see Fig. 3), traffic sounds were also included.

Children receive no instructions other than “Here you can move around on the playground, explore if you want, without falling off” from a pre-recorded voice. The exploration time is three minutes. If the child falls off, the pre-recorded voice will tell that the child has fallen off and they get another attempt to move around freely. Time does not stop, and the children only have three minutes in total, regardless of whether they fall.

All participants initiated the scenario on the flat ground before moving around at the playground where the pillars have different heights and various diameters together with changes in the width of the beams. In order to create a feeling of height, various plateaus have been created. If the children move further out on the playground, they will feel like they are balancing more in height compared to the starting point task. In addition to these different plateaus, the ground is darkened, with spots to create contrasts, and at the end of the playground there is a tree where the leaves hang at height with the stand to give the feeling of being higher above the ground. The playground consists of planks in the colors blue and orange. The colors were chosen to create variation in appearances and to invite movement in the different colors. There are also circles with bubbles that make a sound if the child walk in the circle. These bubbles were only used to create motivation to move around on the play stand.

Fig. 2. Picture of the playground scenario.

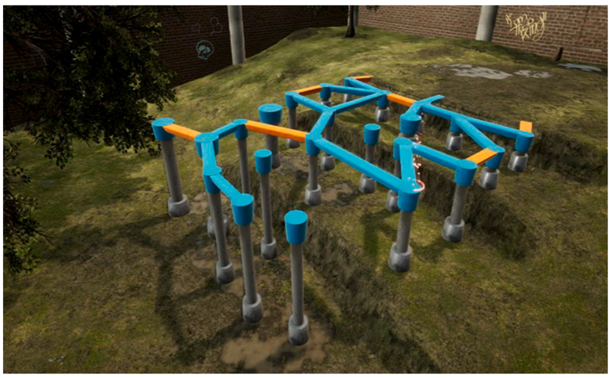

Fig. 3. Picture of the playground scenario.

2.1.4. Movement analysis

Datafiles were reprocessed within the MTv Awinda software (Xsens, Enschede, Netherlands), ensuring that all data were transferred and retransmitted. Raw data were exported and further processed in Matlab R2022a (MathWorks Inc., Natick, Massachusetts, USA) by in-house algorithms. After inspection of the frequency spectrum content of the raw data with the periodogram method, a low pass, zero phase, 4th order, Butterworth filter was applied. Cutoff values for the filter varied between 5 and 15 Hz, depending upon the specific frequency content of the analyzed movements. Visual inspection of data was further applied to ensure that stationary beginning and/or ends (children not moving) of raw signals were removed from further analysis.

There is no consensus in the research literature on how to operationalize movement variability through the lens of Bernstein's concept of freezing-freeing degrees of freedom (Bernstein, 1967); thus, a substantial range of approaches exists (Davids, Bennett, & Newell, 2006; Stergiou, 2018). If one considers the rotational movement (angular displacement) of a specific joint in a kinematic chain, the operationalization of the term *freezing* in an engineering-based approach can imply full locking of the joint (i.e., no movement; Kim, 1998). In the context of human motor control, however, small joint angular amplitudes are typically interpreted as signs of freezing through the restriction of joint movement (Chow, Davids, Button, & Koh, 2007; Hodges, Hayes, Horn, & Williams, 2005; Konczak et al., 2009; Steenbergen, Marteniuk, & Kalbfleisch, 1995). Consequently, higher joint angular amplitudes are thus considered to be signs of freeing degrees of freedom.

In tasks that require predominantly short-duration discrete and ballistic movement phases, joint angular amplitudes are typically measured by the range of motion (ROM), essentially the range between the maximal and minimal joint angular amplitude measured in a movement sequence (Didier, Li, & Magill, 2013; Konczak et al., 2009; Smith et al., 2001; Vereijken et al., 1992). In the current study, however, individual whole-body movement patterns were investigated through the *variability* in freeing/freezing degrees of freedom, as children's movements were measured continuously for 3 min as they freely navigated the balance beam. In this virtual scenario, joint-specific ROM does not capture the continuous and overall variability in children's handling of degrees of freedom. Instead, we applied the standard deviation (SD) across the 3-min epoch as a proxy for freezing-freeing degrees of freedom, computed for each individual joint (se next paragraphs for further description) across the entire movement time series. The standard deviation represents a common metric applied to study variability in joint range of motion and other coordinative patterns (Gray, 2020; Kelso & Zanone, 2002; Rosengren et al., 2009; Wagner, Pfusterschmied, Klous, von Duvillard, & Müller, 2012). The rationale for the current study in line with Bernstein's suggestions, was thus a hypothetical continuum between an overall whole-body freezing degrees of freedom strategy at one end that corresponds to overall lower standard deviations across joints in upper and lower body, towards more release and exploration of a higher number of degrees of freedom available in the motor system at the opposite end in which corresponds to higher whole-body joint-specific standard deviations (Buszard et al., 2020; Guimarães et al., 2020; Vereijken et al., 1992).

The following joint variables were selected to study upper body movement variability: shoulder abduction-adduction, elbow flexion-extension, head yaw, and pitch. Head movements are a key component in orientation, navigation, and visual perception, and thus an integrated part of the perception-action process in locomotion and maintaining balance (Bertenthal & Von Hofsten, 1998; Hollands, Patla, & Vickers, 2002). Active engagement of the arms is also an integrated part of movement strategies for maintaining dynamic stability and balance (Punt, Bruijn, Wittink, & van Dieën, 2015; Wu et al., 2016). Furthermore, the height of the hand segment relative to body height, i.e., lifting the hands, was computed to provide further data on potential dynamic balancing strategies as the children navigated the playground. Lastly, the variability of trunk acceleration was included, as it has been shown to contain important motor control characteristics in relation to movement regularity and symmetry in especially gait research (Moe-Nilssen, Aaslund, Hodt-Billington, & Helbostad, 2010; Moe-Nilssen & Helbostad, 2004).

In the analysis of lower extremities, ankle dorsiflexion-extension, knee flexion-extension, and hip flexion-extension were investigated for joint-specific movement variability. Movement of these joints represents common targets for locomotory analysis, as they contribute to dynamic stability and propulsion (Ko et al., 2003; Winter, 1984). In addition, the distance between foot segments in mediolateral, anterior-posterior, and vertical directions was included. These latter variables are similar to parameters generated by footfall (footprint) analysis, which have previously been shown to detect subtle differences in the variability of locomotory behaviors (Hodt-Billington, Helbostad, & Moe-Nilssen, 2008; Katz-Leurer, Rotem, & Meyer, 2014).

2.2. Statistical analysis

Prior to the main analysis, all variables were tested and confirmed for normality by non-significant Kolmogorov Smirnov tests and inspection of histograms and Q-Q plots (Fig. 4). The relationship between variables was examined with Pearson product-moment correlations, and the dimensional structure of correlation matrices was investigated with principal component analysis (PCA). To preserve statistical power, two independent PCAs were conducted on upper and lower body variability. The Kaiser-Meyer-Olkin measure of sampling adequacy and Bartlett's test of sphericity were applied to examine whether the correlation matrices were appropriate for further factor analysis. After the underlying structure of correlation matrices was established, we applied the following criteria to retain the extracted statistical components: (1) Eigenvalue >1 in accordance with the Kaiser criterion (Yeomans & Golder, 1982), (2) inspection of scree plots (Cattell, 1966), (3) eigenvalues larger than expected for permutations of random data (Horn, 1965),

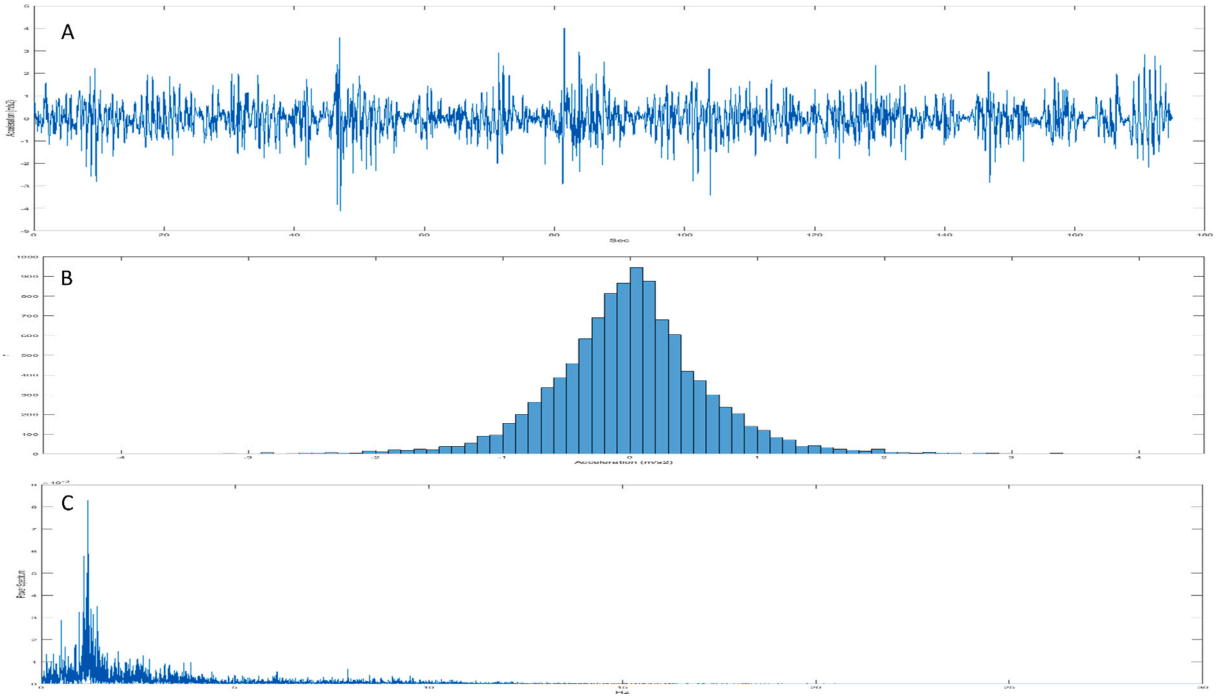

Fig. 4. (A) Representative acceleration timeseries with histogram of corresponding acceleration values (B) and frequency content (C).

and (4) the standard error scree method (Zoski & Jurs, 1996). In the third step of the analyses, factor scores were computed with the Bartlett approach (DiStefano, Zhu, & Mindrila, 2009) representing the shared variance across upper or lower body measures of movement variability, and the relationship between factors scores examined with Pearson correlations. All statistical calculations were performed with the Predictive Analytics Software (PASW, IBM, United States; previously SPSS) Version 29.0 with the criterion for statistical significance at alpha = 0.05.

3. Results

Descriptive statistics can be found in Table 1 (upper body) and Table 2 (lower body). The interrelationship between upper and lower body variability is found in a scatterplot (see Fig. 5). A total of 49 children (80%) found the VR scenarios to be pretty or really realistic.

Table 1
Descriptive statistics, intercorrelations and factor analysis for upper body movement variability.

Movement variability	Mean (SD)	Pearson correlation						PCA	
		1	2	3	4	5	6	F^1	h^2
1. Head – Yaw (deg°)	8.13 (2.52)	1	0.48**	0.39**	0.59**	0.47**	0.46**	0.74	0.55
2. Head – Pitch (deg°)	7.62 (1.86)		1	0.30*	0.41*	0.22	0.31*	0.58	0.33
3. Shoulder (abduction-adduction, deg.°)	7.43 (2.84)			1	0.69**	0.57*	0.42**	0.78	0.60
4. Elbow (flexion-extension, deg.°)	17.22 (7.61)				1	0.47**	0.51**	0.82	0.67
5. Forearm height (%)	2.55 (0.01)					1	0.61**	0.72	0.52
6. Trunk acceleration (m/s^3)	0.75 (0.22)						1	0.74	0.55
						Eigenvalue:		3.22	
						Total explained variance:		53.71%	

F, Factor; PCA, principal component analysis; h^2 are communalities. * $p < 0.05$ (2-tailed); ** $p < 0.01$ (2-tailed).

Table 2
Descriptive statistics, intercorrelations and factor analysis for lower body movement variability.

Movement variability	Mean (SD)	Pearson correlation						PCA	
		1	2	3	4	5	6	F^1	h^2
1. Mediolateral feet distance (cm)	12.61 (2.68)	1	0.62*	0.59*	0.66*	0.46*	0.60*	0.82	0.67
2. Anterior posterior feet distance (cm)	12.20 (2.02)		1	0.52*	0.56*	0.41*	0.70*	0.80	0.64
3. Vertical feet distance (cm)	3.51 (0.71)			1	0.56*	0.66*	0.60*	0.82	0.67
4. Ankle (dorsiflexion-extension, deg.°)	9.57 (1.98)				1	0.36*	0.51*	0.76	0.57
5. Knee (flexion-extension, deg.°)	14.32 (1.84)					1	0.71*	0.74	0.55
6. Hip (flexion-extension, deg.°)	12.06 (2.03)						1	0.86	0.73
						Eigenvalue:			3.83
						Total explained variance:			63.80%

F, Factor; PCA, principal component analysis; h^2 are communalities. * $p < 0.01$ (2-tailed).

3.1. *Upper body movement variability*

The bilateral correlations for movement variability of the shoulder and elbow joints, as well as the variability of the forearm lift, were significantly correlated at $r \geq 0.79$ ($p < 0.001$). Similarly, truncus acceleration was significantly correlated between mediolateral and anterior-posterior variability ($r = 0.95$, $p < 0.001$). Thus, the analysis proceeded with the bilateral average for these measures. The final six upper body variables (see Table 1) were all normally distributed based upon non-significant Kolmogorov-Smirnov tests ($KS < 0.11$, $df = 58$, $p > 0.20$) and inspection of histograms and Q-Q plots. Raw Pearson product-moment correlations across upper body variables that can be found in Table 1 were all significantly correlated, except for head pitch and forearm height ($p > 0.05$). Furthermore, a Kaiser-Meyer-Olkin measure of sampling adequacy at 0.76, and a significant Bartlett's test of sphericity ($\chi^2 = 111$, $df = 15$, $p < 0.001$), thus indicated that the correlation matrix was suitable for factor analysis. Principle Component Analysis (PCA) resulted in a one-factor solution. The factor eigenvalue (above 1 in accordance with the Kaiser criterion), inspection of the scree plot, as well as the standard error scree test indicated that there was only one factor. A Monte Carlo simulation (six variables, 58 subjects, 1000 replications) confirmed that this factor had an eigenvalue larger than expected for randomly generated data. The factor loadings, eigenvalues, and total explained variance are presented in Table 1. It can be found that the retained one-factor solution had relatively high loadings from all factors (range 0.6–0.8).

3.2. *Lower body movement variability*

Similar, to upper body analysis, the bilateral correlations for movement variability of the ankle, knee and hip, and joints were significantly correlated at $r \geq 0.70$ ($p < 0.001$), and the bilateral average was thus computed for further analysis. The final six lower body variables (see Table 2) were all normally distributed based upon non-significant Kolmogorov-Smirnov tests ($KS < 0.11$, $df = 58$, $p > 0.08$), as well as the inspection of histograms and Q-Q plots.

Significant raw Pearson product-moment correlations were found across all upper body variables (see Table 2), and together with the Kaiser-Meyer-Olkin measure of sampling adequacy at 0.80 and significant Bartlett's test of sphericity ($\chi^2 = 181$, $df = 15$, $p < 0.001$) suggested that the correlation matrix was suitable for factor analysis. The PCA on lower body variables indicated a one-factor solution. The factor eigenvalue was >1, in accordance with the Kaiser criterion, and the scree plot, as well as the standard error scree test, also indicated that there was only one factor. Furthermore, a Monte Carlo simulation (six variables, 58 subjects, 1000 replications) confirmed that this factor had an eigenvalue larger than expected for randomly generated data. The factor loadings, eigenvalues and total explained variance are presented in Table 2, and high loadings (≥ 0.74) from all variables were found for the retained one-factor solution.

3.3. *Interrelationship between upper and lower body factor scores*

A scatterplot of the association between upper and lower body factor scores for movement variability can be found in Fig. 1. There was no significant linear relationship between factor scores ($r = 0.25$, $p = 0.06$). However, the results show a possibility for four different movement patterns related to the interrelationship between the variability in the upper and lower body (Fig. 1). Children may use their upper and lower body actively, leading to greater movement variability. In contrast, children may have low variability in both the upper and lower body; this information is illustrated in the scatterplot together with the other two variability possibilities of high variability in lower body and low in upper body and contrasting with high variability in upper body and low in lower body.

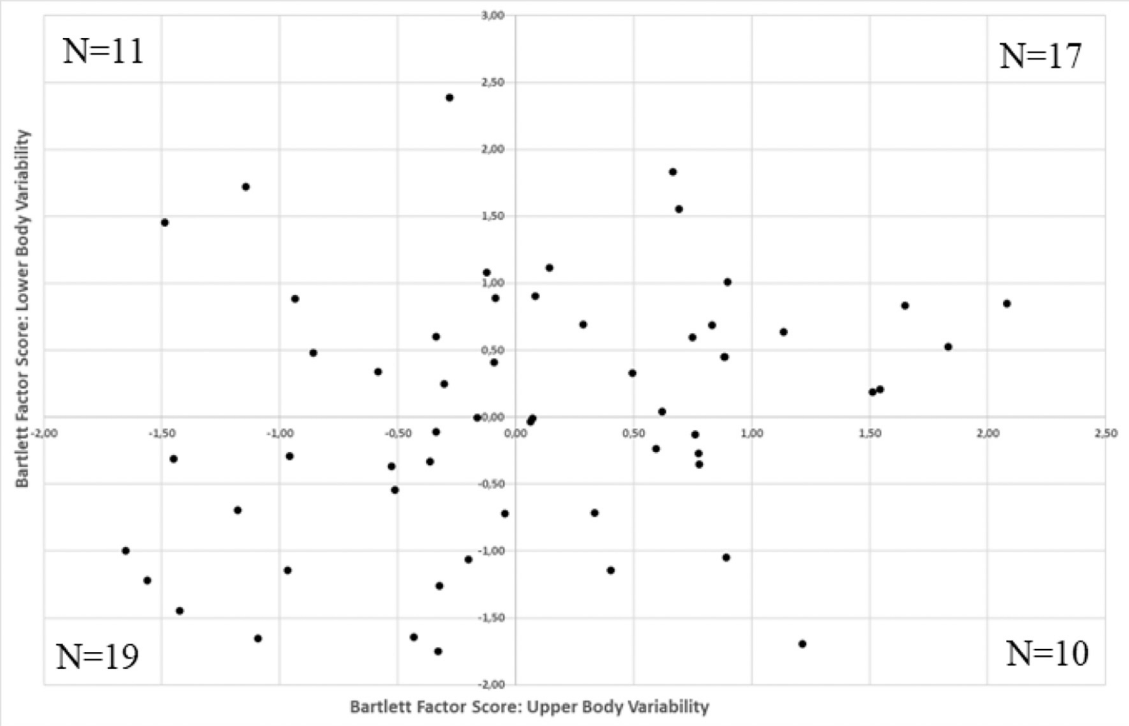

Fig. 5. Scatterplot of the association between upper and lower body factor scores for movement variability.

4. Discussion

The principal aim of the current study was to explore whether consistent patterns of individual differences in children's emergent gross motor movements can be conceptualized through freezing-freeing patterns of degrees of freedom. To this end, whole-body motion capture was conducted on 7–10-year-old children ($n = 58$) as they freely explored a playground task in virtual reality. Correlational and principal component analysis (PCA) on measures of variability of upper extremities (see Table 1), i.e., head, shoulder, elbow, forearm, and trunk movements, indicated significant relationships between nearly all measures ($r = 0.31$–0.69, $p < 0.05$) and a single statistical factor explaining above half of the variance. Similarly, PCA on variability from joint movements in the lower extremities (ankle, knee, and hip), as well as variability of distance between foot segments, indicated relatively high intercorrelations ($r = 0.31$–0.71, $p < 0.01$) and a single statistical component explaining ~2/3rd of the variance. Individual differences in the children's gross motor movements, as operationalized by whole-body measures of movement variability, could further be modeled with two distinct non-correlated components associated with movements of the upper or lower extremities, as a complex and non-linear relationship emerged when correlating factor scores capturing upper or lower body variability (see Fig. 1).

The PCA on the upper body measures of variability indicated a single statistical dimension explaining above half of the variance, reflected in relatively high intercorrelations (see Table 1). This finding suggests that when the participating children navigated the virtual reality playground, a continuum of freezing-freeing degrees of freedom emerged that was represented across upper body measures. That is, if variability is lower in one specific joint, this tends to be followed by reduced variability in other joints or movements. The VR task thus appear to capture individual differences among children in upper body movement, reflected in movement strategies needed for stabilizing and maintaining whole-body stability as they move along the balance beam, e.g., freezing shoulder and elbow joints to maintain arms extended and elevated in a position that assists in maintaining balance. However, the average values for movement variability (Table 1) indicated that the children did not perform excessive head movements, provided the normal range of motion of 130 and 80 deg. for pitch and yaw, respectively. Considering the relatively limited field of view required in the VR balance beam scenario, this is not unexpected, as the children need to focus on their feet and the part of the balance beam structure that is in proximity. There appeared to be more active use of the arms, as the children lifted their arms while balancing. The elbow extension-flexion had a higher average, which may indicate that some children use this joint as a stabilization without lifting the arm so that it would affect the shoulder. Children's elbows may be placed alongside the body and flexed to control unwanted movements or lifted to some extent without using the whole upper body.

The dimensionality of the upper body variability indicated in the current study is according to Bernstein (1967), manifestations of individual differences in the handling of degrees of freedom, and, consequently, indications of differences in motor control. It cannot be said with certainty, however, whether children with higher variability display greater motor control as variations might also occur due to imbalance and a sign of balancing trouble if the shoulders are lifted uncontrolled and difficulties emerge with regulating the body balance. Balancing reactions that involve rapid movements are essential to prevent falls (Maki & McIlroy, 2006) and, in this scenario, avoid falling off. In the playground scenario, the variability in the upper extremities could also be associated with psychological dimensions such as fear of heights and previous experiences that may affect children's movements (Gagen & Getchell, 2006). Still, the current results reflect that the upper body is vital for maintaining balance in locomotion, and that individual differences captured by variation in handling upper body degrees of freedom can indicate variations in emergent outcomes set by the interacting constraints involved in the VR playground.

4.1. Lower body movement variability

Similar to the results obtained for the upper body, the factor analysis on the lower body measures of variability indicated a single statistical dimension explaining nearly two-third of the variance (see Table 2), suggesting an even tighter coupling between freezing/freeing degrees of freedom strategies across measures in the lower extremities. The locomotory pattern demonstrated by the children in the VR scenario was thus reflected by freezing DFs that constrain movements in ankle, knee, and hip joints towards a shuffling/heel-to-toe moving strategy of feet placements reflected in low variability in the three-dimensional distances between the feet (Audu, Kirsch, & Triolo, 2003; Jonsson, Seiger, & Hirschfeld, 2005; Wang, Jordan, & Newell, 2012). At the other end of the freezing-freeing spectrum, higher movement variability of the lower extremities indicates a more complex pattern with more alternating and complex balancing strategies where children need to maintain equilibrium when the whole body's weight is supported by one leg at a time during the swing phase (Assaiante, 1998). These strategies involve an interaction of the force from the muscles on the bones and rotations of several different joints, thus making higher demands on motor control and coordination (Chambers & Sutherland, 2002). For example, children who choose a typical heel-to-toe pattern will have a greater range of motion in the hip than those who display more shuffling of the feet. The lower body movement patterns from the children's navigation of the VR playground thus suggest that individual differences in locomotor skill emerge in the interaction between maintaining forward propulsion of the body and the need to sustain lateral stability of the body (Assaiante, 1998; Winter, 2009).

4.2. Relationship between upper and lower body

As depicted in Fig. 3, no significant linear relationship was found between factor scores representing upper and lower body variability. This clearly illustrates the complex and nonlinear nature of whole-body movement coordination (Button et al., 2020; Kelso, 1995) and might reflect that the VR task allows for substantial variation when children are allowed to express themselves freely and decide how they want to comfortably move around in an open-ended task. However, a close examination of Fig. 1 suggests four overall relationship patterns between upper and lower body variability. First, a subgroup of children ($n = 19$) appears to display lower variability in both upper and lower body compared to the other children in the current sample. This overall pattern of freezing degrees of freedom may indicate a careful locomotor pattern which suggests that these children are very careful when they explore the playground. Bernstein’s (1967) first stage in characterizing degrees of freedom is related to freezing the limb and torso segments in movement execution. A possible explanation for this subgroup's variability might therefore be representative of this first stage of competence, where overall, they freeze their degrees of freedom in order to maintain balance around the playground, with less ability to implement anticipatory control and continuous adaptations to task constraints (Bisi & Stagni, 2020). A more shuffling pattern of movement might be a more secure choice for children with lower motor competence, as it feels more stable when both feet are constantly positioned on the ground.

The second subgroup, with the second highest proportion of children ($n = 17$), was characterized by higher variability in both the lower and upper body compared to the rest of the sample. These children display more dynamic locomotor patterns that put greater demands on gross motor competence, as increased joint range of motion is understood in the literature as a release and exploration of a higher number of available DFs in the motor system (Vereijken et al., 1992; Smith, McCabe and Wilkerson, 2001). It should be noted, however, that more variability in the upper body could also be a sign of uncontrolled movements, for instance, if the child is trying to prevent falling off the balancing beam.

The rest of the children in the sample presented higher variability movements in the upper compared to the lower body or vice versa. The subgroup with low variability in the lower body and higher variability in the upper body ($n = 11$) indicates that the virtual playground can be managed by a shuffling/heel-to-toe pattern of the lower extremities combined with active engagement of the arms and shoulders to regulate the whole-body balance. Thus, for some children, these upper body reactions and rapid movements might be essential to prevent them from “falling off” the virtual balance beams (Maki & McIlroy, 2006). The last subgroup of children displayed higher variability in the lower body compared to the upper body ($n = 10$) compared to the total sample of children. Considering Bernstein's perspective, these children appear to freeze degrees of freedom in the upper body while at the same time to a larger extent freeing their degrees of freedom in the lower extremities. These findings clearly illustrate the nonlinear and dynamic nature of children's gross motor movements and the need to consider whole-body movements. Furthermore, they reflect a neoBernstein perspective on the coordination of DFs, as connecting freezing to lower skill levels might not be a universal feature (Berthouze & Lungarella, 2004; Newell & Vaillancourt, 2001). Indeed, different patterns of reorganizing DFs with skill development have been observed (Chow et al., 2008; Ko et al., 2003; Konczak et al., 2009). Further research appears to be important in disentangling the various emergent patterns of coordinating DFs in shifting environmental and task constraints and their potential significance in understanding the development of young children's gross motor competence.

4.3. Virtual reality and motion capture

VR is an innovative method that has been little used in children's motor competence research. A methodological aspect that informed the design of the current study was the need for measurements that capture children's movements without relying upon highly specific instructions/guidelines, while presenting children with a relatively open-ended and playful task. The assumption was that such a task design would allow individual differences to emerge, and still allow for standardized conditions for everyone. The patterns of movement displayed by children in the current study suggest that innovative approaches such as virtual reality combined with motion capture can assist in better understanding children's movement strategies and their corresponding role in disentangling variation in individual motor competence. Considering Gibson's (1977) theory of affordances, the VR environment allows for a range of possible movement solutions that children must discover and potentially utilize. As motor *competence* is a multidimensional and complex concept, the methodology applied in the current study allows for a stimulating and challenging task where, among other things, children must maintain balance and move from one place to another based on their individual proficiency in locomotor and stability skills (Bardid, Vannozzi, Logan, Hardy, & Barnett, 2019; Niemistö et al., 2020). Furthermore, the VR setup allows for creating an environment with recognizable features and sensations drawn from real-world contexts that can, to a greater degree, appeal to children as they can move around, explore, and play. Previous studies have found that environmental constraints are an essential factor when examining motor competence (Didier et al., 2013; Hulteen et al., 2022). Creating a task that allows children to self-select features such as foot placement, overall movement strategy, posture stabilization, and handling of additional degrees of freedom, contrasts with the assessment of predetermined performance criteria for movement patterns (Gibbons, Amazeen, & Likens, 2019). Thus, children's locomotory and stability skills emerge through their free-movement play and can assist in both product- and process-oriented assessment. Using motion capture systems has indeed been a promising approach for providing a more holistic assessment of children's motor competence (Bardid et al., 2019), and together with VR, provides a different entry point and a possible window into the development of gross motor competence in children to be investigated in further research.

4.4. Methodological considerations and limitations

One primary methodological consideration with the application of virtual reality is to what degree it imitates aspects from the natural environment and how realistic it feels for children. Previously, this technology has been primarily used for creating fiction (Theodoropoulos & Antoniou, 2022), and may therefore be recognized more as a computer game. In the current study, the VR scenario were developed to contain aspects that children might encounter in everyday playful activities, aiming to avoid a gamification approach that might lead children to for instance take greater risks than they typically do outside an VR environment. Although the purpose was to create a more ecological valid environment in VR, especially tactile sensations will differ in contrast to real world applications, as the tactile perception of various surfaces is not yet implemented. Still, attempts were made to amplify the real-world feeling and avoid software game-like objects during the developmental of the scenario, e.g., including familiar surroundings with buildings, cars passing by, and 3D environmental sounds from traffic and birds, and multiple children tested the scenario and provided feedback before the main data collection. In previous research, VR has been used to investigate gross motor functions in children with cerebral palsy and found skill transfers into real-life situations (Massetti et al., 2014) and can thereby be seen as a promising option for environmental simulation in further research.

5. Conclusion

In our study, based upon a modest sample size, principal component analysis of movement variability from whole-body motion capture indicated single statistical factors explaining variance across variability of upper extremities (head, shoulder, elbow, forearm, and trunk movements) and lower extremities (ankle, knee, hip, and movement of the feet) in children 7 to 10 years old freely exploring a virtual playground. Further modeling with the two distinct and non-correlated components associated with movements of the upper or lower extremities indicated a complex and non-linear relationship where four broad sub-groups of children emerged. Those findings suggest that providing children with opportunities for free exploration, as embedded in the VR playground used in our study, can lead to the identification of specific individual differences associated with Bernstein's concept of freezing-freeing patterns of degrees of freedom. Further studies should involve larger samples of children representing different sub-populations, and consider the alignment between virtual reality assessments, perceived motor competence, and in-field evaluations of children's motor competence.

Author contributions

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Conceived and designed the analysis, collected the data, contributed data or analysis tools, performed the analysis, and wrote the paper.

Declaration of Competing Interest

None declared.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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