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BALALI, Marzie, PARVINPOUR, Shahab and SHAFIZADEH, Mohsen <http://orcid.org/0000-0002-7524-1058>

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Effect of motor development levels on kinematic synergies during two-hand catching in children

Marzie Balali[1], Shahab Parvinpour[2], Mohsen Shafizadeh[3]

1- Faculty of Physical Education and Sport Sciences, Islamic Azad University, Iran

2- Faculty of Physical Education and Sport Sciences, Kharazmi University, Iran

3- College of Health, Wellbeing and Life Sciences, Sheffield Hallam University, UK

Abstract The ability to coordinate different body parts under different constraints that are imposed by organism, environment and tasks during motor development might be different in children. The aim of this study was to examine whether children with different motor development levels are different with regard to multi-joint coordination during two-hand catching. Eighty-four children (age: 6.05 ± 0.67years) who were assessed on object control skills were recruited voluntarily. The biomechanical model was defined from 20 movements of 7 segments (shoulders, elbows, wrists and torso), and the principal component analysis was used to quantify the multi-joint coordination and kinematic synergies during the catching. The results showed that the redundancy of joints in two-hand catching is controlled by three kinematic synergies that defined the majority of the variance. The participants that were grouped based on their development levels did not show differences in the numbers and strength of synergies; however, they were different in the utilisation of the kinematic synergies for successful catching. In conclusion, the numbers and the strength of kinematic synergies during two-hand catching are not affected by the developmental levels, and are related to the nature of the task.

Keywords: coordination, children, constraints, task

Corresponding author: Dr Marzie Balali, Faculty of Physical Education and Sport Sciences, Central Tehran Branch, Islamic Azad University, Tehran, Iran. Email: Balalimarzie@gmail.com.

1. Introduction

The fundamental motor skills (FMS) are the building blocks of the advanced sport and recreational skills that should be developed in the childhood because of their significant roles in the later periods of life (Lubans, Morgan, Cliff, Barnett, & Okely, 2010). It is evident that the failure to master the mature level of these skills, as a proficiency constraint, is likely to limit the participation in activities for health or sports (Seefeldt, 1980). For example, it was reported that the development in object control skills of primary school children was strongly associated with physical activity and organised sports in their adolescence years (Barnett, Van Beurden, Morgan, Brooks, & Beard, 2009).

One theory in the study of human motor development is dynamic system theory, as a control model against the traditional theories that emphasise the role of the central nervous system (CNS) as the only system in the body that controls the movements (Kugler, Kelso, & Turvey, 1980; Turvey, 1990). According to this theory, the main challenge during motor development is the way that the motor system controls dimensionality (degrees of freedom; DoFs) in joints, muscles, forces and neural activity in a coordinated manner (Newell, 1986). The emergence of new movement patterns, or refinement of existing movement patterns, are self-organised and occur through interactions of organism, environment and task constraints (Colombo-Dougovito, 2017). The coordination of a multitude of DoFs and the exploitation of redundancy, both at the kinematic and kinetic level, is a key process in the execution of motor skills (Jarque-Bou, Scano, Atzori, & Müller, 2019).

The redundant motor system poses a computational burden to the CNS (Turvey, 1990). One solution is to create a coordination unit named synergies to solve the DoF problem (Bernstein, 1967; Latash & Anson, 2006). Synergies have two important roles in the control of redundant motor systems: dimensional compression and reciprocal compensation (Riley, Richardson, Shockley, & Ramenzoni, 2011). Dimensional compression of synergies refers to the linkages among the independent components by imposing constraints to the independent DoFs so that they change together (Riley & Turvey, 2002). For example, in walking and running, a synergy unit, coordinative structure, emerges between 2 joints (e.g., hip/knee) or segments (e.g., thigh/shank) and imposes constraints to the behaviours of the independent components so that they change together rather than independently (Kelso, 1995). The second characteristic of synergies is reciprocal compensation. Due to interrelationships between the synergic components, they react to each other when it is required (e.g., perturbations). In other words, the motor system through a synergy learns how to co-vary (share) the components effectively to stabilise the performance outcome (Gelfand & Latash, 1998). For example, ball catching with one or two hands requires a combination of coordination and perception (Van Waelvelde, De

Weerdt, De Cock, & Engelsman, 2003). The coordination among different body parts (e.g., legs, torso, head, arms and wrists) are required to move the hands toward the ball (preparation phase), whereas the ball reception at the right place and at the right time (catching phase) is the perceptual-motor requirement of this skill (Cesqui, d'Avella, Portone, & Lacquaniti, 2012; Sekaran, Reid, Chin, Ndiaye, & Licari, 2012). The main task for the CNS is to control the DoFs redundancy, through synergies building to maximise the spatial and temporal accuracy in the hand trajectory (Mazyn, Montagne, Savelsbergh, & Lenoir, 2006).

The type of synergies depends on the nature of coordination (Latash, Gorniak, & Zatsiorsky, 2008). Kinematic synergies are used to describe the inter-joint/segment coordination (Jarque-Bou et al., 2019), whereas muscle synergies are used to describe the coordination among muscles (Krishnamoorthy, Latash, Scholz, & Zatsiorsky, 2003). One way to quantify the multi-joint coordination, kinematic synergy, is the principal component analysis (PCA) method (Jarque-Bou et al., 2019; Latash, Scholz, & Schöner, 2007). The PCA is a statistical procedure that uses an orthogonal transformation to remap a set of correlated variables into a smaller set of uncorrelated variables called principal components (PCs); the number of PCs represents the number of synergies. The highest variance percentage, synergies strength, is found in the first coordinate (first PC), the second-highest variance in the second coordinate, etc. (Witte, Ganter, Baumgart, & Peham, 2010). This method has been used in previous studies to capture the multi-joint coordination in the postural task (Alexandrov, Frolov, & Massion, 1998) and manipulative tasks (Santello, Flanders, & Soechting, 1998).

The strength and numbers of synergy might be changed because of developmental problems (Utley, Steenbergen, & Astill, 2007; Sekaran et al., 2012) and developmental delays (Parvinpour et al., 2019). For example, Parvinpour et al., (2019) identified two kinematic synergies in two-hand catching: one for reaching and one for catching. They also showed that one more synergy, retaining, emerged after the intervention in the transfer test. However, such changes in movement complexity are not visible in the traditional methods of movement assessment. Traditionally, typical development in the FMS is viewed as a stage-like process in which the specific movement pattern is acquired and refined through sequences that were defined by maturation (Haywood & Getchell, 2014; Newell, 1986). This view led to designing the criterion-referenced or normative-referenced tests to assess motor development for clinical screening and intervention. One criticism of such views is underestimating the movement variability, complexity and regularity in the organisation of the movement patterns (Vereijken, 2010). For example, a multi-joint coordination pattern is not easily observable by criterion-referenced or normative-referenced assessments, and its quantification requires access to advanced measurement systems that are measurable by biomechanical analysis (e.g., kinematic, kinetic and coordination).

Quantification of movement patterns generally, and kinematic synergies specifically through biomechanical analysis, help us to test the theoretical principles underpinning the motor development and understand the underlying mechanisms that shape the motor behaviours (Glazier, Wheat, Pease, & Bartlett, 2006).

Despite the conclusive evidence to support the behavioural changes following motor development in two-hand catching (Haywood & Getchell, 2014; Ulrich, 1985), the findings are based on the normative and criterion-referenced assessments, which lack enough information regarding the movement complexity and motor control mechanisms during the development process. The need to understand the motor control through assessing the movement complexity (e.g., kinematic synergies) following natural development even is more important for the tasks with higher complexity, such as two-hand catching (Van Capelle, Broderick, van Doorn, Ward, & Parmenter, 2017). In addition, some studies support the existence of individualised strategies during catching in adults (Cesqui et al., 2012) and children with developmental coordination disorder (Astill & Utley, 2008). For example, the amount of inter-individual variability in catching kinematics such as wrist trajectory, wrist velocity and trunk motion was high (Cesqui et al., 2012). Astill and Utley (2008), in children with coordination disorder, showed that the coupling between transport and grasp phases of the two-hand catching was decomposed and exhibited more inter-individual variability than typical developing children. These findings might suggest that the traditional model for classification of movement quality based on the stage-phase (e.g., initial, elementary and mature) assessment models might obscure the inter-individual variability of control mechanisms in two-hand catching pattern.

In this study, we aimed to examine whether the Kinematic synergies among segments during two-hand catching are associated with the levels of motor development, and whether children with different levels of motor development used the kinematic synergies differently. It was hypothesised that the numbers and the strength of kinematic synergies are different between children with different levels of motor development. We tested this hypothesis through the PCA method to examine whether the individual PC scores (index of synergy) are different between children with different development levels (initial, elementary and mature). We also hypothesised that children use the kinematic synergies differently during the catching task. We tested this hypothesis through a cluster analysis method to classify the children into different groups based on their scores in the kinematic synergies.

2. Method

2.1 Participants

The participants of this study were 84 children (Girls = 64, boys = 20; age: 6.05 ± 0.67 years; stature: 120.5 ± 8.96 cm; body mass: 26.47 ± 8.61 kg) who were selected voluntarily from a nursery school. The children were healthy and without any physical and perceptual problems that could affect their catching skill. The researchers asked their parents to fill the consent form and give their permission to take part in this study. The local ethics committee at the university approved the study.

2.2 Materials

The Test of Gross Motor Development-2 (TGMD-2; Ulrich 1985) was used to measure the proficiency of the participants in the manipulative skills. The test has two main subtests: locomotor and object control. The object control subtest includes six tests such as striking, dribble, catch, kick, throw and roll. If the child meets each performance criteria, he/she will receive one score. The catching skill has three criteria: hands preparation, arms extension and ball caught by hands. The range of score is 0–6.

A developmental sequence model (Haywood & Getchell, 2014) was used to assess the developmental levels of different body components during two-hand catching. This model had three components including arm (A: 1–4 levels), hand (H: 1–3 levels) and body (B: 1–3 levels). The highest level represents the mature stage of development in that body component. In this manner, each child would receive a rank for each component in this skill (e.g., A3H2B1). We further classified them into three levels (initial: A1&2H1; elementary: A3&H2; mature: A4H3). Two experts in motor development evaluated the catching performance of all children. A mean score of the two examiners was considered as a performance profile in catching task. The inter-rater reliability between the two examiners was 0.91. The mean scores of the first examiner and the second examiner were 1.99 (0.59) and 2.02 (0.55), respectively.

Kinematic measures were carried out by a 3D wireless motion capture system (MyoMotion system, Noraxon, USA). This system captured the joint angular displacements during catching through inertial motion unit (IMU) with 9 DoFs; 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer. The joint angle was calculated by the quaternions between the sensors of the adjacent segments. The sensors were attached to the segment by Velcro straps so that the X (Anterior-posterior), Y (mediolateral) and Z (Superior–inferior) were aligned on the segment coordinate system. The segment motion was recorded at the lower back, upper back, head, left and right upper-arms, left and right forearms and left and right hands. In the calibration process, each participant was required to stand still for a few seconds to align all sensors in the coordinate system alongside the reference sensor (upper back).

2.3 Procedure

After determining the development level in the participants, the kinematic measurement took place. The joint motions were analysed during two-hand catching of a ball. All tests were carried out in a quiet room and without any spectator. In the catching task, each participant stood in a specific area (a 50 cm circle) that was located 200 cm from the thrower. The arm was stretched down and relaxed, and the feet were at shoulder-width wide before the start of all trials. The only instruction for the participants was to catch the thrown ball without getting out of the circle. A soft and coloured ball (16 cm diameter) was thrown by underhand throwing pattern to be received centrally between the waist and chest of the participant. Each participant completed 20 successful trials with the same ball. The unsuccessful trials were excluded for the analysis in this study. On average, the participants reached the 20-successful trial criterion after 25 trials. The average ball speed that was thrown by the investigator was 2.63 m/s (0.66).

2.4 Data analysis

The biomechanical model that was created for two-hand catching had 20 DoFs: right and left wrist (2 DoFs: flexion-extension and radial flexion-ulnar flexion), right and left elbow (2 DoFs: flexion-extension and pronation-supination), right and left shoulders (3 DoFs: flexion-extension, abduction-adduction and internal-external rotation), neck (3DoFs: flexion-extension, abduction-adduction and internal-external rotation) and torso (3 DoFs: flexion-extension, abduction-adduction and internal-external rotation). The raw data were sampled at 100 Hz in two-hand catching. The catching time was defined from the start of the hand movement to reach the ball until the ball was trapped completely. The raw data were smoothed using a Butterworth 2nd order low pass filter (10 Hz cut-off frequency) before the calculation of joint angles. Due to differences in catching duration between trials and participants, all trials were interpolated in Matlab 2015 (MathWorks, UK) as a percentage of catching time (0%–100%). Normalised trials for each individual joint angle were averaged for each participant across trials. The joint angles were standardised so that they had zero mean and unit variance.

The multi-joint kinematic synergies during the catching were calculated by the PCA method. This technique, as a reduction method, could group the individual motions into functional units (synergies) as a principal component (PC) that is very useful for quantification of complex movement patterns that require many DoFs (Witte et al., 2010). In addition, this technique is useful to determine the relative contribution (eigenvector) of each joint in shaping the emerged synergies during the action. The orthogonal varimax rotation was used to calculate the total variance (%) and the PC scores during the entire catching. Through this method, a set of correlated variables was remapped into a smaller set of uncorrelated variables (PCs). The number of PCs represents the number of synergies. The highest variance percentage, synergies strength, was found in the first coordinate (first PC), the second-highest variance in the second coordinate. Then, the principal component (PC) load vectors (PC score) were allocated to each time series point. The PC scores are referred to as a correlation between each PC and joints motions. The highest score represents the highest correlation between them. Two criteria were used in the PCA method. Firstly, the saturation level in total variance should be greater than 90% (Deluzio, Harrison, Coffey, & Caldwell, 2014). Secondly, a joint motion could be taken into account as a predictor if the correlation between the PC and joint motion was above 0.50 (Jackson, 1993).

The individual and pooled PCA methods were used in this study. In the individual PCA method, the PCA was used for the mean joint motions of each participant separately. In the pooled PCA method, the mean joints angles of all participants were averaged, and the new PCA was calculated from the mean matrix; 101× 20 [catching time × joint motions]. To test whether TGMD-2 score and kinematic synergies are different between the developmental levels, one-way analysis of variance (ANOVA) was used. The Bonferroni posthoc test was used as a follow-up test if the ANOVA result was significant. A cluster analysis was used to classify the children into different synergies group through the pooled PCA method.

3. Results

3.1 Developmental scores

The results of development scores in the TGMD-2 test showed that the participants mean catching score was 3.58 (1.98). The classification of participants based on the developmental sequence model also showed that they were at different levels of catching development ($N_{Initial} = 34$; $N_{Elementary} = 25$; $N_{Mature} = 25$). The results of ANOVA showed that different development groups are significantly different on the catching score ($F = 43.29$, $p < 0.05$). The post-hoc test results showed that the mature group (5.76 ± 0.52) had significantly higher score than elementary (2.68 ± 1.40) and initial (2.64 ± 1.77) groups.

3.2 Individual PCA on developmental levels

The results of the individual PCA method showed that the participants created three synergies during two-hand catching that captured more than 90% of total variance from a multi-joint coordination pattern. The results of ANOVA failed to show any significant difference ($p > 0.05$) on mean total variance, PC_1, PC_2 and PC_3 scores between 3 development groups (see Figure 1A).

3.3 Pooled PCA and Cluster analysis

The results of the pooled PCA showed that the children formed three synergies with more than 90% of the total variance. The results of PC scores (Figure 2) in different moments of catching in all clusters showed that PC_1 was related to the body preparation towards the ball (reaching synergy), PC_2 was mainly related to the body adjustments before the ball contact (catching synergy), and PC_3 was responsible for keeping the ball after the hand-ball contact (retaining synergy).

The eigenvector values, as a correlation coefficient between each PC and its movements, are presented in Table 1. The highest eigenvector value in each PC represents the most stable movement, whereas the movements with smaller values give more variability to that PC. If the correlation coefficient was ≥0.50, it was included as a synergy component. The results showed that the 'reaching synergy' was mainly composed of upper-limbs movements, whereas the 'retaining synergy' only used the distal limbs of both hands to trap the ball. The 'catching synergy' was composed of shoulders-neck-torso for successful catching.

In the cluster analysis, we defined the number of clusters before analysis based on two criteria: the number of iteration was enough to achieve convergence (no change in the cluster centre), and the sample size in the clusters were not very different. The cluster analysis was completed with three iterations and created three clusters with different sample sizes (C_1: 20%, C_2: 42%, C_3: 38%). As shown in Figure 3, the majority of participants in C_1 had the highest PC_1 score, lowest PC_2 score and average PC_3 score. Thus, this group was known as a group with high PC_1 score. The C_3 was known as the group with high PC_3 score because the majority of participants had the highest score in PC_3 and lowest scores in PC_1 and PC_2. The C_2 group was known as the group with a moderate score in almost all PCs.

4. Discussion

The aims of this study were to examine how the emergence of kinematic synergies among the joints for successful catching is related to motor development levels. The findings showed that the three kinematic synergies that emerged during two-hand catching were not different between children with different levels of motor development. Instead, the children displayed different kinematic synergies based on the task requirements. More specifically, three definitive groups were formed based on the strength of synergies: the reaching-oriented synergy group, catching-oriented synergy group and retaining-oriented synergy group. The following sections further explain the findings of this study.

4.1 Kinematic synergies as a solution for motor redundancy

We used the PCA method to capture the contribution of different joints in the two-hand catching skill. The results of this study showed that the strength of synergy in the two-hand catching that is mainly classified into three functional synergies defined more than 90% of the total variance. The two-hand catching, as a multi-joint movement pattern, requires coordination among the active body parts that are moved in different directions. The control of DoFs in this movement pattern requires that the CNS establish one or more kinematic synergies to use all movement components effectively (Van Waelvelde et al., 2003). Our findings showed that children for the successful execution of the task reduced the DoFs through building synergies (Riley et al., 2011). A recent study on the motor synergies in reaching task showed that the critical period to utilise the elemental variability to stabilise the performance variable (e.g., aiming) was between 5–10 years (Golenia, Schoemaker, Otten, Mouton, & Bongers, 2018). It seems that the children in this study reached this critical period of development and were able to effectively solve the kinematic redundancy by building functional synergies for successful catching.

The organisation of the kinematic synergies to meet the requirements of different phases of catching supports the fact that the synergies are not abstract forms and have a special function in this task (Latash et al., 2007). The emerged synergies that were associated with different parts of the catching pattern could be attributed to one of the main characteristics of the synergies, task specificity, which is essential for neural organisation of the DoFs (Latash et al., 2008). This property gives regularity to the movement pattern despite continuous and simultaneous changes in the joints angles throughout the action (Turvey, 1990). The reduction of joint dimensionality requires that the organization among the units be specified so that the requirements of the main task are accomplished.

4.2 Kinematic synergies are independent of motor development

We compared the strength of the emerged kinematic synergies among pre-determined groups in terms of motor development on two-hand catching and found that there were not any group differences on total variance and any synergy. Despite the children differences in the level of development in manipulative skills (according to TGMD-2 score), the kinematic synergies were not dependent on the developmental levels. In other words, we failed to explain the nature of emerged kinematic synergies based on the current assessment tools for the classification of motor development such as TGMD-2 (Ulrich, 1985) and developmental sequence model (Haywood & Getchell, 2014). Thus, in this study, the emerged kinematic synergies were not determined by organismic constraints, motor development level, in successful ball catchers.

The nature of the kinematic synergies in two-hand catching might be explained by other factors such as inter-individual variability, or might be attributed to preferred control strategies after the acquisition of proficiency in executing this motor skill. We tested this hypothesis through cluster analysis method and found that the children were categorised into three main groups according to their kinematic synergies, regardless of their developmental level. The new-formed groups were characterised merely based on the sequences of the two-hand catching pattern (reaching, catching, retaining). In other words, there was a task-related trend among the children that shaped their preference to utilise the kinematic dimensionality in different phases of the catching pattern. This finding, to some extent, is in contrary to the Cesqui et al. (2012) study that showed that catching kinematics (e.g., wrist trajectory, wrist velocity, timing, trunk motion and catching point) in adults was influenced by inter-individual variability.

By inspection of Figure 3, it can be understood that the children with a strong reaching-oriented synergy preferred to use more variance in the PC_1, and low variance in the PC_2 and PC_3. This type of synergy was found in 20% of the children in this study. The movements that were emphasised in this group were mainly controlled by upper-limb proximal segments, such as shoulders and elbows. As the term implies, the reaching group tried to focus on control of the segments to anticipate the direction and timing of the projected ball. The nature of synergy in this phase of two-hand catching might explain the phylogenetic nature of the synergy that is not affected by the learning process in the development of the FMS. The children with a strong catching-oriented synergy, on the other hand, had the highest variance in the PC_2 and had a moderate variance in the PC_1. These children, who had the highest frequency in this study (42%), used axial movements and shoulders for catching the ball. The catching synergy in two-hand catching requires perception, anticipation and final adjustments in segments before the ball-hands contact (Mazyn, Lenoir, Montagne, & Savelsbergh, 2007). However, active involvements of the torso and shoulders for catching in this group might be explained through the development process or learning opportunities. The retaining-oriented synergy group used the PC_3 tremendously and had a low variance in other PCs. This synergy, which was selected by 38% of the participants of this study, was created only by wrists. One feature that makes catching a relatively difficult task for children is the ability to retain the ball after the contact, which needs a great amount of force absorption after the interception moment (Haywood & Getchell, 2014). Creating synergy for the distal segments in catching have been explained as a difficult ability in children with coordination disorders (Asmussen, Przysucha, & Zerpa, 2014).

The importance of synergies in different phases of the movement pattern might suggest the importance of functional synergies. For example, in the prehensile task like holding a pen and writing, the 2-level synergy was suggested which stabilises the total force. The levels were determined between the thumb and other fingers (Zatsiorsky & Latash, 2008). Tang et al. (2019), in one-hand catching, showed that the coordination between shoulder and elbow was synergised at two levels by four PCs: low-order synergy for acceleration/deceleration of overall movement and high-order synergy for refining the accuracy. They defined the first two PCs as low-order and the last two PC as high-order synergies. It seems that when the complexity of the task requires further control strategy, the needs for additional synergies (high-order) is increased (Côté, Mathieu, Levin, & Feldman, 2002). The inputs for high-order synergy are provided by the task, whereas the low-order synergy acts on the environment (Latash et al., 2008). In this study, we could classify the reaching synergy as a low-order synergy (more phylogenic) and catching and retaining synergies as high-order synergies (more antigenic). It might be interesting to pay attention to this fact that the catching phases of the two-hand catching used more than one synergy (high variance in PC_2 and moderate variance in PC_1), whereas the other phases strongly used a single synergy. Using more synergies in a specific phase of the movement might explain another role of synergies, that of reciprocal compensations when the motor system cannot meet the task demands because of the task difficulty or complexity (Riley et al., 2011). The combined synergies also were reported in a previous study (Santello et al., 1998), and they are named as flexible synergies (Macpherson, 1991).

4.3 Future directions

Classification of children’s ability, based on the kinematic synergies model and its mismatch with developmental levels, might propose a new direction in the assessment and intervention of children in the FMS. The children that acquired the movement pattern to catch the ball successfully cannot be assessed by the traditional methods that use an observational checklist to assess the quality of the movement. This might further mislead the evaluation and classification of motor proficiency (e.g., developmental delays, etc.). The findings of the current study might suggest another method to evaluate the quality of movement based on the coordination of active segments to achieve the goal of the task. Using the current technologies for the field assessment of FMS, such as motion capture systems, is a proper way to quantify the complex movement patterns and multi-joint coordination because the traditional assessment tools, such as TGMD-2, are not accurate to quantify the movement patterns. The need for designing an educational model based on the kinematic synergies also is suggested for both assessment and intervention of the FMS in future studies.

We acknowledge some limitations in this study. The biomechanical model only considered the upper-limbs and torso segments due to the nature of the task (standing still and constant distance between the ball thrower and ball catching). It is possible that the legs also significantly move in variable situations. Future studies could assess the kinematic synergies in two-hand catching in dynamic settings. In addition, such a study could be investigated in a bigger sample size to improve external validity. We only selected the successful attempts for analysis; however, the unsuccessful attempts might require a different control strategy. Finally, the two-hand catching requires a perception-action coupling, and the role of visual perception and attention in successful catching are paramount. Future studies could classify the participants according to their perception and attention score as organismic constraints, and associate the group difference with the kinematic synergies.

5. Conclusion

In conclusion, the children that showed enough competency to catch the ball could utilise the upper-limbs and torso segments as functional synergic units to solve the DoFs problem. The ability to learn how to coordinate the body parts, synergies development, should be the main aim of catching practice in children.

Declaration of interest

The authors report no declarations of interest.

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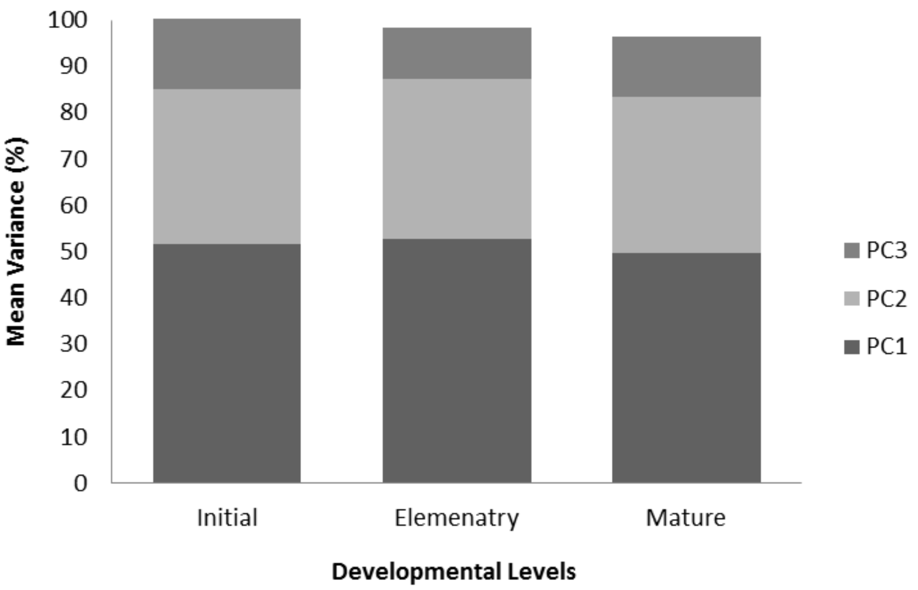
Table 1- The correlation coefficient (eigenvectors) between movements and synergies.

Synergy		
Reach	Catch	Retain
L. Shoulder Ext Rotation(0.99)	R. Shoulder Flexion(0.99)	L. Wrist Extension (0.84)
R. Shoulder Ext Rotation(0.98)	L. Shoulder Flexion(0.98)	R. Wrist Extension (0.70)
L. Forearm Supination(0.97)	Torso Flexion (-0.91)	
R. Shoulder Abduction (0.96)	Torso Rotation (-0.88)	
L. Shoulder Abduction(0.96)	Neck Lateral Flexion (0.86)	
Neck Flexion(-0.95)	Torso Lateral Flexion (-0.83)	
R. Wrist Radial Flexion(0.87)	Neck Rotation (0.68)	
L. Wrist Radial Flexion(0.87)		
R. Elbow Flexion(-0.86)		
L. Elbow Flexion(-0.85)		
R. Forearm Supination(0.80)		

A



B

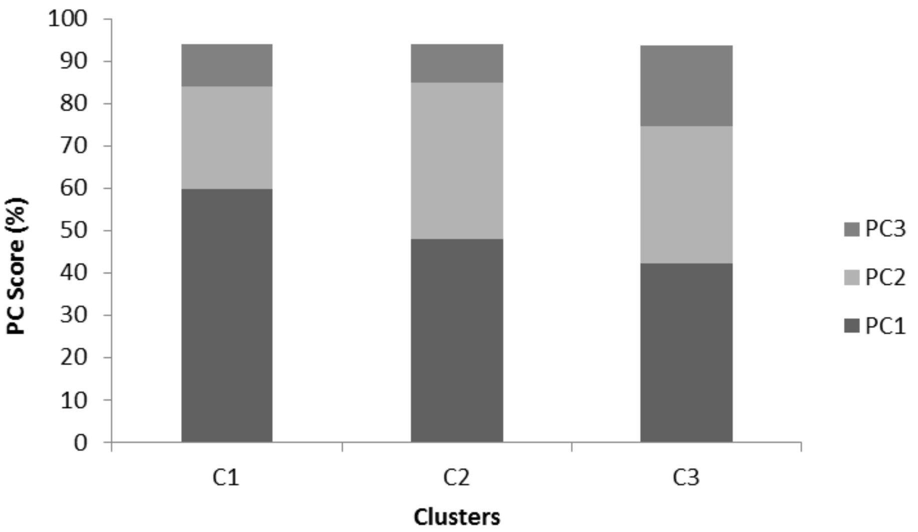


Figure 1- The PC scores of different groups in two-hand catching.

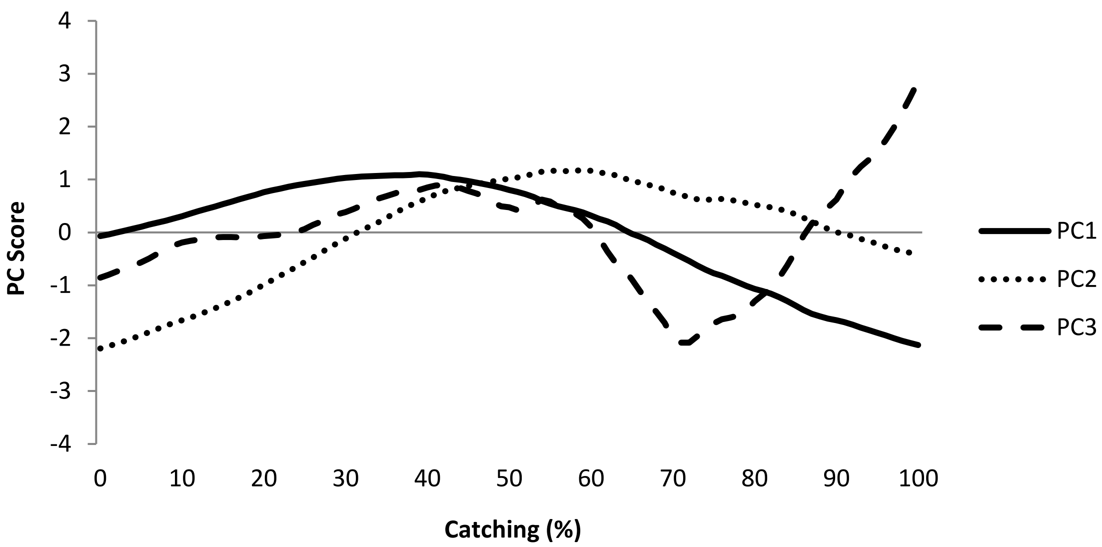


Figure 2- PC scores in different moments of catching in all clusters.

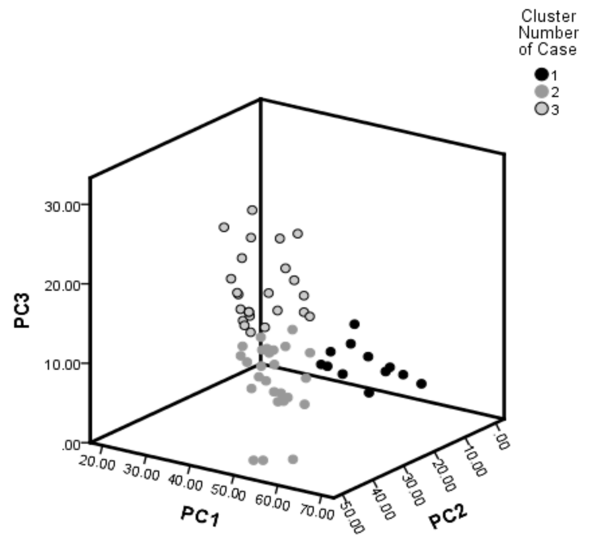


Figure 3- Distributions of participants in different clusters according to 3 PC scores.