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ARTICLE

Effects of Developmental Task Constraints on Kinematic Synergies during Catching in Children with Developmental Delays

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ABSTRACT. The aim of this study was to examine effects of a task intervention on kinematic synergies in catching. Participants were young children (5.58 ± 0.52 years) with the lowest scores on two-hand catching, according to assessments with the Test of Gross Motor Development-2 (TGMD-2) and were allocated into two groups. The constraints group took part in an 8-week intervention, whereas the control group experienced a typical physical education. Both groups were assessed with motor development and kinematic coordination measures with a catching task with a ball thrown from 2 m distance. Kinematic variables were recorded using a wireless motion capture system. A principal component analysis (PCA) was used to measure the kinematic synergies formed among active body parts. Two synergies that emerged in catching were mainly utilised for “reaching” and “catching” the ball. The control group tended to re-organise the majority of active body parts into two functional units in all phases, whereas the constraints group adapted their active parts into functional units according to the requirement of the novel movement in the transfer task. The findings of this study suggested that task constraints could facilitate object control by re-organisation of active body parts into functional synergies to achieve successful performance.

Keywords: Motor development, object control skills, fundamental movement skills, emergent synergetic pattern, task interventions

INTRODUCTION

Early childhood is considered a sensitive period for the development of fundamental motor skills (FMS). The FMS are deemed to provide a foundation for acquisition of specialised motor skills during late childhood and adolescence (Hulteen, Morgan, Barnett, Stodden, & Lubans, 2018), and have a significant role in supporting the participation of children and adolescents in sports and recreational activities (Luban, Morgan, Cliff, Barnett, & Okely, 2010).

The mastery of FMS has been associated with a more active lifestyle and physical, cognitive and social development during childhood (Stodden et al., 2008; Payne & Isaacs, 2012). It has been suggested that failure to master advanced FMS might act as a proficiency barrier, which prevents some children from participating in individual and team sports in later life (Seefeldt, 1980). In this way, movement competency may be viewed as an 'enabler' for future participation in sport, physical activity and exercise. Indeed, greater competency in FMS is associated with better overall health outcomes, such as a lower body mass index and greater aerobic fitness (Luban et al., 2010; Veldman, Jones, & Okely, 2016). A positive correlation between mastery of FMS and level of physical activity has also been observed in children and adolescents (Cliff, Okely, Smith, & McKeen, 2009; Jaakkola et al., 2019). For example, Barnett, van Beurden, Morgan, Brooks, and Beard (2009) showed that object control skills of primary school children were strongly associated with participation in physical activity and organised physical activity in their adolescence years.

The ontogenetic nature of FMS exposes their development subject to the influence of environmental constraints that shape adequate practice experiences, learning opportunities and motivation during the developmental process (Newell, 1986). According to the constraints-led approach, the emergence of FMS is constrained by interactions between organismic (personal), environment and task properties (Newell, 1986). Children not exposed to rich learning environments might display delays in the development of FMS (Goodway & Branta, 2003). For example, it has been reported that children from disadvantaged backgrounds display developmental delays in FMS (Altunsoz & Goodway, 2015; Brian & Taunton, 2018), consequently leaving them at greater risk of health problems and poor social, emotional and cognitive development across the lifespan (Majnemer, 1998) that might require interventions to compensate for delayed development in physical functioning and motor skills (Dweck, 1986; Stodden et al., 2008; Valentini & Rudisill, 2004).

Ball catching is an object manipulating task and a prerequisite for performance in many team sports, which requires perceptual-motor skill and spatiotemporally coordinated actions for successful performance (Van Waelvelde, De Weerdt, De Cock, and Smits Engelsman,

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2003). The coordinated (re)organisation of joint degrees of freedom (DoF) (e.g. shoulders and elbows extension, wrist and fingers flexion) needs to emerge in order to move the hand towards the ball (preparation) and successfully catch the ball (reception) at the right place and at the right time, whilst maintaining upright postural control (Cesqui, d'Avella, Portone, & Lacquaniti, 2012; Davids, Kingsbury, Bennett, Jolley & Brain, 2000; Sekran, Reid, Chin, Ndiaye, & Licari, 2012). The re-organisation of DoFs in active body parts to achieve the catching task goal is facilitated through use of effective strategies to maximise the spatial and temporal accuracy in the hand trajectory (Mazyn, Montagne, Savelsbergh, & Lenoir, 2006). It seems that the central nervous system (CNS) is able to scale the spatiotemporal parameters (hand velocity, interception point) by re-organising the DoFs into synergic units (Słowi~nski et al., 2019). In other words, the complexity of this movement is determined by the abundance of DoFs in active body parts (Bernstein, 1967), since there are functional synergies formed by some body parts which are fundamental to successful performance. The search for, and formation of, functional synergies among relevant joints and limb segments emerges during mid-childhood (5–10 years) which could be a functionally relevant period for implementing task interventions (Golenia, Schoemaker, Otten, Mouton, & Bongers, 2018).

A functional synergy is one that might be re-organised because of developmental challenges (Utley, Steenbergen, & Astill, 2007). For example, it has been reported that children with developmental coordination disorder (DCD), relative to children with typical development pathways, display greater asymmetry in elbow flexion-extension (Sekran et al., 2012) and freeze movement system DoFs, with a smaller range of motion in the joints (Utley et al., 2007) during two-hand catching. However, biomechanical adaptations in children with developmental delay (DD) in two-hand catching have yet to be studied. These children tend to display low competency scores in FMS in those skills that require coordination between upper limbs, between trunk and limbs, and in contralateral actions (Foulkes et al., 2015). These observations might suggest an issue in coordination strategies to organise the motor system DoFs in children with DD.

The development of object control skills generally, and two-hand catching specifically, follows a specific stage-like process in which the organisation of action in different limbs is refined to reach what is deemed to be a mature level (Gallahue, Ozmun, & Goodway, 2012). For example, the coordination of the arms is refined to reach the ball by extending the shoulders and elbows in a synchronised way. These changes are significant because they do not actively contribute to the reaching phase at the initial stage. The hands that are held in a 'palms up' position require more adjustments in response to the ball position at the mature stage. The speed of development in catching actions can be enhanced by task-related interventions (Altunsoz et al., 2015). According to the ecological dynamics theoretical framework, providing appropriate affordances (opportunities or invitations for actions), through manipulating constraints in performance environments, can help children with DD to advance the skills that are not developed at the same rate as children with typical development (Gallahue et al., 2012). Recently, Słowi~nski et al. (2019) demonstrated, in children with DCD, that participating in a short-term, gaze-training intervention improved coordination and facilitated the self-organisation of the multi-joint system in a catching task. In another study of catching and gaze training in children with DCD, Wood et al. (2017) also showed that quiet eye training could act as a remedial therapy to enhance visual perception for hand tracking in a catching task. The effectiveness of remedial or practice interventions to improve catching performance in children with DD has also been evident. For example, Kirk and Rhodes (2011) in a systematic review (n ¼ 11 studies) on the effectiveness of motor skill interventions on FMS in children with DD showed a significant increase in object control score (above the 50th percentile) following the interventions, and the participants reached the similar level of object control as typically developing children. In another systematic review study (Riethmulle, Jones, & Okely, 2009), the efficacy of a motor skills intervention in pre-school children was demonstrated, and the improvement in FMS scores was attributed to intervention duration (longer than 8 weeks and more than three sessions per week). The duration of interventions (6–12 weeks) was also emphasised as a significant determinant of remedial programmes in development of FMS, in a study of children from disadvantaged settings (Brian, Goodway, Logan, & Sutherland, 2016). The role of environmental factors such as access to equipment and space and task-related factors such as developmentally appropriate interventions and theoretically driven intervention models have also been emphasised as key factors in the development of FMS in children with DD (Kirk & Rhodes, 2011). Despite the evidence to support the significant role of task constraints interventions on development of FMS in both typically developing children (Riethmulle et al., 2009) and children with DD (Kirk & Rhodes, 2011), the main outcome measures reported in these studies were normative motor skill test scores that may lack functionality and enough depth and accuracy to evaluate the quality of diverse movement patterns. For example, the TGMD-2 that has been used in many studies only has 3 criteria for assessing two-hand catching skill performance. Indeed, the regulation of a two-handed catch requires proficiency in coordinating many DoFs, involving their

spatiotemporal (re)organisation, for successful performance that is not considered in normative motor skill tests.

Recently, two-hand catching has been analysed in some studies by assessing kinematic parameters in children with DCD (Sekran et al., 2012; Utley et al., 2007), but little is known about the kinematic adaptations following developmentally task-related interventions in children with DD. There are two clear reasons for investigating skill adaptations in two-handed catching in DD participants. First, understanding the biomechanical changes along with normative development scores following a specific intervention in children with DD could provide clear insights on the role of the CNS in the adaptive configuration of body parts in emerging the kinematic synergies. Second, designing an intervention strategy according to a sound theoretical framework (e.g. such as an ecological dynamics rationale for motor synergy formation) could help practitioners to understand the nature of developmental delays in children (re)organising a complex movement pattern that requires perception-action coupling and multi-joint coordination. Thus, the aim of this study was to examine the effects of a developmental task constraints intervention on kinematic synergy formation in children with DD during two-hand catching performance.

METHOD

Participants

Seventeen children (Girls: 10, boys: 7; age: 5.58 ± 0.52 years; height: 115±5.6cm) participated in this study. Initially we identified 30 children, but due to their personal circumstances only 22 children were able to participate in the pre-test. We grouped them according to the TGMD-2 score into intervention (n ¼ 12) and control (n ¼ 10). Five children in the control group left the school or missed the post-test session due to a variety of circumstances beyond our control, and we completed the post-test with 17 children (12 vs. 5). Permission for participation was sought from their parents or guardians. All participants were right-handed. According to normative scores on the TGMD-2 test, they were ranked below the 30th percentile score in manipulative skills and were categorised as children with developmental delays in manipulative skills. The demographic measures and development scores of the participants are presented in Table 1. A developmental sequence model (Haywood & Getchell, 2005) has been used to assess the developmental levels of different body components during two-hand catching. The allocation of participants into control (n ¼ 5) and constraint manipulation (n ¼ 12) groups was carried out according to their score on the TGMD-2 test in the pre-test phase (ABBA method). The participants were ranked from the high to low based on these scores, and then the odd and even rank numbers were allocated to the control (A) and the intervention (B) groups, respectively. The children were apparently healthy and without any physical and perceptual problems that could affect their catching skill performance. Parents or guardians were asked to avoid any change in the activity levels of children throughout the study. The local ethics committee at the university approved all stages of the study.

Measurements

Proficiency in the manipulative motor skills was determined by using the TGMD-2. This test is a reliable and valid test to measure the FMS proficiency in different age groups (Ulrich, 1985). The object control subtest includes six components such as striking, dribbling, catching, kicking, throwing and rolling a ball. If a child meets each performance criteria, he/she will receive one score (1 score was allocated to each catching criterion). The catching skill has three criteria: hands preparation; arms extension; ball caught by hands. The range of score is 0–6, with 0 reflecting lack of development and six representing development in catching performance.

A developmental sequence model (Haywood & Getchell, 2005) was used for qualitative measurement of catching performance in the pre-test and post-test. This method has three components related to the arm (A: levels1-4), hand (H: levels1-3) and body (B: levels 1-3). The highest level (developmental score) represents the mature stage of development in that body component. For example, a child who shows extended arms to meet an object with the hands, and catch a ball, is recorded at level 4 for the arm component of the catching action. If the child extends the arms forward but moves under the object (scoop) and the ball is trapped against the chest, this performance is considered as level 3. In this manner each child would receive a rank for each component in this skill (e.g. A3H2B1). Two experts in motor development evaluated the catching performance of all children in pre-tests and post-tests. A mean score of the two examiners was considered to represent a valid performance profile in the two-handed catching task.

A 3D wireless motion capture system (MyoMotion system, Noraxon, USA) was used to analyse the joint angular displacements of participants during catching. The system consists of nine inertial motion units (IMUs) with nine DoFs (three-axis accelerometer, three-axis gyroscope and magnetometer). Joint angles during catching performance were obtained by calculating the Euler angle (X-Y-Z sequence) between the sensors of the adjacent segments. The sensors were attached to the limb segment by Velcro straps such that the x-, y- and z-axes pointed anteriorly, to the participants left. Sensors were attached to 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 sensor coordinate systems to the reference sensor (upper

TABLE 1. Demographic measures and development scores of the participants.

Participants	Group	Height (cm)	Age (years)	TGMD-2 Manipulative Raw Score	Age Equivalence (years)	TGMD-2 Catching Score (Pre-test)	TGMD-2 Catching Score (Post-test)	Developmental Level-Pre	Developmental Level-Post
1	Control	124	5.7	13	3	2	3	A3H1B1	A3H1B1
2	Control	117	5.1	9	3	1	1	A2H1B1	A2H1B1
3	Control	114	5.4	8	3	3	3	A3H2B1	A3H3B1*
4	Control	107	5	4	3	2	2	A2H2B1	A2H2B1
5	Control	115	5.2	7	3	2	2	A2H1B1	A2H1B1
6	Constraint	119	5.1	22	3.9	2	4	A3H2B1	A4H3B2*
7	Constraint	110	5.2	7	3	1	2	A3H2B1	A3H3B1*
8	Constraint	119	5.7	6	3	1	3	A3H1B1	A3H2B2*
9	Constraint	108	6	21	4.3	0	5	A2H1B2	A4H3B3*
10	Constraint	125	5.7	6	3	0	5	A1H1B1	A4H3B1*
11	Constraint	111	6.4	6	3	0	6	A3H1B1	A4H3B2*
12	Constraint	117	6.5	6	3	1	2	A3H1B1	A3H2B1*
13	Constraint	107	5.4	6	3	0	2	A1H1B1	A3H1B2*
14	Constraint	111	4.9	16	3	0	0	A2H1B2	A3H1B2*
15	Constraint	122	6.6	5	3	3	6	A3H1B1	A3H2B1*
16	Constraint	115	5.5	8	3	0	1	A3H1B1	A3H1B2
17	Constraint	114	5.5	10	3	0	2	A1H1B1	A3H1B2*
Mean		115	5.58	9.41	3	1.05	2.82		
SD		5.6	0.52	5.4	0.35	1.08	1.84		

Developmental levels in Arm (A1-A4), Hand (H1-H3) and Body (B1-B3) components. Participants who progressed the two-hand catching pattern from pre-test to post-test at least in arms or hands components are presented by asterisks (*).

back). The raw data were sampled at 100 Hz from the start of the hand movement (greater than zero velocity) to reach the ball until the ball was trapped completely in the hands (zero velocity).

Task

In each session, and after 5 min general warm up, the participants in the intervention group took part in specific tasks that were designed for improving two-handed catching behaviours. The tasks were designed based on the pedagogical principles of nonlinear pedagogy to afford different opportunities for motor learning, using manipulations of task constraints, with minimum explicit instructions (Chow, Davids, Button, & Renshaw, 2016). As shown in Table 2, the tasks were changed on a weekly basis to enhance the learning experiences of participants. The key changes in task features were using balls with different sizes, shapes and textures, varied practice organisations such as individual, dyadic and group games, and changing the distance and interactions with other objects and equipment (e.g. hoops).

Procedure

The intervention took place in a familiar playground that was appropriate in terms of dimension and safety. The constraints manipulation group took part in an 8-week developmentally-appropriate programme which involved manipulation of key task constraints, repeated in two sessions of 30-min each per week. Two experienced staff members in motor development and physical education at early childhood levels supervised the intervention programme to engage the children in different tasks. The control group throughout the intervention period only participated in typical physical education programme lessons that were a mainly planned for practising basic gymnastic skills without any opportunity to practice manipulative skills. The constraints manipulation group also participated in their typical physical education programme. The physical education programme was one session per week which lasted one hour and in total both groups completed 8 sessions throughout the intervention period.

Assessments Setup

All tests were carried out in a quiet room onsite in a nursery school that was familiar to all participants. Participants met the examiners individually for all assessment tests and each individual stood in a specific area (a 50cm circle provided by a hoop) that was located 200cm from the thrower. A digital camera (Canon PC1742, Japan) was also used for video analysis of the

TABLE 2. Equipment, tasks and variations of the intervention.

Week	Equipment	Tasks	Variations
1	• Inflated beach ball (diameter: 50cm)	• Children in dyads caught and threw the ball while face each other and constrained by hoops	▪ Distance between hoops
2	• Big soft cloth ball (diameter: 22cm) • Small soft cloth ball (diameter: 11cm)	• Children in dyads caught and threw the ball while face each other and constrained by hoops	• Distance between hoops • Balls
3	• Inflated beach ball	• Children in dyads caught and threw the ball over a net placed between them while face each other and constrained by hoops	▪ Distance between hoops
4	• Big soft cloth ball ▪ Small soft cloth ball	• Children in dyads caught and threw the ball over a net which was placed between them while face each other and constrained by hoops	• Distance between hoops • Net height • balls
5	• Big soft cloth ball	• Children in dyads caught and threw the ball through a hoop (diameter: 50cm) which was placed between them while face each other and constrained by hoops	▪ Distance between hoops
6	• Big soft cloth ball ▪ Small soft cloth ball	• Children in dyads caught and threw the ball through a which was placed between them while face each other and constrained by hoops	• Distance between hoops • Hoop height • balls
7	• Big soft cloth ball ▪ Small soft cloth ball	• Children in dyads caught and threw the ball through two hoops in different heights which was placed vertically between them while face each other and constrained by hoops.	• Distance between hoops • Hoops height • balls
8	• Soft cloth balls in different sizes and forms (sizes range from 5 to 11 cm in diameter) ▪ Soft cloth cube of 10 cm	• Children in turn was placed in a hoop which was placed in front of practitioner and caught thrown balls or cubes that passed through a vertical hoop which was placed between them	• Distance between hoops • Hoop height • balls • cubes

catching pattern. It was placed 3 m to the right side of the catching area between the catcher and thrower. The only instruction for the participants was to catch the thrown ball without moving out of the hoop. The ball (soft, coloured texture; 16cm diameter) was thrown using the same underhand throwing technique to be received centrally between the waist and chest of the participant. Each participant completed 10 successful trials in the pre-test and post-test with the same ball. The unsuccessful trials were excluded for the analysis in this study. On average, participants reached the 10-successful trial performance criterion after 12 trials. In the transfer task, a new ball (inflatable PVC; 16cm diameter) was used. The two balls (post-test and transfer task) were different in terms of the bouncing height (no bounce vs. 65 cm bounce) when they were dropped from a 1 m height, reflecting a difference in their coefficient of restitution. The number of trials in the transfer task was five successfully performed trials. For both groups, the pre-test was carried out a week before the intervention period and the post-test and transfer tasks were carried out a week after the intervention.

Data Analysis

The TGMD-2 test and developmental sequence modelling were conducted separately in the pre-test and the post-test. The kinematic analysis by the motion capture system was carried out at three stages including at pre-test, post-test and transfer task.

The motion capture system collected data on the joints motions in all axes. The biomechanical model that was created for two-hand catching had 14 DoFs: right and left wrist (2 DoFs: flexion-extension; radial flexion-ulnar flexion), right and left elbow (2 DoFs: flexion-extension; pronation-supination), right and left shoulders (3 DoFs: flexion-extension; abduction-adduction; internal-external rotation). Due to hand acceleration and deceleration, the raw data were smoothed at 10Hz cut-off frequency using a Butterworth second-order low pass filter before the calculation of joint angles. Due to differences in movement duration between trials and participants, all trials were interpolated in Matlab (Matlab, 2015a, The Mathworks) to 101 data points (0–100%). Then the standardised trial values for each individual joint angle were averaged for each participant across trials for each test phase.

A principal component analysis (PCA) was used to quantify the multi-joint kinematic synergies during the catching. This technique grouped the individual joint motions into functional units (synergies) as a principal component (PC), which is very useful for quantification of complex movement patterns that require continuous (re)organisation of many DoFs (Witte, Ganter, Baumgart, & Peham, 2010). In addition, this technique is useful to determine the relative contribution (eigenvector) of each joint motion in shaping the emergent synergies during the organisation of action. The orthogonal varimax rotation was used to calculate the total variance and the PCs during the entire catching action. To avoid changes in the PC results caused by different ranges of motion of different joints, joint angles were standardised so they had zero mean and unit variance. The pooled PCA method was used in this study. The mean joints angles of all participants were averaged for each group and the new PCA (pooled) was calculated from the mean matrix; 101 x 14 [catching points x joint motions]. This method was used for each phase test (pre, post and transfer). Then, principal component (PC) load vectors were allocated to each time series point. The eigenvectors (PC loading vectors) are referred to an association between each PC and joints motions. Two criteria were used in the PCA method. First, the total variance should be greater than 90% (Deluzio, Harrison, Coffey, & Caldwell, 2014). Second, 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).

To examine the effect of intervention and group on developmental scores, a two-way chi-squared test (group x time), and an independent t test was used to compare the score change (post-pre difference) on the catching score between two groups at 95% confidence interval was used.

Results

The demographic data on participants are presented in Table 1. Results of the development scores on the TGMD-2 showed that the participants' age equivalence in manipulative skills (3 ±0.35 years) was lower than their chronological age (5.58 ± 0.52 years).

Developmental Score

The developmental score in two-hand catching in the pre-test showed that three participants were at level-1, five participants were at level-2 and nine participants were at level-3, when assessing the arm movement component. The majority of participants (n = 13) were at level-1 and only four participants were at level-2 in the hand placement component. The majority of participants (n = 14) were at level-1 and three participants at level-2 in the body movement component.

The results of statistical analysis by t tests showed that catching performance significantly changed ($t= 2.91$, $p < .05$) following the intervention in the constraints manipulation group (2.5 ± 1.88), but not in the control group (0.4±0.51). The results of the two-way chi-squared test showed that there was a significant difference ($V^2 = 6.08$, $p < .05$) between groups in the number of participants who progressed to the upper performance levels in using arm and hand components for catching, from the pre-test to the post-test. In other words, 11 (90%) participants in the constraints manipulation group progressed to the upper levels of performance at least in arm and hand components, whereas in the control group only 1 (20%) participant progressed to the upper level (see Table 1).

Principal Component Analysis

The PCA method was used to quantify the contribution of different joint motions (DoFs) during performance of the two-hand catching task. This method was used to identify the type of coordination patterns that emerged among the joints, through converting the individual DoFs to functional synergy units. Two main synergy scales in this method are synergy function (PC variance) and synergy configuration (eigenvector values).

The average joint motions during two-hand catching in different test phases are presented in Figure 1 for the control and constraints manipulation groups. The reorganisation of upper-limb joints during catching showed a similar pattern between groups and among test phases. In addition, both groups organised a multi-joint movement pattern using shoulder, elbow and wrist joints to catch the ball successfully before and after contact with the ball.

The results of PCA showed that the catching pattern could be decomposed into two main kinematic synergies in the pre-test and post-test phases in the two groups. The only difference between the groups was in the number of synergies that emerged in the transfer task (see Table 2).

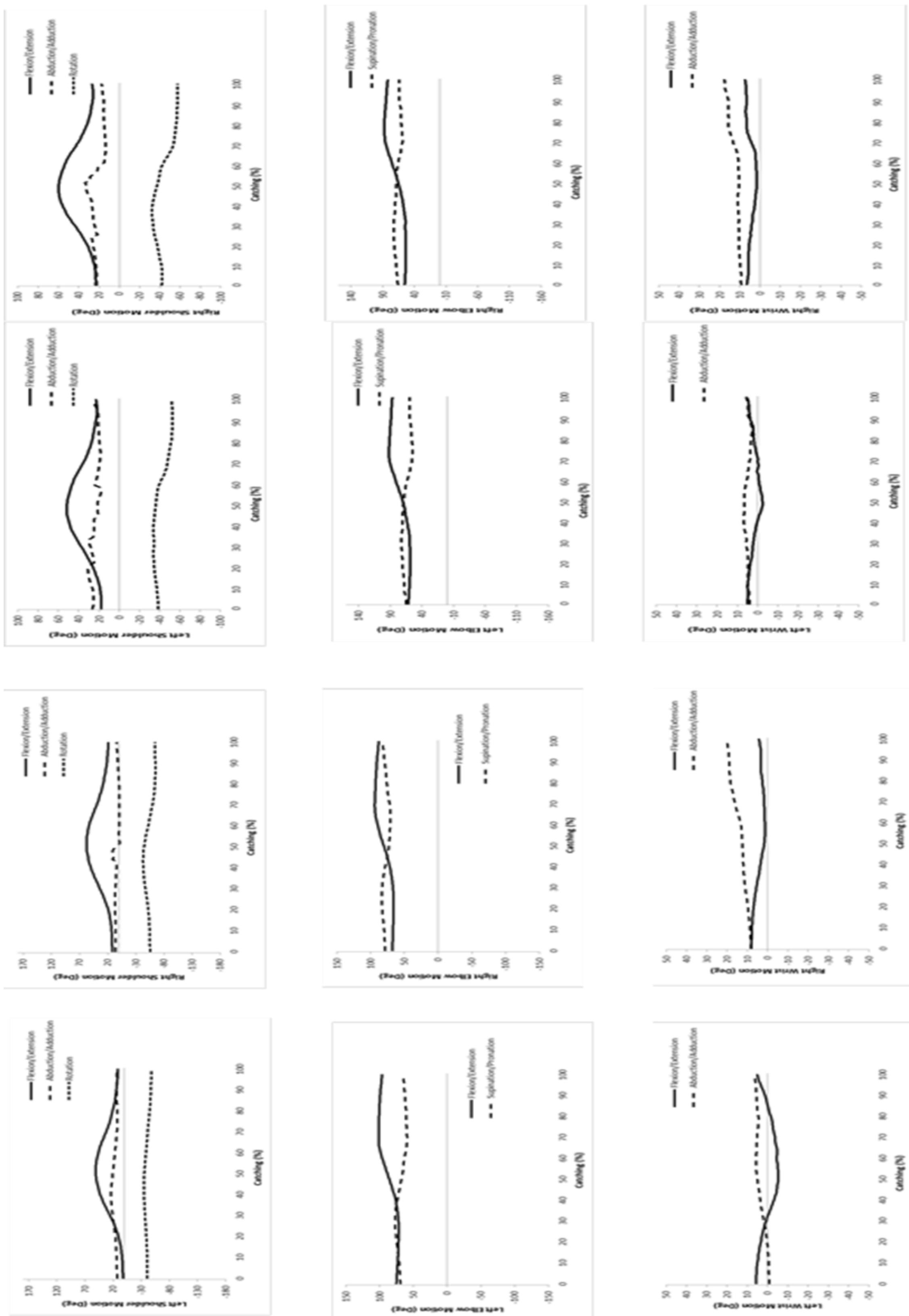


FIGURE 1. Average angular displacements of different joints in pre-test for control (A) and constraint **(B),** post-test for control (C) and constraint **(D)** and transfer test for control (E) and constraint (F). Contact with the ball was at 50-60% the catching action.

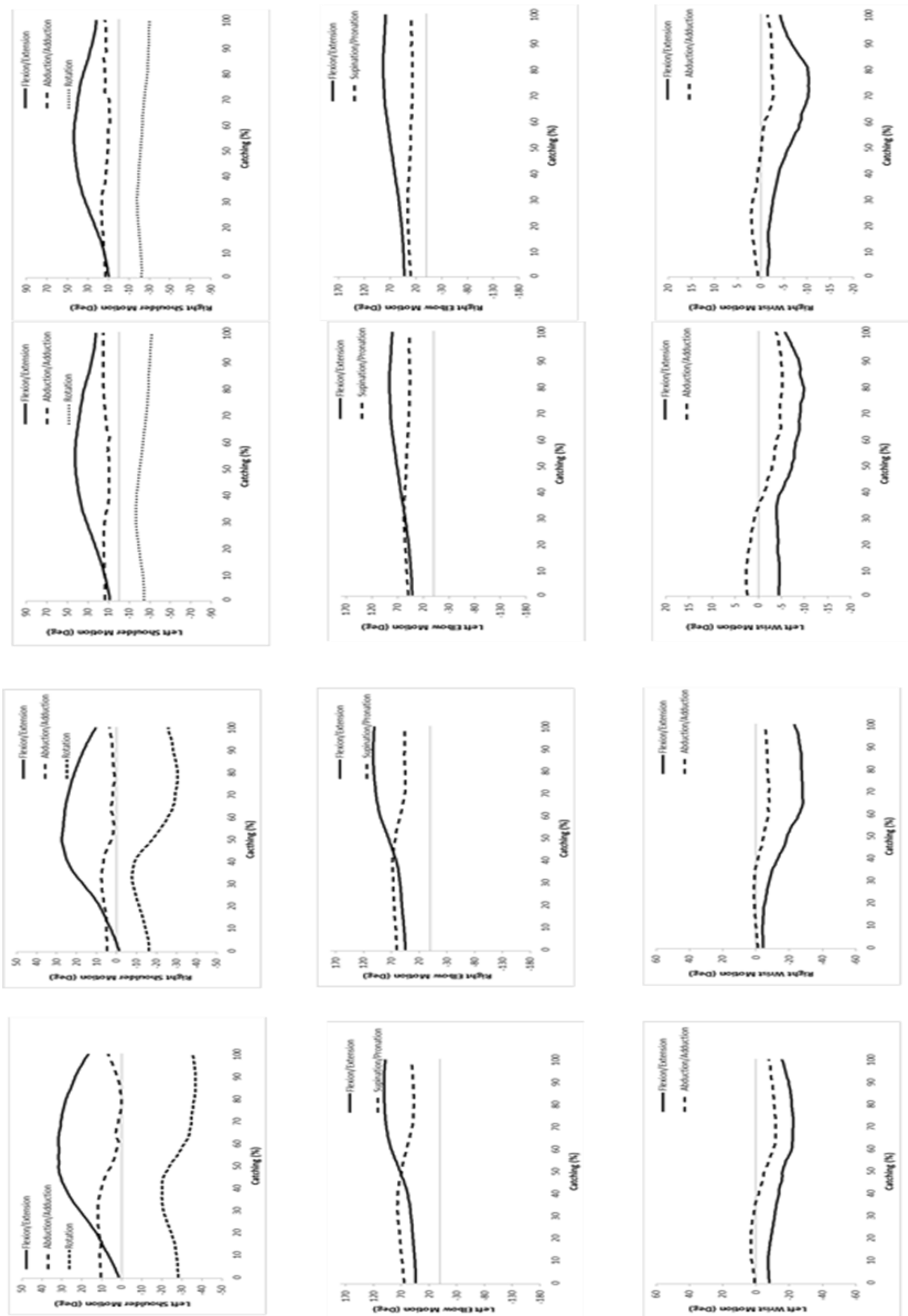
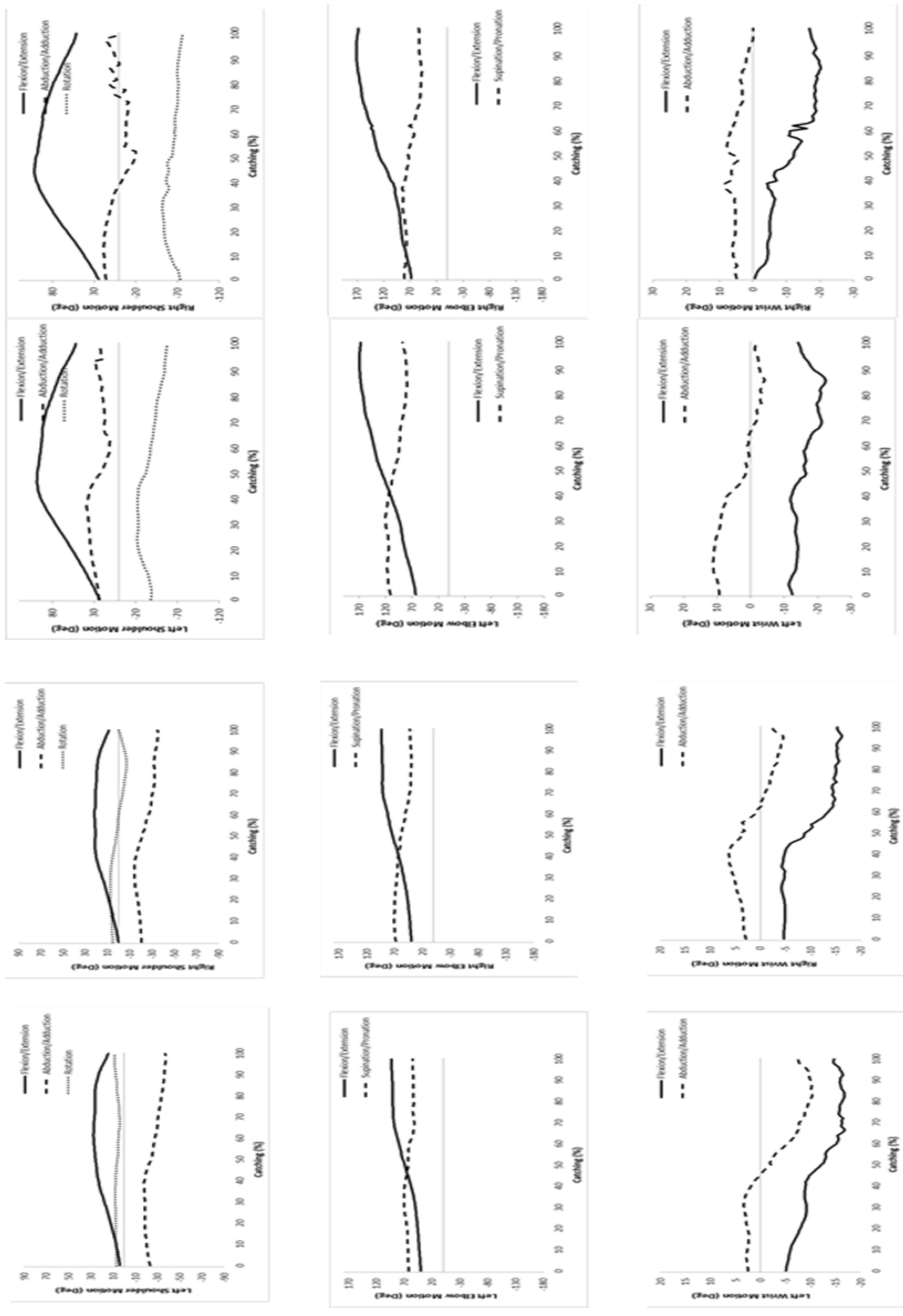


FIGURE 1. Continued


Right Shoulder Motion (Deg)
Left Shoulder Motion (Deg)
Right Elbow Motion (Deg)
Left Elbow Motion (Deg)
Right Wrist Motion (Deg)
Left Wrist Motion (Deg)
Catching (%)
Flexion/Extension
Abduction/Adduction
Rotation
Supination/Pronation

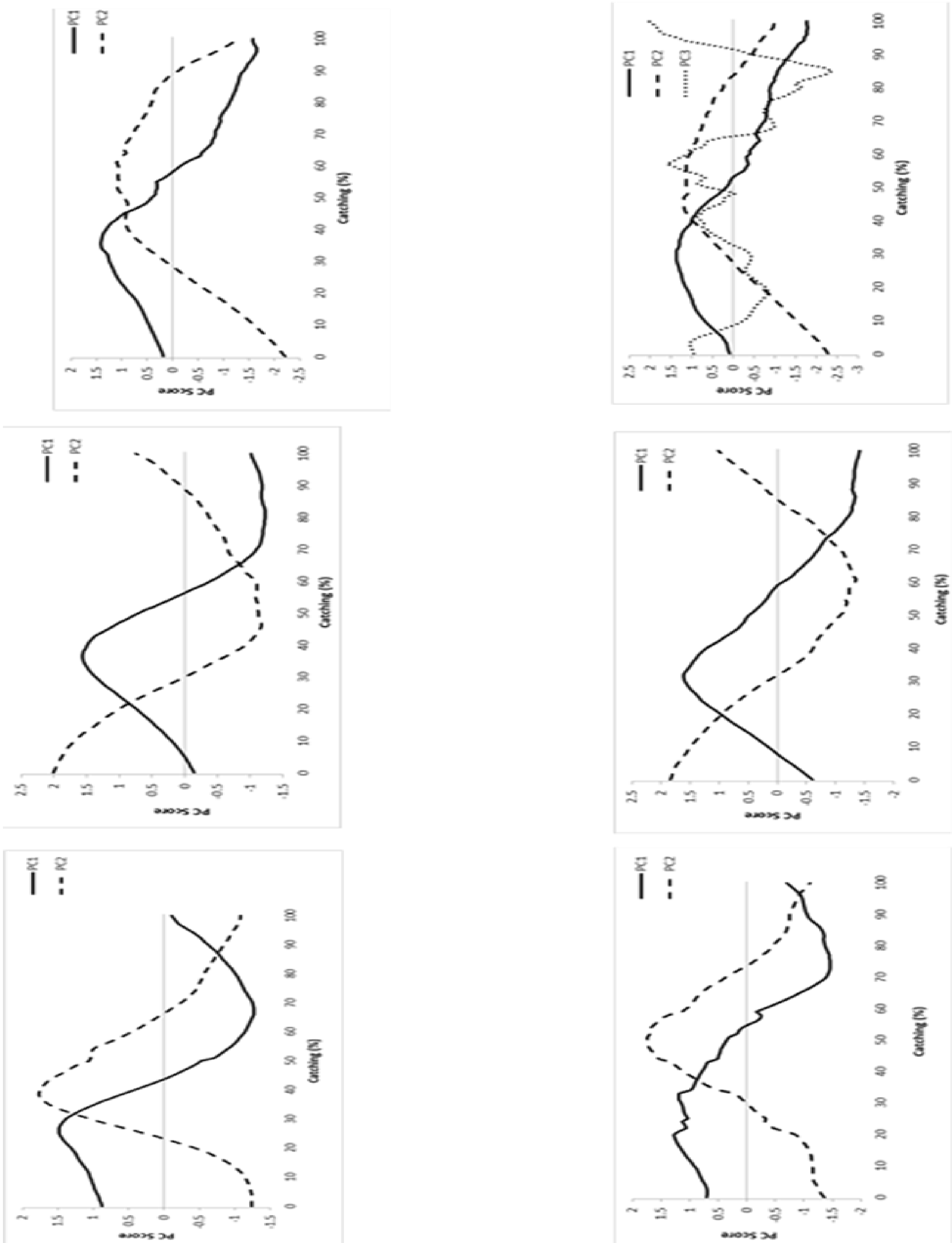


FIGURE 2. PC scores in different moments of catching in control (top) and constraint (bottom) groups in pre-test (left), post-test (middle) and transfer test (right).

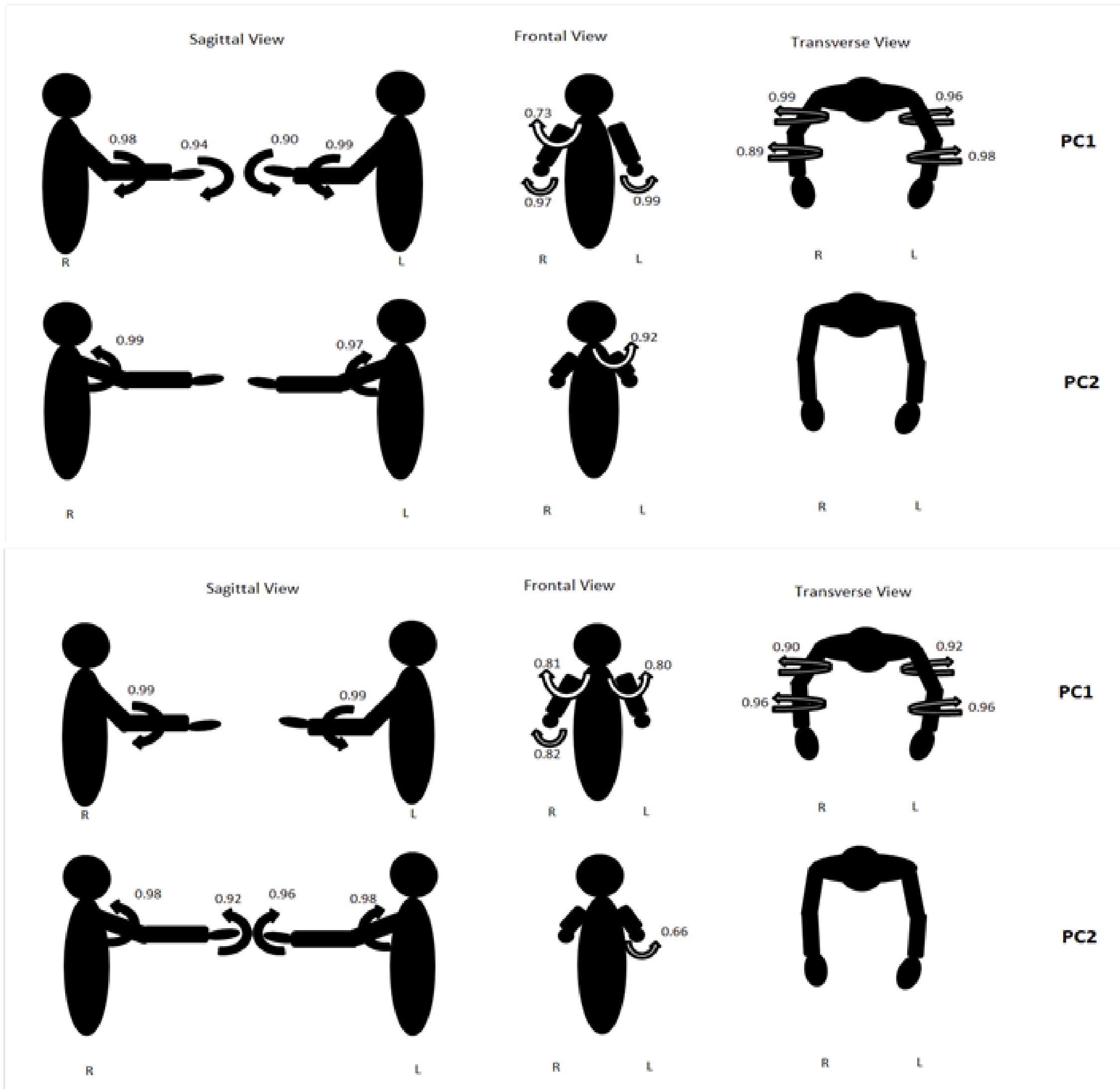


FIGURE 3. Eigenvectors of different joint motions of PC1 and PC2 in pre-test in control (top) and constraint (bottom) groups.

Synergy Functions

The variance of each synergy (PCs) at different moments of catching performance is presented in Figure 2. The PC_1 relative to PC_2 provided a greater contribution to two-hand catching performance in the controls (71% vs. 25%), compared to the constraint manipulation (57% vs. 34%) group in the pre-test. The kinematic synergies in the pre-test were organised to transport the limbs towards the ball (PC_1: reach) and to grasp the ball during contact (PC_2: catch).

Despite the group similarity in the number of synergies used at pre-test and post-test, they were soft-assembled for different functions. The reach synergy remained unchanged in both groups, whereas the secondary synergy (PC_2) had a different role during two-hand catching: at the beginning of the action it was used for preparation and the end it emerged for retaining possession of the ball in the grasp phase. The variance of this soft-assembled, dual-purpose synergy was slightly different between the two groups. Another difference between two groups was in the number of kinematic synergies observed in the transfer test. The control group maintained the synergies of reach (66%) and the catch (27%), whereas the constraints-trained group maintained both the reach (60%) and the catch synergy (26%), but added a retain synergy (9%). The additional synergy was

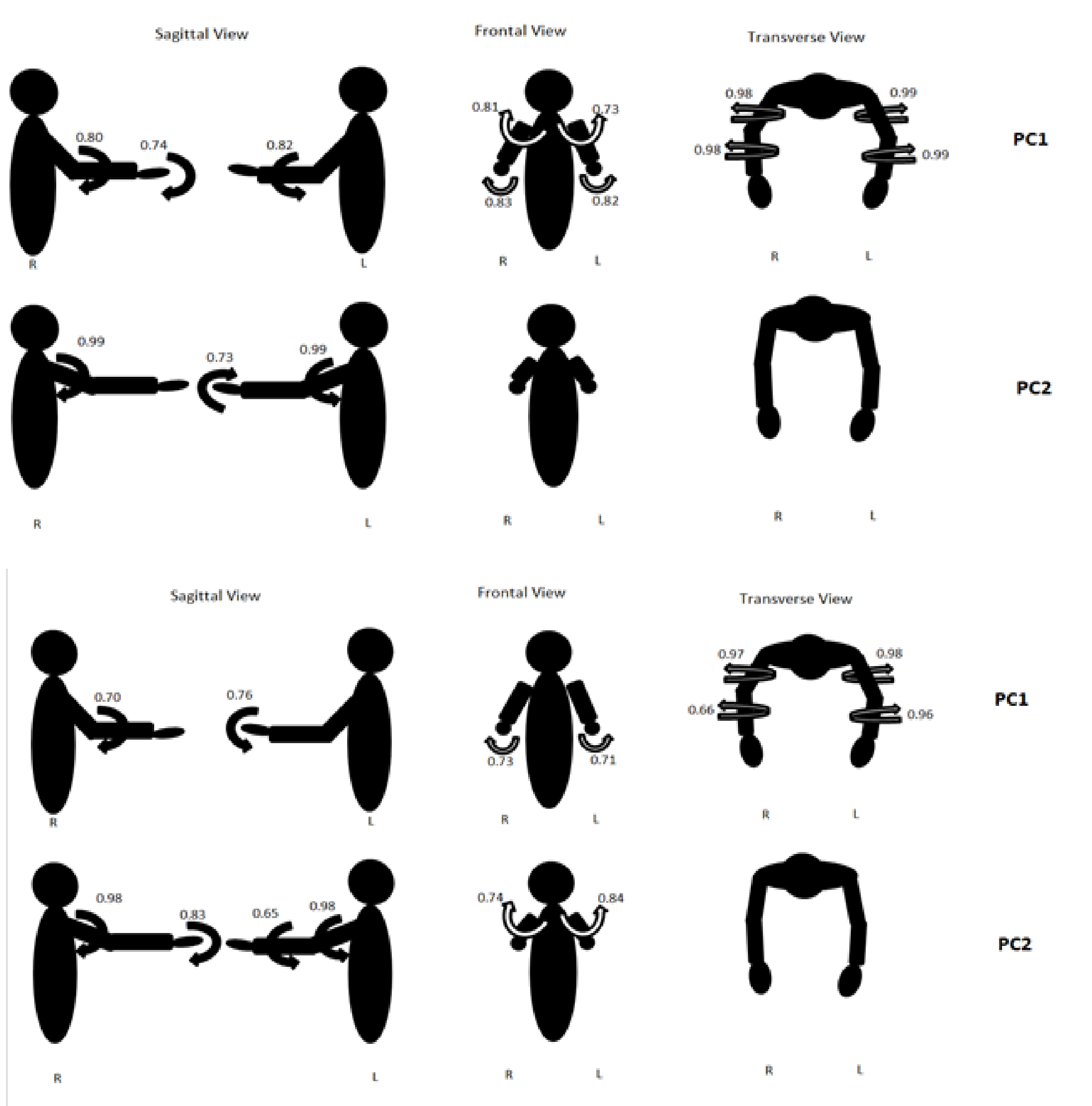


FIGURE 4. Eigenvectors of different joint motions of PC1 and PC2 in post-test in control (top) and constraint (bottom) groups.

employed significantly after the point of ball contact and the end of the catching action (see Figure 2) to secure the ball possession and increase the chance of a successful catch in a novel task situation.

These results showed that transporting the arm towards the ball is an active part of the two-hand catching action that requires regulation of a multi-joint synergic pattern for successful performance.

Synergies Configuration

The joints configuration of the reach synergy was similar between the two groups at all test phases, and it was bimanual (right and left sides), multiaxial (sagittal, frontal and transverse planes) and multi-segmental (arms, forearms and hands) in nature. The eigenvector values, as a correlation coefficient between each PC and its movement components, in the control and constraint groups, are presented in Figures 3 (pre-test), 4 (post-test) and 5 (transfer test). In the reach synergy, the most stable movements in the control group were from the arm and forearm in the transverse plane, involving external rotation of the shoulders and supination of the forearms. Radial flexion and extension of the wrists were other stable movements observed in the pre-test and at transfer. The most stable movement pattern in the constraints

TABLE 3. The main characteristics of emerged synergies in two-hand catching of control and constraint groups in pre-test, post-test and transfer test.

Pre-test	PC1	PC2	PC3
Control			
Level	3-segment	1-segment	
Coordination	Bimanual/multiaxial	Bimanual/biaxial	
Function	Reach	Catch	
Constraint			
Level	3-segment	2-segment	
Coordination	Bimanual/multiaxial	Bimanual/biaxial	
Function	Reach	Catch	
Post-test			
Control			
Level	3-segment	2-segment	
Coordination	Bimanual/multiaxial	Bimanual/Uniaxial	
Function	Reach	Preparation/Retain possession	
Constraint			
Level	3-segment	3-segment	
Coordination	Bimanual/multiaxial	Bimanual/biaxial	
Function	Reach	Preparation/Retain possession	
Transfer test			
Control			
Level	3-segment	1-segment	
Coordination	Bimanual/multiaxial	Bimanual/biaxial	
Function	Reach	Catch	
Constraint			
Level	3-segment	1-segment	1-segment
Coordination	Bimanual/multiaxial	Bimanual/biaxial	Unimanual/Uniaxial
Function	Reach	Catch	Retain possession

manipulation group that remained unchanged in different test phases involved external rotation of the shoulders and supination of the forearms. Movement stability in the arms and forearms during reaching was not changed as a function of the task-related intervention.

The joints configuration of the catching synergy was similar between the two groups in the pre-test and at transfer, being bimanual (right and left sides), biaxial (sagittal and frontal planes) and uni-segmental (arms) in nature (Table 3). The eigenvector values of the two groups at pre-test (Figure 3) and at transfer (Figure 5) showed that the most stable movement was flexion of the shoulders. This observation indicates that the dominant strategy to catch the ball was controlled proximally by both arms before the intervention and in the novel (transfer) task. The joints configuration in the post-test was similar between the groups in terms of the stable movement (shoulder extension). However, there were between-group differences in the coordination pattern that emerged (uniaxial versus biaxial) and the number of active body parts used (2 segments vs. 3 segments). The increased sensory-motor requirements of the catching action, in terms of active body parts and directional control, formed a strategy that emerged following the intervention to retain possession of the ball. When the groups were faced with a novel task at transfer, the adopted strategies for the constraints manipulation group involved the formation of a new synergy through dividing the catching synergy into a catching and retaining synergy. Despite the simplicity of the latter synergy in terms of the included body segments (only left wrist extension was needed), it played an important role after catching the ball, increasing the chance of successful ball retention. This observation indicates a refinement of kinematic adaptation to meet the requirements of the novel (transfer) task following the task constraints intervention.

DISCUSSION

The aim of this study was to examine effects of a developmentally appropriate task constraints intervention on kinematic synergy formation and adaptation in children with DD during two-hand catching. Results showed that a task constraints intervention is effective for development of two-hand catching behaviours in children with DD, in both the quality of movement patterns and multi-joint coordination patterns that emerged. More

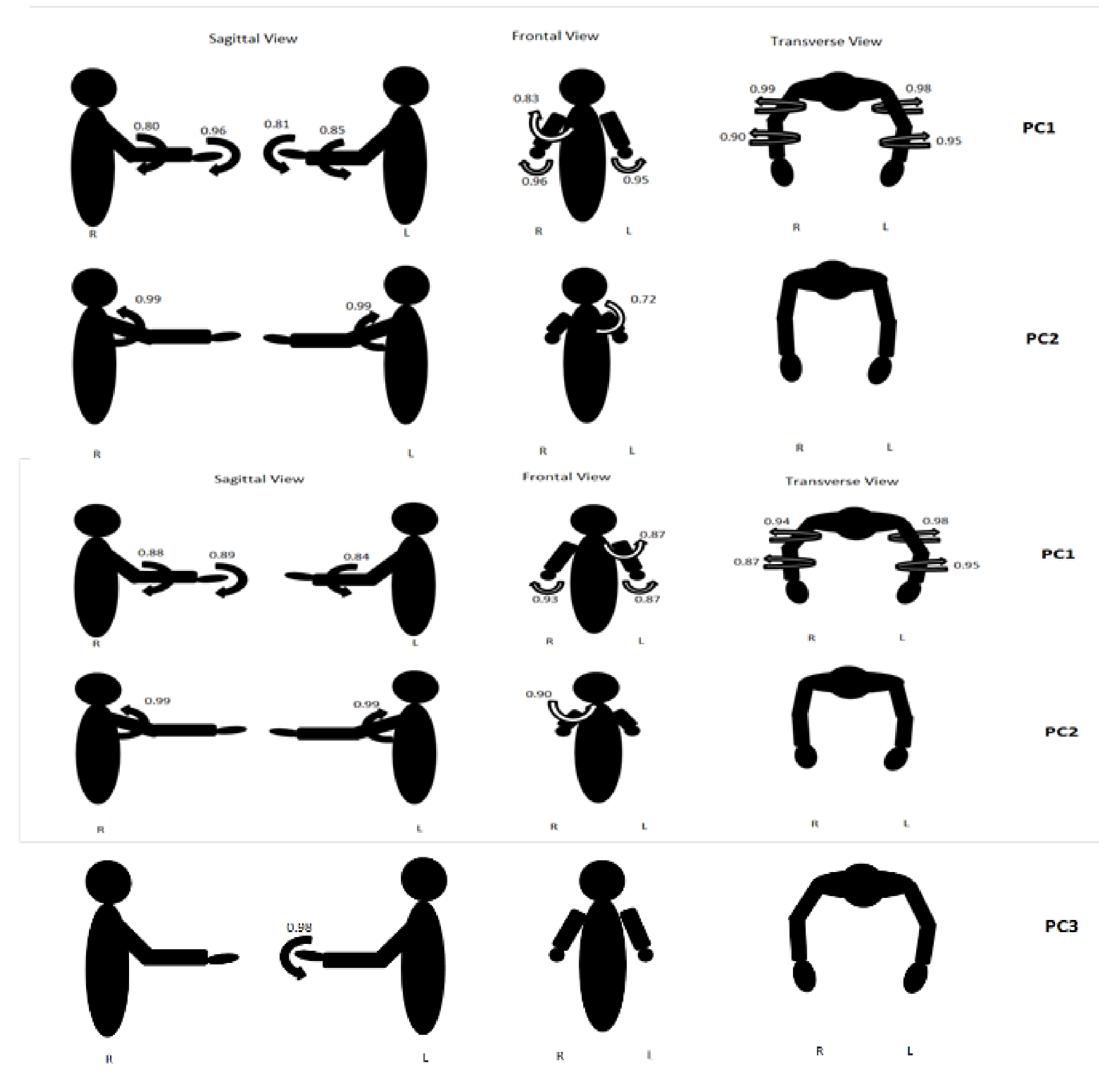


FIGURE 5. Eigenvectors of different joint motions of PC1 and PC2 in transfer test in control (top) and constraint (bottom) groups.

specifically, the catching pattern organised with the arm and hand components progressed to a more advanced development score in 90% of participants in the constraints manipulation group, as opposed to only 20% in the control group. This finding is aligned with data reported in previous studies that have shown the effectiveness of manipulating task constraints on FMS generally, and two-hand catching specifically, in children with DD (e.g. Kirk & Rhodes, 2011). Additionally, the task constraints in this study also resulted in functional changes in coordination in terms of the number of active body parts and an additional strategy to increase the chance of retaining ball possession after the point of ball-hand contact in the transfer task.

Two-handed catching is composed of a multi-joint pattern with a high system dimensionality. The challenge of dimensionality is negotiated by exploiting synergy formation among the segments to maximise spatial and temporal accuracy in the hand trajectory (Mazyn et al., 2006). Emergent synergies from body segments have an important role in re-organisation of DoFs in different axes among joints (Cesqui et al., 2012; Sekran et al., 2012). The findings of the current study showed that the main synergies in two-hand catching are organised for reaching and catching components, and the reach synergy is the most important and consistent element in this coordination pattern. A previous study in children with DCD showed that the amount of joint variability at the early phase of catching is lower than that observed during mid and later phases (Sekran et al., 2012). While this temporal adaptation is attributed to reducing the DoFs in elbow joints (Utley et al., 2007), findings from our study indicated that the most stable movements that remained unchanged, following the intervention, involved the arms (external rotation) and forearms (supination) during the reach phase. These findings may indicate that the proximal movement components during reaching are phylogenetic in nature and are rarely changed by re-organising task and environmental constraints.

The catch synergy, on the other hand, is an adapatable synergy that changed between the pre-test to post-test. While the constraints manipulation group organised the catching action by exploiting more system dimensionality (bimanual/biaxial/3 segments), the control group reduced dimensionality in the catching synergy (bimanual/uniaxial/2 segments). Whether this difference was due to inter-individual variability or a strategy that emerged after the intervention is unclear. However, these findings support the view that the constraints manipulation group, relative to the control group, increased the sensory-motor requirements of the catching action to increase the chance of ball retention after ball-hand contact. When the task required a new adaptation (i.e. at transfer), the constraints manipulation group decomposed this synergy int ‘catch’ and ‘retain possession’ components. Freeing the joints and adding the synergetic units emerging as kinematic adaptations might be an outcome of the interventions in children with developmental problem who typically freeze DoFs during two-hand catching performance (Utley et al., 2007). Functional changes in the movement (re)organisation and catching performance in peope with developmental problems (e.g. DCD) have also been reported following specific interventions such as gaze training (Słowinski et al., 2019; Wood et al., 2017), indicating the adaptability of the multi-segment movement system to self-organise in stimulating and enriched environments. The observed kinematic changes might be compensations in the whole motor system, as a synergetic unit, to successfully intercept the ball (Sekran et al., 2012; Van Waelvelde, De Weerdt, De Cock, and Smits Engelsman, 2004).

Despite the multi-segment coordination pattern that emerged between the two hands of participants during catching, the role of handedness should be taken into account. For example, it is reported that the children between the ages of 6 and 10 years have greater preference to use the dominant hand for performing tasks that cross the midline of the body. Between the ages of 10 and 12 years, children learn to increase the non-preferred hand’s contribution in reaching and catching tasks (Scharoun & Bryden, 2014). Zareba and Ciesla (2013) did not observe any differences between right-handed and left-handed children in performing a two-hand catching task. However, in that study, the groups varied in use of the leading hand in performance of a one-hand catching task. The inconsistencies in these results might be related to the nature of the task used and variations in some practice variables.

Effects of task constraints interventions on development of FMS, in both typically developing children (Riethmulle et al., 2009) and children with DD (Kirk & Rhodes, 2011), have traditionally been assessed with outcome measures in normative motor skill tests that do not provide enough information regarding the quality and complexity of the FMS. Along with normative outcome measures and development sequence levels, the observations in the current study could provide comprehensive and clear insights regarding the clinical significance of a specific intervention and the role of the CNS in re-organisation of body parts in synergy formation in children with DD.

The PCA method used in this study was used to quantify the emergent multi-joint synergies and associated kinematic variability (Latash, Scholz, & Schoner, 2007). Our findings suggest that the children with DD were able to use elemental variability (joint configurations) during the reaching task to aim the hands at the moving target without increasing outcome errors (Golenia et al., 2018). However, the participants had less redundant effectors by rigidly coupling their limbs (Utley et al., 2007). The kinematic synergies observed in human movement is an important characteristic that provides flexibility and degeneracy to the muscloskeletal system to reach the same external target in different ways (Scholz, Schoner, & Latash, 2000). An effective strategy to strengthen the exploration of kinematic system synergies is by constraining the tasks designed during learning (Newell, 1986). This idea characterises how the motor system adapts coordination patterns to changing system states and task or environmental constraints (Davids, Glazier, Araujo, & Bartlett, 2003). It has been shown that a synergy, assembled with motor system components for the purpose of achieving a specific task goal, plays a significant role in mitigating effects of specific system states, for example perturbations, on functional performance behaviours (Riley, Shockley, & Van Orden, 2012). Learning to exploit movement system variability, to consistently achieve successful performance outcomes, could be enhanced by designing developmentally appropriate interventions that emphasise elemental variability.

Our study has implications for physical education teachers and clinical practitioners who work with children with DD.

- The two-hand catching requirements are determined by its temporal phases (reaching then catching) in a constant situation (the same ball, distance and trajectory). The capacity to catch a ball successfully could be slightly changed when the task demands are changed in novel situations. Practitioners should use variable practice modes to provide different affordances for the distal kinematic adaptations through refining the control parameters of ball flight (e.g. height, distance, speed, trajectory, etc.).
- The observation of an addition of a new synergy in the transfer task, following the intervention, suggests a multidimensional adaptation in two-hand catching. The children not only increased their proficiency to catch the ball successfully, according to the values of the TGMD-2 score, they also refined the movement patterns, mainly in the catching phase, through creating a new synergy to support ball retention after contact with the hand.
- Adopting a sound theoretical framework (e.g. synergy formation in ecological dynamics) by praticitioners was also emphasised here. The observational tools and interventions chosen by practitioners should take into account of the coordination between body segments, rather than in isolation, because of interrelationhsips between them (synergic units). Constraining the task, rather than segmentising movement parts, is the preferred practice model for synergy development in pedagogical practice (Chow et al., 2016).

The study has some limitations. The biomechanical model only considered the arm segments due to the nature of task (standing still and constant distance between the ball thrower and ball catching). It is possible that the legs, torso and head also significantly move in variable task situations. Future studies could assess the kinematic synergies in two-hand catching following an intervention in dynamic settings. We used the average score of groups in the PCA calucation, but it was possible that the children with DD had an individualised development pace in this skill that might ovelooken through averaging. Future studies could take into account the role of different developmental levels of the body segments following an intervention.

In conclusion, the findings of this study showed that the developmentally appropriate task interventions could facilitate object control skill development through reorganisation of the active body parts into functional synergies. Through a short-term practice intervention, children were able to develop functional synergies to adapt to new tasks during the transfer test.

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