Qualitative and Quantitative Change in the Kinematics of Learning a Non-Dominant Overarm Throw

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Abstract

This study investigates changes in non-dominant arm throw technique over a 3-week period of practice with respect to three complementary approaches to motor skill acquisition. Ten participants (mean±SD age 22±2yrs, stature 1.71±0.60m, mass 73±14kg) practiced for nine sessions, during which kinematic data were collected. In line with Newell's (1985) learning stages of coordination, control and skill, coupling between the Centre of Mass (CoM) and wrist movement were explored. During initial practice, coupling began in-phase moving to wrist-led coupling. With further practice a more complex backwards wrist-led coupling that progressed to forward wrist-led coupling was observed. The components model of overarm throwing (Roberton & Halverson, 1984) and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom were used to understand technique changes underpinning changes in the collective dynamic. Participants began in mid to high action levels for the torso/arm components, while the step component progressed to higher action levels with practice. A significant increase in joint angle range of motion (ROM) at the lower limb joints and shoulder and a significant decrease in elbow and wrist ROM coincided with the time course of changes in the components model. Key aspects of technique change were taking a contralateral step which was associated with greater ROM of the lower extremities and CoM, and underpinned a more complex CoM-wrist coupling. In identifying stages of learning, commonalities in changes in the collective dynamic were supported by individual strategies at the joint space level.

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Knowledge of the characteristics of technique change during motor learning can provide insight into how the demands of a task influence the process of motor skill acquisition. In this study, non-dominant overarm throwing action was the motor skill used to explore technique changes during learning. The overarm throw is a fundamental discrete motor skill (Knudson, 2007) that requires the formation of qualitative kinematic properties in the organization of the limb segments that constrain the quantitative change in movement technique and task outcome (Kernodle & Carlton, 1992; Roberton & Halverson, 1984; Southard, 2006).

Overarm throwing is a skill for which the non-dominant arm action generally has less advanced movement organization than the dominant arm (Kernodle & Carlton, 1992; Southard, 2006). Two studies have investigated the effect of instruction and feedback on the development of non-dominant overarm throwing in adults (Kernodle & Carlton, 1992; Southard, 2006). Southard (2006) reported an increase in the arm and trunk segments experiencing positive segmental lag, while Kernodle and Carlton (1992) showed that the key cues to technique change related to the lag of the upper arm and elbow with respect to the shoulder. Interestingly, whilst segmental lag provides a biomechanically relevant technique parameter, it is not emphasised in the stages of learning models proposed in motor control literature.

Three complementary approaches for quantifying technique changes in human movement were used in the study; Newell’s (1985) learning stages of coordination, control and skill and Bernstein’s (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom are generalised models for the development of motor skills, underpinned by a dynamical systems theory perspective. The component model of overarm throwing (Roberton & Halverson, 1984) is a model developed specifically for throwing actions. Firstly, Newell (1985) provided a functional distinction between the constructs coordination, control and skill. In Newell’s (1985) framework variables that describe technique and directions of change were purposefully not defined, since it was hypothesised that both were task specific. More recent work has used collective variables to assess the constructs of the learning stages (Ko, Challis & Newell, 2014; Wang, Ko, Challis & Newell, 2014; Dutt-Mazumder, Challis & Newell, 2016; Dutt-Mazumder & Newell, 2017). The assumption is that the collective variable provides the fundamental organization of the system’s macroscopic coordination patterns (Ko et al. 2014). A collective variable or order parameter is defined as a high order, low dimension space variable that is representative of multiple joints at the muscular-articular level (Haken, 1983; Mitra, Amazeen & Turvey, 1998). It has been shown in learning projectile tasks that the collective movements of the body (indexed by CoM) and the end effector during throwing (wrist motion) become more strongly coupled (Verhoeven & Newell, 2016).

Bernstein’s (1967) hypothesis of freezing and freeing the redundant mechanical degrees of freedom captures properties of qualitative and quantitative technique changes. In this view Bernstein (1967) defined coordination as the process of mastering redundant mechanical degrees of freedom (DF), suggesting that movement is coordinated through a three-stage embedded approach of freezing and freeing the joint space DFs, and finally exploiting the reactive forces. Changes in joint angle range of motion (ROM) (Newell, Kugler, Van Emmerik & McDonald, 1989; Vereijken, Whiting & Beek, 1992; Chow, Davids, Button & Rein, 2008) and coordination variables (Ko, Challis, & Newell, 2003; Verhoeven & Newell, 2016) during novel tasks have been investigated in line with the notion of freezing before freeing during motor learning. The postulation of Bernstein (1967) has since been proposed to be task specific and dependent on the level of analysis during learning (Hong & Newell, 2006; Newell & Vaillancourt, 2001). This paper investigates changes in the ROM of the mechanical degrees of freedom with practice in learning the overarm throw.

Lastly, the components model of overarm throwing (Roberton & Halverson, 1984) tracks qualitative technique changes through relative changes in four segmental components: ‘step’, ‘trunk’, ‘humerus’ and ‘forearm’. The components model has been examined extensively in children learning to throw (Roberton & Halverson, 1984; Roberton & Konczak, 2001; Langendorfer & Roberton, 2002; Stodden, Langendorfer, Fleisig & Andrews, 2006*a,b*) and older adults ranging in age from 61 – 82 years (Williams, Haywood & VanSant, 1998). The model was the product of years of longitudinal study in children up to 13-years of age but has yet to be applied to technique changes for young adults or for non-dominant arm throws. It is important to have an understanding of the mechanics of qualitative developmental changes in the fundamental skills to establish if young adult technique changes in line with that of children and older adults.

This paper examines the pathways of change in the movement organization that provide structure to the formation of a new task relevant movement coordination mode for the overarm throw with the non-dominant arm. The aim of this research was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three complementary approaches to qualitative and quantitative change of movement dynamics: Newell’s (1985) stages of coordination, control and skill, Bernstein’s (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom, and the components model of overarm throwing

(Roberton & Halverson, 1984). We expect that collective dynamics capture common changes in technique during learning. It was expected that quantitative changes in joint rotations and Centre of Mass (CoM) movements are embedded in sequential qualitative changes in 'trunk'/arm relative motion during learning to throw with the non-dominant. The approach focuses on the qualitative and quantitative kinematic changes at the individual participant level as a function of practice to reveal the individual pathways of change that are likely to be evident when not masked by averaging procedures.

Method

Participants

Written ethical approval was gained from the host University's Ethics Committee (Faculty Research Ethics Panel, Anglia Ruskin University) prior to study initiation. Ten participants (PT) (4 female, 6 males; age 22±2 yrs, stature 1.71±0.60 m, and mass 73±14 kg), all of whom had no specific experiences with non-dominant arm throwing, gave written voluntary informed consent and successfully completed a health questionnaire. Inclusion criteria were as follows: participants were not participating in a throwing-based activity, had a dominant hand (as determined by Oldfield (1971) Edinburgh handedness inventory), and were free from musculoskeletal injury.

Procedures

The longitudinal practice took place three times per week (Monday, Wednesday and Friday) for 3 consecutive weeks. The same procedures were conducted for each session. Between testing sessions participants were instructed not to practice throwing with either their dominant or non-dominant arm. Baseline data were collected for each participant during 10 overarm throwing movements, with their dominant arm and non-dominant arm. A standard issue tennis ball (Slazenger) was used. Participants were given the ongoing aim of hitting a 0.4m target located 14m in front of them Target height was adjusted to each participant's eye level. Knowledge of results from the target and verbal encouragement were provided, phrases included: “nice”, “well done” and “good job”. The target placement necessitated a forceful and accurate throw from the participant and was best realized with a near horizontal trajectory of the ball to the target.

Data collection

Kinematic data (200 Hz) were collected using 3D motion capture system (CODAmotion, Charnwood Dynamics Ltd, UK). Three CX1 scanners provided a 360° field of view around the participant. Centre of rotation for each joint was estimated and active makers were located on the right and left lateral side of: 3rd metacarpal, ulnar styloid process, lateral epicondyle of the elbow, shoulder joint at the centre of rotation, xiphoid process, greater trochanter, thigh, femoral condyle, tibia, lateral malleolus, calcaneus and 2nd metatarsal. The same researcher marked up each participant each week. Data were collected for every trial performed by the participant. The throwing trials were recorded using a two-dimensional camera (Fastcam high speed video camera, Ultima 512 Photron, Model 32K) placed perpendicular to the sagittal plane of the participant.

Raw marker data in the horizontal and vertical direction were identified from the three-dimensional CODA output. A Butterworth low-pass fourth-order filter was applied to the kinematic data at a cut-off frequency of 6 Hz (Winter, 2005). Data were analysed during the propulsive phase of the throw, defined from the instance that a marker started moving in the direction of the throw until the instance of ball release.

Variables

Newell's (1985) learning stages of coordination, control and skill: Vector coding (VC) was performed on the displacement of the CoM and wrist in the anterior posterior direction (Sparrow, Donovan, Van Emmerik & Barry, 1987). Based on Chang, van Emmerik and Hamill (2008) four key coordination patterns can be defined for vector coding: (1) anti-phase coupling (112.5–157.5° or 292.5–337.5°), variables are moving in opposite direction; (2) in-phase coupling (22.5–67.5° and 202.5–247.5°) variables are moving in the same direction; (3) wrist-led phase coupling (0-22.5° 157.5–202.5° or 337.5–360°), wrist is a more predominant variable; and (4) CoM-led phase coupling (67.5–112.5° 247.5–292.5°), CoM is the more predominant variable. Average standard deviation of the within-session VC profiles was used to determine variability of the movement coordination pattern as a function of practice.

Components Model (Roberton and Halverson, 1984): 'step' 'trunk', 'humerus' and 'forearm' were classified by the principal investigator and were verified by another author for all trials for all participants in line with the components model (Roberton & Halverson, 1984).

Bernstein (1967) joint range of motion: Ankle joint was defined from the 2nd metatarsal, lateral malleolus and calcaneus. The knee joint was defined from lateral malleolus, femoral condyle and greater trochanter. The hip joint was defined from femoral condyle, greater trochanter and xiphoid process. Shoulder joint was defined from lateral epicondyle of the elbow, shoulder joint at the centre of rotation and xiphoid process. Elbow joint was defined from shoulder joint at the centre of rotation, lateral epicondyle of the elbow ulnar and styloid process. The wrist joint was defined from the 3rd metacarpal, ulnar and styloid process and lateral epicondyle of the elbow.

Angles were defined in 3D where an angle of 180° would represent maximum extension, while 0° would represent minimal flexion. ROM of CoM in the anterior-posterior direction was also calculated, where CoM was defined as the average mass of each segment midpoint of all the segments. To estimate the position of total body CoM with 3D trajectories of the 16 active markers, CoM of individual segments were calculated based on the anthropometric data provided by Dempster (1955). Then the total body CoM position was derived from the combined individual CoM to provide weighted summation of individual segment CoM positions (Ko et al. 2014; Winter 1995).

Statistical analysis

IBM 24 Statistical Package for the Social Sciences (SPSS Inc.) was used to determine statistically significant differences between discrete variables: joint ROM of the ankle, knee, hip, shoulder, elbow and wrist, CoM and the coupling variability of CoM-wrist across testing sessions using repeated measures analysis of variance (ANOVA), based on a single subject design ($p < 0.05$). Bonferroni post hoc correction was used for multiple comparison test. Mauchly’s test was used to determine the sphericity assumption within the data; where sphericity was violated, probability was corrected according to the Greenhouse-Geisser procedure.

Results

Newell’s (1985) learning stages of coordination, control and skill

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Fig 1. CoM-wrist coupling for single trial per session for PT06 (representative of PT03, PT04, PT05, PT08, PT09 and PT10) and PT07 (representative of PT01 and PT02).

Two key profiles of this vector-coding angle were identified with practice. The first profile started the propulsive phase with in-phase coupling (22.5–67.5°) and progressed to wrist-led coupling (0-22.5°) at ball release (Fig 1) where the wrist is moving forward and the CoM is nearing stationary (zero degrees). At the start of practice, all participants demonstrated this coupling relation. The second profile started with wrist-led coupling (157.5–202.5°) where the wrist moved backwards and progressed through the following couplings; anti-phase coupling (112.5–157.5°) where the CoM is progressing forward as the wrist moves backwards, CoM-led coupling (67.5–112.5°) followed and is associated with the forwards movement of the CoM. Past 60% of the propulsive phase, coupling angle passes through in-phase characterised by forward progression of CoM-wrist towards wrist-led phase coupling at ball release (Fig 1). With practice, 7 of the 10 (PT03, PT04, PT05, PT06, PT08, PT09 and PT10) participants demonstrated the second profile. The remaining 3 of 10 participants (PT01, PT02 and PT07) continued to display in-phase coupling followed by wrist-led phase coupling at ball release for the duration of practice (Fig 1). Changes in CoM-wrist coupling (Fig 1) occurred at the same session as components model (Roberton & Halverson, 1984) (PT01 and PT03) and ROM (PT01, PT03, PT06 and PT10).

By the end of practice non-dominant arm throws were more closely representative of dominant arm throws for the majority of the participants. Seven of 10 participants (PT03, PT04, PT05, PT06, PT08, PT09 and PT10) were characterised by wrist-led coupling moving towards zero at ball release. Three of 10 participants (PT01, PT02 and PT07) dominant arm throws were characterised by in-phase coupling progressing to wrist-led phase at ball release.

Table 2. Coupling variability with practice for CoM-wrist.

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With practice, 7 of 10 participants (PT01, PT03, PT04, PT05, PT06, PT08, and PT09) significantly increased ($p < 0.05$) CoM-wrist coordination variability (Table 2). Three of 10 participants (PT02, PT07, and PT10) significantly decreased ($p < 0.05$) coordination variability with practice. Seven of 10 participants (PT02, PT03, PT05, PT06, PT07, PT08, and PT09) more closely resembled dominant arm baseline trials with practice (Table 2).

Components model (Roberton & Halverson, 1984)

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Table 1. Developmental action level with practice.

No participants were categorised as action level 1 or over practice regressed down the skill action levels. Most participants progressed up an action level, participants PT01 and PT10 did not progress or retreat with practice. Specifically, from Session 6 onwards, 7 of the 10 participants were categorised as action level 3 for the ‘step’ and 3 of 10 participants at level 4 for ‘step’. For the ‘trunk’ 2 of 10 participants were categorised as action level 2 and 8 of 10 participants were categorised as action level 3. For ‘humerus’ and ‘forearm’ 3 of 10 participants were categorised as action level 2 and 7 of 10 participants were categorised as action level 3. Key changes occurred at Session 2 (PT05), Session 4 (PT02, PT04, PT07), and Session 6 (PT03, PT06). Dominant arm throw configurations were characterised in higher levels (Table 1).

Bernstein (1967) joint range of motion

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Fig 2. Representation of group changes in range of motion of the joints and centre of mass over 3-weeks of practice.

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Fig 3. Group ROM development at the right ankle, knee, hip, left shoulder, elbow and wrist joint as a function of practice. There was a significant increase in ROM of the lower limb joints and shoulder with practice (9 of 10 participants at the ankle and 8 of 10 participants at the knee, hip and shoulder) ($p < 0.05$). Six of 10 participants significantly decreased ROM at the elbow and 7 of 10 participants at the wrist ($p < 0.05$). Eight of 10 participants significantly increased ROM of the CoM in the anterior-posterior direction ($p < 0.05$) (Fig 2).

Changes in ‘step’ (PT02, PT04, PT05, PT06), ‘trunk’ (PT03, PT05, PT07, PT08, PT09), ‘humerus’ (PT03, PT04, PT07, PT08, PT09) and ‘forearm’ action (PT03, PT04, PT05, PT07, PT08, PT09) (Table 1) occurred at the same session as ROM for all participants that changed action level. Six of 10 participants did not change ‘step’ action from level 3 but did significantly increase lower limb ROM (Fig 3).

Discussion

The aim of this research was to investigate the evolution of changes in technique of the non-dominant overarm throw over practice with respect to three complementary approaches to qualitative and quantitative change of movement dynamics: Newell's (1985) stages of coordination, control and skill, the components model of overarm throwing (Roberton & Halverson, 1984), and Bernstein's (1967) hypothesis of freezing and freeing redundant mechanical degrees of freedom. A common single pathway of change in technique with practice was not present across participants. However, for individuals, the findings from the three measurement approaches did complement each other in revealing aspects of the skill progression. There were periods across the multiple practice sessions (4, 5, and 6) where each approach revealed distinct changes in the technique of the participants. Additionally, participants fell into certain subgroups in relation to particular characteristics of technique change, not an uncommon finding in the learning of whole-body motor skills (Williams, Irwin, Kerwin, & Newell, 2015; Teulier & Delignières, 2007; Haibach, Daniels & Newell, 2004); that are likely due to differences in individual constraints and intrinsic dynamics.

Newell's (1985) learning stages of coordination, control and skill

Dynamical systems approaches to motor skill acquisition seek a macroscopic variable(s) that captures the essential properties of the structure and integrity of the movement pattern in action (Kelso, 1995; Mitra et al., 2002). The CoM represents a higher order, low dimensional global space variable that results from the muscle joint actions at the muscular-articular level (Haken, 1983). In this view, the relation between the movement of the CoM and the wrist as the end effector provides information of the macroscopic organization of the system in this throwing task and the link between postural support and instrumental limb action (Verhoeven & Newell, 2016).

Two key coupling relations were observed. At the beginning of practice, all participants demonstrated in-phase coupling at the start of the propulsive phase of the throw, where the CoM and wrist both travelled forwards together, towards zero at ball release (Fig 1). With practice, 7 of the 10 participants began to incorporate differentiated movement of the CoM and wrist, where coupling began at 180° before progressing to 0° at release. The strategy is representative of initial wrist-led coupling where backwards movement of wrist is the predominant influencer on the kinematic chain. Coupling progressed through anti-phase (forward movement of the CoM and backwards movement of the wrist) and CoM-led coupling (forward movement of the CoM) before in-phase coupling and forward wrist-led coupling at ball release (Fig 1).

This later strategy is in-line with dominant arm throws (Verhoeven & Newell, 2016; Ko, Han & Newell, 2018) and provides evidence for the freeing of dynamical degree of freedom (Newell & Vaillancourt, 2001). Specifically, the macroscopic organisation of the system has become more complex, utilising a broader range of phase relations associated with the arm kinematic chain. While this macroscopic variable does not describe the nuances of an individual’s technique, it was able to capture a transition in system organisation despite individual differences in organismic constraints that effect joint space organisation.

In terms of Newell’s (1985) learning stages, 3 of the 10 participants significantly decreased coupling variability with practice, suggesting they had reached the control stage of learning (Newell, 1985), while the remaining 7 participants significantly increased coordination variability with practice suggesting they remained in the coordination stage (Table 2). With practice the coupling variability of 7 of the 10 participants became more similar to that of the dominant arm throws, through either an increase or decrease in coupling variability. A paradox is then set since we can assume variability across dominant arm throws is facilitating functional changes and exploiting redundancy, whereas the variability in the non-dominant arm was used for exploring new coupling strategies in the process of learning (Wilson, Simpson, Richard, Van Emmerick & Hamill 2008; Verhoeven & Newell 2016).

To understand the kinematics underpinning the collective dynamic, technique changes were examined using the components model (Roberton & Halverson, 1984) and Bernstein's (1967) observations of freezing and freeing the redundant mechanical degrees of freedom. Both these approaches provide a distinct description of the movement pattern, and the findings provide support for changes demonstrated in CoM-wrist coupling following practice.

Components Model (Roberton and Halverson, 1984)

To our knowledge this is the first paper to apply Roberton and Halverson (1984) components model to non-dominant arm throwing in adults. As a foundation, the participants did not start practice with a throwing technique at action level 1. This is consistent with the expectations of motor learning and transfer (Adams, 1987), where a previously learnt skill positively influences the learning of a new skill or a skill performed with the other side of the body. For example, this finding is in line with those of Aune, Aune, Ingvaldsen, and Vereijken (2017) who reported motor learning transfer from the dominant arm to the non-dominant arm during a computer simulated tracking task. More generally, our findings are consistent with the pattern of findings on cross-education of upper limb performance (Hore, Watts, Tweed, & Miller, 1996; Sainburg & Kalakanis, 2000).

The findings showed that an advanced action level in one component did not combine with lesser action levels in another component, arguably because the advancement of one component drives forward the development of another component (Langendorfer & Roberton, 2002). For example, taking a contralateral step places the body in a position that progresses trunk and arm components (Stodden et al. 2006*a*). Indeed, by the end of practice (Table 1) the throwing movement patterns were similar to those reported by Stodden et al. (2006*a,b*) who used a cross sectional design to explore developmental changes in dominant arm throwing in children. Stodden et al.'s (2006*a,b*) participants were more advanced than those studied in Halverson et al. (1982) and William et al. (1998), who examined longitudinal developmental changes in children and older adults, respectively. Our results show that participants started non-dominant arm practice with an intermediate developmental profile particularly for the 'humerus' and 'forearm' (Table 1).

At the end of practice, 7 of the 10 participants had not reached the highest 'step' action level, suggesting the skill was not fully developed. The highest action level for dominant arm throws was categorised by 6 of 10 participants for the 'step', 9 of 10 participants for the 'trunk' and 'humerus', and 8 of 10 participants for the 'forearm' (Table 1). The advanced developmental profiles for the dominant arm suggest that non-dominant arm throws can be directly compared to those of adults performing the overarm throwing skill. Moreover, we would expect that if there was a longer period of non-dominant arm practice participants would have continued to advance up the action levels of components. As discussed later, these changes did, however, underpin the key change in CoM-wrist coupling described above but suggest that further organisation changes at the level of components are still occurring at session 9.

Bernstein (1967) joint range of motion

In line with freeing mechanical degrees of freedom, seven of the 10 participants produced an increase in lower limb and shoulder joint ROM with practice (Fig 3). Specifically, a significant increase in ROM at the lower extremities and CoM occurred along with the more advanced ‘step’ action (Table 1; Fig 2). Increased ROM of the lower extremities facilitated increased displacement of the CoM, which provides evidence for increased weight transfer in the act of throwing (Knudson & Morrison, 1996). The development of this fundamental aspect of throwing technique provides evidence for freeing of the mechanical degrees of freedom at the lower limbs, consistent with Bernstein’s (1967) postulation.

Interestingly, ROM of the elbow and wrist significantly decreased for the majority of participants with practice (Fig 3). In parallel, the majority of participants were categorised in advanced action (Table 1) of ‘humerus’ and ‘forearm’ from the beginning of practice. While no other research has analysed ROM for non-dominant arm throwing, Southard (2006) reported that instructional cues positively influenced segmental distal lag, specifically the hand relative to the forearm. When viewed in conjunction with the components model (Roberton & Halverson, 1984) the ROM results suggest that participants had the ability to effectivity use the elbow and wrist joint at the start of practice, and reducing ROM was a common strategy to adopt. This finding provides support for the proposition of Hong and Newell (2006) that freezing or freeing degrees of freedom is task specific, rather than a universal directional rule for skill learning, and furthers the proposition by suggesting that different limb segments (arms or legs) may follow different patterns of change.

At the whole-body level, all participants showed a transition in technique that was captured by a significant change in ROM of three or more joints during one single session. However, the combination of joints involved was individual specific, not an uncommon finding in motor learning literature (Williams, Irwin, Kerwin, & Newell, 2015; Teulier & Delignières, 2007; Haibach, Daniels & Newell, 2004). A drawback of describing technique change through individual degrees of freedom is the inability to explore how these joints are coordinated. Since the timing and the combinations of joints involved in change were individual specific, it is of interest to investigate whether a measure of inter-joint coordination would capture common characteristics of technique change in spite individual constraints and intrinsic dynamics.

Integrating Frameworks to the Acquisition of Overarm Throwing

Exploring different levels of the system is related to different theoretical propositions on motor control (Schoner & Kelso, 1988; Hong & Newell, 2004; Gray, Watts, Debicki, & Hore, 2006). Emphasising a collective variable is based on the theoretical proposition that motor control is associated with overall system dynamics rather than the control of individual degrees of freedom (Ko et al., 2014; Wang et al. 2014; Dutt-Mazumder et al. 2016). Arguably, the components model (Roberton & Halverson 1984) provides collective variables through the hypothesis of four components, however, this model is skill specific and cannot be generalised across movement tasks. In supporting these different emphases on system organisation, our findings suggest that a more complex CoM-wrist coupling is achieved by taking a contralateral step in the throwing action which is associated with greater ROM of the lower extremities. Thus, in increasing the complexity of the collective dynamics, participants followed the sequence of components change in the Roberton and Halverson (1984) components model, while Bernstein's (1967) postulation of freeing mechanical degrees of freedom was limb specific. Founded on Newell's (1985) stage of learning collective dynamics did change, however variability of this collective dynamic was not clearly directional. Overall, a higher order variable was better able to identify commonalities in technique change across individuals than single joint motions, and therefore, might be key to understanding the dynamics of technique change across different task and organismic constraints from a dynamical systems theory perspective.

From an applied perspective, the integration of the three approaches provide a comprehensive view of technique changes during overarm throwing action because each approach explores a different aspect of the system organization that can be practically relevant. This study has revealed experimental evidence of the progression of individual technique changes during non-dominant overarm throwing. The findings highlight the importance of the lower extremities and dynamic postural control in what is usually characterised as an upper extremity action. Specifically, the ability to take a contralateral step to facilitate greater ROM of the lower extremities and CoM movement in weight transfer.

Future work could explore the coordination between multiple joint segments during learning. In addition, future work is required to explore the extent to which these three complimentary approaches characterise technique development in overarm throwing across childhood.

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List of Figure and Table Headings

Figure 1. *CoM-wrist coupling for single trial per session for PT06 (representative of PT03, PT04, PT05, PT08, PT09 and PT10) and PT07 (representative of PT01 and PT02).*

Figure 2. *Representation of group changes in range of motion of the joints and centre of mass during 3-weeks of practice.*

Figure 3. *Group ROM development at the right ankle, knee, hip, left shoulder, elbow and wrist joint during practice. A general trend showed significant increase in ROM of the lower limb joints and shoulder with practice (9 of 10 participants at the ankle and 8 of 10 participants at the knee, hip and shoulder) ($p < 0.05$). Six of 10 participants significantly decreased ROM at the elbow and 7 of 10 participants at the wrist ($p < 0.05$). Eight of 10 participants significantly increased ROM of the CoM in the anterior-posterior direction ($p < 0.05$) (Fig 1.).*

Changes in 'step' (PT02, PT04, PT05, PT06), 'trunk' (PT03, PT05, PT07, PT08, PT09), 'humerus' (PT03, PT04, PT07, PT08, PT09) and 'forearm' action (PT03, PT04, PT05, PT07, PT08, PT09) (Table 1.) occurred at the same session as ROM for all participants that changed action level. Six of 10 participants did not change 'step' action from level 3 but did significantly increase lower limb ROM (Fig 2.).

Table 1. *Developmental action level with practice.*

Table 2. *Coupling variability with practice for CoM-wrist.*