Emergent Perception-Action Couplings Regulate Postural Adjustments during Performance of Externally-Timed Dynamic Interceptive Actions

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Abstract

Studies of postural coordination during performance of externally-timed interceptive actions, such as catching a ball, have been infrequent, with advanced visual information from a thrower's actions towards a catcher, typically excluded in experimental task constraints. Yet evidence suggests that manipulating participant access to such information alters their hand movements and gaze behaviours when catching. In this study, we manipulated participant access to advanced information of a thrower's actions and from ball flight while recording whole body kinematic and kinetic data to investigate effects on postural control during performance of interceptive actions. Twelve participants attempted to make or simulate performance of one-handed catches in three experimental conditions: when facing integrated videos of advanced visual information and ball flight only, videos of a thrower's actions only, and of ball flight only. Findings revealed when integrating advanced visual information and ball flight, and when participants were provided with ball flight information only, lower limb adjustments were primarily used to regulate posture. However, movement was initiated earlier when advanced visual information was available prior to ball flight, resulting in more controlled action and superior catching performance in the integrated condition. When advanced visual information was presented without ball flight, smaller displacements were observed in lower limb joint angles, resulting in upward projection of the centre of mass, compared to a downward trajectory in the integrated video and ball flight, and ball-flight only conditions. Results revealed how postural coordination behaviors are dependent on specific informational constraints designed into experiments, implying that integration of task constraints in studies of human perception and action needs careful consideration.

Introduction

Externally-timed interceptive actions, such as catching a ball with one hand, require precise spatiotemporal coordination between the catching arm and an approaching object in order to bring the intercepting limb to the right place at the right time (Savelsbergh, Whiting, Pijpers, & Van Santvoord, 1993). Previous studies of coordination of multi-articular actions have revealed that movements like interceptions with the arm are 'nested' on to the sub-system for regulation of upright posture (Riccio & Stoffregen, 1988; Savelsbergh, Bennett, Angelakopoulos, & Davids, 2005). The equilibrium of vertical posture is achieved when the center of mass (COM) of the body is positioned over the base of support and is aligned with the center of pressure (COP). External perturbation can shift the projection of the COM closer to the borders of the base of support and the alignment between the COM and COP is disrupted, which may result in the loss of body equilibrium (Santos et al., 2010). Postural regulation is required when catching a passing ball, both to counter effects of raising an arm upwards and towards the object in space, but also to adjust against potential disequilibrium caused by the mechanical impulse of an approaching projectile acting on the hand (Tijtgat et al., 2013; Williams & McCririe, 1988). Indeed, previous research has shown that poor catchers were able to achieve the performance level of good catchers when additional support for postural control was provided to reduce the number of motor system degrees of freedom that need to be coordinated in a synergy (see Angelakopoulos, Davids, Bennett, Tsorbatzoudis, & Grouios, 2005; Davids, Bennett, Kingsbury, Jolley, & Brain, 2000; Savelsbergh, et al., 2005).

Theoretical frameworks dedicated to explaining how the multitude of motor system degrees of freedom can be regulated effectively and efficiently, such as ecological dynamics (Warren, 2006; Kelso, 1995), propose that synergies are formed between system components (i.e. parts of the body such as muscles, joints and limb segments). These synergies or ordered movement patterns have been defined as soft-assembled, compensatory, low-dimensional relations between motor system components that emerge during performance of dynamic activities, constrained by information sources available in performance environments (Kelso, 1995, Kelso, Buchanan, DeGuzman, & Ding, 1993; Riley, Shockley & Van Orden, 2012). Accordingly, in this study, we aimed to examine how the nature of postural coordination is affected by both perceptual task constraints and specificity of a required behavioural response. We achieved this aim by manipulating participants' access to *advanced visual information* (defined as information available from a thrower's movement patterns prior to ball flight), as well as the required action response (interceptive action vs. simulated micro-movement) undertaken during performance.

Ecological dynamics provides a conceptual framework for considering human beings as complex adaptive systems composed of many interacting components or degrees of freedom (such as muscles, joints, limb segments) (Araújo, Davids, & Hristovski, 2006; Davids, Hristovski, Araújo, Balague-Serre, Button, & Passos, 2014; Warren, 2006). In this theoretical rationale for understanding human behavior, how individuals coordinate actions with respect to objects, events and other people, during goal-directed behaviors, has been a longstanding topic of investigation (see Kelso, et al. 1993). The coordination of actions with a performance environment is predicated on the emergence of stable, adaptive behaviors when motor system degrees of freedom become temporarily organized into ordered movement patterns (Bernstein, 1967; Kelso, 1995; Kelso et al., 1993). Perception of information about the world and the body constrains the emergence of these adaptive, functional coordination patterns in human movement systems during goal-directed activity (Warren, 2006; Davids, Araújo, Vilar, Renshaw & Pinder, 2013). Skilled movement performance emerges through the enhanced coupling of perception and action sub-systems via indeterminate interactions of a performer and a performance environment (Barab &

Kirshner, 2001; Chow, Davids, Hristovski, Araújo, & Passos, 2011; Davids, Button, & Bennett, 2008). Previous research has highlighted the importance of advanced information as a critical constraint on the emergence and regulation of postural control during human movement (Riccio & Stoffregen, 1988; Riccio & Stoffregen, 1991; Stoffregen et al., 1999). Both implicit knowledge learned from trial repetition with similar motion characteristics, or explicit prior warning in task constraints (e.g., perceived velocity of an approaching ball), can influence postural control mechanisms during catching (Tijtgat, Bennett, Savelsbergh, De Clercq, & Lenoir 2010, 2011) and upright standing (Aimola, Santello, La Grua, & Casabona, 2011; de Lima, de Azevedo Neto, & Teixeira 2010). Tijtgat et al. (2012) showed that, during a catching task, provision of explicit advanced knowledge of ball velocity enabled a more functional scaling of arm movement during the transport phase, with the initial motor response adapting to the expected ball speed. These adaptions were absent when no advanced information was available and the initial response was similar regardless of ball speed. With the provision of advanced information, a smaller forward momentum of the rest of the body was produced, indicating a less pronounced postural response, which enabled the motor system to maintain balance during the sensitive grasping phase.

The importance of visual information for regulating postural behaviors was also highlighted by Santos, Kanekar, and Aurin (2010a, 2010b). During a predictable perturbation (with eyes open) individuals produced anticipatory postural adjustments, whereas in an unpredictable condition (with eyes shut) significantly smaller anticipatory postural adjustments emerged, being replaced by compensatory postural adjustments *after* the perturbation. Furthermore, centre of pressure and centre of mass changes were much greater in the unpredictable condition, demonstrating how anticipatory postural adjustments allow individuals to maintain postural stability from a perturbation. These data suggest that, with advanced information, earlier (re)organisation of postural control (evidenced by anticipatory postural adjustments) might enable a reduction in compensatory postural adjustments. During catching performance, the availability of visual information is important since it provides greater system stability, which is functional for successfully catching a ball.

Surprisingly, despite these findings, there has been limited research on anticipatory postural adjustments during performance of externally-timed interceptive actions. Existing research has often excluded advanced perceptual information in experiments (e.g. Eckerle, Berg, & Ward 2012; Kazennikov & Lipshits, 2010; Tijtgat et al., 2010, 2012, 2013) and typically, studies of catching behaviors have been designed so that participants are constrained to catch balls launched from a projection machine, to facilitate experimental control of flight trajectory. However, projection machines do not provide access to advanced visual information from a thrower's actions. For example, Tijtgat et al. (2013) covered their machine with black plastic to ensure participants could not anticipate ball delivery. The removal of such informational constraints, although providing some experimental control, significantly alters the *affordances* (invitations for action; Gibson, 1979) available to a participant to regulate their actions. Skilled performers regulate interceptive actions by coupling them to different sources of information that become partially available at different times in dynamic performance contexts (van der Kamp, Rivas, Doorn, & Savelsbergh, 2008). For example, information prior to ball flight has been revealed as important for successful performance of interceptive actions (e.g., Panchuk, Davids, Sakadjian, MacMahon & Partington, 2013; Stone, Panchuk, Davids, North, & Maynard, 2014). This control strategy of adapting actions to emergent task constraints allows skilled performers to harness the information richness of the performance environment and supports successful behavior.

The removal of key advanced information sources significantly alters the task constraints for the performer, which in turn alters the emergent movement organisation (for a detailed review, see Pinder, Davids, Renshaw and Araújo, 2011). Using the framework of

Brunswik's (1956) theory of representative design in experiments, Pinder et al. (2011) highlighted two critical features within representative design: *functionality of the informational constraints in an experiment* and *action fidelity*. *Functionality* enables performers to regulate action with information that is representative of a performance environment and *action fidelity* allows performers to organise actions that would be required in a specific performance environment. Clearly, if the aim of empirical work is to investigate the role of initial movements and postural control during catching, then the information typically available when performing this task needs to be presented to participants (especially the movement kinematics of a ball thrower's actions).

Only recently have technological developments enabled perception (functionality) and action (fidelity) to be fully integrated, while retaining experimental control of key informational constraints, such as ball flight trajectory (for more detail see methods section and Stone et al., 2013). Stone et al. (2014), using technology that integrated visual information of images of an individual throwing a ball, synchronised with controlled ball projection from a machine (Panchuk et al., 2013; Stone et al., 2013), reported more successful catching behaviors in skilled catchers with the integrated technology, compared to using a ball projection machine only. In addition, analysis of their gaze behaviors revealed that more fixations were made, tracking of the ball occurred earlier, and for a longer period of time, when advanced visual information was available for the catchers. Analysis of kinematic measures of hand movements revealed a smaller maximum velocity and quicker time to reach maximum grip aperture, allowing for a more controlled action of the hand, when advanced visual information was combined with ball flight-only, compared to when a ball was projected without advanced visual information available. Findings suggested that perception and action need to be carefully coupled during studies of externally timed interceptive actions, an important experimental constraint, given that in many investigations of interceptive actions, participants are frequently required to make reductionist, simplified micro-movement responses to simulate actions (e.g., McRobert, Williams, Ward & Eccles, 2009; Vignais et al., 2009). To highlight this issue, Stone et al. (2014) also examined the emergence of simulated catching actions in a condition with visual presentation of a thrower's actions only (without ensuing ball flight-only). When simulating catches, participants did not organise the same arm/hand movements observed when they performed catching actions. Arm and hand movements were initiated much later and at a higher velocity, with grip aperture values being greater when simulating catching actions. Clearly, micro-movements do not successfully simulate dynamics interceptive actions like one-handed catching.

Taken together, these findings demonstrate how both vision of a thrower's actions and ball flight can act as critical informational constraints on successful performance of interceptive actions. The data suggest the need to maintain functional couplings between perception and action, which help to regulate postural control during performance of externally-timed interceptive actions. To address this issue, we investigated how visual information from an image of a ball thrower and during ball flight, along with the specific actions produced, affected postural control and coordination of attempted interceptions in participants during a one-handed catching task. To achieve our empirical aims, participants completed a one-handed catching task in three conditions: (i) integrated video-ball flight, when advanced visual information from a ball thrower (i.e. video) and ball flight were combined, (ii) ball flight-only, when only ball flight information was available, and (iii) video-only, when participants were only presented with advanced visual information from videos of a thrower's movement kinematics and were required to simulate a catching action. These three conditions allowed i) a representative design with advanced visual information (functionality of informational constraints) and unrestricted coupling of movement response (action fidelity). Condition ii) removed functionality (no advanced information) but maintained fidelity (actual catch) and condition iii) maintained functionality (advanced perceptual information) but removed action fidelity by making participants simulate the action.

Based on Brunswik's (1956) theory of representative design, and previous findings reported by Stone et al. (2014), we developed two main hypotheses. First, we expected that coordination of postural control and interceptive movements would be initiated earlier when advanced visual information and ball flight were combined (integrated video-ball flight), compared to a ball flight-only condition, due to advanced visual information providing more specifying affordances, resulting in a better-timed and more controlled movement in skilled catchers. We also predicted that during a simulated action (video-only), whole body movements would occur later and a smaller advanced postural adjustment would be produced compared to when a ball is projected. The removal of information from ball trajectory was also expected to affect perception-action coupling, with limited postural adjustments being required due to the removal of ball impact and the need to actually intercept an object.

Method

Participants

Twelve (10 Male, 2 Female; mean age 24.3 ± 4) skilled right-handed catchers volunteered for the study. Participants were classified as skilled catchers since they had at least 5 years' experience in competitive sports that involved catching projectiles such as cricket, Australian Rules Football and handball (obtained by a sport participation questionnaire). During a pre-test they were also required to successfully catch at least 16 out of 20 (M = 18.1 ± 1) balls at 50 km/h from the ball flight-only machine. Skill level was also confirmed by overall catching success rate during the experimental task (M = 91.3 ± 8.6%).

Institutional ethics approval was granted by a Research Ethics Committee and all participants provided informed consent.

Apparatus

A custom-built apparatus (see Stone et al., 2013, for a detailed description) integrated a ball projection machine (Spinefire Pro 2, Spinfiresport, Tennis Warehouse, Victoria, Australia) with a PC (Windows XP, Microsoft, USA), video projector (BenqMP776s, Benq, Australia) and a freestanding projection screen (Grandview, Grandview Crystal Screen, Canada) with a 15 cm whole cut into the screen. This enabled a video to be projected onto the screen and synchronised with ball projection. Videos of an actor throwing a ball were captured from the participant's viewing perspective (see Figure 1). The criteria for a video to be selected for presentation were: in a filmed throw, the ball had to hit a target area of 1 m x 1 m at a speed of 50 ± 2 km/h measured using a radar gun. Five videos were selected to ensure the actor's throw remained consistent across all trials. Three conditions, each with 30 trials, were created; A *video-only* condition where a video of a ball being thrown was shown with no ball being projected; A *ball flight-only* condition, where balls were projected from a machine without an accompanying video of a throw; finally, an *integrated video-ball flight* condition which synchronised videos of a throwing action with ball flight-only from a machine. Final Cut Pro software (Apple, California, USA) was used to edit footage so that the spatial location of ball release occurred at the same position in each trial. Time to ball release was recorded and aligned within the software to ensure accurate synchronisation of the image of the thrower's release of the ball and its projection from the machine.

Kinematic data from participants were collected using a VICON MX System consisting of 10 MX-T-40S cameras recording data at 500 Hz. Markers were placed using a kinematic gait model and marker set (Plug-In-Gait, VICON, Peak, Oxford, UK) on the 7th cervical vertebrae, 10th thoracic vertebrae, clavicle, sternum, right back, left and right shoulder (Acromio-clavicular joint), left and right upper arm, left and right elbow (lateral epicondyle), left and right forearm, left and right wrist a and b, left and right finger (dorsum of the hand just below the head of the second metacarpal), left and right anterior superior iliac spine, sacral, left and right lateral epicondyle of knee, left and right thigh, left and right ankle (lateral malleolus along), left and right tibia, left and right toe (second metatarsal head), and left and right heel (calcaneous at the same height above the plantar surface of the foot as the toe marker). Two additional markers were placed on the end of the right distal phalanges of the index finger and thumb. A 14-segment model consisting of feet, shanks, thighs, pelvis, thorax/abdomen, upper arms, lower arms and hands was created using VICON Nexus Plug-in-Gait. Kinetic data were collected using a force plate (AMTI OR6) at 1000Hz, which was synchronised with VICON Nexus.

Procedure

First, an overview of the apparatus was provided and sport participation questionnaires completed by participants. Without synchronised videos, three practice trials at a ball velocity of 50 km/h were performed, followed by a 20-trial pre-test of participant catching skill. Using the Plug-in-Gait guidelines, reflective markers were attached using double-sided tape. Five further trials were performed with videos of a thrower’s actions available to enable participant familiarisation with equipment. Thirty trials in each of three blocked conditions were undertaken in a counterbalanced design: ball flight-only, integrated video-ball flight, and video-only. Participants were asked to catch the balls during ball flight-only and the integrated video-ball flight conditions. They were asked to simulate a catch during video-only trials by timing and placing their hand at the location where they expected the ball to arrive, had it been projected. Participants were asked to attempt to catch the ball with their dominant (right) hand while standing 7 m away from the screen, starting in a relaxed position with their hand by their side and feet shoulder width apart. The ball (mid-pressed tennis balls, 66mm diameter) was placed into the projection machine and the apparatus was activated after a random interval between 0-3 seconds; depending on the experimental condition, the video and/or ball were projected. The only instructions given to participants were to attempt to catch the ball or simulate a catching action, which enabled analysis of emergent behaviors. Two researchers independently recorded the outcomes of catching performance for each trial to ensure reliability. In order to prevent fatigue, participants were given a 2-5 minute break between blocks. No discomfort or impediment was reported when catching the ball using the equipment. Acoustic information from the apparatus was removed by having participants wear earplugs.

Data Processing and Analysis

During integrated video-ball flight and ball flight-only conditions, each performance outcome was recorded as a catch or drop, with success rate expressed as a percentage of trials (after Stone et al., in press). Kinematic and kinetic data of participant catching actions/simulations were recorded and analysed off-line using VICON Nexus software and MS Excel. Kinematic and kinetic data were smoothed using a Butterworth filter (set to 8Hz and 20Hz respectively). Of 1,080 trials recorded across all participants, 56 trials (5.1%) were removed from analysis due to technical faults. The onset of movement was calculated by calculating the forward acceleration of the right hand marker with a velocity threshold change of 5m/s or greater, with all trials realigned to this point (T_{on}) (after Stone et al., in press). Each trial was analysed from 300 ms before to 800 ms after T_{on} (based on Tijtgat et al., 2013). All joint angles, centre of pressure (COP) and centre of mass (COM) are expressed relative to their baseline values (averaged between 500 and 300ms before T_{on}).

Joint angle data were produced using the Plug-in-Gait (PIG) model. The model consisted of fourteen body segments, pelvis, femur (2), tibia (2), feet (2), humerus (2), radius (2) hands (2) and thorax. Angular displacement (°) of flexion/extension was calculated on the right side for ankle, knee, hip, shoulder, elbow, wrist and the spine and thorax. In the sagittal plane, the positive sign corresponds to flexion and the negative to extension.

Displacement of COP in the anterior-posterior direction was calculated using the approximation method (Winter et al., 1996).

$$COP = My + Fx * d/Fz$$

My = moment in sagittal plane. Fz and Fx are the vertical and anterior components of ground reaction force (GRF) and d is the distance from the origin of the force platform to the surface. Body mass and height with seven anthropometrical measures, leg length, knee, ankle, elbow and wrist width and shoulder offset and hand thickness for each participant were entered into the PIG model. These measures with kinematic data were used to calculate the body's COM position. COM in the sagittal (COMx), front (COMy) and transverse (COMz) planes were analysed. Timing of displacement onset in COP (COP-Onset), COMx (COMx-Onset), COMy (COMy-Onset) and COMz (COMz-Onset) was initially determined by a trained researcher and confirmed by an acceleration rise of the signal of 0.5 m/s^2 (Santos et al., 2010b; Tijtgat et al., 2013). Peak displacements in COP (Peak-COP) and each plane of COM, (Peak-COMx, Peak-COMy and Peak-COMz) and respective times were calculated (Time-to-peak-COP, Time-to-peak-COMx, Time-to-peak-COMy and Time-to-peak COMz) and used as an indication of postural control (Santos et al., 2010b). Time from COP Onset to Peak-COP was calculated by subtracting Time-to-peak COP from COP-Onset and temporal changes in displacement of COP are presented as an average over 50 ms intervals (see Figure 2). Descriptive statistics for the performance outcomes of successful catches and dropped balls in the ball-flight-only and integrated video-ball flight conditions for both COP and

COM variables are also presented (Table 1). With three participants successfully catching all the balls during the integrated video-ball flight condition, mean values for nine participants were used to calculated the values for dropped catches in these conditions. Each of these measures provided insights into participants' regulation of posture during performance of the catching action.

Mean displacement values of each angle were calculated for 4 epochs to examine segmental control (using criteria of Santos et al., 2010b). Epochs 1 and 2 were based on methods from previous studies of anticipatory postural adjustments (Shiratori & Latash, 2001; Santos et al., 2010b). Epochs 3 and Epochs 4 were selected on the corrective postural control adjustments observed in the trunk and leg muscles during catching (Tijtgat et al., 2013).

The epochs used were aligned to T_{on} with epoch 1 (Ep1) -200 ms to -50 ms, epoch 2 (Ep2) -50 ms to +100 ms, epoch 3 (Ep3) +100 ms to 250 ms and epoch 4 (Ep4) +250 ms to 400 ms. Epochs 1 and 2 are considered to reveal advanced postural adjustments, with 3 and 4 showing compensatory postural adjustments. These epochs were used for statistical analysis and a temporal evaluation is also presented for each angle averaged over 50 ms intervals.

Statistical Analyses

A dependent measures t-test was performed on catching performance outcome data observed in integrated video-ball flight and ball-flight only conditions. Multiple repeated measures ANOVAs (Condition (3) x Variable) were used to analyse COP-onset, COMx-onset, COMy-onset, COMz-onset, Peak-COP, Peak-COMx, Peak-COMy, Peak-COMz, Time to Peak COMy Time to Peak COMx and Time to Peak COMz.

Multiple two-way repeated measures ANOVAs were used (Condition (3) and epochs (4)) to analyse joint angles (Ankle, Knee, Hip, Spine, Thorax, Shoulder, Elbow, Wrist). A Greenhouse-Geisser correction was applied to any violations of sphericity with the repeated measures variables. Post-hoc testing was used to further analyse any main effect differences using a Bonferroni correction. If an interaction was present, simple effects analysis, with a Bonferroni correction was applied. Mean and standard error data are presented with all times displayed in ms. Partial eta squared (ηp^2) is used for effect size estimations of ANOVA main effects with Cohen's *d* presented, when appropriate, for post-hoc analyses.

Results

Catching Performance Outcomes

Performance condition affected catching performance outcomes $t(1, 11) = 2.285$, $p < .05$, $d = .79$ with catching success being greater in the integrated video-ball flight condition (94.7% ± 4.8 % of balls caught) than in the ball flight-only condition (88% ± 11.1%).

COP and COM

Statistical outcomes for analysis of both COP and COM measures are summarised in Table 1. Two significant effects of conditions on COP were revealed. First, performance condition had a main effect on COP-Onset ($p < .05$, $\eta p^2 = .40$), with post-hoc tests showing that in the ball flight-only condition, COP-Onset emerged significantly later than in the integrated video-ball flight condition ($p < .001$, $d = 2.1$). Second, performance condition affected the time difference between COP-Onset to Time-of-Peak-COP ($p < .05$, $\eta p^2 = .31$) with post-hoc tests showing a smaller time difference in the ball flight-only condition compared to the integrated video-ball flight condition ($p < .05$, $d = 1.3$).

Changes in COMz and COMy were observed between conditions, with COMz-Onset being affected by performance condition ($p < .001$, $\eta p^2 = .56$). All COMz-Onset values emerged before $T_{on,}$ with post-hoc tests revealing that this effect emerged earlier in the integrated video-ball flight condition than in the ball flight-only ($p < .05$, $d = 1.3$) and video-only conditions ($p < .05$, $d = 1.24$). There was also a main effect of performance condition on Peak-COMz ($p < .05$, $\eta p^2 = .26$) with post-hoc tests showing a smaller peak displacement for Peak-COMz emerging in the integrated video-ball flight condition compared to the video-only condition ($p < .05$, $d = .80$). Performance condition also affected Time-to-peak-COMz ($p > .05$, $\eta p^2 = .30$) with post-hoc tests showing that the Time-to-peak-COMz emerging in the ball flight-only and video-only conditions occurred later than in the integrated video-ball flight condition ($p = .046$, $d = 1.1$, $p < .05$, $d = .88$ respectively).

There was also a main effect of performance condition on COMy-Onset ($p < .05$, $\eta p^2 = .35$). Post-hoc tests showed that in the integrated video-ball flight condition, COMy-Onset emerged before T_{on} and differed in value in the ball flight-only ($p < .05$, $d = .82$) and video-only ($p < .05$ $d = .86$) conditions, with their onsets emerging after T_{on}. Performance condition had a main effect on Time-to-peak-COMy ($p < .05$, $\eta p^2 = .28$). Post-hoc tests showed that Time-to-peak-COMy emerged earlier during the integrated video-ball flight condition than in both the ball flight-only ($p = .071$, $d = .76$) and video-only ($p = .052$, $d = .72$) conditions (see Figure 3).

Angles

Postural Control - Hip, Knee, Ankle, Spine and Thorax

Performance condition had a main effect on ankle displacement values, $F(2, 22) = 19.11$, $p < .000$, $\eta p^2 = .64$. Post-hoc tests showed in the ball flight-only (4.0° ± .8°) and integrated video-ball flight (5.2° ± 1.1°) conditions, ankle displacement values were greater than in the video-only (0.1° ± 0.1°) condition ($p < .000$, $d = 2.10$ and $p < .05$, $d = 1.90$ respectively)(see figure 4). Epochs had a main effect on ankle displacement values $F(1.08, 11.79)$ 19.89, $p < .001$ $\eta p^2 = .64$. Post-hoc tests showed differences between ankle displacement values at all epochs, with greater ankle displacement values observed as time increased; Ep1 (1.0° ± 0.2°) displayed smaller displacement values than Ep2 (1.9° ± 0.4°), Ep3 (3.8° ± 0.7°) and Ep4 (5.8° ± 1.1°) (all p*'s* < .05, $d = .84$, $d = 1.50$, $d = 1.70$ respectively). Ankle displacement values in Ep2 were smaller than in Ep3 ($p < .05$, $d = .89$) and Ep4 ($p < .05$, $d = 1.34$). Ep3 also revealed smaller ankle displacement values than Ep4 ($p < .05$, $d = .63$). There was also a significant performance condition x epoch interaction, $F(1.30, 14.29) = 23.15$, $p < .000$, $\eta p^2 = .68$.

Performance condition had a main effect on knee displacement values $F(2, 22) = 7.93$, $p < .05$, $\eta p^2 = .42$. Post-hoc tests showed that the ball flight-only (5.8° ± 1.6°) and integrated video-ball flight (6.0° ± 1.7°) conditions revealed greater knee displacement values than the video-only condition (-0.1° ± .1°, both p*'s* < .05, $d = 1.30$, $d = 1.31$ respectively). Epochs also affected knee displacement values $F(1.07, 11.78) = 16.53$, $p < .001$, $\eta p^2 = .60$. Post-hoc tests showed that, as time increased, magnitude of knee displacement values increased, (Ep1 1.0° ± 0.4°; Ep2 2.0° ± 0.6°; Ep3 4.9° ± 1.2°; Ep4 7.9° ± 1.8°; with knee displacement values in each epoch significantly different from each other, p*'s* < .05). There was also a condition x epoch interaction $F(1.41, 15.51) = 8.32$, $p = < .05$, $\eta p^2 = .43$.

A summary of descriptive statistics for significant interactions of joint angle x epoch is presented in Table 2. Analysis showed that during the video-only condition, both ankle and knee displacement values did not change across epochs (both $p > .05$). In contrast, in the ball flight-only condition, ankle and knee displacement values increased as time progressed (both $p < .05$). Similarly, during the integrated video-ball flight condition, ankle displacement values increased across all epochs ($p < .05$), with increases in all epochs at the knee, apart from Ep1 and Ep2 ($p > .05$) and Ep3 and Ep4 ($p > .05$). During Ep1 and Ep2 (anticipatory epochs) greater increases in ankle displacement values were seen in integrated video-ball flight condition than ball flight-only condition (Ep1 $p < .05$, $d = 1.30$, Ep2 $p < .05$, $d = 1.01$). Greater knee displacement values were observed at Ep1 in the integrated video-ball flight condition than in the ball flight-only condition ($p < .05$, $d = 1.02$). During the final three epochs, ankle displacement values in the video-only condition were consistently smaller than in the ball flight-only condition (Ep2, $p < .05$, $d = 1.37$; Ep3, $p < .001$ $d = 2.05$; Ep4, $p < .001$, $d = 2.02$) and in the integrated video-ball flight condition (Ep2, $p < .05$, $d = 1.5$; Ep3, $p < .001$, $d = 1.95$; Ep4, $p < .000$, $d = 2.25$). Similar observations were noted for knee displacement values which were smaller in the video-only condition than the ball flight-only condition (Ep2 $p < .05$, $d = 1.38$; Ep3, $p < .05$, $d = 1.44$; Ep4, $p < .05$, $d = 1.43$) and the integrated video-ball flight condition (Ep2, $p = .056$, $d = 1.12$; Ep3, $p < .05$, $d = 1.41$; Ep4, $p < .05$, $d = 1.65$).

Performance condition had no main effect on hip displacement values $F(1.13, 12.42) = 1.90$, $p > .05$, or epochs $F(1.02, 11.23) = 2.05$, $p > .05$. There was also no displacement x epoch interaction $F(1.21, 13.32) = 2.79$, $p > .05$.

Performance condition and epochs had no main effect on thorax displacement values $F(2, 22) = 1.74$, $p > .05$, $\eta p^2 = .14$ and $F(1.14, 12.51) = 3.24$, $p > .05$ respectively. There was also no performance condition x epochs interaction $F(1.79, 19.72) = 1.11$, $p > .05$, $\eta p^2 = .09$.

Performance condition did not have a main effect on spine displacement values $F(2, 22) = 1.76$, $p > .05$, $\eta p^2 = .14$, and nor did Epochs $F(1.06, 11.65) = .53$, $p > .05$. There was also no performance condition x epochs interaction, $F(2.02, 22.25) = .81$, $p > .05$.

Catching Arm

Performance condition had no effect on shoulder displacement values $F(1.23, 13.58) = .39$, $p > .05$, and nor did Epochs $F(1.41, 15.55) = 100.73$, $p < .000$, $\eta p^2 = .90$. Shoulder displacement values differed from one another at all epochs ($p < .001$), with shoulder displacement values increasing as time progressed (Ep1 4.0 ± 1.2°; Ep2 8.5 ± 1.5°; Ep3 25.0 ± 2.1°; Ep4 39.3 ± 2.1°). A significant performance condition x epochs interaction was observed, $F(1.62, 17.80) = 4.69$, $p < .05$, $\eta p^2 = .30$ (see figure 4).

Performance condition had no main effect on elbow displacement values $F(2, 22) = .46$, $p > .05$, $\eta p^2 = .04$. There was a main effect of Epochs on elbow displacement values $F(5.41, 13.28) = 46.92$, $p < .000$, $\eta p^2 = .81$. Post-hoc tests showed elbow displacement values at Ep1 (5.4 ± 1.0°) were smaller than in Ep2 (16.8 ± 2.1°, $p < .000$, $d = 2.01$), Ep3 (34.0 ± 3.8°, $p < .000$ $d = 2.94$) and Ep4 (34.6 ± 4.4°, $p < .000$ $d = 2.65$). At Ep2 elbow displacement values were smaller than in Ep3 ($p < .000$ $d = 1.60$) and Ep4 ($p < .001$ $d = 1.49$). There was also a performance condition x epochs interaction $F\ (2.05, 22.50) = 3.56$, $p < .05$, $\eta p^2 = .25$.

Performance condition did not have a main effect on wrist displacement values $F(2, 22) = .18$, $p > .05$, $\eta p^2 = .02$. Epochs revealed a main effect on wrist displacement values $F(1.22, 2.06) = 54.49$, $p < .000$, $\eta p^2 = .83$. Ep1 (6.0 ± 1.2°) revealed smaller wrist displacement values than Ep2 (17.4 ± 2.5°, $p < .000$, $d = 1.69$), Ep3 (24.7 ± 3.4° $p < .000$, $d = 2.15$) and Ep4 (25.9 ± 3.1°, $p < .000$, $d = 2.4$). Values of wrist displacement at Ep2 were smaller than Ep3 ($p < .001$, $d = .70$) and Ep4 ($p < .000$, $d = .86$). A condition x epochs interaction was present $F(2.06, 22.63) = 6.31$, $p < .05$, $\eta p^2 = .36$ (see Figure 5).

Simple effects analysis revealed limb displacement changes in all three conditions (see Table 2 for descriptive statistics). Shoulder displacement values increased in each epoch as time progressed ($p <.05$), apart from in the ball flight-only condition at Ep1 and Ep2 ($p > .05$). Elbow displacement increased, as time increased, in both integrated video-ball flight and ball flight-only conditions, in all epochs ($p < .000$, $p < .05$ respectively) apart from Ep3 and Ep4 ($p > .05$). Elbow displacement values in the video only condition differed across epochs ($p < .05$), other than in comparisons between Ep2 and Ep4 ($p > .05$) and Ep3 and Ep4 ($p > .05$). At the wrist, changes were observed in the ball flight-only condition in all epochs ($p < .001$), apart from in comparisons between Ep3 and Ep4 ($p >.05$). In the video only condition the wrist displacement values epochs were again different across all epochs ($p <.05$) apart from in comparisons between Ep3 and Ep4 ($p >.05$) and during integrated video-ball flight condition the wrist displacement values were all different, increasing as time progressed ($p < .05$), apart from Ep2 and Ep4, Ep3 and Ep4 ($p <.05$).

At Ep1 increased displacement values were observed in the integrated video-ball flight condition, compared to ball flight-only condition, at the shoulder ($p < .05$, $d = 1.14$), elbow ($p < .05$ $d =1.43$) and wrist ($p < .01$, $d = 1.82$). The integrated video-ball flight condition also revealed greater wrist displacement values at Ep1 than in the video-only condition ($p < .05$, $d = .88$). At Ep2 shoulder displacement values were greater in the integrated video-ball flight condition compared to the ball flight-only condition ($p < .05$, $d = 1.45$). No differences in shoulder displacement values were observed during Ep3 ($p > .05$). However, at Ep4, the integrated video-ball flight condition revealed smaller shoulder displacement values than in the ball flight-only condition ($p < .05$, $d= .81$).

Discussion

In this experiment we examined how manipulating access to advanced visual information from the image of a thrower’s actions, and to vision of ball flight, constrained the organisation of interceptive actions and postural control during performance in a one-handed catching task. Results showed these manipulations produced significant changes in movement patterns, postural regulation behaviors and performance success rates of participants observed under the three different conditions. These findings demonstrated that postural control and interceptive actions are sensitive to the specific perceptual informational constraints present during performance. Our data confirmed that, not only are interceptive actions directly linked to such perceptual information sources, but so too are the anticipatory postural adjustments that precede these movements.

Although similar movement patterns were observed in the two conditions when a ball was physically intercepted by participants (integrated video-ball flight and ball flight-only), changes in COM and COP behaviors, as well as lower limb joint angles, emerged later when advanced visual information sources were removed. This finding supports our first hypothesis that postural regulation behaviors would emerge earlier in the integrated video-ball flight condition, compared to when only ball flight was available. When video and ball flight information were combined, advanced postural adjustments emerged prior to onset of the catching arm, suggesting that participants adapted earlier to the specific postural control requirements of the catching task. The importance of earlier movement initiation during interceptive actions was highlighted when the data were split into catches and drops. It appears that during the integrated video-ball flight conditions earlier movements for COP, COMx, COMy and COMz onsets and time to peak resulted in successful catches. In the ball flight-only condition there was also earlier COP, COMy and COMz onsets during successful catches compared to dropped catches. Yet as the second hypothesis proposed, during a simulated action (video-only condition), limited postural control movements from the lower limbs emerged. Indeed, directional changes emerged upwards in COMz, when catching actions were simulated, compared to a downwards direction in conditions when catches were coordinated. This observation provides support for an ecological dynamics perspective proposing that humans, considered as complex adaptive systems, are capable of functionally altering their behaviors to achieve performance outcomes. Participants in this experiment displayed an emergent tendency to harness processes of perception and action in adapting their movement patterns with respect to available information in a performance environment (Warren, 2006; Davids et al., 2014).

When performing, or simulating, a one-handed catching action, participants showed the same sequence of postural adjustment initiation in each condition with COP-Onset emerging first followed by changes in COMz, COMy and COMx. Yet the timing of these sequences, in relation to the initiation of movement of the catching arm (T_{on}), differed across conditions. During the integrated video-ball flight condition, COP-Onset, COMz-Onset and COMy-Onset emerged before the initiation of movement of the catching arm. This observation suggests that, with access to advanced visual information, anticipatory postural adjustments can emerge prior to the coordination of an interceptive movement with the catching arm. Yet when this visual information source was removed (in the ball flight-only condition), despite COMz-Onset emerging prior to initiation of movement of the catching arm, a much shorter time frame was seen (-18 ms). Consequently, COMy-Onset emerged after initiation of movement of the catching arm. This observation suggests that anticipatory postural adjustments, emerging when only ball flight information is available, differed to when advanced visual information and ball trajectory information were combined. These data support those reported by Tijtgat et al. (2013), who showed no clear evidence of advanced postural adjustments during catching when advanced visual information was not available to a catcher. With added affordances that the videos provide, participants were exposed to richer informational constraints that allowed them to more accurately anticipate ball release and organise advanced postural control adjustments accordingly, which ultimately resulted in improved catching performance.

This proposal is further supported by differences observed in the timing between initiation of COP-Onset to Time-to-peak-COP. This transition period took longer when representative perceptual and action constraints were combined, in contrast to conditions when the images of a thrower's action or ball flight information were removed, suggesting a more controlled change in COP under the former task constraints. Santos et al. (2010b) proposed that the CNS might not only control the magnitude of COP-peak displacement but also the timing of this peak to maintain functional balance. The findings of our study showed that, in the integrated video-ball flight condition, COP-Onset emerged earlier than when advanced perceptual information was removed (ball-flight only). However, both peaks occurred at similar time points. This observation suggests that under more predictable performance conditions, when advanced visual information enables a more accurate anticipation of ball flight-only, then more time is available for COP to reach its peak, which allows a smoother and more controlled action to emerge. Without the affordances picked up from the advanced visual informational constraints, participants were required to rely on ball flight information only to constrain their actions, resulting in a more reactive response and may account for the decreased catching performance. It could be argued that these behaviors have limited functionality in typical performance environments, which are enriched with informational constraints. After all, as Whiting (1991) argued long ago: action is not the same as reaction.

Lower limb joint flexion-extension patterns seemed primarily responsible for COM and COP displacement during the two conditions in which participants were required to physically catch the ball (ball flight-only, and integrated video-ball flight conditions). In these conditions, participants used a combination of movements in the ankle, knee and hip joints. The findings suggest the lower limb joints (in integrated video-ball flight and ball flight-only conditions) played a key role in minimising upper body displacement, enabling the upper body to stay vertical in orientation to help ensure the head and eyes remained stable, allowing a functional behavior that affords tracking of a ball. Yet differences observed in lower limb displacement values, and their magnitudes in the integrated video-ball flight-only and the ball flight-only conditions, provide further evidence of the importance of advanced visual information in postural control and performance accuracy. During integrated video-ball flight, flexion of the ankle and knee began before the initiation of movement of the catching arm (T_{on}). In contrast, when access to these visual information sources was not available (i.e., when only ball flight information was presented), lower limb displacement emerged at an equivalent time to arm movement (see Figure 5). This is an important observation, since in line with previous research (Santos et al. 2010b), it seems that perception of sources of advanced visual information is one of the main behavioral strategies used to regulate postural control. In addition, the earlier movements observed when advanced visual and ball flight information sources were combined may allow the body and head/eyes to be prepared and stabilised in a functional position when the ball is released. This behavioral strategy may enable earlier tracking of the ball and a smoother and more controlled movement of the catching arm, both of which are associated with more accurate catching performance (Panchuk et al., 2013; Stone et al., 2014). This proposal is supported by kinematic data from the catching arm which revealed that displacements of the shoulder, elbow and wrist emerged earlier during the integrated video-ball flight condition compared to when ball flight information only was available.

The simulated catching action, when only advanced visual information was presented (video-only), produced considerably different movement patterns in relation to the two conditions that required actual interception of the ball. Participants showed minimal changes in the lower limbs with an upward Peak-COMz. Without the need to control for the impact of the ball, participants allow COMz to rise with the movement of the arm. Knowledge that interception of an object is not required significantly affects postural control as well as arm movement characteristics and gaze behaviors of participants (see also data reported in Stone et al., in press). This is an important finding if researchers are attempting to use simulated actions to test the role of anticipation in human behavior. The findings show that movement patterns will be adapted, depending on the specificity of the task constraints presented to participants. Action fidelity is a particularly important methodological issue, given the growing use of virtual environments within research and training contexts (e.g. Fink, Foo, & Warren, 2009; Chan, Leung, Tang, & Komura, 2011; Vignais et al., 2009). These virtual environments allow varying levels of immersion by the participant and simulated actions are commonly used. The data presented here suggests researchers and practitioners need to ensure representative designs which allow the greatest level of immersion possible so that adequate feedback is available to elicit the same postural responses as required in the performance environments that are simulated

The findings observed in all three conditions added support for van der Kamp et al.'s (2008) proposal that both *advanced information prior to ball release* and *ball trajectory information* are essential for successful catching performance. Here we have demonstrated that these information sources are also important for anticipatory postural regulation to support the performance of interceptive actions during upright stance. The findings have theoretical implications by highlighting the precise coupling between perception and action to regulate behaviors of different movement sub-systems.

Data on adaptations to postural regulation behaviors and the kinematics of the catching arm in the three conditions suggested that the catching action was 'nested' on the task of postural regulation (see Riccio & Stoffregen, 1988). This coordination strategy reduced the number of system degrees of freedom that the CNS needed to regulate in an “umbrella” control strategy, with posture being dependent on the task being performed. For example, when participants attempted to mediate the potentially destabilizing effects of ball impact on the hand, postural regulation behaviors were adapted during interception compared to when the same participants performed the simulated catching action. This observation suggests that postural control and the nested catching action were integrated and organised together, forming a new synergy from the re-organised motor system degrees of freedom. These results support the proposal that the two sub-systems of postural control and interception should not be considered as functioning independently, requiring two separate control mechanisms. Rather posture is regulated continuously in order to facilitate the performance of other nested actions, such as reaching into space to catch a passing ball (often referred to as supra-postural goals, see Riccio & Stoffregen, 1988; Riccio & Stoffregen, 1991; Stoffregen et al., 1999).

In addition the findings pose significant challenges for research that neglects the careful consideration of an action component (by using micro-movements) (e.g. Aglioti, Cesari, Romani & Urgesi, 2008; Abreu et al., 2012; Tomeo, Cesari, Aglioti & Urgesi, 2012) or which excludes availability of advanced perceptual information sources for participants. Removal of either component, which is common in research, will alter the informational constraints and fail to capture the dynamic, emergent nature of interceptive actions. Finally, practitioners that rely on ball flight-only machines to train performers may wish to reconsider the design of their practice environments considering the findings presented here.

In conclusion, we observed emergent perception-action couplings in three conditions with varying informational constraints during performance of a one-handed catching task. The data support the tenets of ecological dynamics, the theoretical rationale used to frame our investigation of coordination. The findings however could also be interpreted through alternative theoretical explanations such as the theory of event coding (TEC) (Hommel, Müsseler, Aschersleben & Prinza, 2001). For example, the evidence of advanced postural adjustments supports TEC’s proposal that human action is anticipatory in nature and regulates human behavior (Hommel, 2009). The findings also support the importance of considering the intentions and goal-directed actions of participants, a key component of TEC over previous cognitive based theories of human perception and action which have seen actions as merely by products of perception (Hommel, 2009). Our findings showed that simulated actions resulted in considerably emergence of distinct movement patterns under different informational constraints, such as when ball flight information was available and actual interception of an object was required. Further, when visual information of a thrower's action was not available to participants, despite a similar movement strategy and postural control mechanism, the timing of such activation was delayed and prevented effective use of anticipatory postural adjustments, decreasing system stability and resulting in impaired catching performance. Further work should be undertaken to compare kinematic and kinetic patterns emerging in trials resulting in successful and dropped catches which could provide further insight into functional coordination strategies needed for performance of this kind of interceptive action. Additionally, it would be important to examine how changes in ball velocity, participant stance and other manipulations to informational constraints affect coupling of perception and action in performance of dynamic interceptive actions.

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Table 1. COP and the three directions of COM ANOVA and post-hoc outputs for Onset, peak and time to peak between each of the three performance conditions (Video-Ball- integrated video-ball flight; Ball-Only- ball flight-only).

	df	f	p	ηp^2	Video-Ball (M ± SE)	Ball-Only (M ± SE)	Video-Only (M ± SE)	Video-Ball (M ± SE)		Ball-Only (M ± SE)	
								Catch	Drop	Catch	Drop
COP											
Onset (ms)	1.4, 14	7.55	<.05	.407	-356 ± 49**	-36 ± 37**	-232 ± 86	-361 ± 52	-337 ± 112	-41 ± 36	-29 ± 38
Peak Displacement (mm)	2, 22	0.12	>.05	.011	-17 ± 16	-15 ± 12	-17 ± 8	-17 ± 18	-21 ± 21	-15 ± 11	-25 ± 15
Time to Peak (ms)	2, 22	1.04	>.05	.086	190 ± 56	244 ± 43	308 ± 70	182 ± 57	230 ± 104	232 ± 42	284 ± 63
Peak – Onset (ms)	2, 22	4.86	<.05	.316	546 ± 75*	255 ± 43*	539 ± 99	552 ± 73	567 ± 78	273 ± 41	313 ± 46
COM Onset											
COMy (ms)	1.2, 13.3	5.79	<.05	.345	-93 ± 50^{*ab}	18 ± 24^{*a}	153 ± 105^{*b}	-97 ± 53	-6 ± 64	4 ± 32	25 ± 35
COMz (ms)	2, 22	9.04	<.01	.559	-111 ± 27^{*ab}	-18 ± 11^{*a}	-19 ± 13^{*b}	-115 ± 23	-41 ± 34	-21 ± 15	-8 ± 15
COMx (ms)	1.1, 13.4	0.90	>.05	.142	17 ± 46	61 ± 41	203 ± 159	12 ± 49	23 ± 21	61 ± 47	62 ± 30
COM Peak Displacement											
COMy (mm)	2, 22	1.28	>.05	.104	-7 ± 7	-4 ± 8	-14 ± 5	-6 ± 6	-9 ± 8	-5 ± 8	-3 ± 8
COMz (mm)	2, 22	3.80	<.05	.257	-3 ± 9*	-1 ± 12	20 ± 7*	-3 ± 9	2 ± 11	-3 ± 12	2 ± 13
COMx (mm)	1.2, 13	0.90	>.05	.760	-1 ± 14	-11 ± 13	-8 ± 6	1 ± 13	-9 ± 15	-10 ± 13	-11 ± 14
COM Time to peak											
COMy (ms)	2, 22	4.23	<.05	.278	224 ± 53*	352 ± 43	366 ± 59*	220 ± 52	231 ± 69	361 ± 44	286 ± 79
COMz (ms)	2, 22	4.67	<.05	.298	201 ± 42^{*ab}	374 ± 50^{*a}	329 ± 42^{*b}	194 ± 40	234 ± 57	387 ± 45	315 ± 88
COMx (ms)	2, 22	1.28	>.05	.104	369 ± 54	424 ± 51	332 ± 42	391 ± 56	347 ± 87	421 ± 48	445 ± 66

Post-hoc testing: ^{a} denotes significant comparison between Video-ball and Ball-Only conditions, ^{b} denotes significant comparison between Video-Ball and Video-Only conditions, *p < .05, **p < .001

Table 2. Summary of descriptive statistic for ankle, knee, shoulder, elbow and wrist at each epoch (VBP- integrated video-ball flight-only; BPO- ball flight-only only; VO- video only).

	Ep1 M ± SE (°)	Ep2 M ± SE (°)	Ep3 M ± SE (°)	Ep4 M ± SE (°)
Ankle				
VBP	2.4 ± 0.7	4.1 ± 1.0	6.3 ± 1.3	8.3 ± 1.5
BPO	0.3 ± 0.1	1.4 ± 0.4	5.0 ± .1.0	9.3 ± 1.9
VO	0.2 ± 0.1	0.2 ± 0.1	-1.0 ± 0.2	-0.1 ± 0.3
Knee				
VBP	2.7 ± 1.0	4.2 ± 1.5	7.2 ± 2.1	9.8 ± 2.4
BPO	0.2 ± 0.1	1.7 ± 0.5	7.4 ± 2.1	14.0 ± 4.0
VO	0.1 ± 0.1	0.02 ± 0.1	-0.02 ± 0.1	-0.04 ± 0.2
Shoulder				
VBP	9.4 ± 3.1	13.8 ± 3.0	25.0 ± 2.7	33.2 ± 3.5
BPO	0.7 ± 0.4	2.6 ± 1.1	22.24 ± 3.0	44.6 ± 4.6
VO	1.9 ± 1.2	8.9 ± 2.5	27.6 ± 4.0	40.1 ± 5.6
Elbow				
VBP	9.7 ± 2.2	20.5 ± 3.4	32.8 ± 4.6	33.0 ± 4.1
BPO	1.7 ± 0.5	14.2 ± 1.3	38.8 ± 4.0	39.0 ± 4.4
VO	4.8 ± 1.5	15.8 ± 3.3	30.3 ± 5.9	31.8 ± 7.3
Wrist				
VBP	10.5 ± 1.5	20.2 ± 2.7	22.1 ± 2.9	23.7 ± 3.2
BPO	2.1 ± 1.2	15.2 ± 3.0	28.3 ± 5.4	29.6 ± 4.8
VO	5.4 ± 1.9	16.7 ± 3.3	23.6 ± 3.7	24.4 ± 3.5

Figure 1. An example of three screen shots of the advanced visual information projected onto the screen.

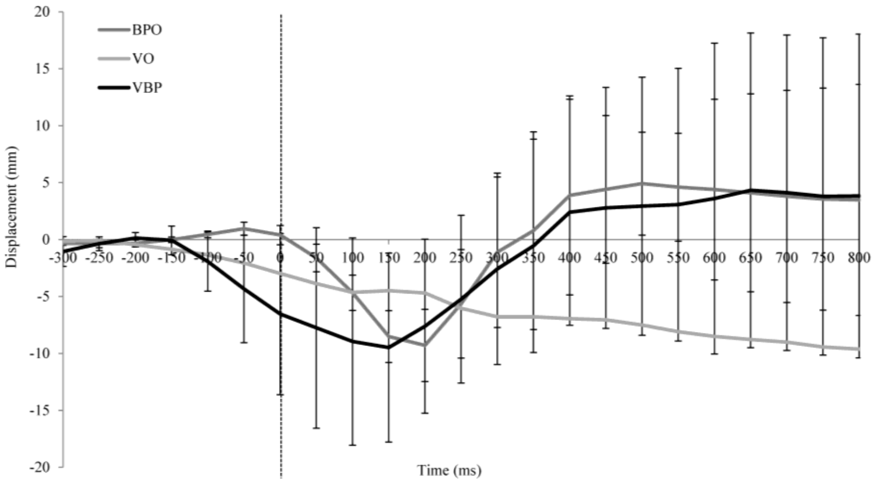

Figure 2. Temporal evaluation of COP from -300ms to +800ms for the three performance conditions. Each point represents COP displacement in the sagittal plane with backward (+) and forward (-). Each time point is averaged over 50-ms intervals (e.g. -200 ms is -201 to -150 and so on) with standard errors presented. The dotted vertical line shows $T_{on.}$

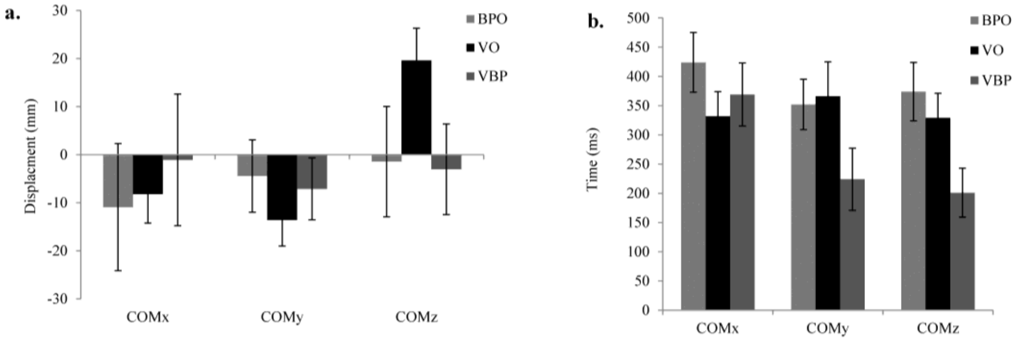

Figure 3. a). Peak displacement and b). Time to peak displacement in COMx, COMy and COMz during the three performance conditions (M ± SE). (VBP- integrated video-ball flight-only; BPO- ball flight-only only; VO- video only)

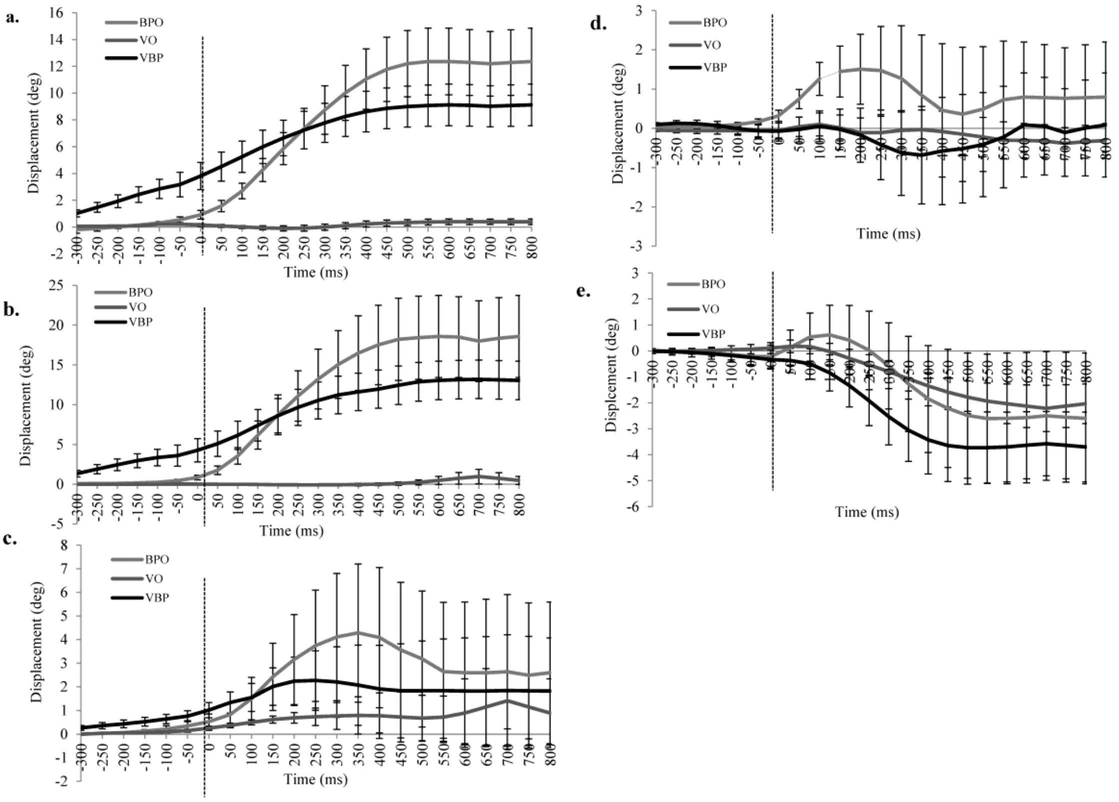

Figure 4. Temporal evaluation (from -300ms to + 800ms in relation to Ton) of the a)ankle, b) knee, c) hip, d) spine and e) thorax during the three performance conditions. Each point represents angular displacement in the sagittal plane with flexion (+) and extension (-). Each time point is averaged over 50 ms intervals (e.g. -200 ms is -201 to -150 and so on) with standard errors presented. The dotted vertical line showed T_{on}. VBP- integrated video-ball flight-only; BPO- ball flight-only only; VO- video only.

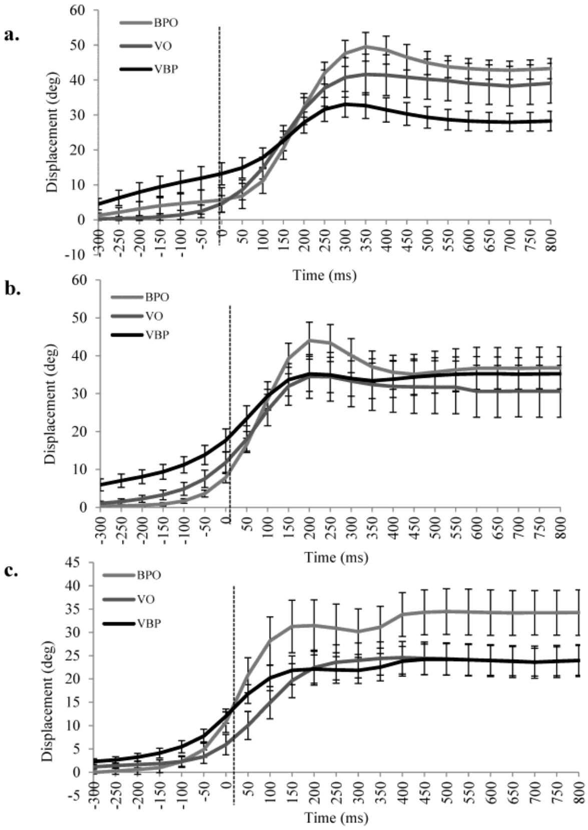

Figure 5. Temporal evaluation (from -300ms to + 800ms in relation to Ton) of the a) shoulder b) elbow and c) wrist during the three performance conditions. Each point represents angular displacement in the sagittal plane with flexion (+) and extension (-). Each time point is averaged over 50 ms intervals (e.g. -200 ms is -201 to -150 and so on) with standard errors presented. The dotted vertical line shows T_{on}.