Rein, Robert and Davids, Keith W. and Button, Chris (2009) *Adaptive and phase transition behavior in performance of discrete multi-articular actions by degenerate neurobiological systems*. Experimental Brain Research.

Adaptive and phase transition behavior in performance of discrete multi-articular actions by degenerate neurobiological systems

Robert Rein[1], Keith Davids[2], Chris Button[3]

In Press: Experimental Brain Research

1: Groupe de Recherche Apprentissage et Contexte, École des Hautes Études en Sciences Sociales, Paris, France

2: School of Human Movement Studies, Queensland University of Technology, Brisbane, Australia.

3: School of Physical Education, University of Otago, Dunedin, New Zealand

Abstract

The identification of attractors is one of the key tasks in studies of neurobiological coordination from a dynamical systems perspective, with a considerable body of literature resulting from this task. However, with regards to typical movement models investigated, the overwhelming majority of actions studied previously belong to the class of continuous, rhythmical movements. In contrast, very few studies have investigated coordination of discrete movements, particularly multi-articular discrete movements. In the present study we investigated phase transition behavior in a basketball throwing task where participants were instructed to shoot at the basket from different distances. Adopting the ubiquitous scaling paradigm, throwing distance was manipulated as a candidate control parameter. Using a cluster analysis approach, clear phase transitions between different movement patterns were observed in performance of only two of eight participants. The remaining participants used a single movement pattern and varied it according to throwing distance, thereby exhibiting hysteresis effects. Results suggested that, in movement models involving many biomechanical degrees of freedom in degenerate systems, greater movement variation across individuals is available for exploitation. This observation stands in contrast to movement variation typically observed in studies using more constrained bi-manual movement models. This degenerate system behavior provides new insights and poses fresh challenges to the dynamical systems theoretical approach, requiring further research beyond traditionally-studied movement models.

Keywords

degeneracy; movement variability; multi-articular actions; constraints; phase transitions

Introduction

To function effectively within their ecological niche, neurobiological systems need to constantly adapt their movements to changes in energy flows and flexibly recruit the numerous structural degrees of freedom at their disposal. As such, a key issue in motor control is the study of how degenerate neurobiological systems (re)organize movements (e.g. Kelso, 1995; Newell & Corcos, 1993). Degeneracy describes the ability of elements that are structurally different to perform the same function or yield the same output (Edelman & Gally, 2001). An important research endeavor is to understand the role of movement variability and has led to its reconceptualization in dynamical systems theory (DST) as having a more functional role rather than the traditional interpretation as a source of system error (Button, MacLeod, Sanders, & Coleman, 2003; Müller & Sternad, 2004; Riley & Turvey, 2002). However, empirical study within DST has been limited largely to the study of continuous actions as movement models (Kelso & Schöner, 1988) even though theoretical treatments of discrete coordination dynamics are readily available in the literature (Jirsa & Kelso, 2005; Schöner, 1990).

One notable exception on reaching and grasping was conducted by Kelso, Buchanan, and Murata (1994), in which participants were instructed to rotate a handle to a specific position, with initial handle orientation systematically varied. Results indicated a two-pattern regime used by participants with supination and pronation of the forearm prior to making contact with the handle depending on orientation of the handle. Participants also exhibited a hysteresis region, where the movement pattern depended on the previous orientation angle (see also Mutsaarts, Steenbergen, & Meulenbroek, 2004 for a similar example). Another insightful experiment by Sorensen, Ingvaldsen and Whiting (2001) investigated performance of a table tennis task under the dynamical systems theoretical paradigm. As a candidate control parameter, the authors varied ball delivery point to participants continuously from left to right, right to left, and randomly, thus varying spatial location characteristics of ball flight. Stroke type (backhand vs. forehand) and distance between the bat and the edge of the table were considered as collective variables. Results revealed characteristics of phase-transition behavior including hysteresis and critical fluctuations (Sorensen, et al., 2001). Although both studies provided support for the tenets of dynamical systems theory, "*studies of phase transitions in the context of discrete movements […] have been few and far between*" (Sternad, 2008; Wimmers, Savelsbergh, Beek, & Hopkins, 1998, p.245).

Whilst the relationship between continuous and discrete movement has recently undergone more detailed scrutiny (Sternad & Hogan, 2007), the nature of the relationship remains unclear and it is currently not apparent at whether both types of movements are generated by the same processes (Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002; Miall & Ivry, 2004; Schaal, Sternad, Osu, & Kawato, 2004; Sternad & Schaal, 1999; Torre & Delignieres, 2008; Wei, Wertman, & Sternad, 2003). However, recent evidence suggests that discrete and rhythmical movements exhibit differences on the level of movement organization as well as in the central nervous system (Huys, Jirsa, Studenka, Rheaume, & Zelaznik, 2008; Huys, Studenka, Zelaznik, & Jirsa, 2008; Sternad, 2008). This lack of clarity can be acknowledged as a gap in the DST literature on neurobiological system function, challenging its scope. A key question is whether DST can be applied beyond the study of continuous rhythmical movement models to investigations of discrete actions (Summers, 1998).

An additional problem to consider pertains to the level of constraint imposed by many laboratory tasks, which Newell and colleagues have argued is too narrow in existing research. In many experiments, the task outcomes are broadly equivalent to an actual movement pattern. That is, the task outcome already prescribes to some extent the underlying movement pattern (Hong & Newell, 2006). This relationship is exemplified by the most popular experimental paradigm in the dynamical systems theoretical framework, which involves phase coupling of rhythmical finger movements or limb segments (see for example Carson, 1995; Haken, Kelso, & Bunz, 1985; Kelso, Buchanan, & Wallace, 1991; Kelso & Jeka, 1992; Kelso, Scholz, & Schöner, 1986; Kostrubiec, Tallet, & Zanone, 2006; Schmidt, Carello, & Turvey, 1990; Turvey, 1990; Zanone & Kelso, 1992). In contrast, in most mundane movements in life, like picking up a cup, the task goal and associated movement patterns are much more loosely coupled and there are several ways to achieve the task involving different segments. As a general behavioral strategy, the potential role of structurally different system components in task performance provides a robust mechanism against system failure and is common to biological systems as noted by Edelman (1987). To distinguish this concept from the notion of redundancy, this system characteristic has been termed "degeneracy" (Edelman, 1987; Sporns & Edelman, 1993). Typically, preferred movement models in most studies of dynamical movement systems have seldom provided the opportunity to study the emergence of behavior in degenerate systems, which has limited the scope of this theory of motor control. The narrow range of preferred movement models may have potentially introduced a result bias and may have underemphasized the role of degenerate behavior in tasks outside the laboratory.

Related to this issue, most actions investigated thus far have required the involvement of relatively few biomechanical degrees of freedom, for example only the joints of the index finger (Obhi, 2004; Walter, 1998). Using low dimensional tasks, the possible number of movement solutions that might emerge are limited already *a priori,* which potentially introduces a false restriction on the way that movement behavior can typically unfold (Fink, Kelso, Jirsa, & de Guzman, 2000). This task bias leads to some difficulties in generalizing experimental outcomes for developing a comprehensive theory of neurobiological coordination and control (Heise & Cornwell, 1997; Hong & Newell, 2006; Sames, 2000; Walter, 1998). When experimental task constraints provide opportunities for neurobiological systems to use more degrees of freedom in task resolution, it might be assumed that they will make use of these additional, available degrees of freedom to support functional behavior (for examples see Bernardin, Isableu, Fourcade, & Bardy, 2005; Buchanan & Horak, 2001; Chow, Davids, Button, & Koh, 2007; Chow, Davids, Button, & Koh, 2008; Fink, et al., 2000; Hatzitaki & Konstadakos, 2007; Ko, Challis, Stitt, & Newell, 2003; Robertson & Miall, 1997; Vereijken, van Emmerik, Whiting, & Newell, 1992). For example, using a dynamical system paradigm, it has been shown how additional degrees of freedom may be used by actors to stabilize previously unstable movements (Fink, et al., 2000).Broadening the types of movement models studied may lead to observations of more complex behavioral outcomes than the simple bimodal state (i.e. 'in-phase' or 'anti-phase' patterns of behavior) often observed in the study of many continuous, rhythmical movement tasks (see Chen, Liu, Mayer-Kress, & Newell, 2005; Chow, Davids, Button, & Rein, 2008; Limerick, Shemmell, Barry, Carson, & Abernethy, 2001 for examples).

In summary, by limiting selected experimental models to a specific subset, such as rhythmical, continuous movements, previous DST research on neurobiological coordination and control has only been able to study movements requiring a limited number of biomechanical degrees of freedom. This limitation has reduced the generality of applying results to the study of more complex movement patterns. In response to these issues, the present study investigated whether the application of the traditional scaling procedure leads to comparable results when applied to the study of a throwing movement. , For this purpose the basketball hook shot was chosen as a movement model, because it involves whole body movements and requires many active biomechanical degrees of freedom during movement execution. The descriptor 'hook shot' in itself does not prescribe an exact movement but rather a whole family of movements, thus providing a degenerate movement model. This degeneracy allows the actor to adapt the underlying movement according to specific task constraints (see Martin, 1992 for explanations of variants). In such a task, a candidate control parameter for the scaling procedure exists in 'throwing distance', as previous research has indicated (e.g. Liu & Burton, 1999; Rein, Button, Davids, & Summers, in press; Southard, 1998, 2002).

Thus, when starting from a specific throwing distance, with increasing or decreasing distance to target, it seems reasonable to assume that transitions between functional movement patterns might occur. This candidate control parameter thus merges the spatial requirements, acting as a precision constraint, as well as force requirements. In the simplest case this manipulation might lead to a bimodal patterning where a movement pattern used at smaller distances becomes unstable and a transition to a different movement pattern might occur in order to achieve the task goal (Southard, 2002). Due to the degenerate nature of the hook shot is seems reasonable to assume that actors can exploit this characteristic and assemble individual solutions to the task. Further, as the hook shot allows for involvement of the whole body, actors can exploit system degrees of freedom in a more individual fashion. It was expected that system degeneracy would yield individual attractor regimes where attractors may be stabilized or destabilized through activation or suppression of biomechanical degrees of freedom. Based on these theoretical insights, movement patterning was expected to be much more variable compared to previous observations of classical rhythmical bimanual movements.

Method

Participants

Eight males (Age=27±5, Height=175cm±16, Weight=81kg±14) participated in the study. Participants JA, NI, and CA were skilled, semi-professional basketball players playing for a New Zealand national franchise in the national league. Participants DU, KE, RY, and BR were intermediate level players who had at least played at club level, whereas participant SH was a novice who had no prior experience in playing basketball. All participants used their dominant right hand for throwing and had not experienced any injuries in the six months preceding the study. Participants provided informed consent prior to the study and all experimental procedures were approved by the ethics committee of the institution conducting the research.

Apparatus

A mobile basket fixed at a conventional height of 3.05m with a Plexiglas backboard and a standard sized basketball (Size 7, FIBA approved) was used for all trials. Sampling frequency was set at 100 Hz during three-dimensional motion capture (Motion analysis corp. Santa Rosa, CA) using 12 digital-cameras. A DV-camera was synchronized with the motion analysis system to enable visual determination of the instant of ball release. Participants were prepared with passive reflective markers (5mm diameter) at the left (l) and right (r) acromion, C7, sternum, lateral epicondyles humerus (l/r), radial styloid (r/l) and ulnar (r/l), back of the right hand, spina illica anterior superior (r/l), spina illica posterior superior (r/l), sacrum, lateral and medial epicondyles femoris (r/l), lateral and medial malleolus (r/l), heel and toe marker (r/l) in order to identify anatomical landmarks. In addition one marker each was placed on the tibia (r/l), on the lateral part of the femur (r/l) and the humerus (r/l) and on the distal, dorsal part of the forearm.

Procedure

Participants attempted to score baskets without rebounding the ball from the backboard using a hook shot technique. In order not to significantly bias emergent movement patterning, limited throwing technique instructions were provided by an experimenter to participants in the form of: “a shot performed with the dominant right hand whilst being airborne”. Participants were also asked to place their body between the basket and the throwing arm as if to prevent a potential defender from interfering with the throw. If the participants felt the need to adapt the movement to the specific distance in a certain way they were allowed to adopt the necessary changes as they desired. Participants started the movement with their backs facing towards the basket and performed one ball bounce before shooting. This routine was intended to simulate a typical game situation.
The throwing distance to the basket was varied from 2m to 9m in increments of 1m after each trial block comprising ten shots, resulting in a total of 160 shots per participant. This range was chosen after initial pilot work in which shots from typical distances between 2m-4m and shots from up to 9m away put sufficient pressure on the actors to trigger noticeable changes in movement patterns (i.e. phase transitions)(see also Rein, et al., accepted). During the ‘increasing distance condition’ (INC) the distance was scaled progressively from 2m to 9m, whereas during the ‘decreasing distance condition’ (DEC), distance was decreased from 9m to 2m, where the throwing distance resembled a candidate control parameter (Kelso & Schöner, 1988; Schöner, Haken, & Kelso, 1986). Before data collection began, participants performed a self-selected warm-up regime for 15 minutes with instructions to perform a range of different shooting techniques. When ready for testing, participants were prepared with the markers and the particular throwing instructions were given after which they performed 10 shots each from 2m, 5m, and 7m to familiarize themselves with the procedure. All participants performed the same protocol starting with the INC condition followed by the DEC condition. In between shots, up to 30s recovery time was provided to help prevent any fatigue effects. For participants BR (1 trial), DU(1 trials), and KE (11 trials) some trials could not be analyzed because of marker occlusion during recording. In total, 1267 hook shots were analyzed. Performance outcomes were recorded on a seven-point nominal scale by an additional experimenter (see Table 1).

Data reduction and analysis

The positions of the reflective markers were reconstructed and three-dimensional coordinates were obtained using Evart 4.6 software (Motion Analysis Corporation, Santa Rosa, CA). After visual inspection of frequency spectra of the displacement data, a 2nd order zero-lag Butterworth filter set at a cut-off frequency of 10Hz was applied. From the position of markers, the hip joint centre was estimated using the procedure by Bell, Pedersen and Brand (1990), and position of the shoulder joint by using the procedure by Rab, Petuskey and Bagley (2002). Subsequently a 13-segment rigid body model was established using Visual3D software (C-Motion, Inc.). Joint angles were calculated using the Euler convention, but only angles in the primary joint plane of motion were used for further analysis, except for the right shoulder joint, assumed to be the main contributor to throwing performance, for which all three Euler angles were maintained. Shoulder joint kinematics of the left shoulder were estimated through the included angle between the upper arm and the trunk for ease of calculation. Movement trials were trimmed from the instance of minimum knee joint flexion before jump-off to the instance of ball release as determined from the DV-camera recording. The right wrist joint flexion angle, the right shoulder joint flexion, abduction, and rotation angles, the included angle of the left shoulder joint, right and left elbow joint flexion angles, right and left hip joint flexion, right and left knee joint flexion, and the left ankle flexion angle were used for analysis (13 input angles). Typical trial lengths were between 15 and 25 frames. In order to avoid skewing the time-series data, movement trials were normalized according to mean trial lengths which resulted in different lengths of normalized times series between participants. Data analysis followed a single-participant approach (Button, Davids, & Schöllhorn, 2006) which ensured that different trial lengths between participants did not affect further analysis.

Typically, experimental analysis from a dynamical systems perspective involves the identification of a system attractor. However, currently no such attractor for a whole body movement has been reported in the neurobiological literature. Therefore, in the present study we resorted to a different approach to identify phase transition behavior in a basketball hook shot. Following previous work it can be assumed that an attractor can be derived from movement pattern kinematics. A transition between global movement patterns should be readily identifiable through the whole body kinematics of the actors and accordingly should be marked by significant changes in the movement patterns. Previously it has been shown that movement patterning can be identified through a cluster analysis approach. For example using a cluster analysis approach it is possible to identify different walking (Kienast, Bachmann, Steinwender, Zwick, & Saraph, 1999; Schöllhorn, Nigg, Stefanshyn, & Liu, 2002) or kicking patterns (see Chow, Davids, Button, & Rein, 2008). Further, in previous work, Rein et al. (in press) showed that a cluster analysis applied to the study of bi-manual anti-phase movement identified the same attractor dynamics as a traditional approach using elative phase measures

Therefore, it seemed reasonable to assume that a cluster analysis approach would be able to identify attractor dynamics in more complex movements, as previously shown in a pilot study of javelin throwing (Schöllhorn, 1993) and golf (Lames, 1992). However, as cluster analysis always groups objects into clusters, further criteria are necessary to unambiguously identify transitions between attractors. Thus, the mere statement that a cluster analysis separated movement trials into different clusters does not warrant a claim for the existence of different attractors. As has been shown in studies of bi-manual coordination, attractor dynamics follow an abrupt change during a transition (see Kelso, 1994; Kelso & Schöner, 1988).

Accordingly, cluster analysis should identify well separated clusters indicated, for example, by high levels of connectivity depicted in a dendrogram and inspection of actual joint kinematics should indicate substantial differences between subsequent patterns.

Further, as phase transitions are marked by critical fluctuations and hysteresis effects, these characteristics should also be identified in order to justify the existence of phase transitions. In general, hysteresis effects merely highlight the extent to which the current state of a system is dependent on its previous states. In relation to phase transitions though, hysteresis serves as one of the key indicators. In relation to the present application of cluster analysis, hysteresis can be identified by inspection of the cluster distribution against varying control parameter values. For example when the transition between movement patterns, as identified through the cluster analysis, shows a dependency on the direction of the control parameter, this observation can be taken as sufficient indication for hysteresis behavior (see Rein, et al., in press for an example). To enable identification of critical fluctuations, the cluster analysis approach must be augmented.

In order to achieve this aim we propose a procedure which generalizes previous approaches (Sidaway, Heise, & Schoenfelder-Zohdi, 1995). First, movement trials are separated into groups according to each control parameter value. In the present case movements were grouped according to throwing distance and the direction of distance change. Afterwards the median differences between all trials for this bin were calculated. This value yields a dissimilarity score for each distance by condition bin. Measurement of the median was chosen since it is more robust against inflation from outliers. When critical fluctuations are present, movement patterning should show greater variation. Accordingly differences between instances of movement execution for a given value of the control parameter should exhibit a sharp increase. Therefore, when plotting median dissimilarity scores against a particular control parameter value, a pronounced peak should be visible in the plot (see Kelso, et al., 1986, p. 281, Figure 2 for an example). Conceptually, this procedure mimics the traditional approach using the standard deviation of the relative phase.

Accordingly, if peak behavior of median scores occurs in the vicinity of cluster switching areas, this may be interpreted as an occurrence of critical fluctuations. Mathematically, this is a similar approach to that used by Chen, Liu, Kress & Newell (2005) in the derivation of the Cauchy criterion, used for their analysis of the acquisition of movement coordination in a pedalo-paddling task. The measurement takes into account all biomechanical degrees of freedom at the same time, and in the present case this involves all 13 input joint angles over the course of the whole movement. Taken together data analysis procedures comprised the following three stages for the identification of attractors: I.) The presence of different movement clusters as identified through the cluster analysis, II.) The presence of critical fluctuations identified through a rise in median dissimilarity score, and III.), The occurrence of hysteresis which warrants identifying different movement patterns as belonging to different attractors. A limitation of this approach is that no determined attractor can be derived and only indirect evidence can be obtained to justify claims of phase transition behaviors.

Identification of a great number of movement clusters does not necessarily imply a suppression of biomechanical degrees of freedom, only that the movement represented by each cluster showed distinct differences. A switch (not necessarily a phase transition) between movement clusters was defined when three criteria were met: (i.) the majority (i.e., at least 60%) of trials from an initial cluster changed at a specific distance. (ii.) the initial cluster had to provide the majority of trials in the preceding distance and (iii.) the new cluster had to provide the majority of trials at the subsequent distance. This approach ensured that a switch between stable movement patterns occurred. Following the recommendations of Toro, Nester and Farren (2007), differences between clusters were subsequently investigated using angle-angle plots (see Rein, et al., in press for further examples) to r justify the identification of phase transitions. To facilitate comparisons between movement clusters, angle-angle plots of right shoulder-right elbow, left shoulder-left elbow, and left hip – left knee are presented. However, since angle-angle plots are only two-dimensional representations of movements it should be noted that this presentation does not always necessarily lead to clearly visible separations between clusters since the actual clustering was determined using the full 12-dimensional input space. All statistical analyses were performed using the R software (R Development Core Team, 2006). Specifically the pvclust (Suzuki & Shimodaira, 2006), scaleboot (Shimodaira, 2006) and fpc (Henning, 2006) packages were used for the cluster validation procedures. All remaining calculations were performed using custom software written in MATLAB 7.1 (The MathWorks, Inc.). Significance levels for all statistical analysis were set at $p < 0.05$.

Results

Performance scores

In Figure 1 the rating of participants according to their mean performance scores is shown. Two of the three expert players (NI and JA) were also the two best performers during the experiment whereas participant CA was the second least successful thrower. Surprisingly, participant SH, the novice performer with no prior experience in using the basketball hook shot or in playing basketball, achieved an intermediate performance in comparison to the remaining participants.

Figure 1 around here

(See Supplementary Figure 1 for individual performance scores across throwing distances and condition).

Friedman Rank-Sum tests for throwing distance attained almost conventional levels of statistical significance, $\chi^2_7 = 13.3$, $p < 0.07$ when averaged over participants and blocking for condition. Further, distance effects were significant when averaging over conditions and blocking for participants $\chi^2_7 = 31.15$, $p < 0.01$. Post-hoc analysis showed significant effects between distances 3-5m, 3-7m, 5-6m, and 5-8m, which all indicated deteriorating performance with increasing distance. Comparisons between participants showed a significant effect when averaging over conditions and blocking for distance $\chi^2_7 = 635.65$, $p < 0.01$. Post-hoc analysis indicated significant effects between CA-JA, CA-NI, JA-KE, JA-RY, KE-NI. Condition effects were statistically significant when blocking for participants $\chi^2_1 = 4.5$, $p < 0.05$ which indicated that they performed better during DEC compared to INC.

Movement patterning

The number of movement pattern clusters was determined according to the bootstrapping values and the results of the Hubert-Γ scores (see Rein, et al., accepted for details). Table 2 displays the summary of results of the bootstrapping procedure together with the number of trials contained in each cluster for all participants. Since p-values could be established only if the cluster nodes contained more than one item, clusters which consisted only of a single trial were marked NA. The range of determined clusters for each participant varied between two and six clusters. Movement clusters were numbered according to their first individual occurrence for each participant. Therefore, clusters *per se* could be readily compared across participants as the cluster analysis was undertaken on a participant basis. Thus, for example the first movement cluster represents different movements for each individual participant.

Insert Table 2 here

(Please compare Supplementary Figures for detailed dendrograms from each participant). Initial analysis suggested the presence of three global strategies used by the participants: 1.) Phase transitional behavior, 2.) Switching behavior only, 3.) No switches between clusters. To compress the presentation of the results, data from one representative participant for each category will be presented except for phase transition behavior, where results from both participants will be presented as these were the main focus of the current investigation.

1) Phase transition behavior

Cluster analysis indicated a two-cluster solution for participant SH. The majority of trials were contained in the 2nd cluster (131 trials, see Table 1). For Participant CA a six-cluster solution was obtained. The sixth movement cluster of Participant CA exhibited a very small p-value (see Table 1). However, the next branch underneath that particular node contained only one main cluster and a singular trial with a p-value of 99 for the former which indicated strong validity for this particular node. Because further separation was rejected by the Hubert-Γ scores, this inferior solution was nevertheless chosen for consistency. The distribution of trials across movement clusters was highly skewed with cluster 6 containing 109 out of 159 trials. Further, the fifth cluster showed a p-value of only 56 which indicated a low level of stability of this cluster.

Movement kinematics

Insert Figure 2 around here

Investigation of the angle-angle plots for the right elbow joint and the right shoulder joint abduction angles indicated some clear differences between the two movement clusters (see Figure 2.a). The main differences in the right arm between the clusters stemmed from the range of motion in the shoulder joint and the absolute values of the elbow joint. Within the 2nd movement cluster, the right elbow was almost completely extended whilst carrying out an abduction-elevation movement at the shoulder joint. In contrast, for the 3rd cluster the movement started from a higher position and mainly followed a shoulder elevation – elbow extension pattern. Kinematics in the left arm showed variations across trials with no clear separation between the two clusters (see Figure 2.b). The left elbow was mostly extended, with much smaller movements in the shoulder joint compared to the right arm. The appearance of the plots was distinctively different between the two movement clusters with the 2nd movement cluster exhibiting greater variation across trials. It is also in the movements of the left arm that the singular trial exhibited the greatest differences with respect to remaining trials. Kinematics of the left leg exhibited great stability across all trials and displayed considerable overlap between trials. The general movement pattern was characterized by a synchronous extension in hip and knee joints.

Insert Figure 3 around here

Movement kinematics for participant CA are shown in Figure 3. Inspection of the movement kinematics showed differences in the coordination of the right shoulder-arm complex (compare Figure 3.a). Focusing on the main movement clusters (2nd, 3rd, and 5th), two qualitatively different strategies can be identified. Movements for the 2nd and the 5th cluster are characterized by parallel shoulder abduction-elevation and elbow extension. In contrast, for the 3rd cluster, segment movements stemmed from the shoulder joint with the elbow being held almost at a constant extended position. The 2nd and the 5th clusters varied due to different ranges of motion in the shoulder. Angles for the 5th cluster indicated a more elevated final posture compared to the 2nd cluster. A similar distinction between movement patterns was visible in the kinematics for the left shoulder-arm complex (compare Figure 3.b). The 1st, 2nd, 4th, and 5th movement clusters started from similar postures but diverged at ball release. Again, the 3rd cluster was distinctly different from the remaining clusters exhibiting small ranges of movement in the shoulder, paired with a flexion movement in the elbow joint. Shoulder abduction angles indicated for the 3rd cluster a more adducted posture compared to the remaining cluster where the arm segment was elevated during the movement. Figure 3.c indicates only small differences in the lower limb kinematics of the left leg with some variations between the movement clusters. The kinematics of movement in the 3rd cluster showed greater ranges of motion in the left knee joint, with greater flexion at the beginning of the movement and similar extension angles at the end of the movement.

Cluster distribution

In Figure 4 the occurrence and the distribution of the individual clusters are shown for participants SH and CA. Fluctuation scores are overlaid onto the distance panels. Inspecting the color distributions within the clusters reveals clear differences between the two participants.

Insert Figure 4 around here

For participant SH the distribution of movement clusters indicated that the 2nd movement cluster was used throughout the INC condition and down to the 4m distance during the DEC condition. , Subsequently two more movements belonging to the 2nd cluster were used after which a transition to the 3rd movement cluster occurred. This patterning clearly indicates a hysteresis effect where the participant used different patterns at the beginning and the end of the experiment. During the switch from the 2nd to the 3rd cluster median dissimilarity scores increased and remained elevated, especially when compared to those values at 2-4m during the INC condition. Interestingly, in both conditions the fluctuation scores decreased at 6m, framed with increasing values at 5m.

For participant CA a different distribution for the movement clusters was observed. The 1st, 2nd, 4th, and 5th movement clusters were used from 2m to 6m during the INC condition. However, none of the movement clusters were stabilized indicated by constant switching between them (see Figure 4). At 7m, a switch to the 3rd movement cluster occurred which was maintained for almost all of the remaining trials. The distribution of the dissimilarity scores showed increasing values prior to switching to the 3rd movement cluster, with subsequently decreased values. A second, smaller peak was visible at 4m where, for some trials, the 4th and the 5th movement clusters were used. Similar to Participant SH, Participant CA concluded the experiment with a different movement pattern compared to the beginning of the experiment, which indicated hysteresis behavior. Interestingly, the 3rd movement pattern which was used for most of the experiment had been used by the participant at 3m distance but was initially not maintained.

Taken together, data from both participants fulfilled all the requirements with regards to the identification of phase transition behavior. Both used two different movement patterns. Both also showed increasing fluctuation measurements during pattern switching and hysteresis behavior. Thus, the results of the cluster analysis and the inspection of the movement kinematics provided strong support for a bimodal adaptation scheme for the two participants.

2) Switching behavior only

In the following only the kinematics from a single representative participant (BR) for this group will be discussed. Although in general the kinematics showed considerable variation across participants, the general scheme seemed to apply across individuals and was characterized by a single movement pattern which was scaled according to distance. Detailed kinematics and discussion for each individual participant can be found in the supplementary information for this article. For Participant BR six different movement clusters were identified. For cluster 5 the bootstrapping p-value was only $p = 0.67$. However, the next branch underneath this cluster node contained two main clusters with p-values of 93 and 97 indicating high stability of these clusters. This specific partition was also supported by the Hubert-Γ scores.

Movement kinematics

Angle-angle plots for the arm segment showed considerable overlap between the different movement clusters (see Figure 5.a). The main differences between movement clusters, as indicated from the plot for the right arm segment, relate to the final posture at the point of ball release. Nevertheless, comparing across clusters the movement patterns appeared to present scaled variants of each other and were characterized by parallel shoulder abduction-elevation and elbow extension. Inspection of the angle-angle plots of the non-dominant arm segment suggested the presence of some more pronounced differences (see Figure 5.b). Elbow joint extension movements featured strongly in the 1st movement cluster, whereas during the 2nd and 3rd movement clusters the elbow joint first flexed and then extended during the end of the movement. Thus, although the differences stemmed mainly from the final postures, the movement patterns did not appear as simple scaled versions of each other. Across movement clusters, the shoulder was slightly elevated at the beginning of the movement followed by an adduction movement. The left leg kinematics exhibited much smaller variations across movement clusters following a hip-knee extension pattern (see Figure 5.c).

Insert Figure 5 around here

Cluster distribution

Insert Figure 6 around here

In Figure 6 the movement cluster distribution for all five participants are shown. In general all participants showed movement cluster switching in relation to throwing distance where movement clusters followed an ordered sequence dependent on throwing distance. Except for a few singular trials, movement clusters were distributed around specific distances. Inspecting the color coding across participant indicated some clear differences with regards to the adaptation of the individual movement patterns.

Specific to all five participants is the occurrence of hysteresis effects. Apart from participant BR, none of the participants terminated the experiment with the same movement pattern they used at the beginning of the experiment. Investigating cluster sequences to establish the first stable occurrence of a specific movement cluster until a switch to another movement cluster occurred showed that, in general, once participants used a particular movement cluster, they persisted with it for a longer period of time. They reverted back to a previous or a new pattern at a later distance compared to the distance at which the movement cluster was initiated. To exemplify, participant BR used the 3rd movement cluster at 9m (INC) but did not switch back to the second movement cluster before 7m (DEC). The same is true for almost all instances of movement clusters across participants.

Investigation of the fluctuation measurements did not indicate any pronounced differences between subsequent throwing distances. Only the absolute levels of fluctuations between participants varied and a Kruskal-Wallis test indicated significant differences between participants, $\chi^2_4 = 55$, $p < 0.01$. Post-hoc multiple comparison testing indicated significant differences between participant BR and participants KE, and NI and between participant DU and participants JA, KE, NI, and BR. Participant BR showed a greater level of fluctuations compared to the others and participant DU showed the smallest fluctuations across participants. Comparing Spearman rank-statistics did not indicate a significant correlation between performance scores and level of fluctuations, $\rho = 0.2$, $p = 0.78$.

In summary, the results from the inspection of the kinematics as well as from the cluster distribution and fluctuation measures provided no support for phase transition behavior in these participants. Results rather indicated that participants used a single movement pattern and varied it according to throwing distance or, related to attractor dynamics, the presence of only a single attractor.

3) No change - Participant RY

For Participant RY, the cluster analysis identified mainly a single movement pattern (1st cluster) which was maintained over all distances with some isolated trials from the 3rd to 5th movement clusters.

Movement kinematics

Insert Figure 7 around here

Angle-angle plots of the dominant segment (compare Figure 7.a) indicated great similarity across the main clusters and the movement pattern was characterized by an extended elbow combined with a shoulder abduction-elevation movement. Four trials which were clearly different from the remaining trials were grouped into the 4th movement cluster. This movement pattern was characterized by parallel shoulder abduction-elevation and elbow extension. The 1st and 2nd movement clusters did not exhibited any clear differences based on the movements of the throwing arm. Inspection of the kinematics of the non-throwing arm, however, showed clearly visible differences (compare Figure 7.b) stemming mainly from the movement in the left elbow joint with somewhat greater shoulder joint movements for the 2nd movement cluster. Qualitatively, regarding the shape of the mean curves, the two movement patterns showed some similarity but were nevertheless well separated from each other. The plots of the lower leg kinematics (see Figure 9.c) showed considerable overlap between all movement clusters with some greater variation for the 1st movement cluster compared to the 2nd movement cluster, as well as some slight differences for the starting points.

Cluster distribution

Insert Figure 8 around here

Movement cluster distributions indicated some relation between movement patterning and throwing distance, where the 2nd movement cluster was used mainly at greater distances and stabilized only at 9m throwing distance in both conditions (Figure 8). Accordingly hysteresis effects could not be identified for participant RY. Median dissimilarity scores showed an increasing trend during the increasing condition with a peak plateau in the vicinity of the main distribution of cluster 1 trials. During the DEC condition, increased fluctuations from 7m to 6m were noticeable followed by increasing values from 4m downwards probably due to the increasing usage of the 4th movement cluster.

Discussion

The present experiment investigated effects of altering throwing distance on coordination and control of a basketball hook shot movement. Previous research has shown that throwing distance serves as a candidate control parameter (Liu & Burton, 1999; Southard, 2002) and it was expected that this methodology would elicit phase-transitions between different attractors based on a bi-model attractor layout. The results provided only partial support for this hypothesis as only two out of eight participants exhibited the expected characteristics typically associated with phase-transition behavior. The remaining participants used only a single attractor and varied the movement pattern according to throwing distance or in the case of participant RY varied the movement pattern only minimally. With regards to the expected inter-individual variability due to the degenerate nature of the task, the results provided support in favor of this view as movement kinematics displayed considerable variations across participants.

For the two participants exhibiting phase-transition behavior (CA & SH) investigation of angle-angle plots clearly indicated qualitatively different movements, as exemplified by the movement kinematics in both shoulder-arm segments. However, the timing of transitions was distinctly different between the two participants. For participant CA the transition occurred during the increasing distance condition at 7m. Thus, the 2nd pattern was used for most of the trials. Comparing this with the findings from the classical finger-flexion-extension task (Haken, et al., 1985), the former movement pattern would equate to the anti-phase pattern which loses stability for increasing values of the control parameter (frequency ≈ throwing distance). In contrast, for participant SH the transition occurred during the decreasing condition at 4m distance. The latter movement pattern exhibited increased values of fluctuation indicating less stability compared to the initial pattern. In both cases, however, the movement patterns used for most of the trials were characterized by an extended elbow – shoulder abduction-elevation movement. The remaining trials were performed with a movement pattern exhibiting parallel shoulder-elevation and elbow extension much more similar to patterns in a normal jump shot (Elliot, 1992). Again mapping the findings from participant SH to in-phase – anti-phase patterns the movement pattern distribution would equate to a jump from an in-phase to anti-phase mode. The question arises: how was the participant able to stabilize this less stable pattern and why did he not continue with the initial more stable strategy? With regards to the former question the increased fluctuation scores suggest that SH activated additional degrees of freedom which served to stabilize the movement. For the remaining 6 participants the different adaptation strategies appeared to resemble more of a pattern scaling approach, where a single movement pattern was adjusted over different throwing distances. Unexpected was the observation of hysteresis behavior in these participants sinceit is typically more associated with switching between different attractors or global movement patterns (Kelso, et al., 1994; Mutsaarts, et al., 2004; Sorensen, et al., 2001; Wimmers, et al., 1998). In contrast, in the present study hysteresis effects were visible in the adaptation of a single movement pattern. As performance was overall better during the decreasing distances, some short-term learning effects might have influenced the different distributions between the increasing and decreasing condition. Adopting a single-attractor interpretation, the pattern-scaling activity can be interpreted as the continual shifting of a single attractor in response to the changing distance constraints similar to the cooperative regime found in learning studies with bi-manual movement models (Zanone & Kelso, 1992, 1997). Recently, Kostrubiec et al. (e.g., 2006; Zanone & Kostrubiec, 2004) have proposed that such a short-term shifting process enables actors to adapt to immediate changes in task constraints. From this view, the present results indicate that this scaling process depends on the previous state of the system. Potential sources of information for this effect may exist in peripheral nervous system structures like muscle spindles (Mel'nichouk, et al., 2007) and/or rapid cortical reorganization in the central nervous system (Classen, Liepert, Wise, Hallet, & Cohen, 1998; Muellbacher, Ziemann, Boroojerdi, Cohen, & Hallett, 2001).

However, this is possibility requires further experimental analysis.

Regarding the lack of phase transition behavior observed for these participants, the results of the present study support to some extent data reported by Sorensen et al. (2001), Limerick et al. (2001), and Buchanan et al. (1997), where different strategies between participants were observed. Interestingly, Limerick et al. (2001) proposed that "*anthropometric variability*"(p.560) might have contributed to the observed differences in their study. In the present case however, a purely anthropometric explanation seems somewhat implausible since participants SH and CA ($Height_{SH}$ = 168, $Weight_{SH}$ = 63, $Height_{CA}$ = 188, $Weight_{CA}$ = 90) marked two extremes in the studied sample despite using similar bi-modal strategies. It seems likely that interactions between neuro-muscular and task constraints contributed to inter-individual differences observed, with system degeneracy providing a platform for individual differences in satisfying task requirements (Bardy, Marin, Stoffregen, & Bootsma, 1999; de Rugy, et al., 2008; States & Wright, 2001). As participants CA and SH both showed intermediate performances within this sample and only CA showed significant lower performance scores, no direct relation between phase transition behavior and throwing performance could be established. The same is true for the groups exhibiting no phase transitions, as participants with very low to high performance scores were included. Interestingly, in the present study different participants stabilized different movement patterns which showed some similarity to those patterns observed in participants CA and SH. For example, participant RY used the shoulder elevation – elbow extension pattern, whereas participant BR used the shoulder abduction-elevation with extended elbow movement pattern.

Unexpected results were observed in that the non-throwing arm often showed greater variations compared to the throwing arm. It is possible that the movements of the non-throwing arm were used to stabilize the kinematics of the throwing arm similar to a dampening mechanism (Haaland, Prestopnik, Knight, & Lee, 2004; Ko, et al., 2003). Through this mechanism, perturbations may have been redistributed across movement components in order to ensure task-achievement (Robertson & Miall, 1997; Saltzman & Kelso, 1987). This possible explanation r indicates that, in multi-articular movements, the distinction into a primary movement, throwing of the ball, and subsidiary movements, such as movements of the non-throwing arm, should not be considered in isolation, but that each may be involved in specific aspects of the task (Haaland, et al., 2004). Recently, Wang and Sainburg (2007) proposed a model of motor lateralization where the non-dominant limb system is not viewed as inferior to the dominant system but rather is occupied with a different aspect of movement control, with overall movement control being distributed across the whole system (Sainburg, 2002). The authors proposed that the dominant controller is responsible for the dynamic features of the movement, like generating joint torques whereas the non-dominant limb system supports the achievement of a desired steady-state posture. Thus, applied to the present study, the dominant arm may have responsible for accelerating the ball in the throw, whereas the non-dominant arm may have stabilized the desired general movement. This explanation could also explain the greater variations in the non-dominant arm across participants, as here individual biomechanical factors might have played a greater role. In contrast, the demand to accelerate the ball according to throwing distance might impose tighter physical constraints yielding more similar movements across participants. Clearly further work is needed to establish more support for these ideas, but it is worth noting that this explanation fits well with the neurobiological characteristic of degeneracy.

Indeed, the results observed in this study provided strong support for the occurrence of functionally degenerate behavior in multi-articular movements across participants (Hong & Newell, 2006). The range of observed movements displayed much greater variation in movement patterning than typically noted in studies of bi-manual finger coordination. It appears that when several movement patterns are available, performers are able to individually exploit degenerate degrees of freedom leading to richer movement dynamics (Hatzitaki & Konstadakos, 2007; Lee, Corcos, Shemmell, Leurgans, & Hasan, 2008; Robertson & Miall, 1997; Scholz & McMillian, 1995). The latter is a hall-mark characteristic of dynamical neurobiological systems performing in complex performance environments. Further, availability of many active biomechanical degrees of freedom provides greater possibilities with regards to movement variability for chosen degenerate movement solutions.

Finally, for discrete, multi-articular actions, intentional dynamics seem to play a much greater role in movement organization compared to relatively constrained, continuous movements. Based on findings from Huys et al. (2008), proposed key differences between discrete and rhythmical movements lies in the necessity for an external timer keeper (see Schöner, 1990 for a similar argument). As shown by Schöner and Kelso (e.g., Schöner & Kelso, 1988) intentions are able to modify the stability properties of attractors and it can hypothesized that, under a discrete regime, where intentions form an integral part of the movement, they can be further used to modify the stability of movement patterns. Together, with the available greater number of biomechanical degrees of freedom, actors are structurally afforded the opportunity to modify attractor dynamics in a much more individualized manner. In attempting to maximize performance effectiveness, individuals use feedback regarding their current and previous attempts to explore the tolerance for variability both within- and between-trials. The complementary strategies of between-trial and within-trial error correction shown in this throwing task, typical of functional human behavior, likely represent a well coordinated union of higher and lower levels of cortical control (Ranganathan & Newell, 2008). Intentional dynamics may have also contributed to the proposed counter-intuitive switch from in-phase to anti-phase patterning in participant SH.

Conclusion

Using a scaling methodology ubiquitous to investigations from a dynamical systems perspective, data from this study provided evidence for phase transition behavior in only two out of eight participants in a multi-articular throwing action. In both cases participants switched between two qualitatively different movement patterns which were identified and validated through a novel cluster analysis approach. In the remaining participants no such clear transitions were found and movement pattern adaptations appeared to follow a continual pattern-scaling activity. The present study provided evidence for distinct differences between traditional (continuous) movement models utilized in studies from a dynamical systems perspective and multi-articular, degenerate actions. The results indicated great variations in selected movement patterns between participants, which highlighted the degenerate features of the chosen movement model. Further, the present study showed that hysteresis behavior is present even without phase transitions, an unexpected finding that warrants further research. Taken together, more research using discrete degenerate actions seem necessary in order to study the dynamical systems perspective on movement coordination and control beyond its present scope.

References

Bardy, B. G., Marin, L., Stoffregen, T. A., & Bootsma, R. J. (1999). Postural coordination modes considered as emergent phenomena. *J Exp Psychol Hum Percept Perform, 25*(5), 1284-1301.

Bell, A. L., Pedersen, D. R., & Brand, R. A. (1990). A comparison of the accuracy of several hip centre location prediction methods. *J Biomech., 23*(6), 617-621.

Bernardin, D., Isableu, B., Fourcade, P., & Bardy, B. G. (2005). Differential exploitation of the inertia tensor in multi-joint arm reaching. *Exp Brain Res, 167*(4), 487-495.

Buchanan, J. J., & Horak, F. B. (2001). Transitions in a postural task: do the recruitment and suppression of degrees of freedom stabilize posture? *Exp Brain Res, 139*(4), 482-494.

Button, C., Davids, K., & Schöllhorn, W. (2006). Coordination profiling of movement systems. In K. Davids, S. Bennett & K. Newell (Eds.), *Movement System Variability* (pp. 133-152). Champaign, IL: Human Kinetics.

Button, C., MacLeod, M., Sanders, R., & Coleman, S. (2003). Examining movement variability in the basketball free-throw action at different skill levels. *Res Q Exerc Sport, 74*(3), 257-269.

Carson, R. G. (1995). The dynamics of isometric bimanual coordination. *Exp Brain Res, 105*, 465-476.

Chen, H.-H., Liu, Y.-T., Mayer-Kress, G., & Newell, K. M. (2005). Learning the pedalo locomotion task. *J Mot Behav, 37*(3), 247-256.

Chow, J. Y., Davids, K., Button, C., & Koh, M. (2007). Variations in coordination of a discrete multi-articular action as a function of skill level. *J Mot Behav*, 463-479.

Chow, J. Y., Davids, K., Button, C., & Koh, M. (2008). Coordination changes in a discrete multi-articular action as a function of practice. *Acta Psychol, 127*(1), 163-176.

Chow, J. Y., Davids, K., Button, C., & Rein, R. (2008). Dynamics of movement patterning in learning a discrete multiarticular action. *Motor Control, 12*(3), 219-240.

Classen, J., Liepert, J., Wise, S. P., Hallet, M., & Cohen, L. G. (1998). Rapid platicity of human cortical movement representation induced by practice. *J Neurophysiol, 79*, 1117-1123.

de Rugy, A., Riek, S., Oytam, Y., Carroll, T. J., Davoodi, R., & Carson, R. G. (2008). Neuromuscular and biomechanical factors codetermine the solution to motor redundancy in rhythmic multijoint arm movement. *Exp Brain Res, 189*(4), 421-434.

Edelman, G. M. (1987). *Neural darwinism - The theory of neuronal group selection*. New York: Basic Books, Inc.

Edelman, G. M., & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proc. Natl. Acad. Sci. USA, 98*(24), 13763-13768.

Elliot, B. (1992). A kinematic comparison of the male and female two-point and three-point jump shots in basketball. *Aust J Sci Med Sport, 24*(4), 111-118.

Fink, P. W., Kelso, J. A. S., Jirsa, V. K., & de Guzman, G. (2000). Recruitment of degrees of freedom stabilizes coordination. *J Exp Psychol Hum Percept Perform, 26*(2), 671-692.

Haaland, K. Y., Prestopnik, J. L., Knight, R. T., & Lee, R. R. (2004). Hemispheric asymmetries for kinematic and positional aspects of reaching. *Brain, 127*(Pt 5), 1145-1158.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). A theoretical model of phase transitions in human hand movements. *Biol Cybern, 51*, 347-356.

Hatzitaki, V., & Konstadakos, S. (2007). Visuo-postural adaptation during the acquisition of a visually guided weight-shifting task: age-related differences in global and local dynamics. *Exp Brain Res, 182*(4), 525-535.

Heise, G. D., & Cornwell, A. (1997). Relative contributions to the net joint moment for a planar multijoint throwing skill: Early and late in practice. *Res Q Exerc Sport, 68*(2), 116-124.

Henning, C. (2006). fpc: Fixed point clusters, clusterwise regression and discriminant plots. (Version 1.2-2) [R package].

Hong, S. L., & Newell, K. M. (2006). Practice effects on local and global dynamics of the ski-simulator task. *Exp Brain Res, 169*(3), 350-360.

Huys, R., Jirsa, V. K., Studenka, B. E., Rheaume, N., & Zelaznik, H. N. (2008). Human trajectory formation: Taxonomy of movement based on phase flow topology. In A. Fuchs & V. K. Jirsa (Eds.), *Coordination: Neural, Behavioral, and Social Dynamics* (pp. 77-92). Berlin-Heidelberg: Springer.

Huys, R., Studenka, B. E., Zelaznik, H. N., & Jirsa, V. K. (2008). Distinct timing mechanisms produce discrete and continuous movements. *PLoS Computational Biology, 4*(4), 1-8.

Jirsa, V. K., & Kelso, J. A. S. (2005). The excitator as a minimal model for the coordination dynamics of discrete and rhythmic movement generation. *J Mot Behav, 37*(1), 35-51.

Kelso, J. A. S. (1994). The informational character of self-organized coordination dynamics. *Hum Mov Sci, 13*, 393-413.

Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*. Cambridge, Mass.: MIT Press.

Kelso, J. A. S., Buchanan, J. J., & Murata, T. (1994). Multifunctionality and switching in the coordination dynamics of reaching and grasping. *Hum Mov Sci, 13*, 63-94.

Kelso, J. A. S., Buchanan, J. J., & Wallace, S. A. (1991). Order parameters for the neural organization of single, multijoint limb movement patterns. *Exp Brain Res, 85*, 432-444.

Kelso, J. A. S., & Jeka, J. J. (1992). Symmetry breaking dynamics of human multilimb coordination. *J Exp Psychol Hum Percept Perform, 18*(3), 645-668.

Kelso, J. A. S., Scholz, J. P., & Schöner, G. (1986). Nonequilibrium phase transitions in coordinated biological motion: critical fluctuations. *Phys Lett A, 118*(6), 279-284.

Kelso, J. A. S., & Schöner, G. (1988). Self-organization of coordinative movement patterns. *Hum Mov Sci, 7*(1), 27-46.

Kennerley, S. W., Diedrichsen, J., Hazeltine, E., Semjen, A., & Ivry, R. B. (2002). Callosotomy patients exhibit temporal uncoupling during continuous bimanual movements. *Nat Neurosci, 5*(4), 376-381.

Kienast, G., Bachmann, D., Steinwender, G., Zwick, E.-B., & Saraph, V. (1999). Determination of gait patterns in children with cerebral palsy using cluster analysis. *Gait and Posture, 10*, 57.

Ko, Y. G., Challis, J. H., Stitt, J. P., & Newell, K. M. (2003). Organization of compensatory postural coordination patterns. *J Mot Behav, 35*(4), 325-342.

Kostrubiec, V., Tallet, J., & Zanone, P.-G. (2006). How a new behavioral pattern is stabilized with learning determines its persistence and flexibility in memory. *Exp Brain Res, 170*, 238-244.

Lames, M. (1992). Synergetik als Konzept in der Sportmotorik. *Sportpsychologie, 3*, 12-18.

Lee, D., Corcos, D. M., Shemmell, J., Leurgans, S., & Hasan, Z. (2008). Resolving kinematic redundancy in target-reaching movements with and without external constraint. *Exp Brain Res, 191*(1), 67-81.

Limerick, R. B., Shemmell, J., Barry, B. K., Carson, R. G., & Abernethy, B. (2001). Spontaneous transitions in the coordination of a whole body task. *Hum Mov Sci, 20*, 549-562.

Liu, S., & Burton, A. W. (1999). Changes in basketball shooting patterns as a function of distance. *Percept Mot Skills, 89*, 831-845.

Martin, T. S. (1992). *The art of shooting baskets: from the free throw to the slam dunk*. Chicago: Contemporary Books.

Mel'nichouk, A. P., Bulgakova, N. V., Tal'nov, A. N., Hellstrom, F., Windhorst, U., & Kostyukov, A. I. (2007). Movement-dependent positioning errors in human elbow joint movements. *Exp Brain Res, 176*(2), 237-247.

Miall, R. C., & Ivry, R. (2004). Moving to a different beat. *Nat Neurosci, 10*(7), 1025-1026.

Muellbacher, W., Ziemann, U., Boroojerdi, B., Cohen, L., & Hallett, M. (2001). Role of the human motor cortex in rapid motor learning. *Exp Brain Res, 136*(4), 431-438.

Müller, H., & Sternad, D. (2004). Decomposition of variability in the execution of goal-oriented tasks: Three components of skill improvement. *J Exp Psychol Hum Percept Perform, 30*(1), 212-233.

Mutsaarts, M., Steenbergen, B., & Meulenbroek, R. (2004). A detailed analysis of the planning and execution of prehension movements by three adolescents with spastic hemiparesis due to cerebral palsy. *Exp Brain Res, 156*(3), 293-304.

Newell, K. M., & Corcos, D. M. (1993). *Variability and motor control*. Champaign IL: Human Kinetics Publishers.

Obhi, S. S. (2004). Bimanual coordination: An unbalanced field of research. *Motor Control, 8*, 111-120.

R Development Core Team (2006). R: A language and environment for statistical computing (Version 2.3.1). Vienna, Austria: R Foundation for Statistical Computing.

Rab, G., Petuskey, K., & Bagley, A. (2002). A method for determination of upper extremity kinematics. *Gait and Posture, 15*, 113-119.

Rein, R., Button, C., Davids, K., & Summers, J. J. (accepted). Investigating coordination in discrete multi-articular movements using cluster analysis. *Motor Control*.

Riley, M. A., & Turvey, M. T. (2002). Variability and Determinism in Motor Behavior. *J Mot Behav, 34*(2), 99-125.

Robertson, E. M., & Miall, R. C. (1997). Multi-joint limbs permit a flexible response to unpredictable events. *Exp Brain Res, 117*(1), 148-152.

Sainburg, R. L. (2002). Evidence for a dynamic-dominance hypothesis of handedness. *Exp Brain Res, 142*(2), 241-258.

Saltzman, E., & Kelso, J. A. S. (1987). Skilled actions: A task-dynamic approach. *Psych Rev, 94*(1), 84-106.

Sames, J. N. (2000). The Relation between Human Brain Activity and Hand Movements. *NeuroImage, 11*, 370-374.

Schaal, S., Sternad, D., Osu, R., & Kawato, M. (2004). Rhythmic arm movement is not discrete. *Nat Neurosci, 7*(10), 1137-1144.

Schmidt, R. C., Carello, C., & Turvey, M. T. (1990). Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *J Exp Psychol Hum Percept Perform, 16*(2), 227-247.

Schöllhorn, W. (1993). *Biomechanische Einzellfallanalyse im Diskuswurf: Prozeß- und produktorientierte Technikanalyse mechanischer Energieformen*. Frankfurt am Main: Thun.

Schöllhorn, W., Nigg, B. M., Stefanshyn, D. J., & Liu, W. (2002). Identification of individual walking patterns using time discrete and time continuous data sets. *Gait and Posture, 15*(2), 180-186.

Scholz, J. P., & McMillian, A. G. (1995). Neuromuscular coordination of squat lifting, II: Individual differences. *Phys Ther, 75*(2), 133-144.

Schöner, G. (1990). A dynamic theory of coordination of discrete movement. *Biol Cybern, 63*, 257-270.

Schöner, G., Haken, H., & Kelso, J. A. S. (1986). A stochastic theory of phase transitions in human hand movement. *Biol Cybern, 53*, 247-257.

Schöner, G., & Kelso, J. A. S. (1988). A dynamic pattern theory of behavioral change. *J Theor Biol, 135*, 501-524.

Shimodaira, H. (2006). Scaleboot: Approximately unbiased p-values via multiscale bootstrap (Version 0.2-2) [R package].

Sidaway, B., Heise, G., & Schoenfelder-Zohdi, B. (1995). Quantifying the variability of angle-angle plots. *Journal of Human Movement Studies, 29*, 181-197.

Sorensen, V., Ingvaldsen, R. P., & Whiting, H. T. A. (2001). The application of co-ordinative dynamics to the analysis of discrete movements using table-tennis as a paradigm skill. *Biol Cybern, 85*, 27-38.

Southard, D. (1998). Mass and velocity: control parameters for throwing patterns. *Res Q Exerc Sport, 69*(1), 355-359.

Southard, D. (2002). Change in throwing pattern: Critical values for control parameter of velocity. *Res Q Exerc Sport, 73*(4), 396-407.

Sporns, O., & Edelman, G. M. (1993). Solving Bernstein's problem: A proposal for the development of coordinated movement by selection. *Child Development, 64*, 960-981.

States, R. A., & Wright, C. E. (2001). Interplay of biomechanical constraints and kinematic strategies in selecting arm postures. *J Mot Behav, 33*(2), 165-179.

Sternad, D. (2008). Towards a unified theory of rhythmic and discrete movements - Behavioral modeling and imaging results. In A. Fuchs & V. K. Jirsa (Eds.), *Coordination: Neural, Behavioral, and Social Dynamics* (pp. 105-133). Berlin-Heidelberg: Springer.

Sternad, D., & Hogan, N. (2007). On rhythmic and discrete movements: reflections, definitions and implications for motor control. *Exp Brain Res, 181*, 13-30.

Sternad, D., & Schaal, S. (1999). Segmentation of endpoint trajectories does not imply segmental control. *Exp Brain Res, 124*, 118-136.

Summers, J. J. (1998). Has ecological psychology delivered what it promised. In J. P. Piek (Ed.), *Motor behavior and human skill: A multidisciplinary approach*. Champaign, IL: Human Kinetics Publishers, Inc.

Suzuki, R., & Shimodaira, H. (2006). pvclust: Hierarchical clustering with p-values via multiscale bootstrap resampling (Version 1.2-0) [R package].

Toro, B., Nester, C. J., & Farren, P. C. (2007). Cluster analysis for the extraction of sagittal gait patterns in children with cerebral palsy. *Gait and Posture, 25*(2), 157-165.

Torre, K., & Delignieres, D. (2008). Distinct ways of timing movements in bimanual coordination tasks: contribution of serial correlation analysis and implications for modeling. *Acta Psychol, 129*(2), 284-296.

Turvey, M. T. (1990). Coordination. *Am. Psychol., 45*(8), 938-953.

Vereijken, B., van Emmerik, R. E. A., Whiting, H. T. A., & Newell, K. M. (1992). Free(z)ing degrees of freedom in skill acquisition. *J Mot Behav, 24*(1), 133-142.

Walter, C. (1998). An alternative view of dynamical systems concepts in motor control and learning. *Res Q Exerc Sport, 69*(4), 326-334.
Wang, J., & Sainburg, R. L. (2007). The dominant and nondominant arms are specialized for stabilizing different features of task performance. *Exp Brain Res, 178*(4), 565-570.
Wei, K., Wertman, G., & Sternad, D. (2003). Interactions Between Rhythmic and Discrete Components in a Bimanual Task. *Motor Control, 7*, 134-154.
Wimmers, R. H., Savelsbergh, G. J. P., Beek, P. J., & Hopkins, B. (1998). Evidence for a phase transition in the early development of prehension. *Dev Psychobiol, 32*(3), 235-248.
Zanone, P. G., & Kelso, J. A. S. (1992). Evolution of behavioral attractors with learning: Nonequilibrium phase transitions. *J Exp Psychol Hum Percept Perform, 18*(2), 403-421.
Zanone, P. G., & Kelso, J. A. S. (1997). Coordination dynamics of learning and transfer: Collective and component levels. *J Exp Psychol Hum Percept Perform, 23*(5), 1454-1480.
Zanone, P. G., & Kostrubiec, V. (2004). Searching for (dynamic) principles of learning. In V. Jirsa & J. A. S. Kelso (Eds.), *Coordination dynamics: Issues and trends* (pp. 57-89). New York: Springer.

Figure Headers

Figure 1: Performance scores.

Figure 2: Angle-angle plots for all movement clusters of participant SH. (a) Angle-angle plot of right shoulder joint abduction angles against right elbow joint flexion angles. (b) Angle-angle plot of left included shoulder joint angle against left elbow joint flexion angle. (c) Angle-angle plot of left knee joint flexion angle against left hip join flexion angle. * indicates the beginning of the movement.

Figure 3: Angle-angle plots for all movement clusters of participant CA. (a) Angle-angle plot of right shoulder joint abduction angles against right elbow joint flexion angles. (b) Angle-angle plot of left included shoulder joint angle against left elbow joint flexion angle. (c) Angle-angle plot of left knee joint flexion angle against left hip join flexion angle. * indicates the beginning of the movement.

Figure 4: Distribution of movement clusters of participants SH and CA. Movement clusters are color coded based on their occurrence during the experiment. Actual movement clusters vary between participants. Panels represent throwing distances in the order used during the experiment. Bottom small ticks indicate individual trials in their actual sequence. (●) indicates fluctuations scores (coordinates are shown on the right ordinate)

Figure 5: Angle-angle plots for all movement clusters of participant BR. (a) Angle-angle plot of right shoulder joint abduction angles against right elbow joint flexion angles. (b) Angle-angle plot of left included shoulder joint angle against left elbow joint flexion angle. (c) Angle-angle plot of left knee joint flexion angle against left hip join flexion angle. o indicates the beginning of the movement.

Figure 6: Distribution of movement clusters of participants BR, DU, JA, KE, and NI. Movement clusters are color coded based on their occurrence during the experiment. Actual movement clusters vary between participants. Panels represent throwing distances in the order used during the experiment. Bottom small ticks indicate individual trials in their actual sequence. (●) indicates fluctuations scores (coordinates are shown on the right ordinate)

Figure 7: Angle-angle plots for all movement clusters of participant RY. (a) Angle-angle plot of right shoulder joint abduction angles against right elbow joint flexion angles. (b) Angle-angle plot of left included shoulder joint angle against left elbow joint flexion angle. (c) Angle-angle plot of left knee joint flexion angle against left hip join flexion angle. o indicates the beginning of the movement.

Figure 8: Distribution of movement clusters of participant RY. Movement clusters are color coded based on their occurrence during the experiment. Panels represent throwing distances in the order used during the experiment. Bottom small ticks indicate individual trials in their actual sequence. (●) indicates fluctuations scores (coordinates are shown on the right ordinate)

Table Headers

Table 1: Performance scores (adapted from XY)

Table 2: Results of multi-scale bootstrapping procedure (p-values) for each cluster for each participant and number (no.) of trials contained in each cluster.

Figure 1

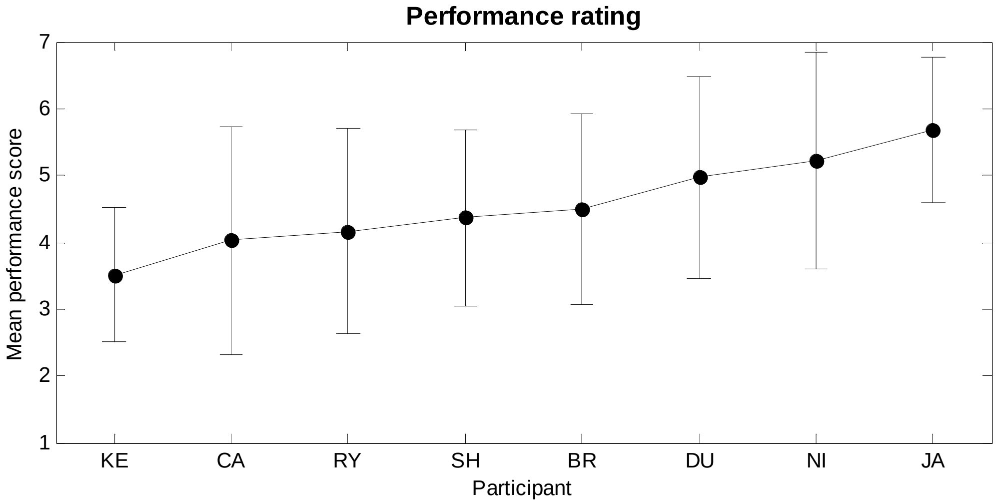

Performance rating
Mean performance score
1
2
3
4
5
6
7
KE
CA
RY
SH
BR
DU
NI
JA
Participant

Figure 2

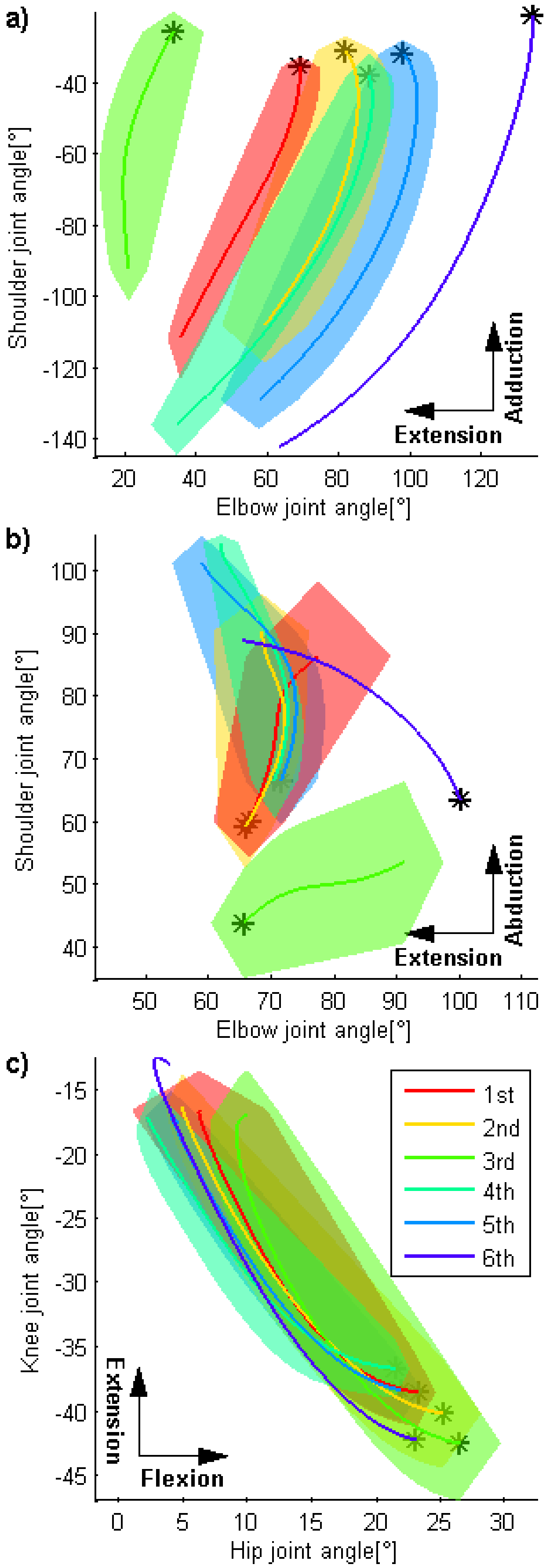
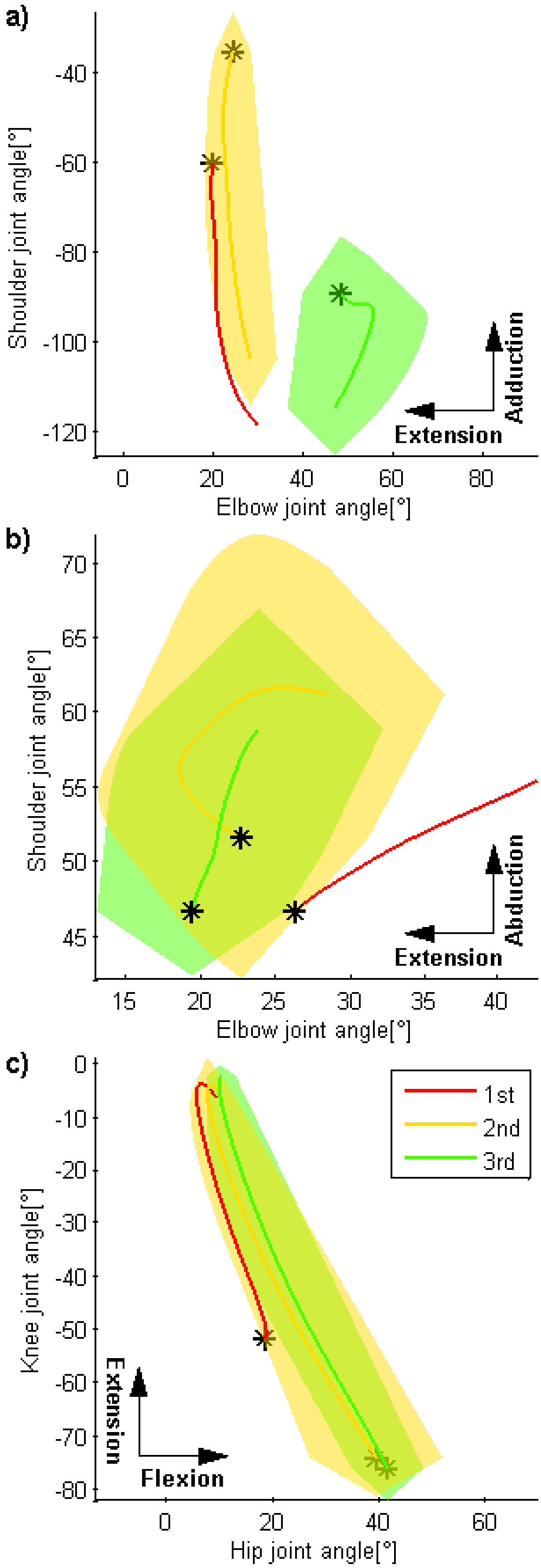

a)
Shoulder joint angle[°]
-40
-60
-80
-100
-120
-140
20
40
60
80
100
120
Elbow joint angle[°]
Adduction
Extension
b)
Shoulder joint angle[°]
100
90
80
70
60
50
40
50
60
70
80
90
100
110
Elbow joint angle[°]
Abduction
Extension
c)
Knee joint angle[°]
-15
-20
-25
-30
-35
-40
-45
0
5
10
15
20
25
30
Hip joint angle[°]
1st
2nd
3rd
4th
5th
6th
Extension
Flexion

Figure 3



a)
Shoulder joint angle[°]
Elbow joint angle[°]
Adduction
Extension
b)
Shoulder joint angle[°]
Elbow joint angle[°]
Abduction
Extension
c)
Knee joint angle[°]
Hip joint angle[°]
Extension
Flexion
1st
2nd
3rd

Figure 4

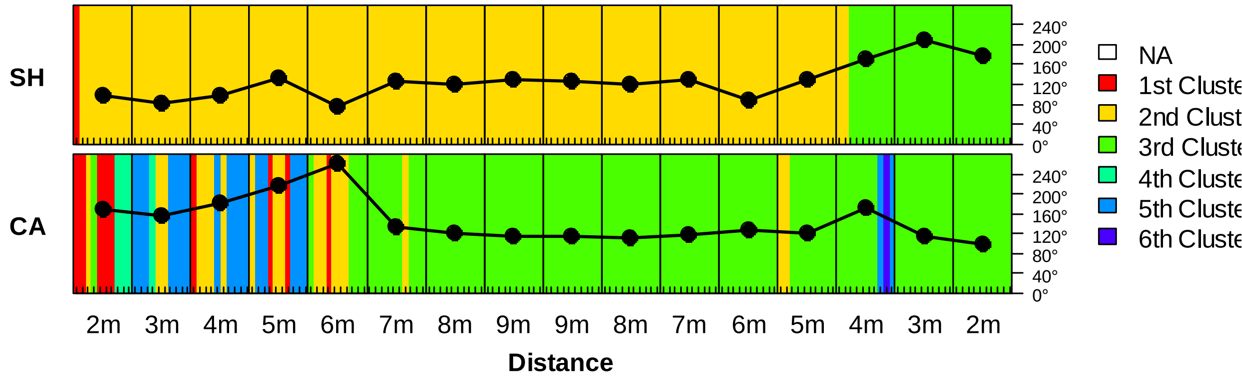
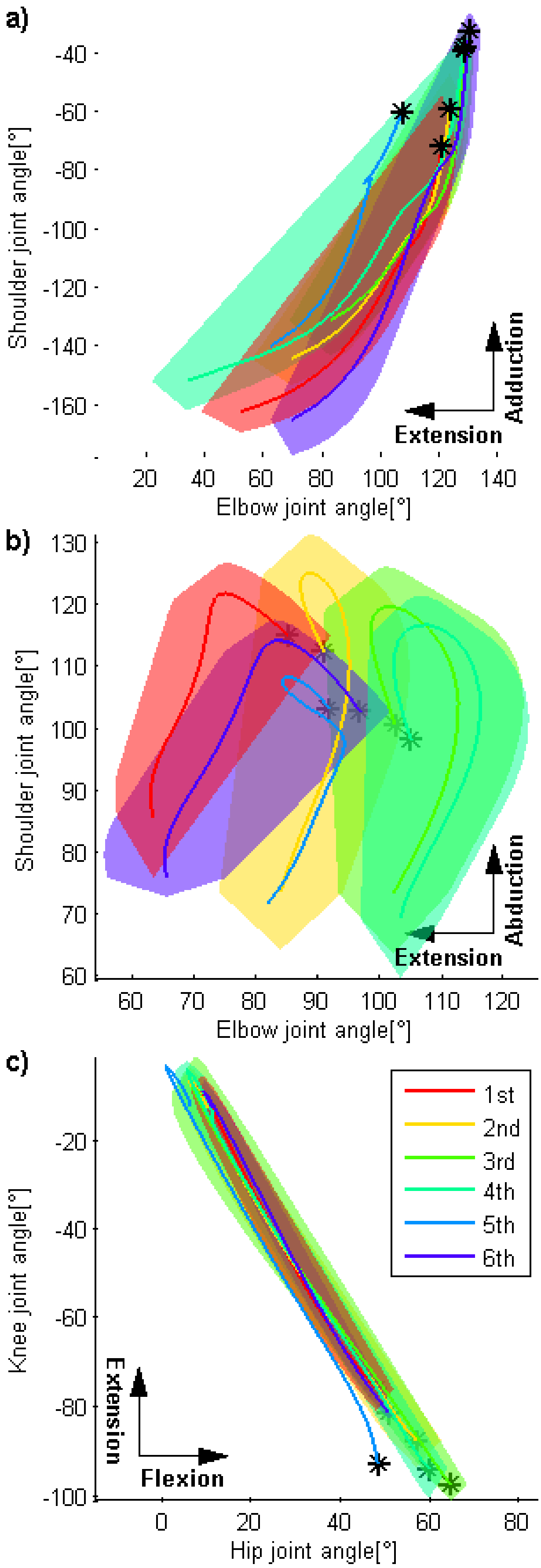

SH
CA
240°
200°
160°
120°
80°
40°
0°
NA
1st Cluste
2nd Clust
3rd Cluste
4th Cluste
5th Cluste
6th Cluste
2m 3m 4m 5m 6m 7m 8m 9m 9m 8m 7m 6m 5m 4m 3m 2m
Distance

Figure 5



a)
Shoulder joint angle[°]
-40
-60
-80
-100
-120
-140
-160
Adduction
Extension
20
40
60
80
100
120
140
Elbow joint angle[°]
b)
130
120
110
100
90
80
70
60
Shoulder joint angle[°]
Abduction
Extension
60
70
80
90
100
110
120
Elbow joint angle[°]
c)
1st
2nd
3rd
4th
5th
6th
-20
-40
-60
-80
-100
Knee joint angle[°]
Extension
Flexion
0
20
40
60
80
Hip joint angle[°]

Figure 6

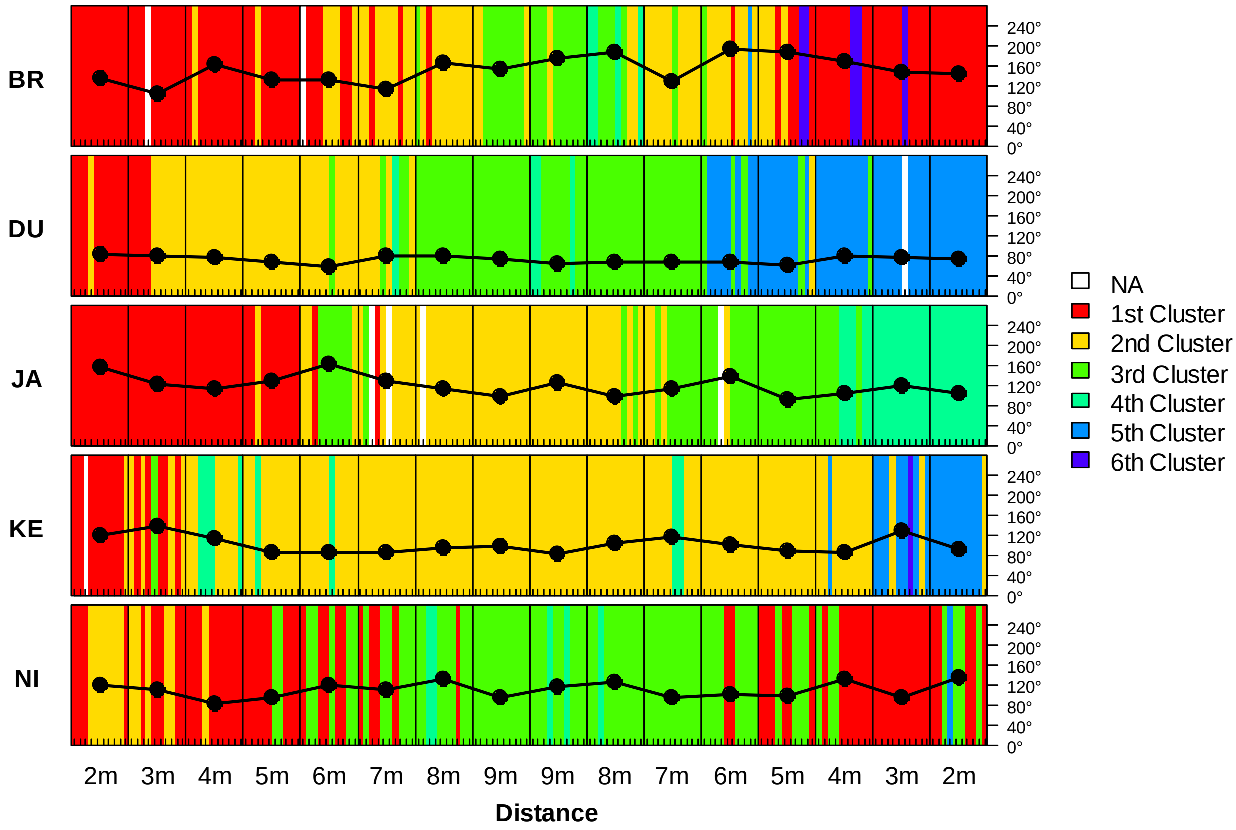

BR
DU
JA
KE
NI
0°
40°
80°
120°
160°
200°
240°
NA
1st Cluster
2nd Cluster
3rd Cluster
4th Cluster
5th Cluster
6th Cluster
2m 3m 4m 5m 6m 7m 8m 9m 9m 8m 7m 6m 5m 4m 3m 2m
Distance

Figure 7

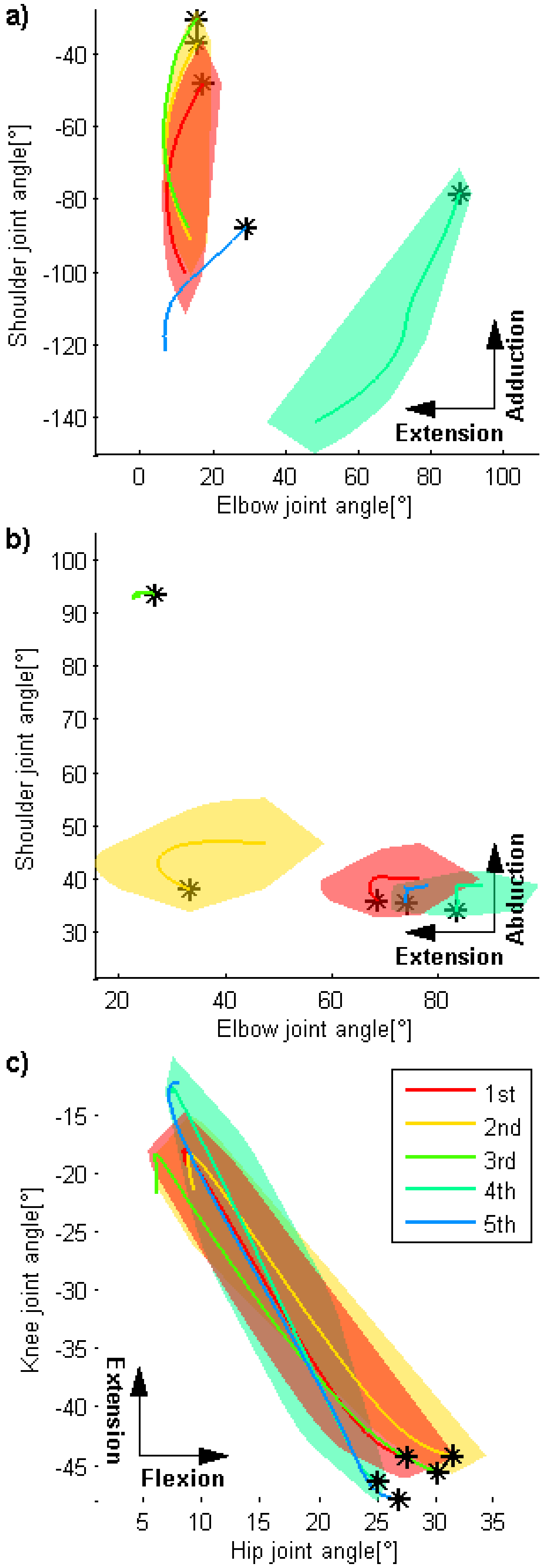

a)
Shoulder joint angle[°]
Elbow joint angle[°]
Adduction
Extension
b)
Shoulder joint angle[°]
Elbow joint angle[°]
Abduction
Extension
c)
Knee joint angle[°]
Hip joint angle[°]
1st
2nd
3rd
4th
5th
Extension
Flexion

Figure 8

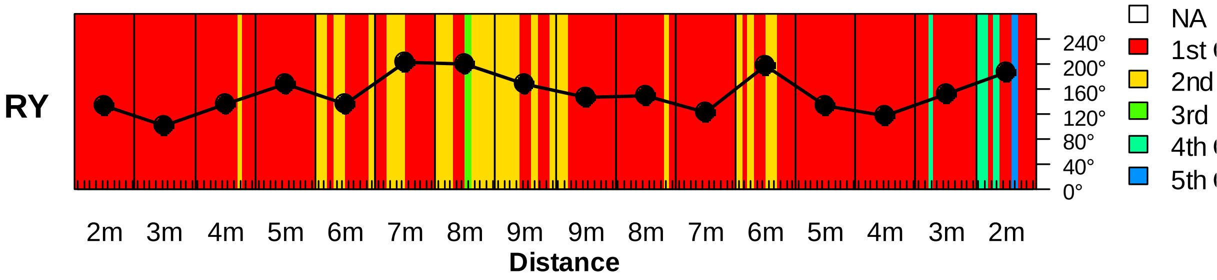

RY
240°
200°
160°
120°
80°
40°
0°
NA
1st
2nd
3rd
4th
5th
2m 3m 4m 5m 6m 7m 8m 9m 9m 8m 7m 6m 5m 4m 3m 2m
Distance

Table 1

Score	Characteristics
1	Airball, Ball misses completely by at least 2m
2	Airball less than 2m
3	Ball hits backboard first no score
4	Ball hits backboard first score
5	Ball hits outside of rim score or no score
6	Ball hits inside of rim score or no score
7	Ball passes cleanly through the basket with touching the rim

Table 2

Subject	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5		Cluster 6	
	p	no.	p	no.	p	no.	p	no.	p	no.	p	no.
BR	NA	1	94	48	92	4	96	23	67	5	79	78
CA	98	4	56	19	93	18	78	9	NA	1	82	109
DU	98	56	95	4	95	43	87	43	79	13		
JA	94	40	81	25	56	41	92	54				
KE	99	119	96	8	NA	1	90	13	96	7	NA	1
NI	98	12	98	66	94	5	100	76	NA	1		
RY	99	29	99	125	NA	1	NA	1	100	4		
SH	NA	1	93	131	100	28						