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A dynamical system perspective to understanding badminton singles game play

Jia Yi Chow [a,*], Ludovic Seifert [b], Romain Hérault [c], Shannon Jing Yi Chia [d], Miriam Chang Yi Lee [a]

[a] *Physical Education & Sports Science, Nanyang Technological University, Singapore*
[b] *Centre d'Etude des Transformations des Activités Physiques et Sportives (CETAPS), Faculty of Sports Sciences, University of Rouen, France*
[c] *Laboratoire d'Informatique, du Traitement de l'Information et des Systèmes (LITIS), National Institute of Applied Science (INSA de Rouen), France*
[d] *Sport Science and Management, Nanyang Technological University, Singapore*

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By altering the task constraints of cooperative and competitive game contexts in badminton, insights can be obtained from a dynamical systems perspective to investigate the underlying processes that results in either a gradual shift or transition of playing patterns. Positional data of three pairs of skilled female badminton players (average age 20.5 ± 1.38 years) were captured and analyzed. Local correlation coefficient, which provides information on the relationship of players' displacement data, between each pair of players was computed for angle and distance from base position. Speed scalar product was in turn established from speed vectors of the players. The results revealed two patterns of playing behaviors (i.e., in-phase and anti-phase patterns) for movement displacement. Anti-phase relation was the dominant coupling pattern for speed scalar relationships among the pairs of players. Speed scalar product, as a collective variable, was different between cooperative and competitive plays with a greater variability in amplitude seen in competitive plays leading to a winning point. The findings from this study provide evidence for increasing stroke variability to perturb existing stable patterns of play and highlights the potential for speed scalar product to be a collective variable to distinguish different patterns of play (e.g., cooperative and competitive).

* Corresponding author. Address: Physical Education & Sports Science, National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore. Tel.: +65 6790 3692; fax: +65 6896 9260.
E-mail address: jiayi.chow@nie.edu.sg (J.Y. Chow).

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1. Introduction

Game dynamics is dependent on the complex and specific interactions among players in a game and a framework based on complex systems involving various interacting factors such as player–player relationships, the size of the court or the rules of the game can be used to describe game situations (McGarry, Anderson, Wallace, Hughes, & Franks, 2002). A common feature for complex systems is self-organization whereby, regularity emerges from within a system which consists of "many degrees of freedom in constant flux" (McGarry et al., 2002). The observable state of a system and in this case, the game dynamics that emerges is not due to an overarching controller deciding on how the game will evolve. Rather, the game may move through or self-organized into different preferred and stable conditions of play due to the interactions of the players in the game (e.g., Duarte et al., 2012 in soccer; Bourbousson, Sève, & McGarry, 2010 in basketball; Vilar, Araújo, Davids, & Button, 2012; Vilar, Araújo, Davids, & Travassos, 2012 in futsal) within the regulated environmental (e.g., surface, temperature) and task constraints (e.g., rules of the game, equipment available).

The specific game play dynamics that emerges is dependent on how players, with their inherent tactical and technical proficiencies, interact with each other. The specific dimensions of the court size and the rules of the game force certain behaviors to exist during the game. For example, there exists a predisposition for players within the game of badminton, seen as complex system, to return to a "base" position while exchanging strokes with their opponents during a game (Lames, 2006). McGarry and colleagues further elucidated that there is a tendency for players to "oscillate around a given point or locus" (McGarry et al., 2002, p. 778) as seen in squash, badminton and tennis.

This playing behavior, where the player oscillates to and from a base position, was first described in terms of a relative phase relationship by McGarry, Khan, and Franks (1999) in the context of squash. Specifically, McGarry and colleagues adopted the use of a time–motion analysis to express the behavioral patterns in terms of phase relation between the two players. In particular, players would only demonstrate two patterns of relative motions, either in-phase or anti-phase in a game situation. An in-phase pattern is used to describe a situation where the players move in the same direction. In contrast, an anti-phase pattern is observed when the players move in opposite directions (Palut & Zanone, 2005). Suitably, relative phase can be seen as a variable to describe the 'behaviour' of the system as it resides in different patterns or states of behaviors. Such a collective variable or *order parameter* can be defined as variables that characterize the collective state of the system (Davids, Button, & Bennett, 2008; McGarry et al., 2002). For example, a study by Palut and Zanone (2005) on tennis revealed that two stable behaviors with phase transitions were present, with the anti-phase pattern being the preferred stable behavior adopted by players during the game. Another study by Passos et al. (2008) on rugby 1v1 situation also found that the angle between players and distance act as a *control parameter* (i.e., a variable that can be manipulated to effect a change in the behavior of the system) that determine successful and unsuccessful tackles by players. However, in net barrier games such as badminton, where players attempt to return to a base position after every shot to gain optimal coverage of their court, it is unclear if distance and angle from this base position are determinant control parameters for a player to gain an advantage in winning a rally and therefore alter the state of the game system.

Palut and Zanone (2005) in their investigation of tennis clearly used relative phase as a collective variable to describe the patterns of play with no specific constraints on the type of tennis strokes to be executed. The distinct differences seen in phase relations were appropriate to describe the two play conditions (rallies with indirect winning point vs rallies with direct winning point). Participants were required to play each other under indirect winning point (i.e., winning points only from a mistake from their opponent) prior to the seventh rally before direct winning points were allowed. However, the analysis undertaken was restricted to mainly examining lateral movement of the players (due to the task constraint of the tennis game where lateral movements are more typical and also the instruction to trade baseline strokes in their study). Moreover, it is not known if other higher order derivatives such as speed of movement coupled with direction between players (e.g., a variable such as a speed scalar product that captures both distance and angle of movement of players) during game play could better describe the game dynamics. The investigation of a singles badminton game could offer more degrees of freedom in terms of movement of the players and how they may interact with each other during different play conditions (i.e., indirect winning point and direct winning point). For example, will an in-phase (i.e., players moving to and fro the base position at the same time) or anti-phase pattern (i.e., players moving to and fro the base position at different time) of movement between players be seen? It would be insightful to therefore examine how a singles badminton game can be modeled as an example of a dynamical system and allow greater understanding on the change to game play dynamics (e.g., change to stroke variations or displacement alteration in players) as the game transits from one play condition to another when task constraints (i.e., rules governing rallies on indirect winning point or direct winning point) are manipulated. Such phase transitions where one preferred stable game pattern transits to a new preferred stable game pattern as the game task constraints change could be evident of the badminton game behaving like a dynamical system. The examination of stroke variations for the two different play conditions will also be insightful to determine how strokes may change as the players move from rallies with indirect winning point to direct winning point. For example, will the participant exhibit more stroke variations prior to a winning point? Are there specific stroke patterns that are more likely to lead to a winning point?

The purpose of this study is to analyze the movement behaviors (e.g., angle and distance from the base position) and stroke variations of players involved in a badminton singles game from a dynamical systems perspective. Based on past studies (e.g., Palut & Zanone, 2005), it is expected that players engaged in a game of badminton singles to reside in mainly one of the two patterns of movement behaviors, in-phase or anti-phase. It is also predicted that relative phase relations could be different under indirect (i.e., under more cooperative play condition where no offensive shots are allowed and the aim is to keep the rally going) or direct winning point rallies (e.g., under competitive play) when players who were previously in a stable preferred pattern transits to a new pattern of behavior as each player attempts to destabilize the system to win the rally. It is likely that higher variability in stroke patterns and displacement of position and angle relationship between players could be observed as players attempt to gain an advantage in competitive play.

2. Methods

2.1. Participants

Three pairs of skilled female badminton players from the participating tertiary institute's badminton team were recruited for this project. The age range of the participants was 19–22 years, with a mean of 20.5 ± 1.38 years. All skilled participants had at least 8 years of competitive playing experience and were part of the championship winning team in the inter-university games for the last 2 years. Voluntary and informed consent were obtained from all participants, and the procedures used in the study were in accordance with the participating institution's ethical guidelines.

2.2. Task

The participants were randomly assigned to form a pair to play against each other for the purpose of this investigation and they were all similarly matched without any player being exceedingly more proficient than the other skilled players. Each pair of participants was required to play badminton singles game of 10 trials with each trial consisting of eight initial 'cooperative rallies' before they can attempt to win a point with offensive shots. The 'cooperative rallies' is similar to the requirement for indirect winning point condition as seen in Palut and Zanone (2005) with the additional constraint of encouraging the participants to keep the trial going before the competitive condition sets in after the eighth rally. The purpose of the 'cooperative play condition' was to encourage longer lasting trials that will transit eventually to a competitive condition so that initial stable displacement modes can be induced to allow for meaningful analyses between different potential patterns of behaviors that could emerge under the two play conditions (see Palut & Zanone, 2005). In addition, the requirement of the cooperative play condition was also to simulate badminton game play contexts where players may attempt to keep the rallies going in order to outlast and wear their opponents down (i.e., play characteristics seen in more defensive oriented games). Such rallies without offensive shots are features of consistent defensive playing styles seen in some players (see Chen & Chen, 2009; Badminton singles, 2013http://www.badminton-information.com/badminton_singles.html). The change in task constraint to allow for offensive shots in the competitive play condition subsequently induces the players to attempt to win the rally in this study. No specific requirement for the type of strokes to be executed was constrained upon the participants to ensure that ecological validity was maintained to best examine game play patterns in either the cooperative or competitive rallies (see Pinder, Davids, Renshaw, & Araújo, 2011). The game was played according to the rules of a singles badminton match as set by the Badminton World Federation (BWF).

2.3. Apparatus

The experiment was performed on an indoor badminton court located in a multi-purpose hall (MPH) of the institute. At a frequency of 25 Hz, a closed-circuit television (CCTV) system which had been installed on the ceiling of the MPH was used to capture the participants' positional displacements over the entire badminton court. A digital video disk recorder, connected to the CCTV system, was used to store the captured video clips for subsequent analysis using the A-Eye motion analysis software (see Barris, 2008). In addition, two side-on digital video cameras (Canon, Legria HF S100) were used to capture the different strokes employed by the participants. In addition, an "X" was used to mark the base position in each half of the court for subsequent analysis. This base position was deemed to be in the center of the court and approximately one yard behind the center line (Brahms, 2010). See Fig. 1 for screen shot of capture area.

2.4. Procedure

The participants were given five minutes to warm-up with their randomly assigned partner prior to the actual data collection. The warm up consisted of a light jog followed by stretching and friendly badminton exchanges between the participants. Following this, each pair of participants was required to perform 10 trials. For each trial, the participants were required to complete eight initial cooperative rallies before they were allowed to win a point. Trials where indirect winning points were won during the cooperative play condition were not included for analyses as this would not have provided adequate displacement behaviors to emerge under the two playing conditions (i.e., cooperative and competitive). No specific badminton strokes were required from the participants for both the cooperative and competitive play as the purpose was to allow the participants to use the badminton strokes that they deem most comfortable and suitable to ensure that ecological validity is maintained in this representative performance context.

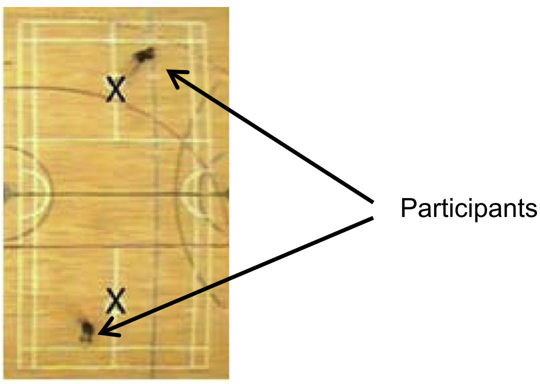

Fig. 1. Screen shot of actual video clip captured for a representative trial. '*X*' is the base position in the participant's respective court.

Participants alternated between the left and right service courts as well as took turns to serve, regardless of which participant won the point in the previous trial. Rest between each trial was self-determined by the participants to ensure that fatigue did not impact game play behavior.

2.5. Data processing and analysis

2.5.1. Stroke execution

A side-on camera was used to capture and record the badminton strokes executed by the participants to identify and classify the strokes executed by them (e.g., the type of serve, drop-shot, net play or an overhand clear, forehand or backhand drive as described by Brahms, 2010). The information on the variation of badminton strokes for each trial was used to provide meaningful insights to how each pair of participants may alter their stroke patterns when the task constraints were altered (i.e., from cooperative to competitive play). Specifically, 5 strokes within the *competitive condition of play* per pair leading to the winning point for trials with clear wins (i.e., not due to unforced errors) was identified to determine the presence of specific stroke patterns leading to a winning point. However, it was also anticipated that some trials may not have the necessary minimum 5 rallies preceding a winning point. In such instances, less than 5 rallies were used for analysis. In addition, the number of trials with long rallies (i.e., 10 or more rallies) was also determined to examine the frequency of the occurrence of such long trials per each pair of participants.

2.5.2. Displacement data

Thirty trials of eight rallies or more (i.e., the shuttle crossing the net at least eight times), were selected from the three pairs of participants to determine the displacement of the participants using x, y coordinates with respect to two badminton courts from a base position identified from the area of capture. The total number of trials is adequate to provide an insight to the changes in game dynamics for this study although it would have been better if more trials were analyzed (slightly less than the 41 trials that Palut & Zanone, 2005 analyzed but only trials with at least 6 rallies from four participants were examined in that study). Position data relating to radial distances from base position for each participant for each trial was determined and included the polar coordinates (angle and distance) of the current participant's position relative to the assigned base position. The base position was not individualized but since the base position was fixed, this served as a reference point for any displacement undertaken by the participants in the courts. Subsequently, the data was processed using Python (version 2.1) and relevant displacement variables were derived to examine the movement behaviors of the pairs of participants.

2.5.3. Local correlation coefficient

In order to determine the relationship of displacement data embedded in the polar coordinates of each pair of participants, a statistical tool, based on correlation coefficient, (defined here as local correlation coefficient) was used.

Local correlation coefficient was established similar to a standard correlation coefficient between the same kind of signal (angle or distance) from participant 1 and participant 2. Nevertheless, the correlation was not computed on the whole signal but solely on a 2s sliding window. By doing so, the synchronized information embedded in each pair of participants on a local scale can be retrieved as such synchronized information evolved along the trial and cannot be sum-up by just a single measure.

Local correlation coefficient is computed by the following formula:

$$C(t) = \frac{cov(S_1(t:t'), S_2(t:t'))}{std(S_1(t:t')) * std(S_2(t:t'))}$$

where C is the local correlation, S_1 and S_2 are the signals for participant 1 and 2 respectively, t' equals $t + w^*fs$, where fs is the sample frequency in Hertz and w the sliding window duration in seconds (2 s in this study). $S(t{:}t')$ denotes the signal S taken from time t to time t'.

2.5.4. Local correlation coefficient of distance

From the displacement data captured for each pair of participants within a trial, a local correlation coefficient of distance was determined to indicate if the displacement characteristics displayed specific phase-lag relationships. In order to quantify the nature of the inter-participant coordination, three thresholds of coefficient correlation were selected. An in-phase pattern was deemed to be present if the local correlation coefficient was more than .25; a no-phase pattern was present if the local correlation coefficient was between −.25 and .25; an anti-phase pattern was present if the local correlation coefficient was less than −.25 (see Amblard, Assaiante, Lekhel, & Marchand, 1994; Temprado, Della-Grasta, Farrell, & Laurent, 1997 on the rationale for such a selection). A no-phase pattern in this context refers to a phase pattern that is neither in-phase nor anti-phase based on the criteria allocated for this study.

2.5.5. Local correlation coefficient of angle

Similar to the local correlation coefficient of distance, the local correlation coefficient of angle was determined based on the angle between the participant, base position and a virtual horizontal line that cuts across the court for each pair of participants within each trial. Angle values are positive when the player goes closer to the back of the court for player who is in the top half of the court (see Fig. 1) and the values are negative when the player goes closer to the net. Conversely, for the player who is in the lower half of the court, angle values are positive when the player goes closer to the net and the angle values are negative when the player goes closer to the back of the court. Angle signals were passed through an unwrap function to prevent a −180 to 180 abrupt change.

2.5.6. Speed scalar product

The speed vector is estimated from position at time t and position at time $t' = t + .48$ s:

$$\vec{v}(t) = \begin{pmatrix} Vx(t) \\ Vy(t) \end{pmatrix} = \begin{pmatrix} x(t') - x(t) \\ y(t') - y(t) \end{pmatrix}$$

where (x,y) is the player's position. Subsequently, a speed scalar product is calculated according to:

$$p(t) = \vec{v}_1(t) \cdot \vec{v}_2(t)$$

where $p(t)$ is the scalar product, $v_1(t)$ and $v_2(t)$) is the speed vector for participant 1 and participant 2 respectively in each pair.

The speed vector provides information about the absolute (i.e., the actual value whatever the bases positions are) magnitude and direction of each participant's speed. The speed scalar product indicates how well the speed directions match. A positive speed scalar product indicates that participants were moving in the same ground direction while a negative value would indicate that participants were moving in the opposite ground direction. The ground direction is a real direction in relation to North, South, East and West etc.

2.5.7. Statistical analysis

The normality of the distribution (Ryan Joiner test) and the variance homogeneity (Bartlett test) were checked before using parametric statistics.

Two ways within pairs (or repeated measures) ANOVA (pair *x* playing condition) completed by post hoc Tukey tests were performed to examine the differences between the three pairs and the difference between cooperative and competitive playing conditions. In addition, three ways within pairs (or repeated measures) ANOVA (phase relation *x* pair *x* playing condition) was done to determine whether the inter-player relation exhibits significant difference for patterns of coupling (in-phase, anti-phase, weak relation) throughout the game and for each playing condition.

All tests were conducted with Minitab 15.1.0.0® software (Minitab Inc., Paris, France, 2006). To protect against the increased probability of making a Type I error, we applied Bonferroni correction factors in our analyses. When comparison was made for the three pairs of players, statistical significance was adjusted to $p < .0167$ (.05/3). When comparison was made between cooperative and competitive conditions, statistical significance was adjusted to $p < .025$ (.05/2).

3. Results

3.1. Differences between playing conditions

It was found that there were greater stroke variations during the competitive condition than the cooperative condition for all pairs of participants (see Table 1).

The cooperative rallies were dominated by the overhand clear while stroke patterns in the competitive condition include the drop, smash, backhand clears, drives, push shots across the three pairs of participants. See Table 1. From data observed for the preceding 5 strokes to a winning point (for clear wins) within the competitive rallies, there were no clear indications on the specific stroke (or series of strokes) that would result in a termination of a rally.

A further correlation test between the number of shots accomplished during competitive phase and the six parameters was also undertaken. Positive correlation ($r = .48$, $p = .007$) occurred between local correlation of angle and number of shots, suggesting that higher number of shots was associated with higher values of angle. In addition, for the lowest number of shots (4 or 5 shots), local correlation of angle was very negative suggesting that anti-phase angular displacement of players could be associated with a winning point. Last but not least, positive correlation between number of shots and standard deviation of local correlation of angle ($r = .421$, $p = .021$) was also found which suggested that high variability in angular displacement of pairs of players was associated with higher number of shots. It seemed that players were moving around in the court more to hit the shuttle in conjunction with higher number of shots before a winning point was achieved.

Based on the result of local correlation coefficient of distance and angle between player and base position variables, the results of the ANOVA showed "coupling" effect [for distance $F(2,172) = 361.05$; for angle, $F(2,172) = 56.75$; $p < .025$] and significant interaction between "coupling" and "playing condition" [for distance, $F(2,172) = 11.16$; for angle, $F(2,172) = 5.46$; $p < .0167$], but no "pair" effect. In particular, post hoc Tukey tests showed that anti-phase relation dominated throughout the game (both for competitive and cooperative playing conditions). This predominance of anti-phase relation indicates that when one player goes closer to her based position, the other player goes further away. See Tables 2–4 and see Figs. 2 and 3 for an example of one trial. In Fig. 2 (top plot), it can be seen qualitatively that there is a strong tendency for an alternative displacement of the distance to base position (i.e., anti-phase) for the two participants respectively (more in competitive play but still on the whole, anti-phase relations tends to dominate). This is further exemplified in the bottom plot in Fig. 2 where it can be observed that local correlation coefficient of distance tends to reside in the anti-phase region. Even when angle data was examined, local correlation coefficient of angle for the pair of participants resided mainly in the anti-phase region as well ($<-.25$). See Fig. 3.

While local correlation coefficient of distance and angle provides evidence of distinct patterns of behavior between the cooperative and competitive conditions, further analysis showed that the speed scalar product was around $-.2$ and .2 in cooperative condition. This was clearly evident from Fig. 4 for a representative trial. However, in the competitive condition, the speed scalar product fluctuated over a bigger range ($-.4$ to .6) and this fluctuation was very close to significance [$F(1,54) = 5.13$; $p = .028$]

Table 1
Range of strokes used by players during cooperative and competitive rallies.

Pair	Range of strokes	
	Cooperative rallies	Competitive rallies
Pair 1	(03) g,h,i	(08) b,c,d,e,f,g,h,i
Pair 2	(02) g,h	(09) a,b,c,d,e,f,g,h,i
Pair 3	(02) g,h	(08) b,c,d,e,f,g,h,i

Number of the type of strokes indicated in parentheses and type of strokes indicated by alphabets.
a: smash, b: net(backhand), c: net(forehand), d: drop, e: Backhand Drive, f: forehand drive, g: overhand forehand clear, h: forehand push (hits to the middle of the court), i: backhand push (hits to the middle of the court).

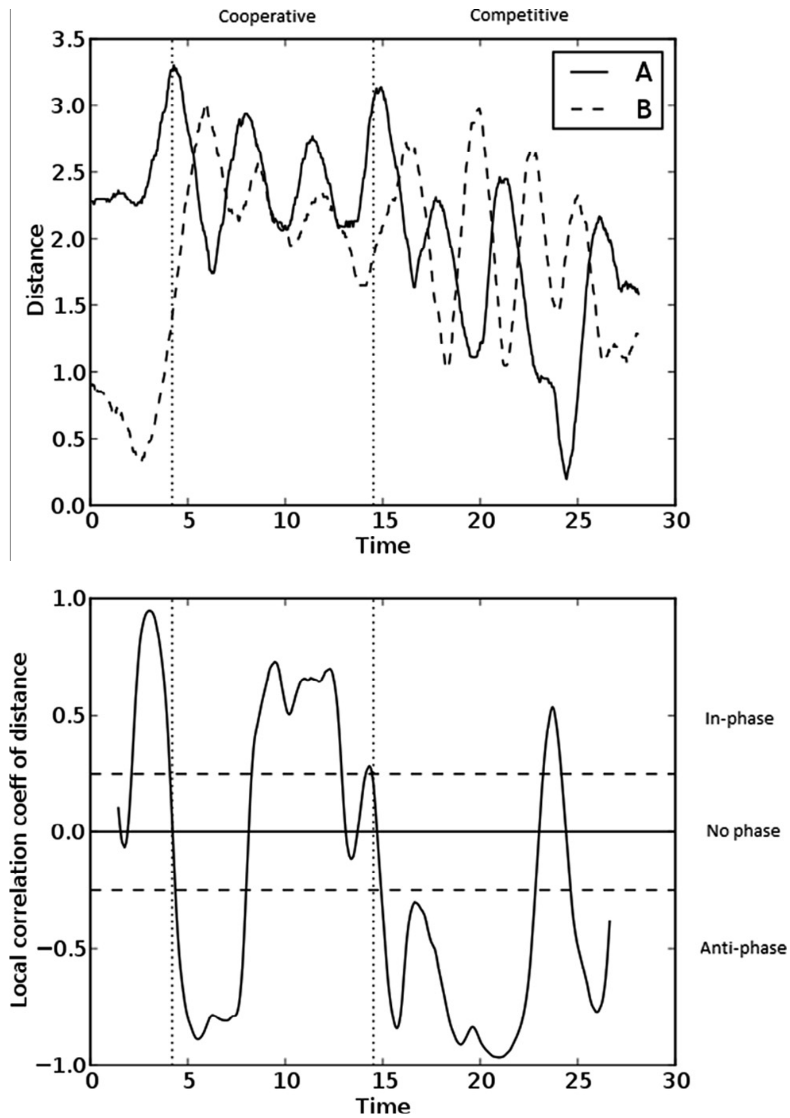

Fig. 2. Plot depicting distance to base position and local correlation coefficient of distance for a pair of participants during the cooperative condition and competitive condition of play. A and B represents participants A and B respectively in the pair of participants.

(see Fig. 4). Moreover, the results of the ANOVA showed coupling effect [$F(2,114) = 195.72$; $p < .025$] and significant interaction between coupling and playing condition [$F(2,114) = 5.62$; $p < .025$]. In particular, post hoc Tukey tests showed that movement in the opposite directions (e.g., one towards the base position and the other away) for the two players dominated throughout the game (both for competitive and cooperative playing conditions) in comparison to movement in the same direction (e.g., both towards the base position or away). In addition, high value of correlation coefficient of speed scalar product standard deviation ($r = 2.17$) can be observed with a significant change between the two playing conditions [$F(2,54) = 14.06$; $p < .025$], which indicated that speed scalar product could discriminate between the cooperative and competitive conditions of play effectively. From Fig. 4, this is distinct where it can be seen in terms of the qualitative difference in the levels of fluctuations for speed scalar product between the cooperative and competitive play conditions.

Further in-depth analysis of the interaction between "playing condition" and "pair" effects showed that changes in the inter-player coupling (angle and distance from the base position, SD, same direction and opposite direction of speed scalar product) between cooperative and competitive conditions mostly occurred for pair 3, whereas pairs 1 and 2 retained similar inter-player relationships throughout the game (Tables 2–4).

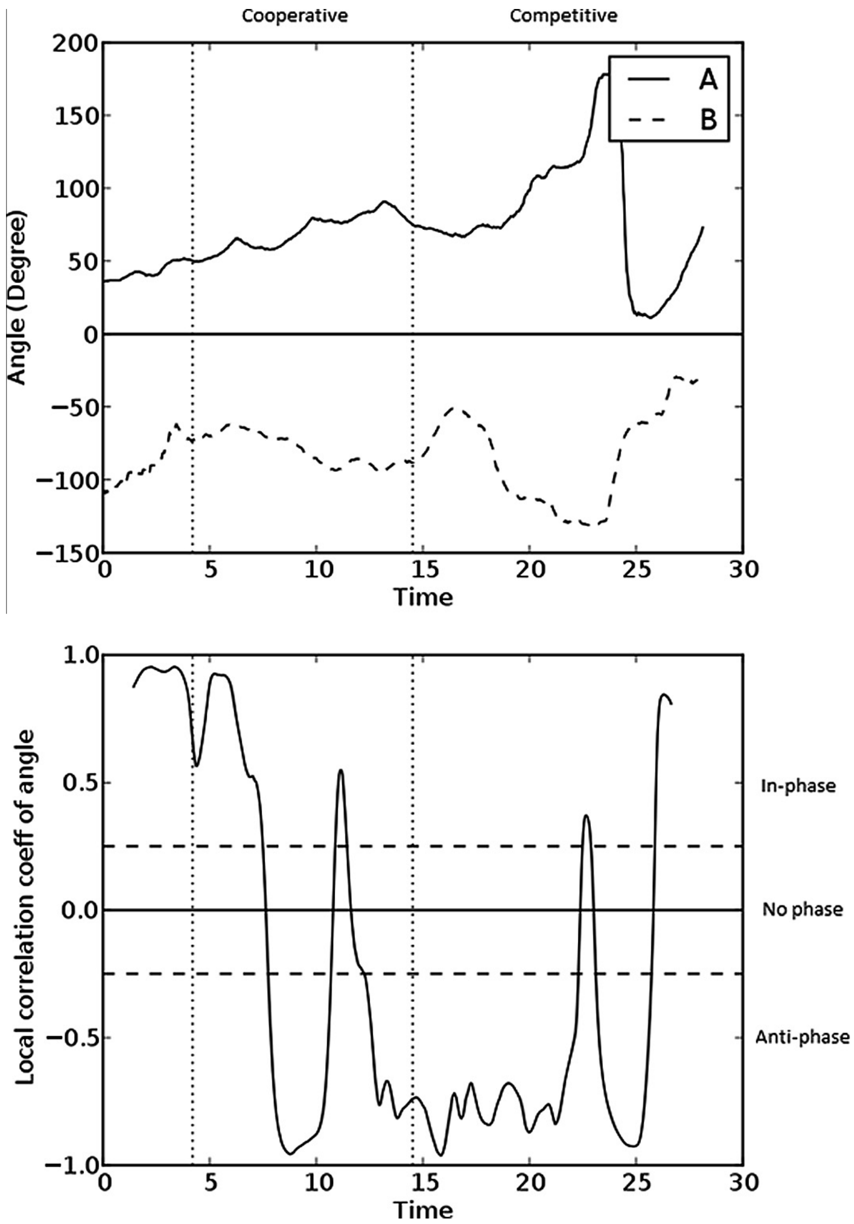

Fig. 3. Plot for angle between participants and local correlation coefficient of angle for the same trial as seen in Fig. 2. Angle values are positive when the player goes closer to the back of the court for player who is in the upper part of the court and angle values are negative when the player goes closer to the net. Conversely, for player who is in the lower part of the court, angle values are positive when the player goes closer to the net and the angle values are negative when the player goes closer to the back of the court (also refer to Fig. 1).

3.2. Differences between pairs of players

In relation to the length of rallies in the competitive condition of play, both pairs 1 and 2 had generally longer rallies than pair 3. For trials with 10 or more rallies, pair 1 and 2 had 3 and 6 of such trials respectively while pair 3 only had one such trial.

Moreover, there was a pair effect for eight indicators: (1) mean value of correlation coefficient for the distance players-base position [$F(2,54) = 16.44$; $p < .0167$]; (2) standard deviation of correlation coefficient concerning the distance players-base position [$F(2,54) = 14.69$; $p < .0167$]; (3) percentage time spent in in-phase relation for the distance players-base position [$F(2,54) = 7.42$; $p < .0167$]; (4) percentage time spent without phase relation for the distance players-base position [$F(2,54) = 9.10$; $p < .0167$]; (5) percentage time spent in anti-phase relation for the distance players-base position [$F(2,54) = 10.13$; $p < .0167$]; (6) percentage time spent in in-phase relation for the angle players-base

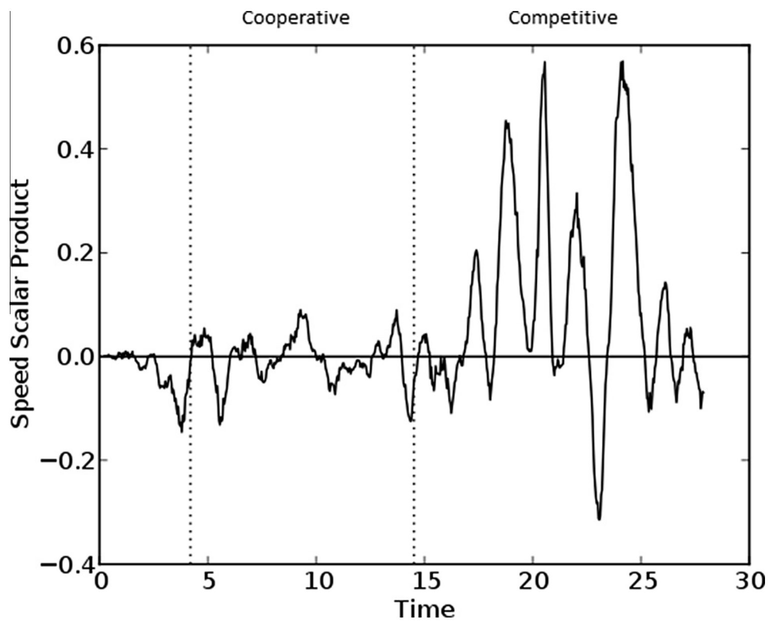

Fig. 4. Plot for speed scalar product during cooperative and competitive conditions of play for the same trial as seen in Fig. 2.

position with horizontal axis [$F(2,54) = 17.54$; $p < .0167$]; (7) percentage time spent in anti-phase relation for the angle players-base position with horizontal axis [$F(2,54) = 11.04$; $p < .0167$]; (8) standard deviation of speed scalar product [$F(2,54) = 14.06$; $p < .0167$]. Based on the analysis, it can be determined that most of these above indicators showed that when the whole game was examined, pair 1 was different compared to both pairs 2 and 3.

However, when the pairs were compared regarding the two playing conditions, the findings indicated that the three pairs of participants were different mostly for the cooperative playing condition when distance and angle from the base position were taken into account. For an example, from Figs. 5 and 6, it can be seen that the local correlation coefficients for distance and angle seem to be

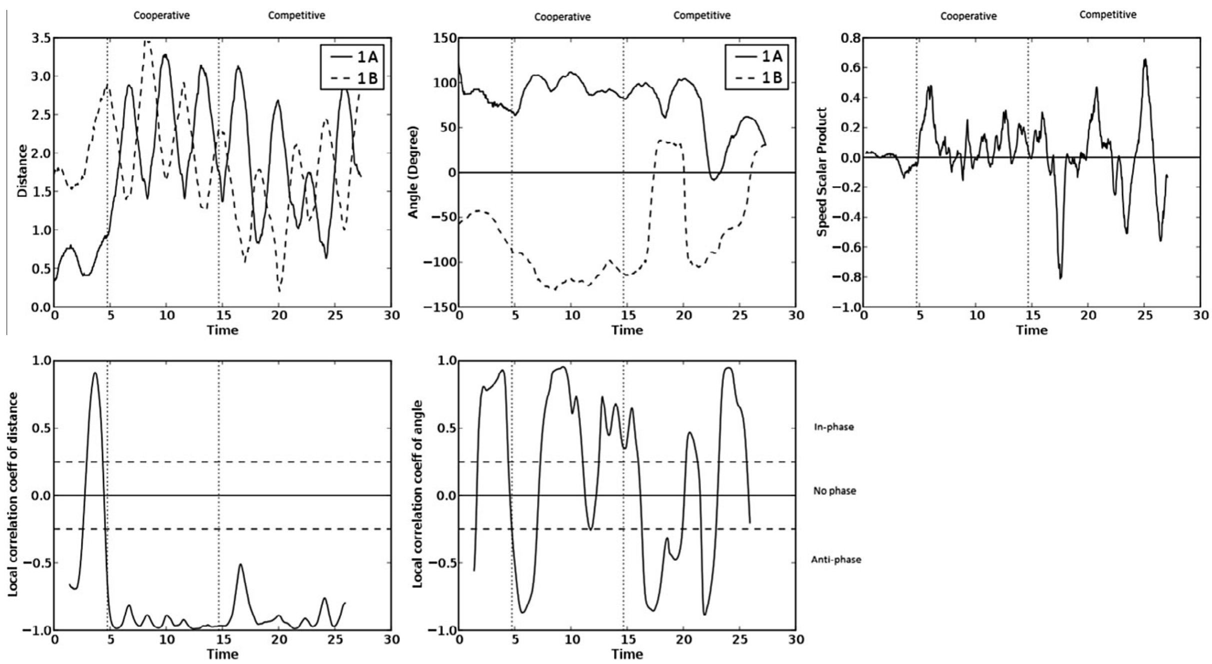

Fig. 5. Plot for pair 1 for distance, angle and speed scalar product variables during cooperative and competitive conditions of play.

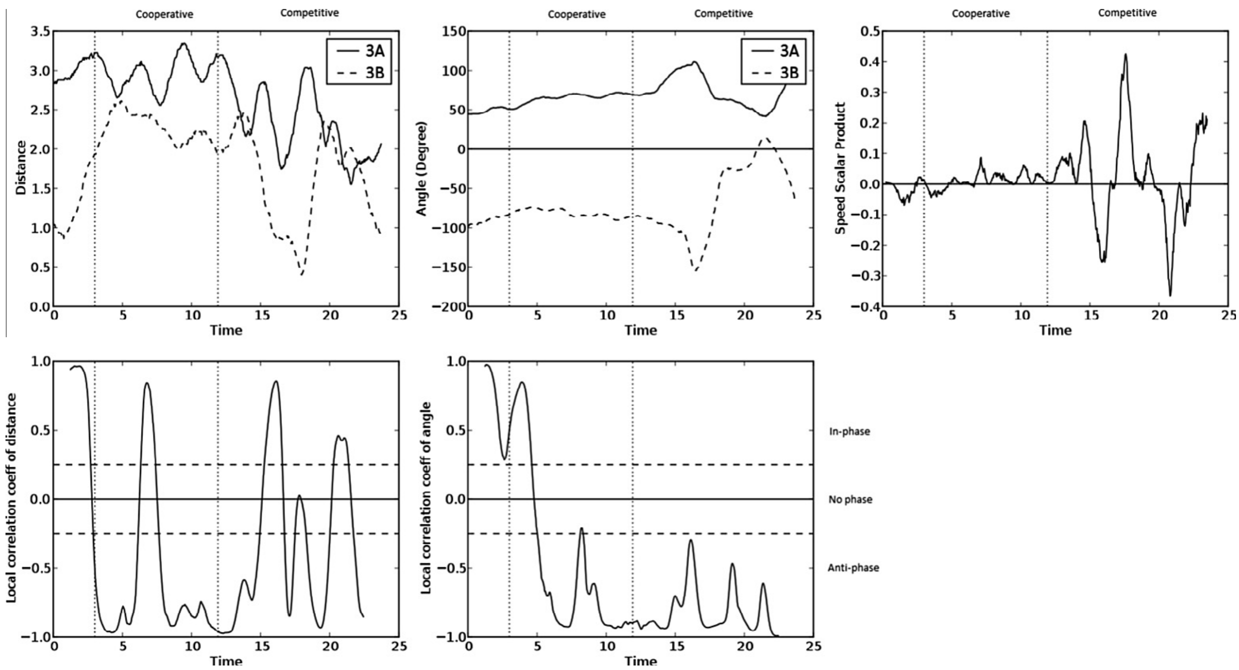

Fig. 6. Plot for pair 3 for distance, angle and speed scalar product variables during cooperative and competitive conditions of play.

qualitatively different especially in the cooperative play condition between pairs 1 and 3. When the speed scalar product (for SD, same direction and opposite direction) was examined, difference between pairs only occurred for competitive condition. It could mean that in the competitive condition, higher speed in the displacement was observed when players moved in similar or opposite directions, leading to higher standard deviations of speed scalar product. Indeed, the interaction between pair effect and playing conditions effect showed significant differences for five behavioral indicators: (1) mean value of correlation coefficient for the distance players-base position [$F(2,54) = 9.32$; $p < .0167$] with main effect for pair 3; (2) percentage time spent in in-phase relation for the distance players-base position [$F(2,54) = 6.70$; $p < .0167$] with main effect for pair 3; (3) standard deviation of speed scalar product [$F(1,54) = 14.06$; $p < .0167$] with main effect for all pairs; (4) percentage of speed scalar product in same direction [$F(1,54) = 14.68$; $p < .0167$] with main effect for pairs 2 and 3; (5) percentage time of speed scalar product in opposite direction [$F(1,54) = 15.73$; $p < .0167$] with main effect for pair 3 (Tables 2–4).

4. Discussion

The purpose of this study is to examine the movement behaviors of participants in a badminton singles game play from a dynamical systems perspective. Specifically, an investigation was undertaken to determine how stroke variation and inter-player coupling between pairs of players changed as the conditions of play (i.e., cooperative to competitive) was manipulated.

4.1. Differences between playing conditions

Based on the data collected, the badminton singles game can be examined from a dynamical systems perspective and relative phase was a suitable variable to describe the dynamics of the game. It was found that the anti-phase relation was more apparent (as a mode of coupling between players in their pairs) as compared to that of an in-phase relation (for both distance and angle). It seemed that the anti-phase pattern was a more stable attractor (i.e., stable states in a system) for the game of badminton and especially so in the competitive condition. This is congruent with the findings of McGarry et al. (2002) and Palut and Zanone (2005) who revealed that the anti-phase relation was more stable

Table 2
Table showing distance correlation coefficients and percentage time in various phase relations for distance.

		Dist correlation Coeff			Dist correlation SD			Dist in-phase%			Dist no-phase%			Dist anti-phase%		
		Com	Cop	Game	Com	Cop	Game	Com	Cop	Game	Com	Cop	Game	Com	Cop	Game
Pair 1	Mean	−.85	−.58	−.71	.13	.24	.18	.02	.03	.03	.02	.05	.04	.96	.91	.94
	SD	.12	.22	.22	.20	.16	.18	.05	.06	.05	.03	.09	.07	.08	.13	.11
Pair 2	Mean	−.54	−.22[*]	−.38[*]	.36	.43	.39[*]	.08	.13	.11	.13	.17	.15[*]	.79	.70	.74
	SD	.29	.33	.34	.14	.17	.15	.15	.12	.13	.10	.13	.11	.20	.22	.21
Pair 3	Mean	−.72	.18[*,**,$]	−.27[**]	.35	.52	.43[**]	.04	.33[*,**,$]	.19[**]	.09	.14	.11[**]	.87	.53	.70
	SD	.16	.33	.52	.12	.14	.15	.05	.24	.22	.07	.07	.08	.08	.26	.26
All	Mean	−.70	−.21[$]	−.45	.28	.39[$]	.34	.05	.16[$]	.11	.08	.12	.10	.87	.72[$]	.79
	SD	.23	.42	.42	.19	.19	.20	.09	.20	.17	.09	.11	.10	.15	.26	.22

[*] Different with previous pair.
[**] different with pair 1.
[$] Different with competitive condition.

and preferred as compared to the in-phase relation. Such anti-phase patterns were clearly more visible especially in the competitive condition of play based on the percentage time spent in the anti-phase pattern, when participants attempted to destabilize the stable pattern of play previously present in the cooperative condition of play.

Beyond relative phase, it was also found in this study that a collective variable, speed scalar product, could meaningfully capture the dynamics of the singles game play for both cooperative and competitive game play. The very distinct task constraints between cooperative and competitive game play was meant to elicit differentiated movements and playing patterns for the participants and indeed, the speed scalar product captured the key dynamics present for the two different conditions of play. Nevertheless, the extent of the differences in speed scalar product between cooperative and competitive plays as well as the end of a series of rallies can be dependent on the specific performer constraints within each pair of participants in the singles game. The control of behavior is located at the performer-environment system level and it is therefore not surprising that the specific performer and environmental constraints had a huge impact on the eventual observed behaviors of the participants (see Fajen, Riley, & Turvey, 2008). This was clearly seen in how the pairs of players differed with other pairs in both cooperative and competitive play conditions.

While it is pertinent to determine the relevant collective variables that can be used to describe the dynamics of the game, it is also critical to understand and examine the variables (i.e., potential control

Table 3
Table showing angle correlation coefficients and percentage time in various phase relations for angle.

		Angle correlation coeff			Angle correlation SD			Angle in-phase%			Angle no-phase%			Angle anti-phase%		
		Com	Cop	Game	Com	Cop	Game	Com	Cop	Game	Com	Cop	Game	Com	Cop	Game
Pair 1	Mean	−.42	−.43	−.43	.51	.47	.49	.57	.32	.44	.18	.19	.19	.25	.49	.37
	SD	.37	.36	.36	.11	.15	.13	.15	.20	.21	.06	.12	.09	.17	.23	.24
Pair 2	Mean	−.60	−.48	−.54	.62	.41	.51	.32	.21[*]	.26	.13	.18	.15	.55	.62	.59[*]
	SD	.28	.46	.38	.07	.14	.15	.13	.21	.18	.07	.11	.09	.15	.29	.23
Pair 3	Mean	−.61	−.52	−.57	.45	.39	.42	.15	.12[*,**]	.14	.17	.19	.18	.68	.69	.68[**]
	SD	.21	.24	.22	.13	.14	.14	.14	.15	.14	.09	.14	.12	.17	.24	.20
All	Mean	−.55	−.48	−.51	.53	.42[$]	.47	.35	.21[$]	.28	.16	.19	.17	.50	.60	.55
	SD	.30	.35	.33	.13	.14	.14	.22	.20	.22	.08	.12	.10	.24	.26	.26

[*] Different with previous pair.
[**] Different with pair 1.
[$] Different with competitive condition.

Table 4
Table showing speed scalar product SD in various phase relations.

		Speed scalar product SD			Speed scalar product SD same direction			Speed scalar product SD opposite direction		
		Com	Cop	Game	Com	Cop	Game	Com	Cop	Game
Pair 1	Mean	.14	.21[$]	.17	.69	.61	.65	.31	.38	.35
	SD	.04	.07	.06	.10	.09	.10	.11	.09	.10
Pair 2	Mean	.06	.21[$]	.13[*]	.55[*]	.67[$]	.61	.44[*]	.33	.38
	SD	.01	.06	.09	.09	.07	.10	.08	.08	.10
Pair 3	Mean	.03[*,**]	.16[$]	.10[*,**]	.74[*]	.56[$]	.65	.23[*]	.43[$]	.33
	SD	.01	.05	.08	.09	.10	.13	.08	.10	.13
All	Mean	.08	.19	.14	.66	.62	.64	.33	.38[$]	.35
	SD	.05	.06	.08	.12	.09	.11	.12	.09	.11

[*] Different with previous pair.
[**] Different with pair 1.
[$] Different with competitive condition.

parameters) that participants manipulate to effect a change in the dynamics of the singles game. For this study, it was clear that participants across the three pairs tend to use a greater variety of strokes (e.g., clear, drives, drop-shot, smash, push shots) to perturb the system to try to gain an advantage (refer to Table 1) during the competitive rallies. The increase in stroke variety is concomitant to the intention of the participants to send their opponents out of position and away from the "base position" so that more court area was available in the opponent's court for a winning shot to be made. As described by McGarry and Franks (1996), a common observation of competitive tennis and squash is that the rally exchange between the two players would be relatively stable until a certain shot forces a player to move out of his preferred state. For example, by executing a forehand drive, the opponent is sent into the rear court, away from the "base position", hence slowing the return to the "base position". Following this, a drop-shot could be executed, with the shuttle landing right in front of the net, requiring the player to sprint to the front in order to receive the shot. McGarry and colleagues also indicated an increase in variability prior to a transition from one behavioral state to another. In this case, the increased variability of strokes executed by the participants (drop-shot, backhand, forehand drive, overhead clear, push shots) after the cooperative condition served as a form of perturbation causing instability to the opponent's playing behavior. This is similar to the findings of Palut and Zanone (2005) who concluded that the observed enhanced variability can be seen as "unmistakable signatures of self-organized dynamical systems" (Palut & Zanone, 2005, p. 1029). Nevertheless, there was no clear trend to a specific or series of strokes that was determinant of a winning point in the competitive condition. More importantly, it was possible that strokes which moved their opponents around more to present an opportunity for an attacking stroke was likely to lead to a winning point. Thus, these strokes could be any type of strokes (e.g., drop shot, smash, overheard clear, drives or push shots). Nevertheless, it was also likely that relative speed of participants to each other and critical distance at racket-shuttlecock contact point can be pertinent variables to influence a winning point. In addition, the resulting speed and accuracy of the shuttle trajectory will be critical in a winning shot despite the strokes used although the coordination of the stroke pattern will provide the basis to examine shuttle trajectory.

The dynamic interaction of distance coverage, angle of movement and stroke variations all have an interactive impact on each other to allow the emergence of a winning shot. Such strong interactive relations among the constraints present in the badminton game only serve to highlight how the behavior of players in a badminton game function like a complex dynamical system and this is further supported by the varied interactions seen in the pairs of participants with the different playing conditions. The challenge for future work is to determine the critical thresholds for this potential control parameter (e.g., cooperative vs. competitive playing condition) to effect a change in the collective variable (e.g., speed scalar product). For example, a possible research design could be to examine the strategies (critical values of angle, distance and scalar product, evolution of strokes) to win the rally as fast as possible. In addition, the examination of the coordination of the stroke patterns is a non-trivial issue that is often overlooked and perhaps, future studies could place greater emphasis on examining technique beyond just displacement variables in relation to positional data.

4.2. Differences between pairs

There were some slight variations to how the relative phase patterns changed for *both distance and angle variables* for all pairs. Particularly, it was observed how pair 3 tend to alter their behavior between playing conditions (i.e., cooperative and competitive) as compared to both pairs 1 and 2. This was indicated by the main effects seen between pairs and playing conditions for pair 3 especially. From the results, the three pairs of participants were different mostly for the cooperative playing condition when distance and angle from the base position were taken into account. Further in-depth analysis of the "playing condition" effect showed that for most occasions, pair 3 significantly changed their inter-player coupling between cooperative and competitive conditions. This difference among the three pairs for the cooperative playing condition could indicate that a low task constraint enabled each pair to exhibit different behavioral responses. However, when the speed scalar product was examined, difference between pairs only occurred for the competitive playing condition. Since speed scalar product is not calculated from the base position but from the previous location of the player, it could mean that in competitive condition, higher speed in the displacement was observed when players moved in similar or opposite directions, leading to higher standard deviation of speed scalar product. Interestingly, it was also observed that pair 3 had the shortest rallies in the competitive playing condition. The high variability in the playing behaviors in the competitive condition probably led to shorter rallies where either player in the pair attempted to perturb the game play dynamics to achieve a winning point.

5. Conclusion

The evidence obtained from this study suggest that a badminton singles game can be studied as a dynamical system instead of previous approaches which tends to focus on identifying invariant features of the players and omitting the critical interactive processes that occurs in real game settings. Clearly, the interaction between the players and external factors is a dynamic process which changes constantly and players are continuously searching for a successful outcome (Lames, 2006; Vilar, Araújo, Davids, & Button, 2012; Vilar, Araújo, Davids, & Travassos, 2012). Suitable control parameters and collective variables were identified under distinct task constraints for cooperative and competitive game play contexts. Implications for future research and practice were also discussed to further extend our understanding of complex game play interactions. Particularly, information on speed and accuracy of shot trajectory relative to position of players will be pertinent to help researchers better understand the underlying processes that can result in a winning shot. In addition, future work could also consider the use of more trials, participants and players at a higher skill level (e.g., national or international players) and specific variations in stroke patterns, which could extend the current findings in this study. With the increased understanding on how games such as badminton singles can be modeled as a dynamical system, greater insights can be elicited on how different game strategies and playing patterns can alter the dynamics of the game.

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