International Journal of Human Movement and Sports Sciences 11(6): 1188-1200, 2023 http://www.hrpub.org
DOI: 10.13189/saj.2023.110603

Patterns of Change in the Relative Phase of Velocity Latent at the Moment of Striking from the Bargaining in Kendo

Saiya Kawabe[1,*], Norimasa Yamada[2]

[1]Graduate School of Health and Sport Sciences, Chukyo University, Japan
[2]School of Health and Sport Sciences, Chukyo University, Japan

Received April 25, 2023; Revised July 21, 2023; Accepted August 15, 2023

Cite This Paper in the Following Citation Styles

(a): *[1] Saiya Kawabe, Norimasa Yamada , "Patterns of Change in the Relative Phase of Velocity Latent at the Moment of Striking from the Bargaining in Kendo," International Journal of Human Movement and Sports Sciences, Vol. 11, No. 6, pp. 1188 - 1200, 2023. DOI: 10.13189/saj.2023.110603.*

(b): *Saiya Kawabe, Norimasa Yamada (2023). Patterns of Change in the Relative Phase of Velocity Latent at the Moment of Striking from the Bargaining in Kendo. International Journal of Human Movement and Sports Sciences, 11(6), 1188 - 1200. DOI: 10.13189/saj.2023.110603.*

Abstract In previous studies focusing on the bargaining between two players in one-on-one interpersonal competitions, the relative phase of the velocity shows a certain characteristic. Studies have shown that the phase switches depend on the slight difference in the distance between two players. However, no study has been conducted on the series of movements from the bargaining phase to the settlement of the game. Therefore, this study aimed to quantitatively examine the characteristics of kendo from the bargaining phase to the moment of the strike, focusing on the relative phase of velocity and interpersonal distance. Participants were asked to play a kendo match, with a few restrictions. There were 80 trials, and the experiment ended when one of the participants struck the other. Based on the pattern of change in the relative phase of velocity of the waists, and the interpersonal distance, it was determined that one pattern accounted for 35% of the total trials. The pattern is that at 1–2s before the strike, the two players were in anti-phase, moving in opposite directions with an interpersonal distance of approximately 2.71m between them. Furthermore, at the time of the strike, the two players were in in-phase, moving in the same direction at an interpersonal distance of about 2.38m.

Keywords Interpersonal Synchronization, Strike Pattern, Relative Phase, Martial Arts, Kendo

1. Introduction

In interpersonal competitions, there is a constant struggle to find the right moment to make a move, and it is the ability to seize this moment that determines the outcome of the match. In these interpersonal competitions, both sides are constantly repeating complicated movements while attacking and defending, and the decisive moment of opportunity rarely arrives.

Kendo developed after the invention of the Japanese sword in the mid-Heian period [1]. Kendo is one of the martial arts. Like judo and karate, kendo involves a one-on-one attack and defense with an opponent. Kendo is not to fight with just one’s body; rather, in addition, one must manipulate the shinai (bamboo sword) while fighting. In a kendo match, the winner is determined when the opponent's striking point is struck with the shinai. With these kendo characteristics, in kendo, the focus of this study, equilibrium often prevails in matches. Okumura et al. [2,3] reported that the time required for a strike is approximately 0.34s–0.36s, from the time the shinai (a Japanese bamboo sword) is raised or the right foot begins to move until the strike is completed. Thus, kendo can be settled in an instant, as the accepted simple reaction time is 0.2s. Although it can be settled instantaneously, kendo is a game in which offense and defense are based on the relationship between the movements of the two opponents. It is difficult to win a match based on one’s own movements alone without considering those of the opponent. This also applies to other competitions where offense and defense are expected in a one-on-one situation.

It is important to improve individual skills in interpersonal competitions. Several studies have focused on individual movements [4–7], especially techniques performed during competitions. Sorel et al. [8] examined the performance of fencers doing lunge attacks under three conditions: (1) fixed condition, (2) moving condition, and (3) uncertain condition. The screened target does not move during the attack under the fixed condition, but it does under the moving condition. Under the uncertain condition, the target may move. The results of their study showed that when the target finally moved during the uncertainty condition, the success rate and accuracy of the attack were significantly lower than those during the fixed condition. In other words, previous studies have succeeded in capturing the characteristics of techniques that may determine victory or defeat from the movements of individuals in interpersonal competition. However, to win in a competition like kendo, where the outcome is decided in an instant, it is insufficient to simply perform several techniques due to the danger of being struck by your opponent when you are about to strike, or of being struck in reverse when you react to a strike. Instead, it is essential to be skillful in bargaining leading up to the technique's execution.

Many studies have examined the characteristics observed in interpersonal competition, especially during the one-on-one bargaining phase, indicating that bargaining is vital. Yamamoto et al. [9] focused on the bargaining between two players in kendo and identified that the offense and defense could be classified into six patterns based on the relationship between interpersonal distance and velocity. In kendo, the attacker and the defender are always switching sides; thus, both sides are in a complex motion from which they have succeeded in deriving a specific pattern. Maloney et al. [10] identified the section of interpersonal distance where two players were most frequently located during a taekwondo match. They also reported that the distance was constantly maintained by the players in the defensive situation and broken in the offensive situation, forming a bilateral relationship, such as attacking without being attacked during bargaining. However, it is difficult to quantify one-on-one bargaining. Therefore, one method to resolve this issue, apart from the aforementioned, is to use an analytical method that expresses the movements of two players in the relative phases. For example, Palut and Zanone [11] calculated the relative phases of positions from the movement trajectories of the two players in a tennis rally, defining in-phase to be the movement when the players move in the same direction and anti-phase as that when they move in opposite directions. The phases of the two players in the rally were stable during in-phase and anti-phase synchronization, and the phase switched proportionally to the direction. This phase switching was confirmed in other tennis studies [12], as well as in ball-striking sports, such as squash [13]. In team sports such as basketball, the relative phase of the displacement of players facing each other in each position, when moving laterally, showed that the frequency of in- and anti-phase synchronization was different [14]. However, these studies showed that the movement of the ball during a competition strongly influenced the movement of both players, which is different from the one-on-one relationship in boxing and martial arts where the players fight only due to their own movements.

Kijima et al. [15] examined movement using the relative phase of the velocity of two players facing each other who struggled for the tag attached to their waist, as seen in martial arts. The results showed that the frequency of anti-phase synchronization was higher in trials with longer game durations. In the case of kendo, Okumura et al. [2] identified the most frequent distance between the locations of two players and reported that a shift of only 0.1m between them causes a shift in the phase of velocity while approaching or moving away from the opponent. While this may have characterized the bargaining moves, the features of these moves until the game was settled were not examined. Furthermore, synchronization is defined using statistical analysis that compares representative values, such as the mean and standard deviation (*SD*) of all trials, which do not accurately capture the original characteristics of the two players.

In previous studies focusing on the bargaining between two players in one-on-one interpersonal competitions, the relative phase of the velocity shows a certain characteristic. Studies have shown that the phase switches depend on the slight difference in the distance between two players. However, no study has been conducted on the series of movements from the bargaining phase to the settlement of the game. Furthermore, synchronization during the bargaining phase between two players is defined as a relative, constituting a feature of the movement.

Therefore, this study aimed to quantitatively clarify the bargaining to the moment of striking in a kendo competition. For this purpose, it focused on the relative phase of the velocity of the two players, and the interpersonal distance. Additionally, we examined the characteristics of their movements by setting a threshold and defining the synchronization by analyzing each trial.

2. Materials and Methods

2.1. Participants

The participants included five male members of the Chukyo University Kendo Club (age: 20.2 ± 0.4 years, height: 167.7 ± 4.7 cm or 5'5" ± 1.9"). They had 12 or more years of competition experience; therefore, the bargaining phase of a kendo match could easily occur.

The study was conducted according to the Declaration of

Helsinki. The research was approved by the Ethics Committee of Chukyo University (approval number: 2020–078) and adhered to the code of ethics. All study participants provided written informed consent before their participation.

2.2. Equipment

Three-dimensional positional locus data were obtained using 14 motion capture systems in the experiment. Reflective markers were attached to the bilateral and occipital regions of the head, waist, and both greater trochanteric regions and their midpoints. Three points each were attached to the tip of the shinai, tip of the tsuba, and center of the shinai.

2.3. Procedures

The experiment began with two players in a stance, as shown in Figure 1, and 100 trials were planned with the five participants. In kendo, a noticeable difference in the height of the players can affect the impact of the strike. Therefore, only 80 trials were conducted after excluding the pairs in which the participants had a height difference of 10 cm or more, and the pair in which one participant reported fatigue before the final trial. The participants were requested to fight one another, as in an actual match; however, two constraints were set for the experiment. First, as there is no quantitative study on kendo from the bargaining phase to the strike, we decided to simplify the test by limiting the possible striking positions to only *men* to observe the basic pattern of the strikes. Second, as kendo movements are highly complex, they were limited to back-and-forth motions to simplify the extraction of the relative phases. Under these two constraints, the trial ended when one of the participants made a strike. Ten trials were conducted per pair.

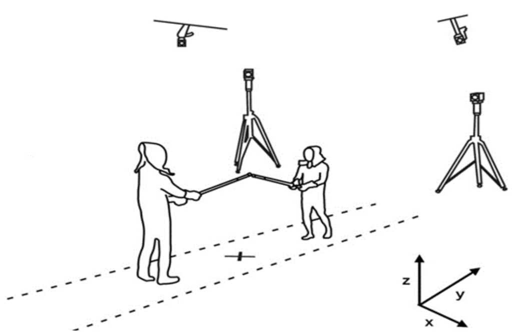

Figure 1. Experimental configuration drawing

The experiment began with a signal from the researcher. The dotted lines in the figure do not actually exist but are shown to make it easier to understand that the players moved only in forward and backward directions. The inertial coordinate system for this experiment is also shown.

2.4. Obtaining the Relative Phase—Hilbert Transform

The relative phase was obtained by numerically differentiating the coordinate data of the two players' waists and calculating the velocity, the data to which the Hilbert transform was applied. Figure 2 shows how to obtain the relative phase using the Hilbert transform. The two waveforms shown in Figure 2-① represent the velocities of each of the two players, which were used as the original data (the velocity data obtained by numerical differentiation from the coordinate data of the waists of the two players). Thereafter, the two waveforms were transformed using the Hilbert transform.

By conducting the Hilbert transform, the different frequency components can be calculated as waveforms with an instantaneous phase shift of $\pi/2$ (Figure 2-②). Subsequently, the two vectors and their angles were obtained by extracting the data of the same moment from the original data and the Hilbert transformed data, and representing them in the polar coordinate system (Figure 2-③). By expressing the velocity data of the two players' waists and the data transformed by the Hilbert transform in the polar coordinate system, one data point at a time, we obtained the instantaneous phase difference at each point of time (Figure 2-④).

2.5. Definition of the Moment of Striking

The moment of striking is referred as the moment when the shinai strikes the opponent's head after it has been raised. The definition was theoretically set up following a calculation based on the z-coordinates of markers attached to the tip of the shinai and back of the head, and finally then verified by looking at the images to see if the moment was correct.

Definition: "The moment of striking is the moment when the z-coordinate of the shinai tip exceeds the z-coordinate of the marker on the back of the head (the intersection in the figure), then reaches its maximum value, and finally reaches its minimum value (extreme value)."

A typical example is shown in Figure 3. This figure depicts the four seconds leading up to the moment of striking.

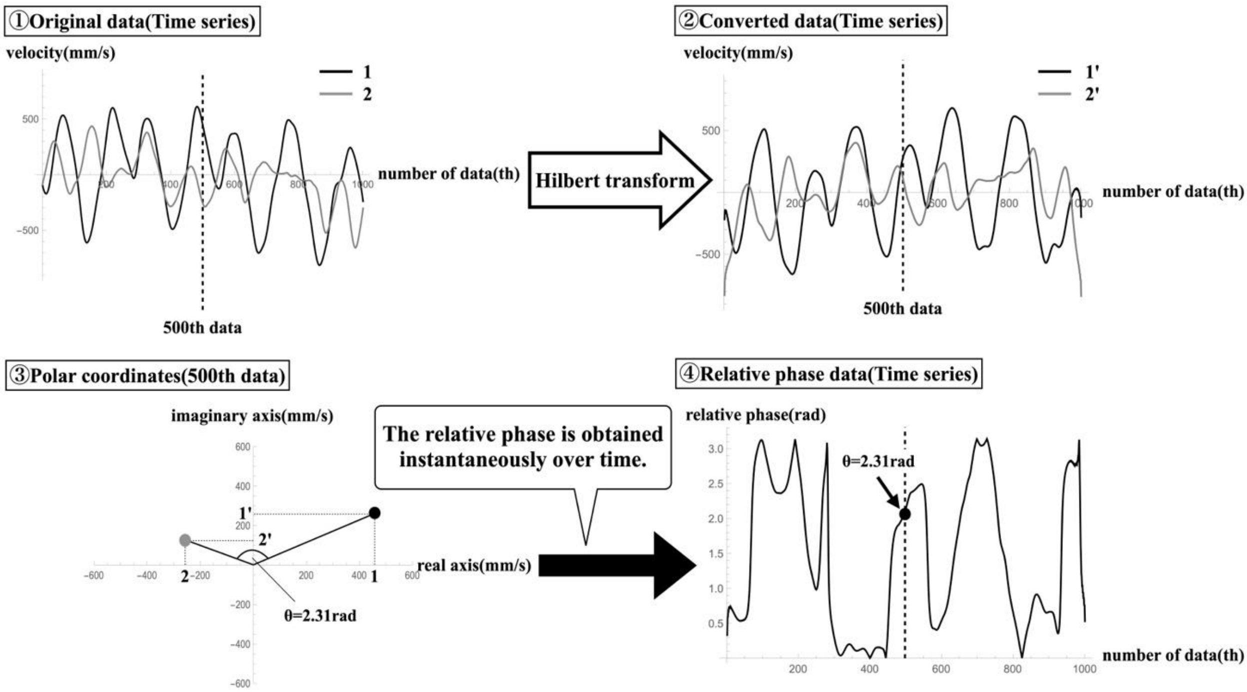

Figure 2. How to obtain the relative phase—Hilbert transform (500th data example)

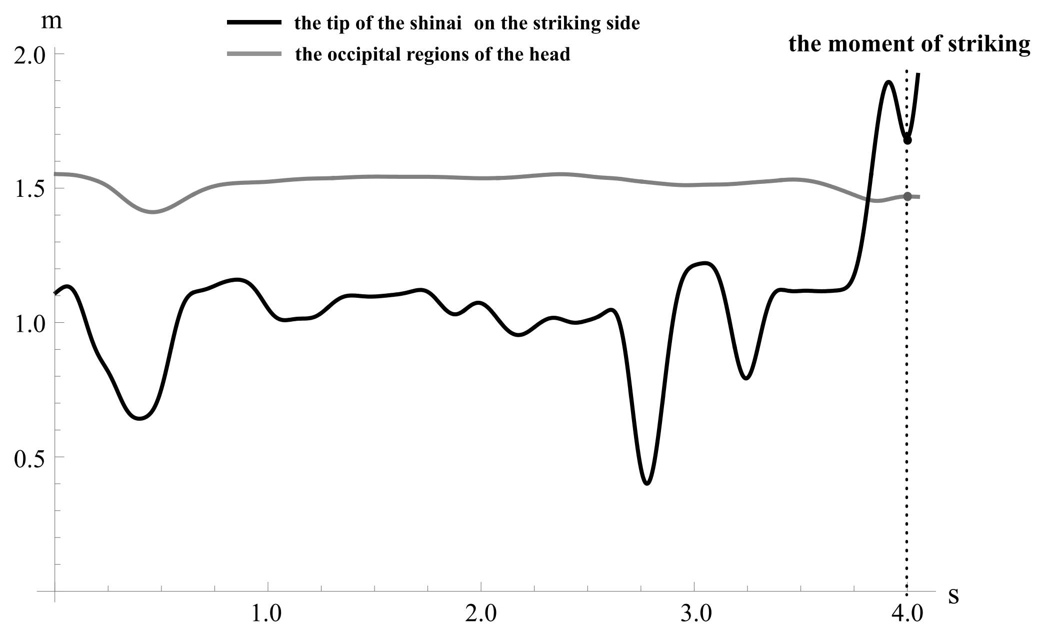

Figure 3. Typical time series data of the shinai tip and back of the head (z-coordinate) up to the moment of striking.

2.6. Relative Phase up to the Moment of Striking

The time taken from the initiation of the strike to its completion during a match is approximately 0.34s–0.36s [2,3]. In this study, the patterns of the movements of the two players, from bargaining to the moment of striking when the tip of the shinai touches the men, were examined from the relative phase. To allow sufficient time for the striking action (approximately 0.4s), 4s, which is about 10 times longer than the striking action, was used for analysis. The relative phase was divided into 1-second segments. The last second was divided into 0.5s to analyze the relative phase in greater detail, because the last second includes the strike and moves with greater violence than the 4–1s section. In other words, the relative phase was analyzed by dividing the 4s until the moment of the strike into five sections (4–3s, 3–2s, 2–1s, 1–0.5s, and 0.5s-strike).

2.7. In-, Anti-Phase, and No Synchronization

In- and anti-phase synchronization were defined by dividing the relative phase of each of the five analysis sections (4–3s, 3–2s, 2–1s, 1–0.5s, and 0.5s-strike) into three regions of π/3. Figure 4 shows an example of the time series data of the relative phase for 4s (The black dotted line indicates the division into three regions of π/3, and the gray line indicates the five analysis sections). The following definitions are for in-phase, anti-phase, and no synchronization.

- In-phase synchronization: When the incidence of the relative phase of π/3 or less exceeds the statistical threshold (41%, 44%) in 1s and 0.5s.
- Anti-phase synchronization: When the incidence of the relative phase of 2π/3 or more exceeds the statistical threshold (41%, 44%) in 1s and 0.5s.
- No synchronization: When the incidence of the relative phase of π/3 or less and 2π/3 or more do not exceed the statistical threshold (41%, 44%) in 1s and 0.5s.

The above statistical thresholds were determined according to the analysis method of Varlet and Richardson [16].

2.8. Waist Movement during In- and Anti-Phase Synchronization

The inertial coordinate system used in this experiment is shown in Figure 1. The motion of the waist in the y-direction was analyzed. We defined in-phase synchronization as the movement when two players simultaneously move in the same direction with a velocity component being in a positive or negative direction, and anti-phase synchronization as the movement when two players simultaneously move in opposite directions, with one having a positive velocity component and the other a negative one.

2.9. Interpersonal Distance

Interpersonal distance was defined as the distance between the waists of the two players. It was calculated according to the method described by Okumura et al. [2]. The 4s interval immediately before the strike of the trial showing the constant pattern of relative phase changes shown in the results and discussion was analyzed. The average values of each of the five sections (4–3s, 3–2s, 2–1s, 1–0.5s, and 0.5s-strike) were calculated.

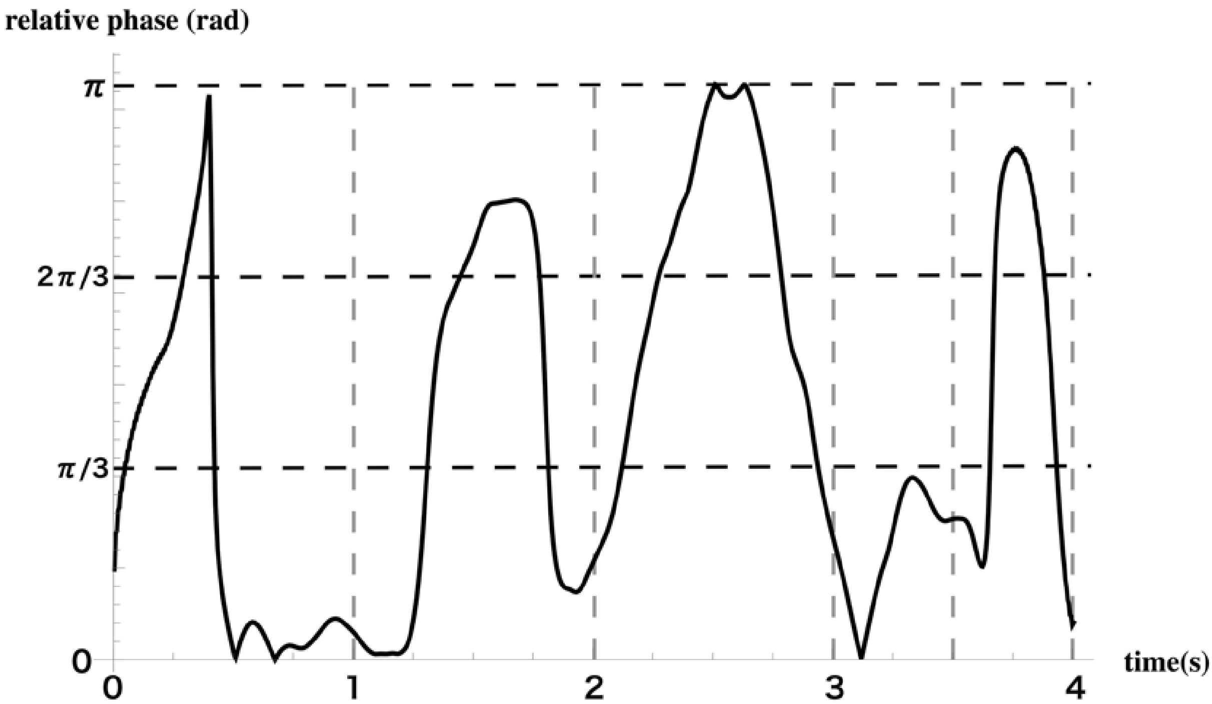

Figure 4. Time series data of relative phase for 4s (the black dotted line = the division into three regions of π/3, the gray dotted line = the five analysis sections)

2.10. Statistics

For the relative phase, a 3 (synchronization state) × 5 (sections) cross tabulation table was prepared for the number of in-phase synchronizations, anti-phase synchronizations, and no synchronization confirmed in each interval (4–3s, 3–2s, 2–1s, 1–0.5s, and 0.5s-strike) in all 80 trials, and a χ^2 test was performed. Subsequently, residual analysis was conducted to identify which cells in the cross-table had significant differences based on the results of the χ^2 test. Statistical significance was set at $p < 0.05$ for both the χ^2 test and residual analysis.

Interpersonal distances were calculated as mean ± *SD*. Significant difference tests were conducted using the *t*-test for interpersonal distances in the phase including strikes, and the bargaining phase for trials that showed a constant pattern of relative phase changes. Statistical significance was set at $p < 0.05$. Mathematica (version 11.3, Wolfram Research, IL, USA) was used for all the statistical analyses.

2.11. Sample Size and Its Consistency

The number of experimental trials indicates the sample size in this study. Statistical analysis was conducted using the number of synchronizations in each interval obtained from all 80 trials after the experiments. Thereafter, the intervals with significant differences were selected to examine the pattern of synchronization and its interpersonal distance. Therefore, the sample size could not be determined before the experiment. We measured the consistency of the sample size by calculating power using G*Power 3.1 after the experiment trials and the statistical analysis.

3. Results

3.1. Statistical Power

Although Cohen [17] stated that a statistical power of 0.8 or less indicates a high likelihood of committing a type II error, the statistical power of the tests was all above 0.8 (as shown below). This is a statistically significant result, which means that the sample sizes used in the statistical analysis were appropriate.

3.2. Patterns of Relative Phase Changes

Table 1 shows the results of the χ^2 test and residual analysis for the trials. The results indicated that 44 trials with anti-phase synchronization in the 2–1s section and 48 trials with in-phase synchronization in the 0.5s-strike section were significantly more frequent ($\chi^2 = 44$, $df = 8$, $p = 5.61 \times 10^{-7}$, $p < 0.001$). Moreover, 16 trials with in-phase synchronization in the 2–1s section and 13 trials with anti-phase synchronization in the 0.5s-strike section were significantly less frequent ($\chi^2 = 44$, $df = 8$, $p = 5.61 \times 10^{-7}$, $p < 0.05$, $p < 0.001$). The statistical power of this result was 0.94. Focusing on the 0.5s-strike interval, including the striking, we found that the two players in 48 of the 80 trials struck in the in-phase synchronization, moving in the same direction. Therefore, to examine the pattern of change in the relative phase by reverting to these trials, we performed the χ^2 test and residual analysis, as shown in Table 2.

The results indicated that 28 trials of anti-phase synchronization in the 2–1s section and 18 trials of no synchronization in the 3–2s section were significantly more frequent (2–1s anti-phase synchronization: $\chi^2 = 94.2$, $df = 8$, $p = 6.36 \times 10^{-17}$, $p < 0.001$, 3–2s no synchronization: $\chi^2 = 94.2$, $df = 8$, $p = 6.36 \times 10^{-17}$, $p < 0.05$). Eight and 12 trials of in-phase synchrony in the 2–1s and 3–2s section, respectively, were significantly less frequent (2–1s in-phase synchrony: $\chi^2 = 94.2$, $df = 8$, $p = 6.36 \times 10^{-17}$, $p < 0.001$, 3–2s in-phase synchrony: $\chi^2 = 94.2$, $df = 8$, $p = 6.36 \times 10^{-17}$, $p < 0.05$). The statistical power of this result was 0.99.

Upon examination of the pattern of relative phase changes focusing on the moment when the two players synchronize, both players were in anti-phase synchronization, moving in the opposite direction in the 2–1s section before the 0.5s-strike section. Figure 5 is a representative example of a trial showing this pattern. In the 2–1s section, the incidence of relative phase in the $2\pi/3$-π region exceeds the statistical threshold of 41%. In the 0.5s-strike section, the incidence of relative phase in the 0-$\pi/3$ region exceeds the statistical threshold of 44%. The state transition diagram is shown in Figure 6. The "in", "anti", and "no" represent in-phase synchronization, anti-phase synchronization, and no synchronization. The black arrows represent state transitions from in-phase synchronization, the dark grey arrows represent state transitions from anti-phase synchronization, and the light grey arrows represent state transitions from no synchronization. The numbers above the circles indicate the number of states that occurred at that time, indicating that the trials that showed in-phase synchronization during the 0.5s-strike interval had many transitions from anti-phase synchronization that occurred in the 2–1s interval. In other words, 28 out of 80 trials showed a pattern of relative phase changes in which the players synchronized in anti-phase just before striking, and finally struck in the in-phase synchronization. In the following section, we focus on these 28 trials.

3.3. Relative Phase and Interpersonal Distance

The interpersonal distance in the 28 trials with a pattern of relative phase changes between anti- and in-phase synchronization occurring in the 2–1s immediately before the strike and the last 0.5s (hereafter, the phase including the strike) was examined. The interpersonal distance was calculated from the mean and *SD* of the interpersonal distances in the phase including the strike (Figure 7). The results were 2.71 ± 0.11m in anti-phase synchronization (Dark gray in Figure 7), and 2.38 ± 0.09m in in-phase synchronization (Light gray in Figure 7). In addition, the pattern of relative phase changes observed in the phase including the strike was also observed in the non-strike bargaining phase (two sections: 4–3s and 3–2s) in 3 out of 28 trials. As shown in Figure 8, the interpersonal distance was calculated using the same method, as described above. The anti-phase synchronization was 2.68 ± 0.12m (Dark gray in Figure 8) and the in-phase synchronization was 2.65 ± 0.10 m (Light gray in Figure 8). In the *t*-test (Figure 9), the interpersonal distances of the same condition in these two phases showed a significant difference in the in-phase synchronization (t_{27} = -5.05, p < 0.001, d = 2.84), but not in the anti-phase synchronization (t_{27} = 0.47, p = 0.64, d = 0.26). The statistical power of the test was 1.0.

Table 1. Results of χ^2 test and residual analysis for all 80 trials

Synchronization	Section					Total trials
	4–3s	3–2s	2–1s	1–0.5s	0.5s–strike	
In-phase	22	22	16*	22	48***	130
Anti-phase	31	30	44***	36	13***	154
No	27	28	20	22	19	116
Total trials	80	80	80	80	80	400

*p < 0.05,***p < 0.001, χ^2 = 44 (df = 8), p = 5.61 ×10^{-7}

Table 2. Results of χ^2 test and residual analysis for the 47 trials that showed in-phase synchronization in the final interval

Synchronization	Section					Total trials
	4–3s	3–2s	2–1s	1–0.5s	0.5s-strike	
In-phase	17	12*	8***	14	48***	99
Anti-phase	18	18	28***	23	0***	87
No	13	18*	12	11	0***	54
Total	48	48	48	48	48	240

*p < 0.05, ***p < 0.001, χ^2 = 94.2 (df = 8), p = 6.36×10^{-17}

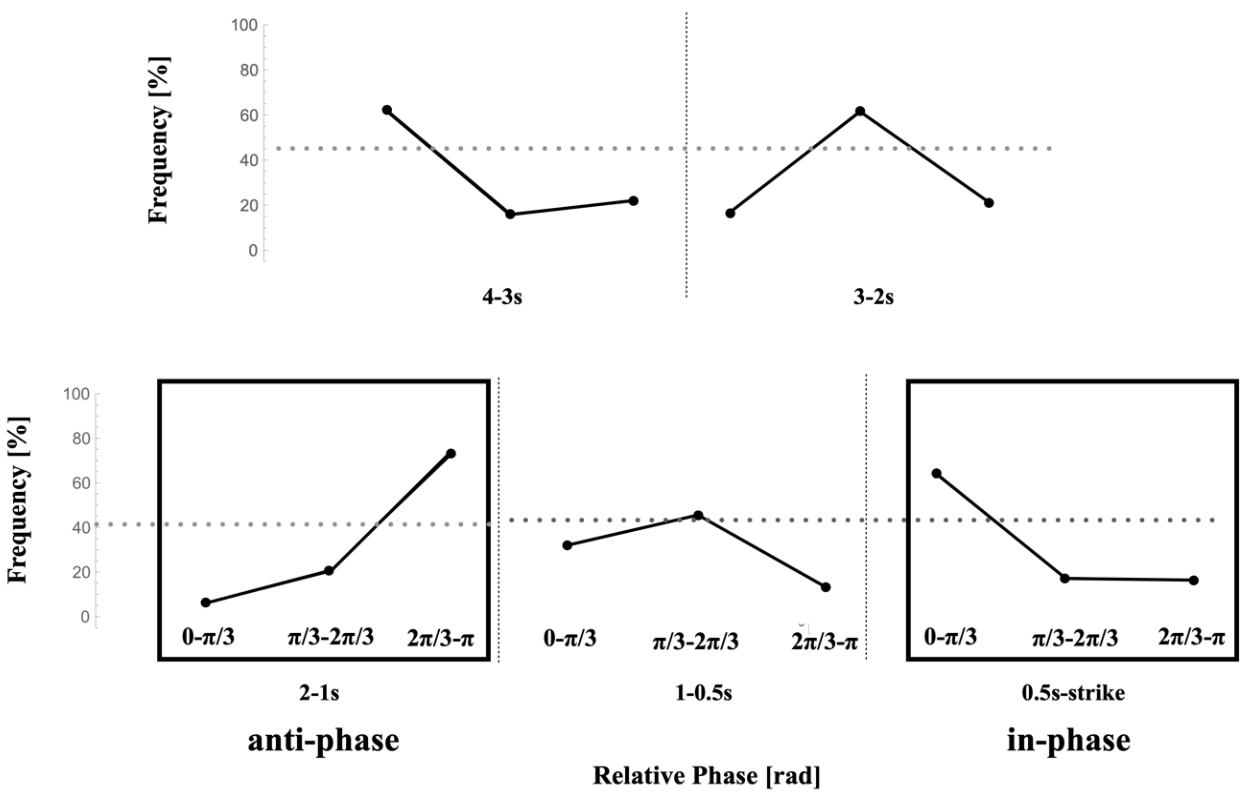

Figure 5. Patterns of change in the relative phase from anti-phase synchronization to in-phase synchronization

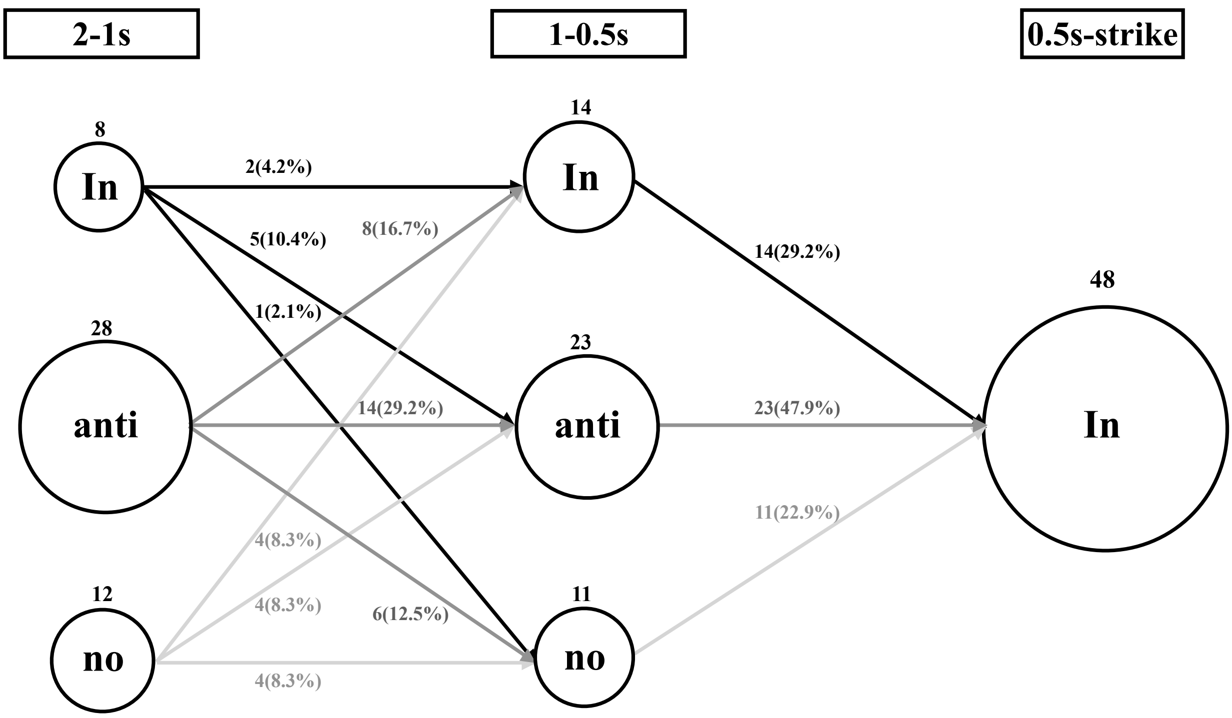

Figure 6. State transition diagram of strike patterns (in = in-phase synchronization, an = anti-phase synchronization, no = no synchronization)

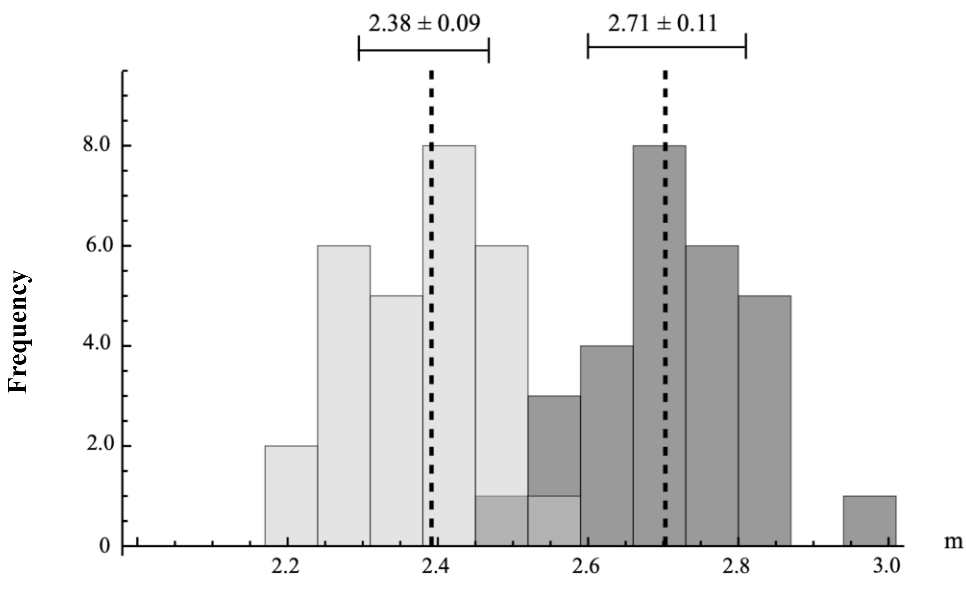

Figure 7. Relative phase and interpersonal distance in the phase including the strike (dark grey = anti-phase synchronization, light grey = in-phase synchronization, grey = interpersonal distance when the two states overlap)

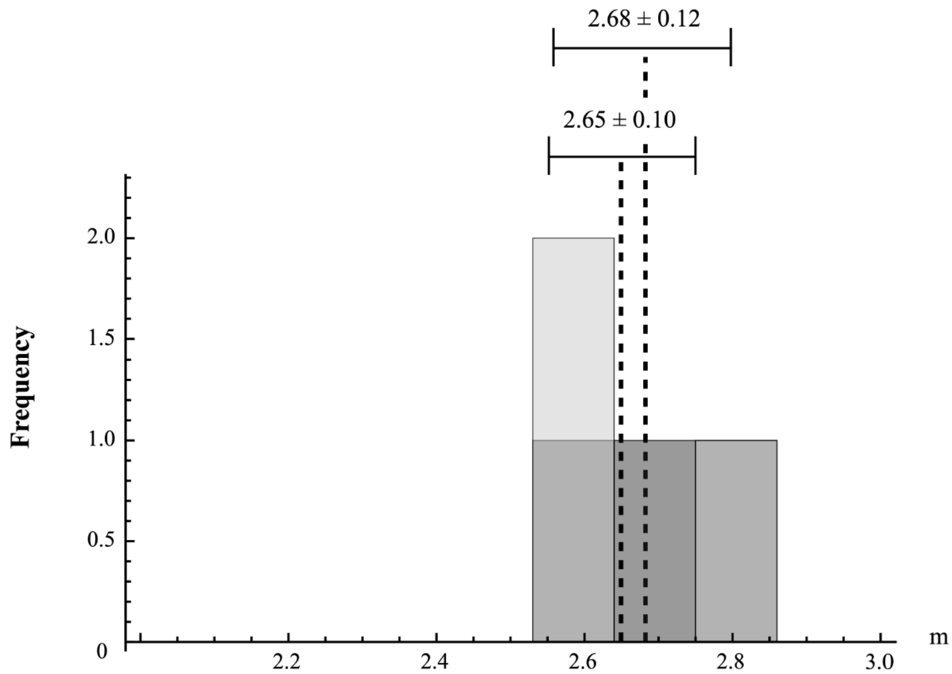

Figure 8. Relative phase and interpersonal distance in the bargaining phase (dark grey = anti-phase synchronization, light grey = in-phase synchronization, grey = interpersonal distance when the two states overlap)

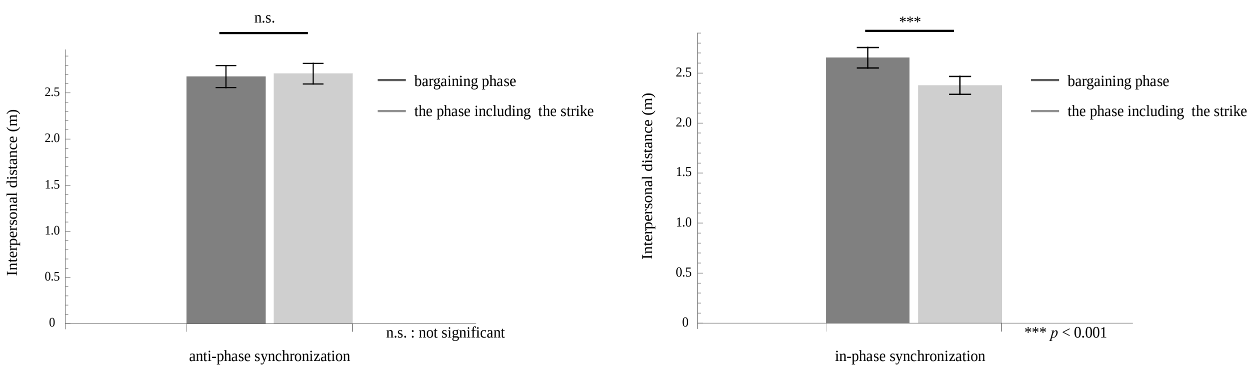

Figure 9. Comparison of interpersonal distances for the same condition in the phase including the strike and the bargaining phase

4. Discussion

4.1. Quantification of the Movement of Both Players

This study focused on the decisive moment in an interpersonal competition. The aim was to quantitatively clarify the movement of two players in a kendo competition from the bargaining phase to the moment of striking by focusing on the relative phase of velocity. When we focused on the last 0.5s including the strike, 48 out of 80 trials showed in-phase synchronization. In 28 of the 48 trials that showed in-phase synchronization, the 2–1s section showed anti-phase synchronization, in which the two players moved in opposite directions. In other words, from the bargaining to the moment of the strike, there is a 35% probability of a pattern of relative phase changes in which anti-phase synchronization occurs in 2–1s just before the strike and in-phase synchronization occurs in the last 0.5s. Conversely, 65% adopted different striking patterns which were not explored in this study. While the 35% probability for a specific relative phase pattern found in this study is small, it is considered an important finding as it includes approximately 1/3 of the phase structure of striking movements, which has been perceived to be infinite.

Previously, studies focusing on the phenomenon of synchronization reported that two people synchronize by watching each other's movements [18–21] and that synchronization occurs during interpersonal competitions, such as in kendo [2]. Okumura et al. [2] discovered that the phase of the velocity also switched depending on the slight difference in the distance, which characterized the bargaining movement between the two players. Although their study included the strike, they did not focus on the moment of the strike that can settle the game and failed to characterize the series of movements from the bargaining phase to the moment of the strike. In this study, we examined the movements of the two players from the relative phase of each trial for the 4s interval between the bargaining phase and the moment of striking. Therefore, we could characterize their movements from the relative phase, including the moment of the strike, which had not been previously studied.

Additionally, several striking opportunities in kendo are empirically verbalized. They are referred to as the three Sen, the "Sen of Sensen," "Sen of Go," and "Sen." The pattern of relative phase changes from anti- to in-phase synchronization including the strike observed in this study quantified the opportunities for the "Sen" strikes in kendo. The "Sen" opportunity to strike arises when the opponent is distracted [1]. In other words, if we consider the last 0.5s of in-phase synchronization as the moment when a player is struck by the movement that seemed to escape from the striking side, the anti-phase synchronization that occurs just before the last 0.5s of in-phase synchronization may be a trigger to create a distraction.

Thus, this study found a specific relative phase pattern that accounts for 35% of the series of movements from bargaining to the moment of the strike. This is thought to be the result of analyzing one experimental trial at a time, further dividing them into five sections, and analyzing the state of the two players in detail from the relative phase.

4.2. Pattern of Relative Phase Changes From Anti- to In-Phase Synchronization

We found a pattern of relative phase changes in the complex movements of the two players in the phase including the strike. However, as the in-, anti-, and asynchronous phases occurred randomly during the trial, we considered the possibility that the same patterns occurred in the other phases. Therefore, we re-examined the trials that showed the pattern of relative phase changes in the phase that included the strike and observed the same pattern in the bargaining phase. In other words, the occurrence of a change pattern similar to that of the relative phase in the phase that includes the strike does not necessarily mean that the strike will be made. To clarify whether a strike will be made when a pattern of relative phase changes that is the same as the phase that includes the strike occurs, we focused on interpersonal distance [2,9], which is considered important in kendo. First, the interpersonal distance in the in-phase synchronization was 2.38m in the phase including the strike and 2.65m in the bargaining phase, indicating that the former was significantly closer than the latter. However, the interpersonal distance was closer in this section than in others because of the actual striking. Therefore, we examined the interpersonal distance of the anti-phase synchronization in the phase including the strike and the bargaining phase.

There was no significant difference in the interpersonal distance during the anti-phase synchronization of the phase including the strike and the bargaining phase. However, the interpersonal distances of these two phases are comparable to those identified by Okumura et al. [2], approximately 2.7–2.8m, as the locations where the two players frequently remain during the match. They reported that at this distance, the player can either attack or defend. In kendo, it is also considered the basic distance [1] at which one can strike by stepping forward or avoid the strike by stepping back. Therefore, although this study was conducted through a simplified version of a kendo match, the interpersonal distance was adjusted in the same way as in a typical match.

At least from the experimental situation of this study, although the pattern of relative phase changes occurs in a phase such that the phase including the strike also occurs during bargaining, it is not possible to accurately determine whether a strike will be made from the difference in interpersonal distance when the pattern of relative phase changes from anti- to in-phase synchronization. The nature of kendo is such that the attacker and defender switch quickly and perform complex motions. It is therefore necessary to examine this considering various factors and perspectives beyond interpersonal distance.

4.3. Possibility of Synchronization to Break Free From Entrainment

Kelso's [22] intraindividual synchronization through control of bimanual finger movements and Schmid et al.'s [23] interindividual synchronization through coordinated movements explain that periodic movements are caused by the attraction of trajectories to attractors, which are stable fixed points by the passage of time. These phenomena have also been observed to occur during competition in sports such as tennis, basketball, and kendo [2, 11, 14]. In this study, in- and anti-phase synchronization also occurred frequently during the nonlinear periodic motion from kendo bargaining to striking, suggesting that entrainment occurred between the two players. In addition, as mentioned above, when focusing on the last 0.5s including the strike, more than half of the trials were performed in which the two players were in in-phase synchronization.

Considering that kendo striking time is approximately 0.34s–0.36s [2, 3] and a match is decided in an instant, instantaneous synchronization between the two players could be the key to victory. We illustrated the movement of the two players when synchronization occurred in the 0.5s-strike segment and the previous four segments using a typical example of the coordinate and velocity data (Figure 10). First, for the striking side (black line in Figure 10) and the struck side (gray line in Figure 10), the velocity varies in a range of about 0.1–0.7m/s in the first four intervals (4–3s, 3–2s, 2–1s, 1–0.5s), which is quite small considering that the average human walking speed is 1.4 m/s [24]. Furthermore, when the coordinate data at this time are examined together, the maximum change is only about 0.2m, which means that the back-and-forth movement of the two players is slight, and they remain in that position.

However, in the 0.5s-strike section, the striking side's velocity increases rapidly to over 2.5m/s, and the coordinate data show that the striking side is much closer to the opponent by about 0.65m. In contrast, the player being struck is moving away from the opponent with a slight delay of about the same speed as before.

Next, a phase space was drawn from the coordinate and velocity data to examine the state of synchronization that occurs between the two. Figure 11 shows a typical example of a phase space in which the striking side is on the left and the side to be struck is on the right. Both are shown as stable limit-cycle attractors in the four sections up to the 0.5s-strike section. However, in the 0.5s-strike section, both of them do not stay at the limit cycle attractor, but rather they deviate from it. Based on these results, it is possible that the synchronization that occurs in the 0.5s-strike section can be viewed as a new synchronization that breaks out of entrainment, rather than a synchronization that is drawn into the attractor. Therefore, the key to winning the game may not be the aforementioned instantaneous synchronization of the two players, but rather the breaking of a stable equilibrium state; that is, one of them may need to intentionally make a move that breaks the limit cycle attractor. In this study, synchronization that breaks out of the limit cycle attractor in the 0.5s-striking section was observed in many trials, similar to the typical example shown in Figure 11. Until now, many studies have focused on bargaining in sports, and the characteristics of that phase have been clarified. However, further analysis of the new synchronization shown by this study has the potential to quantitatively capture the characteristics of the movements of two players in the interpersonal competition, not only in the bargaining phase, which shows synchronization that stays within the limit-cycle attractor but also in the final phase that follows. In other words, in other interpersonal competitions besides kendo, the above analytical method can elucidate the characteristics of the most important decided moments in interpersonal competitions.

4.4. Research Limitations

A limitation of this study is that two constraints were set on the experimental task to simplify the complex repeated movements in kendo. As described in the methods section, they were implemented so the basic patterns leading up to a strike could be observed and the relative phases could be easily extracted. In an actual kendo match, in addition to the men strike, there are three other possible strikes (kote, do, and tsuki), and there are no restrictions on the direction of movement; the player can move freely back and forth, left and right, and diagonally. However, there have been no attempts to quantify the series of movements from bargaining to striking; thus, we first conducted a basic experiment with restrictions. Despite these constraints, we were able to extract the patterns that led to the winners and losers. In the future, the removal of the limitations of experimentation, replicating situations seen in competitions, and analyzing the myriad of possible kendo movement patterns will be necessary.

5. Conclusions

About one-third of the phase structure of striking movements, which previously had been thought to be infinite, formed one characteristic phase pattern. The two players synchronize in opposite directions just before striking, which can be a trigger to challenge a game, and thereafter synchronize in the same direction at the moment of striking.

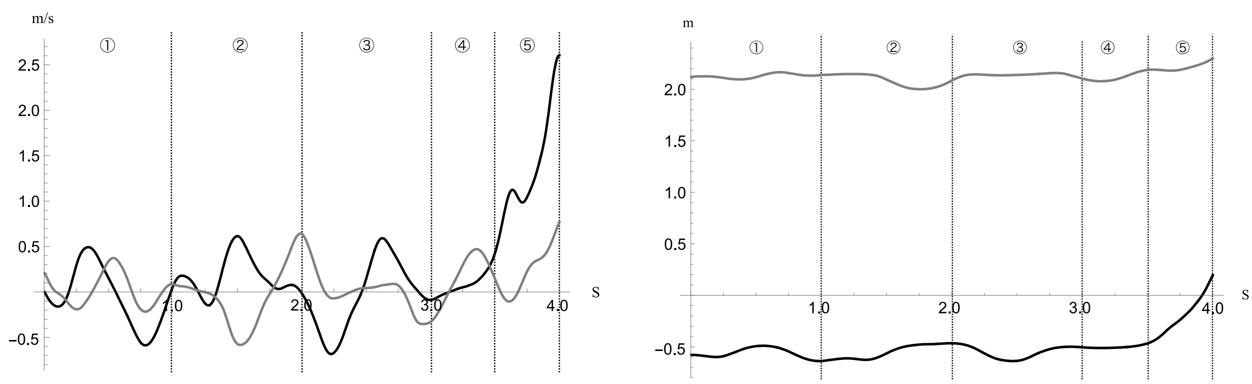

Figure 10. Typical example of velocity and coordinate time series data (the left figure = time series data of velocity, the right figure = time series data of coordinates, the black line = the striking side, the gray line = the struck side, Figures ①–⑤ in the figure = the five sections of the analysis section [①: 4-3s, ②: 3-2s, ③: 2-1s, ④: 1-0.5s, and ⑤: 0.5s-strike])

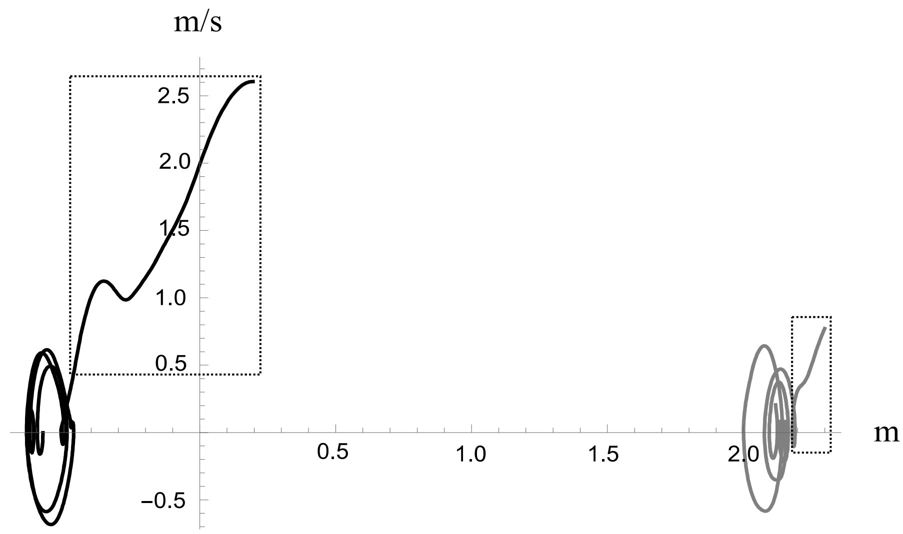

Figure 11. Phase space of velocity and coordinate data (the left side = striking side, the right side = its opponent, the dotted line = 0.5s-striking section (the section where the player breaks out of the limit-cycle attractor))

Acknowledgements

The authors thank the participants for their involvement in the present study.

REFERENCES

[1] Mitsuhashi, S. "Kendo," Taishukan Publishing Co., 1972.

[2] Okumura, M., Kijima, A., Kadota, K., Yokoyama, K., Suzuki, H., Yamamoto, Y. "A critical interpersonal distance switches between two coordination modes in kendo matches," PLOS ONE, vol. *7*, no. 12, p. e51877, 2012. DOI: 10.1371/journal.pone.0051877.

[3] Okumura, M., Kijima, A., Yamamoto, Y. "Perception of affordances for striking regulates interpersonal distance maneuvers of intermediate and expert players in kendo matches," Ecological Psychology, vol. 29, no. 1, pp. 1–22, 2017. DOI: 10.1080/10407413.2017.1270147.

[4] Calmet, M., Ahmaidi, S. "Survey of advantages obtained by judoka in competition by level of practice," Perceptual and Motor Skills, vol. 99, no. 1, pp. 284–290, 2004. DOI: 10.2466/pms.99.1.284-290.

[5] Franchini, E., Sterkowicz, S., Meira, C. M., Jr., Gomes, F. R. F., Tani, G. "Technical variation in a sample of high level judo players," Perceptual and Motor Skills, vol. 106, no. 3, pp. 859–869, 2008. DOI: 10.2466/pms.106.3.859-869.

[6] Murase, N., Horiuchi, G., Sumi, K., Horiyama, K., Sakurai, S. "Biomechanical factors to shorten the movement time of *men* striking motion in Kendo," International Journal of Sport and Health Science, vol. 15, pp. 36–45, 2017. DOI: 10.5432/ijshs.201611.

[7] Williams, L. R. T., Walmsley, A. "Response timing and muscular coordination in fencing: A comparison of elite and novice fencers," Journal of Science and Medicine in Sport, vol. 3, no.4, 460–475, 2000. DOI: 10.1016/s1440-2440(00)80011-0.

[8] Sorel, A., Plantard, P., Bideau, N., Pontonnier, C. "Studying fencing lunge accuracy and response time in uncertain conditions with an innovative simulator," PLOS ONE, vol. 14, no. 7, p. e0218959, 2019. DOI: 10.1371/journal.pone.0218959.

[9] Yamamoto, Y., Yokoyama, K., Okumura, M., Kijima, A., Kadota, K., Gohara, K. "Joint action syntax in Japanese martial arts," PLOS ONE, vol. 8, no. 7, p. e72436, 2013. DOI: 10.1371/journal.pone.0072436.

[10] Maloney, M.A.; Renshaw, I.; Farrow, D. "The interpersonal dynamics of taekwondo fighting," International Journal of Performance Analysis in Sport, vol. 21, no. 6, pp. 993–1003, 2021. DOI: 10.1080/24748668.2021.1968660.

[11] Palut, Y., Zanone, P. G. "A dynamical analysis of tennis: Concepts and data," Journal of Sports Sciences, vol. 23, no. 10, pp. 1021–1032, 2005. DOI: 10.1080/02640410400021682.

[12] Lames, M. "Modelling the interaction in game sports–relative phase and moving correlations," Journal of Sports Science & Medicine, vol. 5, no. 4, pp. 556–560, 2006.

[13] McGarry, T., Khan, M. A., Franks, I. M. "On the presence and absence of behavioural traits in sport: An example from championship squash match-play." Journal of Sports Sciences, vol. 17, no. 4, pp. 297–311, 1999. DOI: 10.1080/026404199366019.

[14] Bourbousson, J., Sève, C., McGarry, T. "Space–time coordination dynamics in basketball: Part 1. Intra- and inter-couplings among player dyads," Journal of Sports Sciences, vol. 28, no. 3, pp. 339–347, 2010. DOI: 10.1080/02640410903503632.

[15] Kijima, A., Kadota, K., Yokoyama, K., Okumura, M., Suzuki, H., Schmidt, R. C., Yamamoto, Y. "Switching dynamics in an interpersonal competition brings about 'deadlock' synchronization of players," PLOS ONE, vol.

7, no. 11, p. e47911, 2012. DOI: 10.1371/journal.pone.0047911.

[16] Varlet, M., Richardson, M. J. "What would be Usain Bolt's 100-meter sprint world record without Tyson Gay? Unintentional interpersonal synchronization between the two sprinters," Journal of Experimental Psychology: Human Perception and Performance, vol. 41, no. 1, pp. 36–41, 2015. DOI: 10.1037/a0038640.

[17] Cohen, J. "A power primer," Psychological Bulletin, vol. 112, no. 1, pp. 155–159, 1992. DOI: 10.1037/0033-2909.112.1.155.

[18] Okano, M., Shinya, M., Kudo, K. "Paired synchronous rhythmic finger tapping without an external timing cue shows greater speed increases relative to those for solo tapping," Scientific Reports, vol. 7, p. 43987, 2017. DOI: 10.1038/srep43987.

[19] Richardson, M. J., Marsh, K. L., Schmidt, R. C. "Effects of visual and verbal interaction on unintentional interpersonal coordination," Journal of Experimental Psychology: Human Perception and Performance, vol. 31, no. 1, pp. 62–79, 2005. DOI: 10.1037/0096-1523.31.1.62.

[20] Richardson, M. J., Marsh, K. L., Isenhower, R. W., Goodman, J. R. L., Schmidt, R. C. "Rocking together: Dynamics of intentional and unintentional interpersonal coordination," Human Movement Science, vol. 26, no. 6, pp. 867–891, 2007. DOI: 10.1016/j.humov.2007.07.002.

[21] Schmidt, R. C., Richardson, M. J., Arsenault, C. A., Galantucci, B. "Visual tracking and entrainment to an environmental rhythm," Journal of Experimental Psychology: Human Perception and Performance, vol. 33, no. 4, pp. 860–870, 2007. DOI: 10.1037/0096-1523.33.4.860.

[22] Kelso, J. A. "Phase transitions and critical behavior in human bimanual coordination," American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, vol. 246, no. 6, pp. R1000–R1004, 1984. DOI: 10.1152/ajpregu.1984.246.6.R1000.

[23] Schmidt, R. C., Carello, C., Turvey, M. T. "Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people," Journal of Experimental Psychology: Human Perception and Performance, vol. 16, no. 2, pp. 227–247, 1990. DOI: 10.1037//0096-1523.16.2.227.

[24] Pachi, A., Tianjian, J. "Frequency and velocity of people walking," The Structural Engineer, vol. 83, pp. 36–40, 2005.