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The spatial and spatiotemporal interpersonal coordinations in aikido's *jiyu waza*

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Abstract

Over the past few years, interpersonal coordination has been increasingly recognised as an important concept in understanding sports performance. It refers to the interactions between individuals. The present study aimed to investigate the interpersonal coordination in *jiyu waza*. Specifically, it sought to identify the spatial and spatiotemporal measures that characterised interpersonal coordination in *jiyu waza*. Twenty aikido practitioners participated in the study, with a mean age of 30 years (± 5 years), with a minimum rank of *shodan* (1st degree black belt) and a minimum of 8 years of aikido practice. The task was *jiyu waza*, which consisted of a defending aikido practitioner avoiding being surrounded and/or hit by three opponents. Triangular area, triangular shape/type, and interpersonal distance, together with their respective measures of change rates (variability and velocity) were used as measures of interpersonal coordination. The *x* and *y* coordinates of the participants' displacement were obtained from 30-second filming (1800 frames at 60 fps) using the semi-automatic tracking software Kinovea 0.9.5. The filming was performed from above, considering the top of each participant's head as the tracking point. Results revealed that: (1) the attackers' interpersonal coordination's in the form of scalene and obtuse triangles, with more variable areas, as well as the greater interpersonal distances between the defender and the triangles characterised the defenses; (2) the attacks in which the defender was attacked from the front, but was unable to neutralise it, were characterised by greater interpersonal distances that emerged with greater positive velocities; (3) the defender consistently failed to neutralise attacks from behind; these situations were characterised by the interpersonal coordination represented by the scalene and obtuse triangles. The findings of this study suggest that the triangular measures (area and shape/type) were able to capture the interpersonal coordination of cooperation between the attackers, and the interpersonal distance enabled access to the interpersonal coordination relative to the opposition in *jiyu waza*.

Keywords: Martial arts; combat sports; aikido; *jiyu waza*; interpersonal coordination; dynamic systems; systemic approach; ecological dynamics.

La coordinación interpersonal espacial y espacio-temporal en el *jiyu waza* del aikido

Resumen

En los últimos años, la coordinación interpersonal, que se refiere a las interacciones entre individuos, se ha reconocido como un concepto cada vez más importante para comprender el rendimiento deportivo. El presente estudio tuvo como objetivo investigar la coordinación interpersonal en el *jiyu waza*. En concreto, se trató de identificar las medidas espaciales y espacio-temporales que caracterizaban la coordinación interpersonal en esta

As coordenações interpessoais espaciais e espaço-temporais no *jiyu waza* do aikido

Resumo

Nos últimos anos, a coordenação interpessoal tem sido cada vez mais reconhecida como um conceito importante para compreender o desempenho esportivo. Ela se refere às interações entre indivíduos. O presente estudo teve como objetivo investigar a coordenação interpessoal no *jiyu waza*. Especificamente, buscou-se identificar as medidas espaciais e espaciotemporais que caracterizaram a coordenação interpessoal no *jiyu waza*.

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práctica del *jiyu waza*. Participaron veinte practicantes de aikido, con una edad media de 30 años (± 5 años), con un rango mínimo de *shodan* (cinturón negro de primer grado) y un mínimo de 8 años de práctica de aikido. La tarea de *jiyu waza* consistía en que un practicante de aikido defensor debía evitar ser rodeado y/o golpeado por tres oponentes. Como medidas de la coordinación interpersonal se utilizaron el área triangular, la forma/tipo triangular y la distancia interpersonal, junto con sus respectivos índices de cambio (variabilidad y velocidad). Las coordenadas *x* e *y* del desplazamiento de los participantes se obtuvieron a partir de una filmación de 30 segundos (1800 fotogramas a 60 fps) utilizando el software de seguimiento semiautomático Kinovea 0.9.5. La filmación se realizó desde arriba, considerando la parte superior de la cabeza de cada participante como punto de seguimiento. Los resultados mostraron que: (1) la coordinación interpersonal de los atacantes en forma de triángulos escalenos y obtusos, con áreas más variables, así como las mayores distancias interpersonales entre el defensor y los triángulos caracterizaron las defensas; (2) los ataques en los que el defensor fue atacado frontalmente, pero no pudo neutralizarlos, se caracterizaron por mayores distancias interpersonales, que se realizaron con mayores velocidades positivas; (3) el defensor no logró neutralizar los ataques por detrás; estas situaciones se caracterizaron por la coordinación interpersonal representada por los triángulos escalenos y obtusos. Los resultados de este estudio sugieren que las medidas triangulares (área y forma/tipo) fueron capaces de captar la coordinación interpersonal de cooperación entre los atacantes, y que la distancia interpersonal permitió acceder a la coordinación interpersonal relativa a la oposición en la práctica del *jiyu waza*.

Palabras clave: Artes marciales; deportes de combate; aikido; *jiyu waza*; coordinación interpersonal; sistemas dinámicos; enfoque sistémico; dinámica ecológica.

Vinte praticantes de aikido participaram do estudo, com idade média de 30 anos (± 5 anos), com grau mínimo de *shodan* (1º grau da faixa preta) e um mínimo de 8 anos de prática de aikido. A tarefa foi o *jiyu waza*, que consistiu em um praticante de aikido em defesa evitar ser cercado e/ou atingido por três oponentes. Área triangular, forma/tipo triangular e distância interpessoal, juntamente com suas respectivas medidas de taxas de mudança (variabilidade e velocidade) foram usadas como medidas de coordenação interpessoal. As coordenadas x e y do deslocamento dos participantes foram obtidas a partir de filmagem de 30 segundos (1800 quadros a 60 fps) utilizando o software de rastreamento semiautomático Kinovea 0.9.5. A filmagem foi realizada de cima, considerando o topo da cabeça de cada participante como ponto de rastreamento. Os resultados revelaram que: (1) a coordenação interpessoal dos atacantes na forma de triângulos escalenos e obtusos, com áreas mais variáveis, bem como as maiores distâncias interpessoais entre o defensor e os triângulos, caracterizaram as defesas; (2) os ataques em que o defensor foi atacado pela frente, mas não conseguiu neutralizá-los, foram caracterizados por maiores distâncias interpessoais, que surgiram com velocidades positivas maiores; (3) o defensor falhou consistentemente em neutralizar os ataques realizados pelas costas; essas situações foram caracterizadas pela coordenação interpessoal representada pelos triângulos escalenos e obtusos. Os resultados deste estudo sugerem que as medidas triangulares (área e forma/tipo) foram capazes de capturar a coordenação interpessoal de cooperação entre os atacantes, e a distância interpessoal permitiu o acesso à coordenação interpessoal relativa à oposição no *jiyu waza*.

Palavras-chave: Artes marciais; esportes de combate; aikido; *jiyu waza*; coordenação interpessoal; sistemas dinâmicos; abordagem sistêmica; dinâmica ecológica.

1. Introduction

Over the past few decades, studies in ecological dynamics have increasingly provided evidence-based insights on how athletes interact in the forms of cooperation and opposition in sports environments, as well as how these interpersonal coordinations constrain their decision-makings (Denardi et al., 2017; Passos et al., 2016; Rothwell et al., 2023; Vilar et al., 2012). The main assumption here is that athletes make decision based on their perceptions of what action the physical properties emerging from their interpersonal and extrapersonal coordinations tendencies afford (Corrêa, 2024; Farrokh et al., 2025; Immonen et al., 2022; Millar et al., 2013). For this purpose, studies have used physical measures like interpersonal distance (Maloney et al., 2021), relative angle (e.g., Oliveira et al., 2023), interpersonal area (e.g., Denardi et al., 2017), and relative velocity (e.g., Passos et al., 2008) as collective variables.

For instance, regarding combat sports and martial arts, studies have shown that: (i) novice boxers who were tasked with freely performing punches on a punching bag made decision on jabs, hooks, or uppercuts to best strike a target based on critical values of distance between they and the punching bag, approximately 0.6 meters (Hristovski et al., 2006); (ii) experienced kendo fighters decided on two types of distances: the shorter distance (approximately 1.00–1.10 m) was associated with direct contact situations (*tsubazeriai*), in which they clashed their swords and remained in a situation similar to a boxing clinch, but with the goal of pushing and destabilizing the opponent to execute an attack. In contrast, greater distances (2.70–2.80 m) allowed for better performance of offensive and defensive movements (Okomura et al., 2012); (iii) experienced aikido fighters were able to maintain stable the synchrony of their positional relationships (relative phase) under the perturbation condition. Conversely, inexperienced aikido fighters exhibited greater difficulty in maintaining such synchronization (Caron et al., 2017); (iv) in competitive contexts taekwondo fighters decided to position themselves close to the opponent in order to create attack opportunities that enabled faster and more precise strikes (Maloney et al., 2018); in order to make possible attacks and defenses, taekwondo fighters maintained the interpersonal distance ranging between 101-200 cm (Maloney et al., 2021); and, (v) kendo fighters decided to diminish or increase the interpersonal distance based on their perception on opportunities for striking or be striked based on subtle interpersonal distance changes (Okumura, et al., 2017).

In summary, these studies allow understanding the (i) performance differences between experienced and novice fighters, (ii) existence of critical values in the fighters' decision-making, and (iii) displacement synchrony between attackers and defenders. Notwithstanding these advancements, it is important to recognise that the foregoing studies were developed by considering artificial and controlled fighting situations. For instance, they often involved a single fighter in a controlled environment or two fighters opposing each other with predefined roles of attacking and defencing (Krabben et al., 2019). Moreover, although the interpersonal coordination analyzed in these studies — 1 vs. 1 dyadic situation — characterizes the essence of martial arts and combat sports, there are other fighting situations that additionally involve cooperation between fighters. This is the case of *jiyu waza* of aikido.

The *jiyu waza* is a fighting situation in which usually three fighters cooperate to surround and hit another fighter who, in turn, opposes to them by performing whatever aikido motor skills he/she deems necessary to avoid being surrounded and attacked (Westbrook & Ratti, 1996). The *jiyu waza* situation could be seen as similar to those original of martial arts, in which combats took place in war contexts with collective battles (Lawler, 1996; Mitchell, 1984; Udo Moenig et al., 2023). *Jiyu waza* is an integral and advanced part of the aikido curriculum, often required in grading examinations for black belts, which attests to its importance and formality within the martial art.

Therefore, considering *jiyu waza* as a system that emerges from the simultaneous interactions of cooperation and opposition over specific time and space, the question was: what collective variables characterize interpersonal coordination in *jiyu waza* and how do they affect the performances of the attackers and the defender? This study sought to add to the existing knowledge by investigating the interpersonal coordination in *jiyu waza*. Specifically, we aimed to identify what and how spatial and spatiotemporal measures characterize interpersonal coordination in *jiyu waza*.

2. Method

2.1. Participants

Twenty male aikido practitioners, whose average age was 30.0 years (SD = 4.11), voluntarily took part in this study. They had a minimum of 8 years of aikido practice and held at least a *shodan* (1st-degree black belt). The participants were recruited from an open invitation made to practitioners from several aikido dojos in Sao Paulo-Brazil, all of whom were volunteers and met the inclusion criteria. The research protocol was approved by the local ethics committee of the University of São Paulo (CAAE Number: 61172122.5.0000.5391). All participants gave their informed written consent, following our detailed explanation of the study.

2.2. Task and Instruments

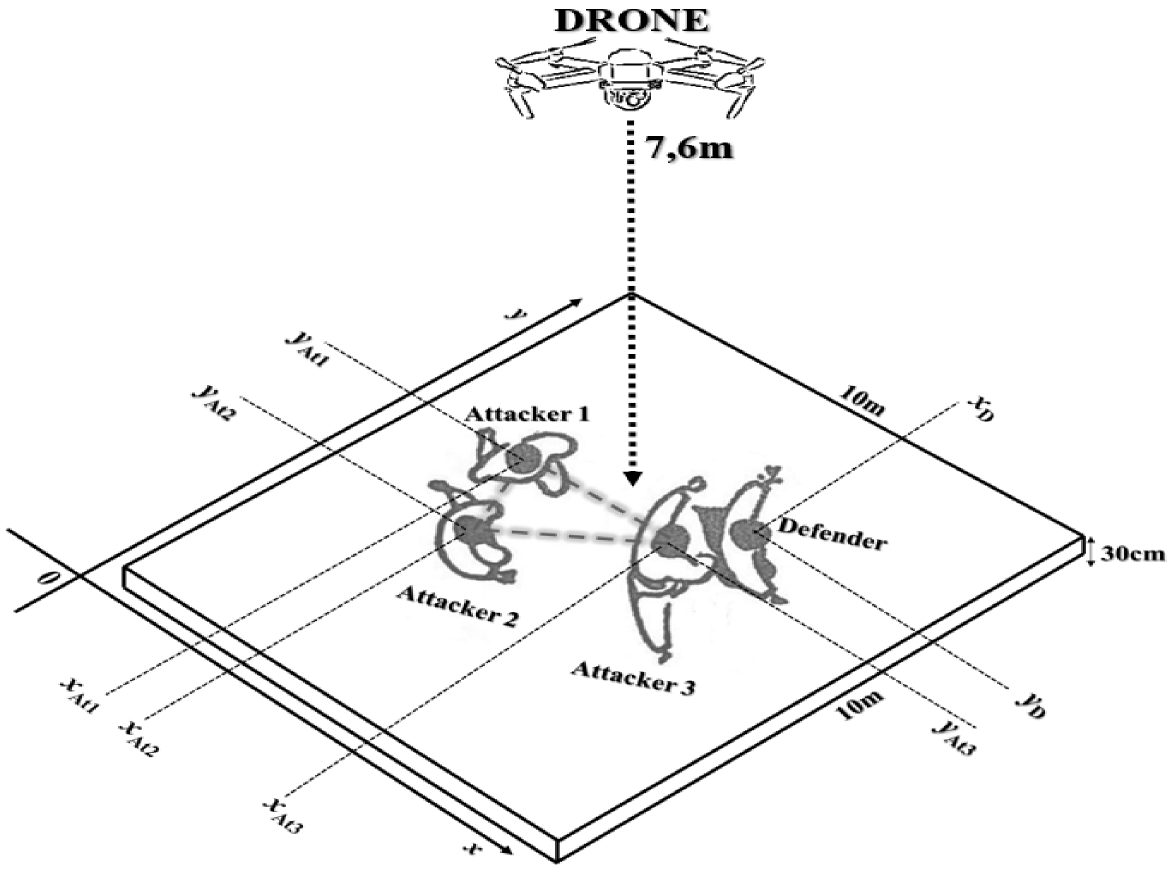
The task was the *jiyu waza* of aikido, in which usually three aikido fighters cooperated to surround and hit another aikido fighter who, in turn, opposed to them by performing whatever aikido motor skills he/she considered necessary to avoid being surrounded and hit (Westbrook & Ratti, 1996). The *jiyu waza* is performed for fighters who have mastered most or all of the aikido skills, usually from the green belt onwards. It can also be a requirement in belt exams. Therefore, it can be said that the main characteristic of *jiyu waza* is the interactions of cooperation and opposition, that is, the attackers cooperate to oppose a defender who, in turn, opposes to the cooperation.

Data collection employed a DJI Phantom 4 drone with HD camera for aerial video recording at 60 frames per second; Kinovea 0.9.5 software for semi-automatic tracking of *x* and *y* coordinates and RStudio (version 2023.09.1+494) software for statistical analyses.

2.3. Procedures

Participants were organised into five groups of four fighters (one defender and three attackers per group). Within each group, the roles were rotated so that each individual performed as the defender once. Consequently, the participants were assessed four times (trials of 30-second). Each trial started with the command "*hajime*" and ended with two hand claps. A 5-minute rest was provided between trials. Participants were instructed to perform the *jiyu waza* throughout 30 seconds. The *jiyu waza* task was performed on a 10x10 m EVA mat under a drone positioned 7.6 meters above (Figure 1)

Figure 1. Data collection environment.



2.4. Data Acquisition and Outcomes

The *x* and *y* coordinates of the participants' displacements were obtained from 30-second recordings (1800 frames at 60 fps) using the semi-automatic tracking software Kinovea 0.9.5 (Kinovea, 2021). The reliability of this software for angular and linear measurements is well-documented in the literature (e.g. Diví et al., 2019; Gemas Neto et al., 2021; Suhairi et al., 2023). During the tracking process, the software recorded the coordinates frame by frame, while the researcher manually corrected instances where the reference was not detected. The recording was conducted from an overhead perspective, and the top of each participant's head was used as the tracking reference point.

To analyze *jiyu waza*, six possible outcomes were defined by three black belts in aikido:

1. The defender is attacked *from the front* by the attacker, but the attack is *neutralized* with a counterattack, defense, or evasion;
2. The defender is attacked *from the front* by the attacker but *fails to neutralize* the attack with a counterattack, defense, or evasion;
3. The defender is attacked *from behind* by the attacker, but the attack is *neutralized* with a counterattack, defense, or evasion;

4. The defender is attacked *from behind* by the attacker but *fails to neutralize* the attack with a counterattack, defense, or evasion;
5. The defender is attacked *from both the front and behind*, but the attack is *neutralized* with a counterattack, defense, or evasion;
6. The defender is attacked *from both the front and behind* but *fails to neutralize* the attack with a counterattack, defense, or evasion.

These outcomes were important for determining 'cycles' within the 1800 frames of *jiyu waza* in order to calculate the measures. When a specific outcome occurred in a given frame, the preceding frames were considered to form the 'cycle' of that outcome. For example, if a certain outcome occurred in frame 25, then a 'cycle' of that outcome was determined from frame 1 to 25. Subsequently, if an outcome occurred in frame 100, the 'cycle' for the next outcome would be from frame 26 to 100. This logic was followed throughout the 1800 frames. However, during the video analysis, it was noted that outcomes 3 and 5 did not occur. Thus, the outcomes were renumbered as follow:

O1 – The defender is attacked *from the front* but manages *to neutralize* the attack;

O2 – The defender is attacked *from the front* but *fails to neutralize* the attack;

O3 – The defender is attacked *from behind*, surrounded, but fails to neutralize the attack;

O4 – The defender is attacked *from both the front and behind*, surrounded, but *fails to neutralize* the attack.

The definition of the outcomes was carried out by three experts. Each expert was an aikido black belt with a minimum of 15 years of practice and a rank of 3rd dan or higher. The assessment was conducted independently, where each expert watched all the videos and classified each attack/defense cycle. The agreement among the evaluators was then calculated using Fleiss' Kappa coefficient to ensure the reliability of the classifications. This coefficient adjusts the observed agreement for chance expectation, providing a robust measure for categorical data. The calculation, performed in RStudio software (version 2023.09.1+494), indicated substantial agreement ($\kappa = 0.79$).

2.5. Measures

The geometric shape of a triangle was used to capture the interactions among the three attackers, as they cooperate to surround the defender and, therefore, aim to avoid remaining in a straight line. Based on the *x* and *y* displacement coordinates of each participant and the outcomes that occurred throughout the *jiyu waza*, the following interpersonal coordination measures were calculated:

- *Triangular area*: considering a triangle in the cartesian plane, the area was calculated using the formula:

  $$A = \frac{1}{2}\left|(x_{at1} - x_{at3})(y_{at2} - y_{at1}) - (x_{at1} - x_{at2})(y_{at3} - y_{at1})\right|,$$

  where A represents the area, x_{at1} represents the x-coordinate of attacker 1, x_{at2} represents the x-coordinate of attacker 2, x_{at3} represents the x-coordinate of attacker 3, y_{at1} represents the y-coordinate of attacker 1, y_{at2} represents the y-coordinate of attacker 2, and y_{at3} represents the y-coordinate of attacker 3. The triangular areas were analysed regarding their initial, final, and emergent values. This latter referred to the difference between final and initial areas. They were also analysed regarding the variability and velocity of emergence. The first was calculated based on the coefficient of variation through $CV = \sigma / \mu$, where CV refers to the coefficient of variation, σ is the standard deviation, and μ represents the mean. And, the latter was calculated using $v = A / t$, where v is the velocity (m^2/s), A is the emerging area (m^2), and t is the time interval of each attack/defense (s).

- *Triangular shape and type*: classified based on side lengths (e.g., scalene) and angles (e.g., obtuse). Initial and final shapes/types were analyzed in terms of absolute frequency. It was also analyzed regarding the variability: (i) how many times the triangle changed shape throughout each attack/defense (variability A); (ii) how many different triangle types occurred throughout each attack/defense (variability B); and (iii) total variability (TV), resulting from the multiplication of both variabilities: TV = VA x VB.

- *Interpersonal distance*: the distance between the defender and the nearest boundary line of the triangle formed by the attackers was calculated using the formula:

  $$d = \frac{|Axd+Byd+C|}{\sqrt{A^2+B^2}}$$

  where A, B, and C are the coefficients of the equation of the plane defined by the attackers. Then, to determine whether the defender was inside or outside the triangle formed by the attackers (encircled or not), an approach was used based on comparing the areas of the triangles formed by the defender with each pair of attackers to the total area of the triangle formed by the attackers. This approach, based on the Shoelace formula or Gauss's area formula, is more straightforward and does not depend on the specific geometry of the triangle formed by the attackers, making it more robust across different triangle configurations (Braden, 1986).

Using the shoelace formula or Gauss area formula for robustness, the distance between the defender and the triangle formed by the attackers, referred to as interpersonal distance, was used to assess how the dynamics of surrounding and avoiding being surrounded occurred. Negative distance values indicated that the defender was inside the triangle formed by the attackers, while positive values indicated that the defender was outside the triangle. The step-by-step process for this calculation is as follows: first, the area formed by the attackers is calculated using the formula

$$A_{triangle} = \frac{1}{2}\,|\,x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2)|.$$

Then, the area of the triangle formed by the defender and two attackers is determined using the same formula, considering the vertices (x_d, y_d), (x_i, y_i), and (x_j, y_j), where *i* and *j* are different indices among attackers 1, 2, and 3. To determine whether the defender is inside or outside the triangle, the total area of the attackers' triangle is compared to the sum of the areas of the three triangles formed by the defender with each pair of attackers. The total triangle area is given by:

$$= \frac{1}{2}\,|\,x_1(y_2 - y_3) + x_2(y_3 - y_1) + x_3(y_1 - y_2)| +$$

$$\frac{1}{2}\,|\,x_d(y_2 - y_3) + x_2(y_3 - y_d) + x_3(y_d - y_2)| +$$

$$\frac{1}{2}\,|\,x_1(y_d - y_3) + x_d(y_3 - y_1) + x_3(y_1 - y_d)| +$$

$$\frac{1}{2}\,|\,x_1(y_2 - y_d) + x_2(y_d - y_1) + x_d(y_1 - y_2)|.$$

In a simplified form, this means that the sum of the areas of the triangles including the defender is equal to the area of the attackers' triangle plus the area of the triangle with attacker 1, plus the area of the triangle with attacker 2, plus the area of the triangle with attacker 3. If the sum of the areas of the triangles including the defender is equal to the total area of the triangle formed by the attackers, then the defender is inside the triangle. If the sum is greater, the defender is outside the triangle.

The interpersonal distances were analysed regarding their initial, final, and emergent values. This latter referred to the difference between final and initial distances. They were also analysed regarding the variability and velocity of emergence. The first was calculated based on the coefficient of variation through CV = σ / μ, where CV refers to the coefficient of variation, σ is the standard deviation, and μ represents the mean. And, the latter was calculated using v = A / t, where v is the velocity (m/s), A is the emerging distance (m), and t is the time interval of each attack/defense (s).

2.6. Statistical Analysis

To assess whether and how each interpersonal coordination measure influenced *jiyu waza*, they were individually compared in relation to the four outcomes. Given the unequal sample sizes for each outcome (O1 = 20; O2 = 11; O3 = 18; O4 = 7), analyses of means, medians, and normality tests were performed for all measures to determine the appropriate approach. Normality tests indicated non-normal distributions for one or two specific variables, such as final area and emergent area in

O1 (20 samples). Considering the ANOVA is a robust parametric test capable of handling deviations from normality assumptions when sample sizes are not small (Green et al., 2000; Ramsey & Schafer, 2002; Weir & Vincent, 2020), it was selected for use. Additionally, Welch's ANOVA was applied to account for differences in sample sizes between outcomes. Instead of pooled variance estimates, this test uses sample variances and sizes for each group to calculate the F statistic. It is particularly suited for unequal group sizes and is conservative in such situations (Corrêa et al., 2014; Denardi et al., 2017; Green et al., 2000; Ramsey & Schafer, 2002; Weir & Vincent, 2020).

For the two measures related to triangular shape/type, comparisons were made using the Chi-square test, as they involved frequency counts. When significant differences were found, a post hoc proportions test was applied to determine specific group comparisons (Agresti, 2018).

A significance level of $\alpha \leq 0.05$ was adopted for all inferences. Partial eta squared (ηp^2) was used as an indicator of effect size for Welch's ANOVAs (Cohen et al., 2003). When Welch's ANOVA identified differences, the Games-Howell post hoc test was conducted. This test, which does not assume homogeneity of variances or equal sample sizes, is ideal for heteroscedasticity. It is often used alongside Welch's ANOVA to identify specific group differences. In this study, it was used to determine which outcomes differed (Games & Howell, 1976; Ruxton & Beauchamp, 2008).

3. Results

The main results are presented here, specifically those that were revealed statistically significant difference.

For the variability of the triangular area, the results are shown in Figure 2. The outcomes O1, O2, and O4 had similar and higher mean triangular variability compared to O3 (O1 = 0.46; O2 = 0.43; O3 = 0.30; O4 = 0.46). The ANOVA with Welch correction found significant differences between the variability of areas across outcomes [$F(3; 17.86) = 5.3268$, $p = 0.0084$, $\eta p^2 = 0.226$]. The Games-Howell post hoc test identified a significant difference only between O1 (CV = 0.48) and O3 (CV = 0.25), with O1 having the highest mean variability rate. This result suggests that O1 had a more variable triangular area than O3.

In practical terms, the 'area variability' measures the stability of the attackers' formation (the triangle). The results indicate that successful defenses (O1) occurred when the attackers' formation was more unstable and varied in size more irregularly. In contrast, when the attackers managed to maintain a more consistent and stable formation (lower variability), as observed in the successful attacks from behind (O3), the defense failed. This suggests that instability in the attackers' coordination created affordances for the defender.

For the absolute frequency of triangular shape, Table 1 presents the absolute frequency values of the initial (ITS) and final (FTS) triangular shapes across the four outcomes (O1, O2, O3, and O4). It was observed that only the scalene triangle occurred at both moments, with the highest frequency in O1 and the lowest in O4. Regarding the comparisons between outcomes, the Chi-square test found significant differences for ITS ($p < 0.05$) and FTS ($p < 0.05$) for the scalene triangle. The post hoc proportions test revealed significant differences between O1 and O2 ($p = 0.04$), O1 and O4 ($p = 0.001$), and O3 and O4 ($p = 0.004$).

This finding shows that irregular, asymmetrical formations (scalene triangles) were dominant, particularly during successful defenses (O1). The frequency of this less-structured formation was significantly higher in successful defenses compared to failed frontal attacks (O2) and failed simultaneous attacks (O4). This indicates that the defender's success is strongly associated with situations where the attackers adopt a less geometrically regular and possibly less coordinated formation.

Table 1. Absolute frequencies of initial and final triangular shapes for O1, O2, O3, and O4.

Shape	Initial				Final			
	O1	O2	O3	O4	O1	O2	O3	O4
Scalene	20	11	18	7	20	11	18	7
Isosceles	0	0	0	0	0	0	0	0
Equilateral	0	0	0	0	0	0	0	0

For the absolute frequency of triangular type, Table 2 presents the absolute frequency values for ITT and FTT across the four outcomes (O1, O2, O3, and O4). It was observed that the obtuse triangle had the highest occurrences at both moments (initial and final). For ITT, the highest frequencies were in O1 and O3. For FTT, O1 showed the highest frequency. Interestingly, at both moments, there were no occurrences of the right-angled triangle. Regarding the statistical comparisons, the Chi-square test revealed significant differences between obtuse and acute triangles in ITT-O1 ($p = 0.0017$) and ITT-O3 ($p = 0.004$). In FTT, a significant difference was observed between obtuse and acute triangles only in O1 ($p < 0.001$).

These results show a clear preference for wide-angled (obtuse) formations by the attackers. These open formations were significantly more prevalent than tight, aggressive (acute) formations, especially during successful defenses (O1). The complete absence of right-angled triangles suggests a tendency to avoid rigid geometric structures. In essence, the defender succeeded most often when the attackers were spread out in a wide, obtuse formation.

Table 2. Absolute frequencies of the initial and final triangle types for O1, O2, O3, and O4.

Type	Initial				Final			
	O1	**O2**	**O3**	**O4**	**O1**	**O2**	**O3**	**O4**
Scalene	17	5	15	6	20	7	10	6
Isosceles	3	6	3	1	0	4	8	1
Equilateral	0	0	0	0	0	0	0	0

Regarding the comparisons between the outcomes, the Chi-square test identified differences in ITT for the obtuse triangle type ($p < 0.05$). The post hoc proportion test revealed differences between O1 and O2 ($p < 0.001$), O1 and O4 ($p = 0.0012$), O2 and O3 ($p = 0.006$), and O3 and O4 ($p = 0.02$). In FTT, the Chi-square test found significant differences for the obtuse triangle type ($p < 0.05$). The post hoc proportion test showed differences between O1 and O2 ($p < 0.001$), O1 and O3 ($p = 0.006$), and O1 and O4 ($p < 0.001$). Additionally, in FTT, the Chi-square test identified significant differences for the acute triangle type ($p < 0.05$), with the post hoc proportion test revealing differences only between O1 and O3 ($p = 0.03$).

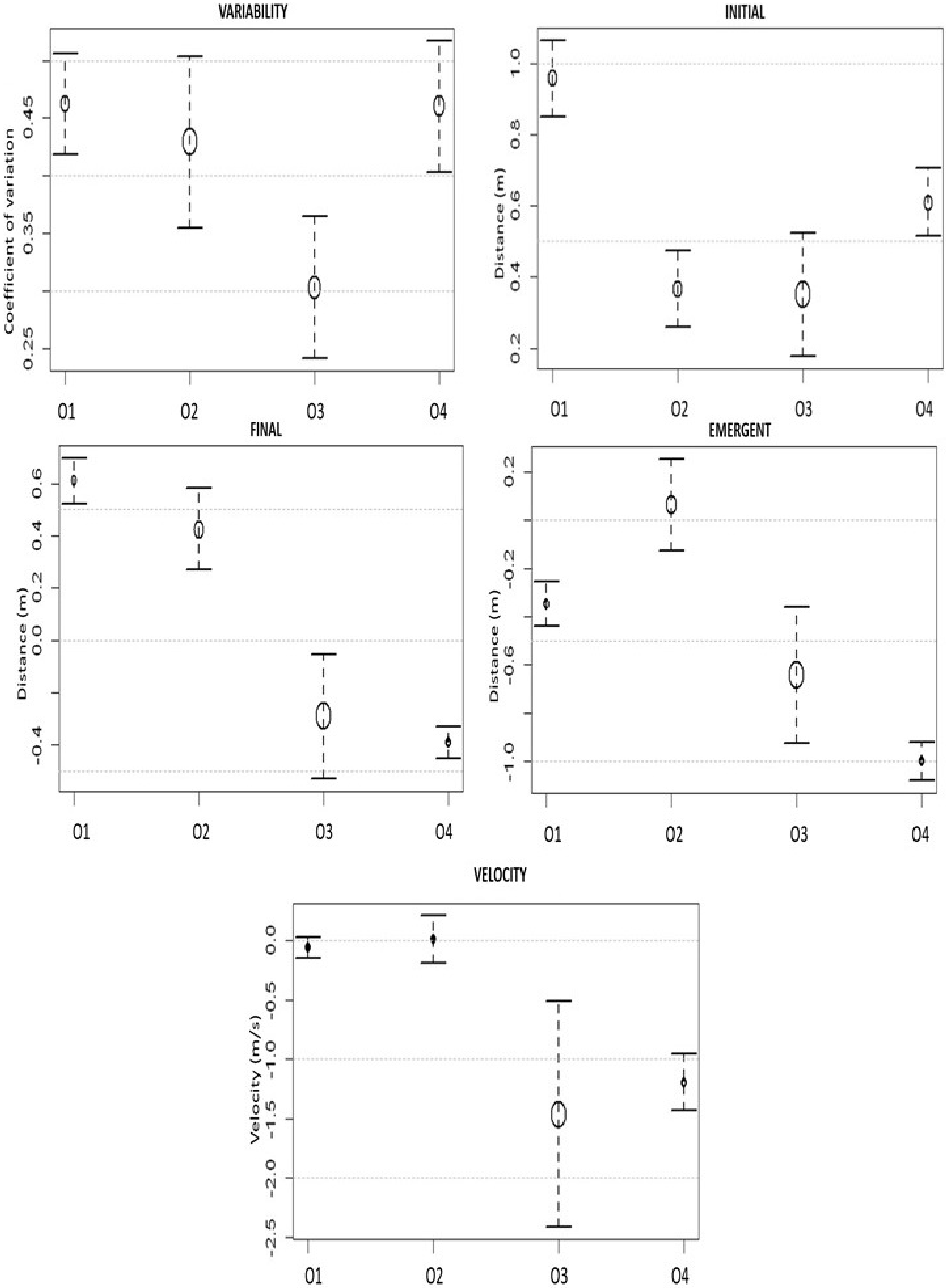
This analysis reinforces the previous point by showing that the prevalence of open (obtuse) formations in successful defenses (O1) was statistically significant when compared to unsuccessful attacks (O2, O3, and O4). Practically, this means the attackers' success depended on their ability to avoid these wide formations and maintain tighter coordination. The defender's success, therefore, is linked to his ability to disrupt the attackers and force them into these less effective, wider-angled configurations.

For the initial distance between the defender and the triangle, Figure 2 shows that the initial distances between the defender and the triangle in O2 (0.37 m) and O3 (0.35 m) were close to and lower than O4 (0.61 m), which was lower than O1 (0.96 m). Nevertheless, the ANOVA with Welch correction found significant differences between the outcomes [$F(3; 19.258) = 16.243$, $p < 0.001$, $\eta p^2 = 0.509$]. The Games-Howell post hoc test indicated a significant difference between O1 and O2, and O1 and O3, meaning that the initial distance between the defender and the triangle in O1 was greater than in O2 and O3.

This result clearly demonstrates that the starting distance was a critical determinant of success. Successful defenses (O1) consistently began with the attackers positioned significantly farther away from the defender. In contrast, when attackers were able to initiate their attack from a closer range (O2 and O3), the defender was consistently unsuccessful. This indicates that creating and maintaining distance from the outset is a key tactical component for a successful defense in this context.

In relation to the distance between the defender and the triangle, Figure 2 shows that the final average distances between the defender and the triangle differed across the outcomes. O1 recorded the largest distance (0.61 m), followed by O2 (0.43 m). The distances for O3 (-0.2 m) and O4 (-0.4 m) yielded negative values. The ANOVA with Welch correction revealed statistically significant differences between the outcomes [$F(3; 19.363) = 43.817$, $p < 0.0001$, $\eta p^2 = 0.8385$]. The Games-Howell post hoc test indicated significant differences between O1 and O3, and between O1 and O4, as well as between O2 and O3, and between O2 and O4. These results suggest that the final distances between the defender and the triangle in O1 and O2 were greater than those in O3 and O4.

Figure 2. Means and 95% confidence intervals of the coefficients of variation of triangular areas, of the initial, final and emergent interpersonal distances, and of the distancing speeds across the four outcomes (O1, O2, O3, and O4).



The negative values for the final distance in outcomes O3 and O4 are a key finding. They signify that, by the end of the attack cycle, the defender was positioned inside the perimeter of the attackers' triangle, meaning he had been fully encircled. In contrast, in all frontal attacks (both successful O1 and unsuccessful O2), the defender managed to remain outside this perimeter. This empirically confirms that being surrounded is a defining characteristic of failed defenses, particularly against attacks originating from behind or from multiple directions.

Concerning the emergent distance between the defender and the triangle, Figure 2 shows that in most of the outcomes, the emerging average distances between the defender and the triangle were negative (O1 = -0.35; O3 = -0.64; O4 = -1.00 m). Although O2 had a positive distance, it was just slightly above zero (0.06 m). The ANOVA with Welch correction found statistically significant differences between the outcomes [$F(3; 18.164) = 12.344$, $p < 0.0001$, $\eta p^2 = 0.7202$]. The Games-Howell post hoc test indicated significant differences between O1 and O4, between O2 and O3, and between O2 and O4, indicating that the emerging distances between the defender and the triangle in O1 were greater than in O4; and in O2, they were greater than in O3 and O4.

Emergent distance (final minus initial) quantifies the overall change in spacing. The large negative values, especially in simultaneous attacks (O4), show how effectively and rapidly the attackers closed the distance on the defender in the most complex scenarios. Even in successful defenses (O1), the space still compressed, but to a significantly lesser degree. This highlights the constant spatial pressure the defender faces. The unique positive value for failed frontal attacks (O2) suggests that in those instances, the defender was actively creating space but was hit despite this effort, pointing to a different tactical failure.

For the distancing velocity, Figure 2 shows most of the outcomes had negative values: O1 = -0.06 m/s, O2 = 0.01 m/s, O3 = -1.46 m/s, and O4 = -1.20 m/s. The ANOVA with Welch correction revealed significant differences between the outcomes [$F(3; 16.092) = 5.7363$, $p = 0.007$, $\eta p^2 = 0.31$]. The Games-Howell post hoc test indicated a difference between O2 and O3. Therefore, it can be suggested that the distancing speed between the defender and the triangle in O2 was positive, which differed from the negative speed in O3.

The high negative speeds during attacks from behind (O3 and O4) show that the attackers closed in on the defender with extreme rapidity. In practical terms, this speed of encroachment was a key factor in the defender's failure. In contrast, the slightly positive velocity for failed frontal attacks (O2) indicates that the defender was actually succeeding in creating distance in those moments, even though the attack was ultimately successful. This highlights a clear tactical distinction: frontal attacks are a contest of managing space, whereas attacks from behind are characterised by the defender being overwhelmed by the attackers' speed.

4. Discussion

This study aimed to identify what and how spatial and spatiotemporal measures characterize interpersonal coordination in *jiyu waza*. Results suggest that the triangular area in the scalene and obtuse-angled ways allowed to capture the attackers' interaction. And, the initial, final, and emergent distance, as well as the velocity of emergence made possible to capture the characteristics of displacement of defender-attackers opposition.

Specifically, it was found the scalene triangle was the only triangular form of interpersonal coordination used in *jiyu waza*. Additionally, it was more evident in successful defensive situations than in those of attacks. Interestingly, it was accompanied of obtuse-angled triangle. Moreover, successful defenses exhibited greater variability in the area of triangular interpersonal coordination.

This variability may have been influenced by the defender's continue trying of maintaining larger interpersonal distances, which hindered the formation of more effective triangles by the attackers. This interpretation aligns with findings from Maloney et al. (2021), who highlighted that the larger interpersonal distances are associated with more effective defensive behaviours, while smaller distances favor attackers.

Concerning the interpersonal distances, they were greater during successful defensive actions. It is possible that the defender's ability to maintain distance from the attackers led these latter to adopt ineffective patterns of interaction (scalene and obtuse-angled), meaning they were unable to complete the attacks successfully. One could also interpret that the efficiency of the defense occurred because this distance prevented a certain organization in the attackers' interpersonal coordination, as evidenced by their variable triangular area.

In sum, by considering these findings, variability in interpersonal coordination could be interpreted as maladaptive or non-functional (Benda & Tani, 2005; Corrêa et al., 2015). Indeed, the issue of area variability could be a key factor in the success or failure of the defense/attack. In this regard, from the perspective of ecological dynamics, variability is seen as a desirable characteristic, as it reflects the complexity and unpredictability of interactions, being essential for the effectiveness of actions in contexts where decisions need to be made quickly and based on constantly changing perceptions (Corrêa et al., 2012; Corrêa et al., 2014; Corrêa et al., 2020). Additionally, greater interpersonal distances may have helped the defender remain perceptually attuned to the attackers as a whole in order to perceive the affordances of their interpersonal coordination (Denardi et al., 2017; Vilar et al., 2012). These findings are consistent with Okomura et al. (2017), who emphasized the importance of perceiving and adjusting interpersonal distances in real-time, which is crucial for both defensive and offensive success in combat sports.

Regarding the successful attacks, two results stood out. The first referred to the interpersonal distances between the defender and the attacking triangle (final and emergent) in the attack outcome O2 (where the defender is attacked from the front but fails to neutralize the attack), which were higher than in outcomes O3 (the defender is attacked from behind, surrounded, but fails to neutralize the attack), and O4 (the defender is attacked from both the front and behind, surrounded, but fails to neutralize the attack). It is important to highlight that in the O2 outcome, these distances increased with positive velocity, while in O3, they were negative (they decreased). These results suggest that the attacks where the defender is attacked from the front, but fails to neutralize the attack, were characterised by higher interpersonal distances that emerged with higher positive velocities.

Considering that the interpersonal distance referred to the distance between the defender and the boundary line of the triangle, these results can be explained by the fact that in O3 and O4, the defender is inside the triangle. The main difference between O3 and O4 compared to O2 concerns the encirclement. That is, in the former, the attack is completed with encirclement, whereas in the latter, it is not. As seen in the results, O3 and O4 showed negative values, meaning the defender was inside the triangle. In contrast, in O2, the value of the interpersonal distance was positive, indicating that the defender was outside the triangle.

The second result concerned the greater number of scalene triangles in attack outcome O3 compared to O4, and the higher greater of obtuse triangles in outcome O3 compared to O2 and O4 attacks. These suggest that the situations where the defender is attacked from behind, surrounded, but fails to neutralize the attack, were characterised by interpersonal coordination represented by scalene and obtuse triangles. The difference between O3 and the other attack outcomes is that in O3, the defender is only attacked from behind. Scalene triangles, with sides of different lengths, can take on various forms, providing an advantage for surrounding the defender from behind. On the other hand, obtuse triangles, with one angle greater than 90º, allow a wider distribution of attackers around the defender. This wider angle creates fewer observable lines of attack because the attackers are not directly aligned with each other, making it more difficult to read the fight, i.e., the defender's movement (Williams et al., 2000). Furthermore, the two smaller angles that complete this triangle help the attackers' approach from different directions, pressuring the defender from multiple points and limiting their effective defense options.

Interestingly, there were no outcomes in which the defender successfully neutralized an attack from behind or a simultaneous attack (front and back). This result empirically validates the main tactical premise of *jiyu waza*: the defender's primary strategy is to manage the interpersonal system to avoid being surrounded. Our data show that, once the surrounding condition is established with one or more attackers outside the visual field, the probability of a successful defense is very low, even for experienced practitioners. From an ecological dynamic perspective, skilled performance occurs when athletes operate within their 'action boundaries' (Krabben et al., 2019). This result suggests that the attack from behind is beyond the defender's availability to act, resulting in the collapse of his defensive system. It could be said that the skill in *jiyu waza* involves not only the ability to neutralize any attack, but also the ability to perceive and act to prevent the system from reaching this critical and unstable state. This result highlights the critical factors that may determine the success and failure during the in *jiyu waza*.

These findings are consistent with the studies by Okomura et al. (2012) and Okomura et al. (2017), which emphasized the importance of perceiving action possibilities (e.g., affordances) and maneuvering interpersonal distances in combat sports. In kendo, for example, players adjust their interpersonal distances based on striking opportunities, alternating between offensive and defensive behaviours quickly and precisely. Additionally, in conjunction with other studies on combat sports, greater interpersonal distances were decisive for the success of defense in *jiyu waza*, but conversely, smaller interpersonal distances led to success for the attackers (Caron et al., 2017; Hristovski et al., 2006; Krabben et al., 2019; Maloney et al., 2018; 2021; Okomura et al., 2012; 2017), just as the negative distancing speed in O3 indicated that the triangle indeed approached the defender, enabling the encirclement for a successful attack.

5. Conclusion

The present study concludes that: (1) the attackers' interpersonal triangular coordination, scalene and obtuse, with more variable areas and larger interpersonal distances between the defender and the triangle characterised the successful defenses; (2) the attacks in which the defender is attacked from the front but fails to neutralize the attack were characterised by higher interpersonal distances that emerged with higher positive speeds; (3) the situations in which the defender is attacked from behind, surrounded, but fails to neutralize the attack, were characterised by interpersonal coordination represented by scalene and obtuse triangles; and (4) defenders were consistently unable to neutralize attacks from behind or simultaneous attacks from the front and behind.

Given the assumption that individuals make decisions and act based on the perception of opportunities/possibilities for action (e.g., affordances) that emerge from their interpersonal coordination's interactions (Denardi et al., 2017; Vilar et al., 2012), it can be said that it is a requirement for the defender to be perceptually tuned with the attackers in order to stay away from them and prevent they form consistent team patterns. On the other hand, the attackers must be perceptually tuned with each other and with the defender in order to reduce the distances between them and the defender, facilitating the consistent formation of an efficient type of triangular interpersonal coordination.

One of the limitations of this study is that it only considered attacks carried out from in front of and behind the defender. Therefore, future studies should consider the diversity of directions that an attack can be performed during the *jiyu waza.* In addition, further investigations could include other variables, such as the defender's reaction time to different types of attacks, as well as the attackers' movement velocities in relation to the formation of the triangle and the changes of direction of both defender and the attackers. Although more research is needed to consolidate the knowledge produced in this study, it can be speculated that aikido *senseis* could instruct their students to pay more attention to interpersonal coordination and strategic positioning, aiming for efficiency in situations where they are attacked by multiple people simultaneously. Moreover, the methodology used in this study, which employed the calculation of the Gauss area, could have potential for adaptation in behavioural investigations in other combat sports/martial arts that incorporate elements of *jiyu waza*, as well as in the components of other martial arts and team sports in which the triangulations between players play a crucial role in tactical effectiveness by involving positioning and coordinated movement of several fighters/players, creating geometric formations that facilitate ball circulation and breaking through the opponent's defensive lines (Yokoyama & Yamamoto, 2011; Yokoyama et al., 2020). The approach based on the shoelace formula, by not depending on the specific geometry of the triangles formed, offers a robust and flexible tool for analyzing interactions in various configurations and contexts, expanding the understanding of strategies and interpersonal dynamics in competitive environments. Thus, future research could benefit from this approach, exploring the complexities of interactions in multiple sports and combat scenarios.

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