Determining Partnering Effects in the "Rise and Fall" Motion of Competitive Waltz by the Use of Statistical Parametric Mapping

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ABSTRACT

Background. Competitive dance, also known as "DanceSport," is a competitive style of ballroom dance. The waltz features a particular movement in which the dancer lifts and lowers his/her body while dancing. In ballroom dance terms, this movement is known as the "rise and fall." The purpose of this research was to examine partnering effects in relation to the vertical component of dancers' center of mass when performing the competitive waltz.

Methods. This investigation was conducted through statistical parametric mapping of the movements of 13 national level competitive dance couples and a world champion couple as they danced both solo and in pairs. The Xsens MVN system was used to record their movements, using a capture rate of 240 Hz.

Results. We consequently found that, in the pair condition, the vertical component of the center of mass was smaller for the male dancers and larger for the champion male dancer when compared to their respective solo conditions. However, for the female dancers and the champion female dancer, unlike the males, no significant partner effects were found.

Conclusion. Therefore, in terms of partner effects, the "rise and fall" motion was smaller for the male dancers and larger for the champion male dancer.

Keywords: DanceSport, ballroom, kinematics, partnering, statistical parametric mapping.

INTRODUCTION

Competitive dance, also known as "DanceSport," is a competitive form of ballroom dance, and features Latin-American and ballroom dance divisions. Each division comprises five dances. In ballroom, the waltz, tango, Viennese waltz, slow foxtrot, and quickstep are danced by couples using the closed-hold position (Vaczi et al., 2016). This position causes many forces to act on the bodies of the male and female dancers. For instance, in the waltz, one of the most popular competitive dances in the world, a turning movement occurs on the second of each three beats. A characteristic movement in

the waltz is lifting and lowering the body across each three beats. In ballroom dance terms, this movement is called the "rise and fall." Notably, the "rise and fall" has not yet been investigated through biomechanical analysis.

A previous study conducted by the present authors (Yoshida et al., 2020) focused on partnering skill, which is one of the main judging components in competitive dance (Premelč, Vučković, James, & Leskošek, 2019; WDSF, 2015). In the course of this research, we investigated partnering effects in the waltz through analysis of a world champion dance couple and national level competitive dance

couples. The study revealed that, for the champion dance couple, their step lengths and ranges of joint motion were greater when they danced as a pair than when they danced solo. However, the parameters of this previous investigation were limited to step lengths and joint motion ranges. The "rise and fall" movement, which continuously changes over time, has not yet been investigated. In the ballroom dance textbook (WDSF, 2013), there is no clear description of which part of the body segment the "rise and fall" movement refers to. Therefore, for the present study, the variable was assumed to be the vertical component of the center of mass of the whole body.

In recent years, the use of the continuous statistical analysis method called statistical parametric mapping (SPM), which was originally developed for neuroimaging assessments, has become common in biomechanical analysis (Eerdekens, Deschamps, & Staes, 2019; Nüesch, Roos, Egloff, Pagenstert, & Mündermann, 2019; Pataky, 2010; Sole, Pataky, Tengman, & Häger, 2017). This method allows comparisons of subjects or groups during movements, and the clear determination of movement elements that statistically differ. Prior to the present study, only one point, changes in data over time, was mainly extracted and statistically processed. Therefore, a lot of data have been overlooked. However, SPM can analyze all data produced in a trial. When SPM is adapted to biomechanical analysis of movement in the waltz, it is likely that the manner by which the vertical component of the waltz movement differs as a result of partnering effects will become statistically clear.

The purpose of this research is to examine, using SPM, partnering effects on the movement of the vertical component of dancers' center of mass as they perform the competitive waltz. This is conducted by examining a group of national level competitive dance couples and a world champion couple. We hypothesize that SPM is capable of extracting changes caused by such partnering effects.

METHODS

The methods used in the current research have been described in our previous study (Yoshida et al., 2020).

Participants. Table 1 shows the participants' characteristics in relation to age, height, body mass, and experience dancing with their partner. Thirteen national level competitive ballroom dance couples participated, all were certified as grade A or B by national dance organizations. Seven couples were finalists or semifinalists in the standard division of The Imperial Highness Prince Mikasa Cup, which is regarded as the most prestigious amateur competition in Japan. Additionally, a world champion couple participated to represent distinctively skilled dancers. This couple has held the world championship for the past 10 years. All participants were free of injury, and wore their own, comfortable, dance shoes. This study was approved by the Committee for Ergonomic Experiments, National Institute of Advanced Industrial Science and Technology (No. 2018-0823), Tokyo, Japan, and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants prior to testing.

Experimental setup. An inertial measurement units (IMUs) system (MVN; Xsens, Netherlands) (Blair, Duthie, Robertson, Hopkins, & Ball, 2018; Jurkojć, Michnik, & Czapla, 2017) was used to obtain three-dimensional kinematic data. A capture rate of 240 Hz was applied. Both the male and female dancers, by donning specialized Lycra suits, wore 17 IMUs each. These were placed on the feet, shanks, thighs, pelvis, sternum, head, upper arms, forearms and hands. To build the Xsens biomechanical model, anthropometric measurements were collected from each participant. Model calibration was performed by asking the participants to make walking movements while assuming an upright posture (N-pose). For the trials, the slow waltz song "Without You" (28 bars per minute), from the dance

Table 1. **Mean and standard deviations for participants' age, physical attributes, and experience dancing with their partners** Parameters	Male Dancers (*n* = 13)	Female Dancers (*n* = 13)	Champion Male Dancer (*n* = 1)	Champion Female Dancer (*n* = 1)
Age (years)	24.3 ± 5.6	22.6 ± 4.7	40	40
Height (cm)	173.4 ± 6.3	161.2 ± 6.1	183	169
Mass (kg)	61.1 ± 4.9	47.6 ± 5.0	76	52
Couple Experience (years)	4.4 ± 4.1		11	

| CL | SS | FS | PRE | Start |

Figure 1. **Descriptions of the male and female waltz movements, respectively**

Notes. PRE – preparation step; FS – first step; SS – second step; CL – closing legs.

music album "Ballroom Symphony" (Casa Musica, Germany), was used.

Protocol. There were two conditions, solo and pair. Each couple was examined separately. First, the male danced solo. Next, the female danced solo. Then, they danced together in the closed-hold position. This trial set was repeated 4–5 times. The waltz movements performed in each trial were as follows (numbers in parentheses represent beats):

1. Preparation (123123).
2. Natural spin turn (123123).
3. Second half of reverse turn (123).

Data Processing. Analyses of lower limb kinematics and the centers of mass of the dancers' from the preparation step to the end of the first half of the natural spin turn were retained for further analysis. The waltz movement was divided into four phases based on step length, "preparation step" (PRE), "first step" (FS), "second step" (SS), and "closing legs" (CL; Figure 1). Step length was defined as the distance between the right and left ankles on a horizontal plane. In addition, the duration of each phase during each trial was calculated.

For the male dancers, PRE began with the minimum step length during the preparation movement and ended when the left heel contacted the ground with a maximum step length. Next, FS began from the end of PRE and continued until the right heel contacted the ground with a maximum step length. Then, SS began from the end of FS and continued until the left toe contacted the ground with a maximum step length. In the SS phase, the male dancer changes the couple's direction on the dance floor from forwards to an approximately 90-degree clockwise direction. This rotation is performed using the right leg. Lastly, CL began

from the end of SS and ended when the dancer made a minimum step length. As male and female dancers moved while facing each other and in closed-hold position, the right and left sides were reversed for female dancers.

The vertical component of the centers of mass of the dancers' whole bodies, normalized by their respective leg lengths, was calculated during the waltz movement. The time was normalized into percent. For the champion male and champion female dancers, the data for five trials were used. For the 13 male and female dancers, the average values for each participant were used. A paired t-test was used to assess the differences in the durations of each phase between the solo and pair conditions. Statistical analysis was conducted using R software (ver. 3.6.0; The R Foundation). SPM was analyzed by using open source code for Python. A paired t-test was used to assess between the solo and pair conditions. Furthermore, a one sample t-test was used to compare the champion dancers and the 13 dancers in terms of respective solo and pair conditions. Statistical significance was set at $p < .05$.

RESULTS

Duration of movement. Table 2 shows the durations of movements of the male dancers and the champion male dancer, respectively, in both the solo and pair conditions. For the male dancers, the duration of the CL in both actual time and normalized time was significantly shorter in the pair condition than in the solo condition ($p = .039$, $p = .024$, respectively). For the champion male dancer, the duration of the SS in actual time was significantly greater in the pair condition than in the solo condition ($p = .046$).

Table 2. **Actual and normalized durations for the preparation, first step, second step, and closing legs phases of the male dancers' and champion male dancer's waltz performances (solo and pair conditions)**

Duration	Male Dancers (*n* = 13)			Champion Male Dancer (*n* = 1)		
	Solo Mean ± *SD*	Pair Mean ± SD	*p*	Solo Mean ± *SD*	Pair Mean ± SD	*p*
Total (s)	2.74 ± 0.19	2.73 ± 0.18	.847	2.61 ± 0.12	2.65 ± 0.05	.489
PS (s)	0.68 ± 0.12	0.69 ± 0.17	.826	0.60 ± 0.06	0.58 ± 0.04	.417
FS (s)	0.69 ± 0.03 0.69 ± 0.04		.731	0.75 ± 0.02	0.77 ± 0.01	.104
SS (s)	0.67 ± 0.03	0.68 ± 0.03	.365	0.68 ± 0.01	0.74 ± 0.03	.046
CL (s)	0.70 ± 0.08	0.67 ± 0.06	.039	0.58 ± 0.08	0.56 ± 0.05	.639
PS (%)	24.39 ± 2.87	24.79 ± 4.72	.719	22.93 ± 1.29	21.75 ± 1.36	.152
FS (%)	25.29 ± 1.82	25.49 ± 1.96	.637	28.68 ± 1.63	29.20 ± 0.46	.457
SS (%)	24.68 ± 1.45	25.15 ± 1.70	.339	26.16 ± 1.54	27.86 ± 1.72	.180
CL (%)	25.64 ± 2.30	24.57 ± 2.71	.024	22.23 ± 2.22	21.18 ± 1.58	.451

Notes. PRE – preparation step; FS – first step; SS – second step; CL – closing legs; *SD* – standard deviation.

Table 3. **Actual and normalized durations for the preparation, first step, second step, and closing legs phases of the female dancers' and champion female dancer's waltz performances (solo and pair conditions)**

Duration	Female Dancers (*n* = 13)			Champion Female Dancer (*n* = 1)		
	Solo Mean ± *SD*	Pair Mean ± SD	*p*	Solo Mean ± *SD*	Pair Mean ± *SD*	p
Total (s)	2.72 ± 0.15	2.77 ± 0.13	.264	2.70 ± 0.10	2.99 ± 0.17	.022
PS (s)	0.71 ± 0.08	0.75 ± 0.11	.291	0.55 ± 0.06	0.91 ± 0.18	.018
FS (s)	0.60 ± 0.05	0.58 ± 0.06	.025	0.66 ± 0.02	0.67 ± 0.02	.378
SS (s)	0.66 ± 0.04	0.71 ± 0.04	.003	0.65 ± 0.04	0.79 ± 0.03	.001
CL (s)	0.74 ± 0.07	0.72 ± 0.06	.526	0.84 ± 0.10	0.63 ± 0.02	.009
PS (%)	26.17 ± 2.35	26.99 ± 2.82	.393	20.30 ± 1.74	30.14 ± 4.48	.018
FS (%)	22.23 ± 1.55	21.10 ± 1.81	.021	24.40 ± 1.38	22.34 ± 1.28	.055
SS (%)	24.39 ± 1.38	25.69 ± 0.83	< .001	24.25 ± 1.88	26.45 ± 2.37	.013
CL (%)	27.21 ± 2.13	26.22 ± 3.00	.357	31.05 ± 2.96	21.07 ± 0.98	.005

Notes. PRE – preparation step; FS – first step; SS – second step; CLL – closing legs; *SD* – standard deviation.

Table 3 shows the durations of movements of the female dancers and the champion female dancer, respectively, in both the solo and pair conditions. For the female dancers, the duration of FS in actual time and normalized time was significantly shorter in the pair condition than in the solo condition ($p = .025$, $p = .021$, respectively). Meanwhile, the duration of SS in actual time and normalized time was significantly greater in the pair condition than in the solo condition ($p = .003$, $p < .001$, respectively). For the champion female dancer, the total time was significantly greater in the pair condition than in the solo condition ($p = .022$). The duration of PRE in actual time and normalized time was greater in the pair condition than in the solo condition ($p = .018$, $p = .018$, respectively). Similarly, the duration of SS in actual time and normalized time was greater in the pair condition than in the solo condition

($p = .001$, $p = .013$, respectively). Finally, the duration of CL in actual time and normalized time was shorter in the pair condition than in the solo condition ($p = .009$, $p = .005$, respectively).

SPM. The paired *t*-test in SPM revealed, for the champion male dancer, a significant difference between the solo and pair conditions from approximately 0 to 50% in the normalized time period ($p < .001$, Figure 2 (a)). In this section, the vertical component was lower in the pair condition than in the solo condition. Meanwhile, for the male dancers, significant differences were found between the solo and pair conditions at approximately 50% and at approximately 80% in the normalized time period ($p < .001$, $p < .001$, respectively, Figure 2 (b)). At approximately 50%, the vertical component in the pair condition was higher than that in the solo condition. At approximately 80%, the vertical

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component in the pair condition was lower than that in the solo condition. The one-sample *t*-test found significant differences between the champion male dancer and the male dancers in the solo condition at approximately 30% and at approximately 100% in the normalized time period ($p = .042$, $p = .046$, respectively, Figure 2 (c)). At approximately 30%, the vertical component of the champion male dancer was higher than that of the male dancers. At approximately 100%, the vertical component of the champion male dancer was lower than that of the male dancers.

Significant differences were found between the champion male dancer and the male dancers in relation to the pair condition at approximately 50% in the normalized time period ($p = .037$, Figure 2 (d)). In this section, the vertical component of the champion male dancer was lower than that of the male dancers.

For the champion female dancer, the paired *t*-test did not reveal any significant differences between the solo and the pair conditions (Figure 3 (a)). Nevertheless, the vertical component during the first half of the pair condition tended to be lower when compared to the same period in the solo condition. Meanwhile, for the female dancers, no significant differences were found between the solo and pair conditions (Figure 3 (b)). At approximately 50% in the normalized time period, the vertical component in the pair condition tended to be higher than that in the solo condition. The one-sample *t*-test found, for the solo condition, significant differences between the champion female dancer and the female dancers at approximately 0–40% and at approximately 90%
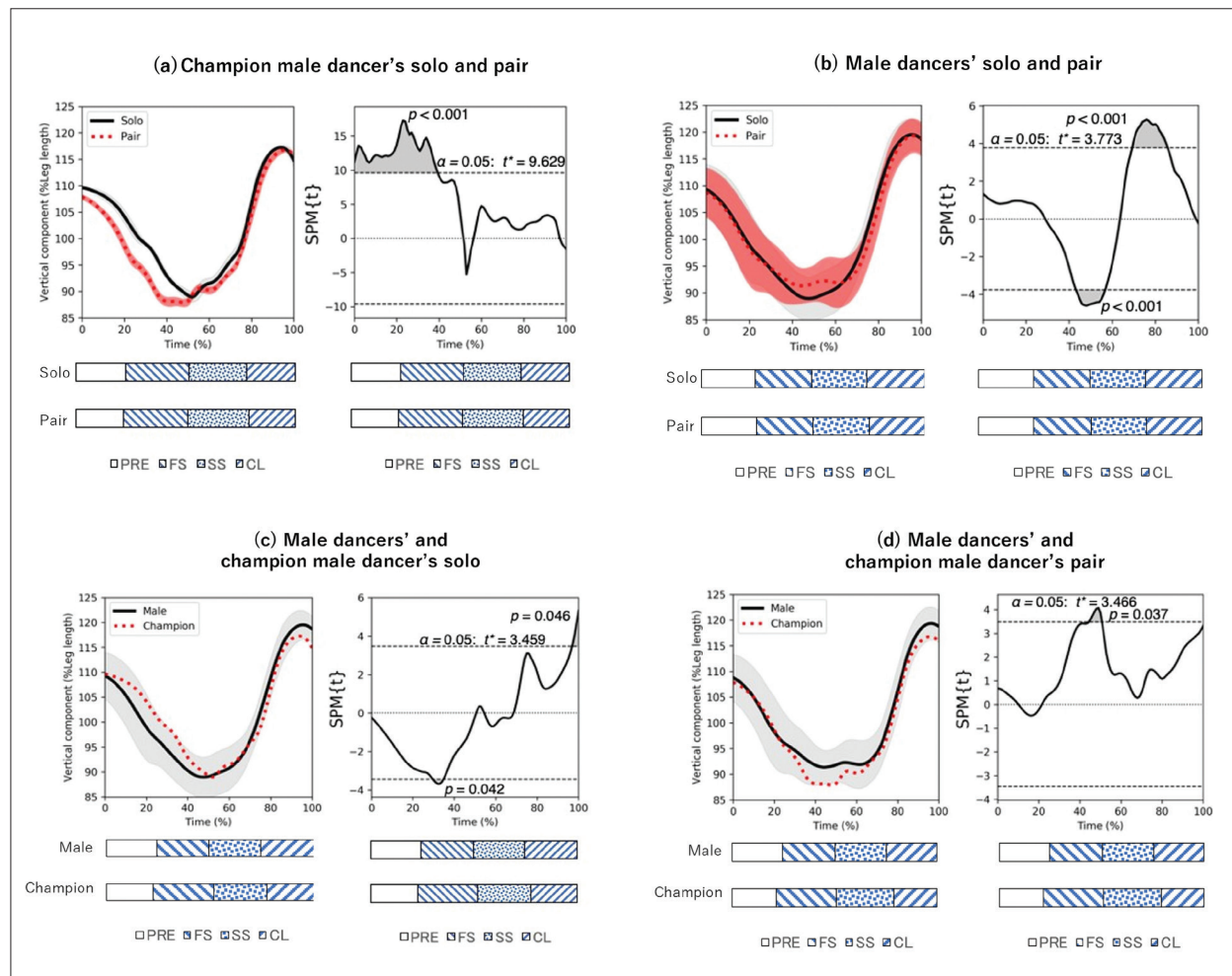

Figure 2. **(a) Comparison of the champion male dancer's solo and pair performances; (b) Comparison of the male dancers' solo and pair performances; (c) Comparison of the male dancers' and the champion male dancer's solo performances; (d) Comparison of the male dancers' and the champion male dancer's pair performances**

Notes. PRE – preparation step; FS – first step; SS – second step; CL – closing legs. The left graphs for a–d show change over time in mean vertical component (and standard deviation clouds) of the vertical component of the dancers' center of mass during the waltz. The right graphs display SPM *t*-test results. Horizontal dotted lines represent the threshold for statistical significance (*t**) and the corresponding *p*-values. The gray-shaded areas indicate time points that show statistically significant differences. Below each graph, the relative duration of each phase is shown.
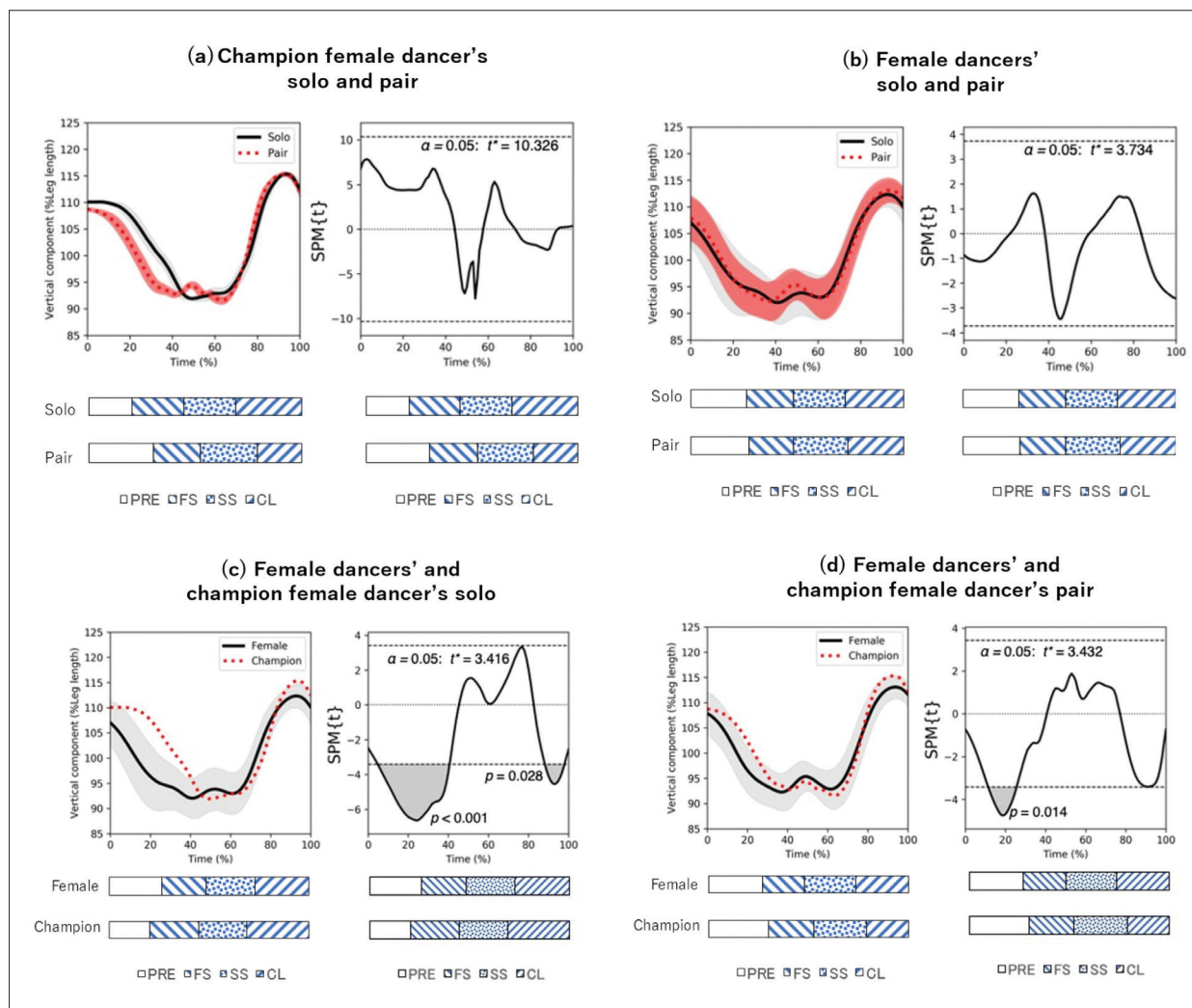
Figure 3. (a) **Comparison of the champion female dancer's solo and pair performances; (b) Comparison of the female dancers' solo and pair performances; (c) Comparison of the female dancers' and the champion female dancer's solo performances; (d) Comparison of the female dancers' and the champion female dancer's pair performances**

Notes. PRE – preparation step; FS – first step; SS – second step; CL – closing legs. The left graphs for a–d show change over time in mean vertical component (and standard deviation clouds) of the vertical component of the dancers' center of mass during the waltz. The right graphs display SPM *t*-test results. Horizontal dotted lines represent the threshold for statistical significance (t^*) and the corresponding *p*-values. The grey-shaded areas indicate any time points that show statistically significant differences. Below each graph, the relative duration of each phase is shown.

in the normalized time period ($p < .001$, $p = .028$, Figure 3 (c)) Additionally, significant differences were found between the champion female dancer and the female dancers for the pair condition at approximately 20% in the normalized time period ($p = .014$, Figure 3 (d)).

DISCUSSION

The SPM results regarding the time-series change in the vertical component of dancers' centers of mass when waltzing clearly show the features of the waltz. These results revealed that, during the waltz movement, the center of mass descends during the first half, corresponding to the PRE and FS phases, and ascends in the second half, corresponding to the SS and CL phases.

It has previously been highlighted that the number of studies on the biomechanics of ballroom dance remains small (McCabe, Wyon, Ambegaonkar, & Redding, 2013). A possible reason for this is a tendency to attempt to use an optical motion capture system rather than an IMUs type motion capture system (Picerno, 2017). Using an optical motion capture system can cause difficulties in such research because, when the closed-hold position is adopted in the pair condition, the reflective marker attached to the body cannot be

seen and tracked by the optical system. On the other hand, when using an IMUs type system, the proximity and/or obscuring of the male and female dancers' bodies does not impact measurement. The present study shows that the IMUs system is suitable for successfully measuring and quantifying the "rise and fall" motion, which is a fundamental concept in competitive waltz.

Our analysis clearly showed the different strategies applied by the champion male dancer in the solo condition when compared to the pair condition. Compared to the solo condition, the champion male dancer's center of mass in the pair condition had a lower initial position, descended earlier, and reached a lower point. On the other hand, during the second half of the trial there was no significant difference between the two conditions regarding movements. Thus, the champion male dancer's strategy was to change only the movement in the first half, and consequently enlarge the vertical movement of the center of mass. On the other hand, the male dancers showed different results than the champion male dancer. Unlike the champion male dancer, the lowest point of the male dancers' position in the pair condition was significantly higher than that in the solo condition. Then, in the final stage the vertical component was significantly lower in the pair condition when compared to the solo condition. Thus, in the pair condition the vertical movement of the center of mass lessened. This is a crucial difference when compared to the movement of the champion male dancer.

The results of this study could be partly explained by combining them with the results of our previous research (Yoshida et al., 2020). The champion male dancer's step length in PRE was larger in the pair condition. Furthermore, the lower initial position of his center of mass in the pair condition may have made it possible to make a faster descent in the first half of the trial. For the male dancers, the step length during FS was significantly shorter in the pair condition, and the range of motion of the left hip joint and knee joint during FS was significantly narrowed. The fact that the lowest point of the male dancers' center of mass was higher in the pair condition may be related to these results.

The characteristics of the "rise and fall" performed by the champion male dancer can be further clarified by comparing his movements with those of the male dancers. In particular, in the pair condition the vertical component of the champion male dancer's center of mass reached a lower position than did that of the male dancers. In the second half of the trial, it was necessary to ascend while keeping both toes in contact with the floor, so there was a physical limit to how high the dancers could reach during this phase. In contrast, during the first half of the trial greater control of the lower limb joints can allow the center of mass to reach a lower position. The data indicate that the champion male dancer had sufficient skill and control to reach lower positions in the pair condition. These findings are notable and contribute to the literature. A previous study fixed a camera on the ceiling of a hall and analyzed the trajectory of a couple's movement during the waltz using a tracking algorithm (Zaletel, Vučković, James, Rebula, & Zagorc, 2010). In that study, the male and female movements were not measured separately, nor was the vertical movement of their centers of mass measured. Thus, our analysis can supplement and bridge gaps in existing ballroom dance related research.

Unlike the male dancers and the champion male dancer, the SPM data for the female dancers and the champion female dancer did not reveal any significant differences between the solo and pair conditions. Similar to the champion male dancer, the champion female dancer had a tendency to adopt a lower initial position in regard to her center of mass in the pair condition, and descended faster in the pair condition when compared to the solo condition. One reason for this is that, for the champion female dancer, the proportion of the total time represented by the PRE stage was longer in the pair condition. In addition, according to our previous research (Yoshida et al., 2020), the champion female dancer's step length during PRE was longer in the pair condition. As found for the male dancers, the lowest point of the vertical component of the female dancers' centers of mass was higher in the pair condition when compared to the solo condition. For both the female dancers and the champion female dancer, SPM did not detect any significant partner effects regarding of the vertical component, but they showed the same general movement tendencies as the male dancers and the champion male dancer, respectively.

Even through comparison with the female dancers, the strategy applied by the female champion dancer during the pair condition could

not be clearly discerned. The vertical component of her center of mass descended later than did that of the female dancers in both conditions. Differing from the champion male dancer, the lowest point of her vertical component was not significantly different from that of the female dancers. The cause cannot be clarified using the data obtained in this study. It is possible that the difference in roles, because the male moves forwards and the female moves backwards, and physiological characteristics have an impact in this regard (Liiv et al., 2014).

This study has some limitations. First, it was not possible to analyze the male and female dancers concurrently. This is because, in the IMUs motion capture system, each person has an independent global coordinate system. This problem could be solved by combining the optical measurement approach and the IMUs measurement approach. A suitable motion capture system for sports applications should be selected (van der Kruk & Reijne, 2018). Moreover, the center of mass of the whole body was considered, but the kinematics of the lower limbs were not analyzed. In future, it will be necessary to further analyze the first half of the waltz movement through consideration of lower limb kinematics. Despite the above limitations, no previous biomechanics-related studies have focused on the "rise and fall." In other words,

no researchers have previously quantitatively considered the "rise and fall" movement, meaning this study is the first to successfully perform such quantification.

CONCLUSIONS

SPM analysis of dancers' movements during the waltz indicated that, when dancing in pairs, the lowest position of the vertical component of the male dancers' center of mass was higher, and the highest position was lower, when compared to solo dancing. On the other hand, for the champion male dancer, the lowest position of the vertical component of his center of mass was lower when dancing in a pair. Therefore, in terms of partner effects, the vertical movement was smaller for the male dancers and larger for the champion male dancer. In the case of the female dancers and the champion female dancer, unlike the males, no significant partner effects were found, but the tendencies of their movements were similar to that of the males.

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