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The effect of three run-up techniques on kinetic and kinematic variables of the stag ring leap with throw-catch of the ball in rhythmic gymnastics

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Purpose: The aim of this study was to compare the effect of three run-up steps on the kinetic and kinematic variables of the stag ring leap, with throw-catch of the ball, in high-level rhythmic female gymnasts. The three run-up steps used are a chassé step, glissade, and assemblé. *Methods*: Seven high-level rhythmic female gymnasts participated in this study. Three run-up steps (i.e., chassé step, glissade and assemblé) were used randomly to perform a stag ring leap with throwing a ball on the jump take-off. 2D kinetic and kinematic analysis was conducted. *Results*: The results indicated that the assemblé step used in the run-up technique generated greater values of the rate of force development, the highest values of vertical velocity, and the best vertical displacement. In addition, the assemblé step allows for the best opening angle of the split leap and the best closest angle of the ring leg. The same was noted for the front leg's angular velocity. *Conclusion*: We concluded that the assemblé step used in the run-up technique appears to favor a greater stag ring leap that meets the Code of Points' condition for admitting the jump, as well as numerous studies that focus on improving jumping abilities in rhythmic gymnastics.

Key words: *motion analysis, run-up, leaps, take-off, apparatus, rhythmic gymnastics*

1. Introduction

In 1984 in Los Angeles, California, the admission of rhythmic gymnastics (RG) to the Olympic Games (OG) was granted [29]. It was born of a mixture of gymnastics, artistic expression, ballet, dance, and aesthetic aspects [16], [39], conducted by a code of points (COP) made by the International Gymnastic Federation (FIG) and updated after each Olympic cycle [38].

RG is a full discipline that combines grace, rhythm and talent, requiring a variety of skills, including force, balance, flexibility, endurance, and coordination [7], [13], [20].

It is an excellent sport with accompanying fascinating music suggesting a method and a specific coordination with the body when handling apparatus: hoop, ball, clubs, ribbon and rope [7], [13], [38], wherein the gymnast must develop a chain of Body Difficulty (BD) (leaps/jumps; balances and rotations), dance steps combination (S), dynamic elements with rotation (R), and apparatus difficulty [3], [8], [11], [18], while demonstrating his technique, keeping the timing of her motions, and satisfying the jury's aesthetic standards.

RG is a very demanding sport that requires you to have the ideal body weight, in which the gymnast mustn't only follow a well-balanced diet, but they must improve their psychophysical health [28] in order to achieve the life of high-level athletes, hence the need to start it at a very young age [14] compared to other sports.

The level of technical expertise as well as the motor and physical performance of the gymnast are all

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directly related to the quality of execution in RG. This is also true for the coordination of the body and the handling of the apparatus [6], [9], [11], [38]. This execution quality is evaluated by body difficulties, which are recognized by the FIG COP and divided into three groups: leaps/jumps, balances and rotations, with the group of jumps classified as fundamental gymnast motions among them [6].

The leaping degree is one of the most difficult and extensively studied rhythmic gymnastics skills. This is because it has to do with a very flexible activity that depends on diverse key skills like muscular strength, explosive force, body composition, muscular speed, flexibility and motor coordination [9], [35] in order to adhere to a few fundamental standards set forward by international gymnastics federation: defined and fixed shape while in flight, as well as sufficient height (i.e., elevation) during jumps or leaps to reveal the appropriate shape [18]. As a result, if these criteria are not met, the jump will not be considered acceptable and will receive an execution penalty [3], [31].

The preparatory phase, take-off, flight and landing are the four main phases of a leap in rhythmic gymnastics. To perform the take-off perfectly and have a great flight phase (jump), the gymnast must choose the best run-up step during the preparatory phase. This step is crucial in terms of forward and upward direction [34]; as long as it complies with the rules, it can be done with one foot or two feet [18].

The "stag ring leap" is one of the jumps provided by the international federation that can be accomplished with either method of take-off, in accordance with the rules established by the FIG COP, choosing the optimal technique results in a better realization of the element. In addition, leaps in rhythmic gymnastics must combine at least one technical element of an apparatus, either fundamental or non-fundamental [18].

In order to compare and analyze the kinematics and kinetics variables, particularly the force, flexibility and velocity that were developed during the three stag ring leaps (Fig. 1), this study also threw the ball during each jump. Three preparatory phase approaches were used for the jumps, two of which were for one leg take-off and one for two leg take-offs. The chassé throw ball stag ring leap (CS), glissade throw ball stag ring leap (GS) and assemblé throw ball stag ring leap (AS) were the three techniques. As far as we know, rhythmic gymnastics has never looked at these.

According to the COP [18], its use does not impose the technique used during the preparatory phase on condition that it could create a single and clearly visible image of a fixed and well-defined shape during the flight rather than two different images and shapes [18].

Fig. 1. Stag ring leap

It was hypothesized that using a run-up step with both legs take-off (i.e., assemblé) is more efficient than using one leg take-off (i.e., such as a glissade or chassé step). We also predicted that employing the assemblé in the preparatory phase may improve jumping mechanical factors and the range of motion.

However, this study aimed to compare the kinetic and kinematic parameters of stag ring leap following three different technical of takes offs, performed during the preparatory phase in high-level female gymnasts. More precisely, we proposed to identify which of the three takes offs techniques during the preparatory phase results in a more efficient and defined shape jump with a minimum execution fault.

The results of this study may be used to optimize the take-off processes while also developing the preparatory phase for achieving excellent jumps in execution and aesthetics.

2. Materials and methods

Participants

A priori power analysis with type I error of 0.05 and 80% statistical power was computed using G*Power software (Version 3.1, University of Dusseldorf, Germany [17]). The analysis indicated that a minimum of 7 participants is sufficient to observe a significant, large effect size (f = 40) for kinetic (i.e., vertical ground reaction force) and kinematic variables (i.e., joint angles and velocity) [4], [5].

In order to conduct this study, seven senior national team rhythmic gymnasts from Tunisia (age of 18.71 ± 2.69 years; height of 1.67 ± 0.04 m; weight of 58.43 ± 4.03 kg; body mass index of 20.78 ± 1.43 kg/m^2; training average 20 ± 2 h/week; experience 10.57 ± 1.84 years of practice) volunteered. The participants had no neurological, muscle nor tendon injuries and were in good condition. Each participant agreed to participate in the study by signing a permission form after being fully told about the procedures, methods, various benefits, and potential risks of the study in advance. The trial was conducted in conformity with the Declaration of Helsinki and was approved by the Ethical Committee of the National Centre of Medicine and Science in Sport (LR09SEP01).

Experimental design and procedures

The experimental procedure began with each gymnast doing a 10-min warm-up that included trunk and lower-limb stretches. Following this, they were permitted to test the leaps three times (with a 2-min break in between repeats) in order to receive their marks on the force-plate. It is a double method called "kinetic and kinematic", and it is done across three days from 14:00 to 16:00. Through the time code "TC-Link", video acquisition is synced with the force--plate. Following that, each gymnast was instructed to do three-stag ring leaps with a throw-catch of the ball.

Following that, each gymnast was randomly selected to do three-stag ring leap execution modes with throw-catch of the ball while employing the chassé, glissade, and assemblé for takeoff chassé step consists of throwing the ball on the stag ring leap and catching it on the landing phase (CS) (Fig. 2a): the gymnast standing up, torso straight, feet firmly planted on the half-point, holding a ball in her hand she takes a chassé step while swinging her arms backwards to throw the ball during the stag ring leap with arm straight and captures it in reception without committing any technical mistakes.

Glissade consists if throwing the ball on the stag ring leap and catching it in the landing phase (GS) (Fig. 2b): the gymnast standing up, clutching a ball in her hand, with therir body straight and feet firmly planted on the half-point. They should utilize the glissade in the second technique as a run-up step for take-

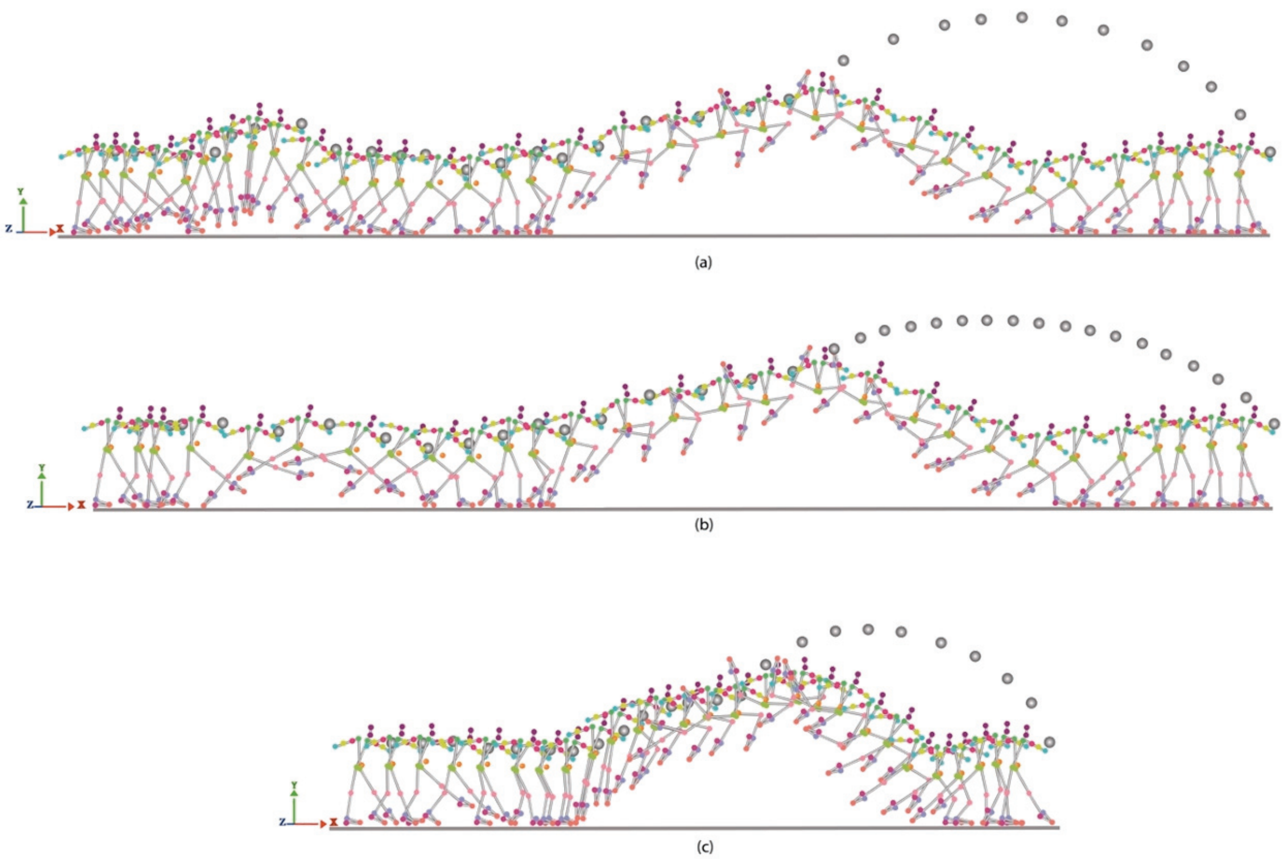

Fig. 2. Experimental protocol: (a) chassé step throw ball on the stag ring leap and catch on the landing phase (CS), glissade step throw ball on the stag ring leap and catch on the landing phase (GS), (c) assemblé step throw ball on the ring leap and catch on the landing phase (AS)

offs while throwing the ball on the technical element and catching it at the end of the leap.

Assemblé consists of throwing the ball on the stag ring leap and catching it on the landing phase (AS) (Fig. 2c): in the final technique, the gymnast uses the assemblé as a run-up step for take-offs, throwing the ball in the technical element and catching it during the landing phase of the leap.

The jump leaps order was established using Latin Square's randomized protocol [43]. There was a 2-minute interval in between each repetition of the jump leap, which was performed three times. Two international judges choose the best performance from each participant to use in the comparative study. A jump was considered valid when the hip joint was almost stretched to 180° [36].

We included a uniaxial force-plate (i.e., vertical axis) [Kistler Quattro Jump, type: 9290AD, ref. 2822A11, sampling frequency 500 Hz, Kistler Group, Winterthur, Switzerland] in the experiment, which was conducted on a gymnastics carpet. In the kinetic investigation, the vertical ground reaction force (GRF), the rate of force development (RFD) and the time to reach the max GRF (TMF) were assessed. The video analysis was recorded in twodimensions with two mini-DV cameras, Sony DCR PC105[E] [1-megapixel CCD, 50 fps, 1 Lux minimum sensitivity] with wide conversion lens. The video analysis was computed in two-dimensions (2D). The first camera was positioned 5 m from the mat, while the second was 3 m away from the gymnast's side axis of advancement, in order to record the complete exercise. Twenty reflective markers were affixed to every participant using the Hanavan model modified by Deleva [12] and digitized (i.e., semi-automatic digitalization) using the video-based data analysis system SkillSpector® (Version 1.3.2, Odense S – Denmark [10]) with quantic-spline data filtering. Linear and angular kinematic data of digitized points and of the center of mass (COM) were used in the study. A full frame, uncompressed video capture was made using the FireWire interface (iLink/IEEE 1394). The construction of key positions and 2D kinograms was developed by Adobe Illustrator© [Adobe 1987–2019].

Statistical analysis

The data analysis was done using the SPSS 20 package (SPSS, Chicago, IL, USA) software as part of the statistical analysis. For all variables, descriptive statistics (i.e., means SD) was conducted. The interpretation of the effect size (*d*) was accomplished using the following scale: <0.2, (trivial); 0.2–0.6, (small); 0.6–1.2, (moderate); 1.2–2.0, (large); and >2.0, (very large) [23]. For all variables, the Shapiro–Wilk test's estimate of the distribution's normality was acceptable ($p > 0.05$). Therefore, to compare various stag-leaps, repeated measures ANOVA were applied. A pairwise comparison was conducted using the Bonferroni post-hoc test. Additionally, the relative and absolute reliability of stag ring leap modes (i.e., CS, GS and AS) were examined using the intra-class correlation coefficient (ICC) and the typical error of measurement (TEM) expressed as coefficient of variation (CV), respectively. The SWC was assumed by multiplying the between-subject SD by 0.2 ($SWC_{0.2}$) indicating the typical small effect [24]. The ability of the test to detect a change was rated as "good", "OK" or "marginal" when the TEM was below, similar or higher than $SWC_{0.2}$, respectively [24]. The minimal detectable change ($MDC_{95\%}$), which represents 95% CI of the difference in score between paired observations, was determined as $MDC_{95\%} = TEM \cdot 1.96 \cdot \sqrt{2}$ [42]. As a standard for significance, an a priori level of less than or equal to 0.5% ($p \leq 0.05$) was applied.

3. Results

The absolute and relative reliability of vertical ground reaction force (GRF) measured during the take-off of the stag ring leap across the three execution modes (i.e., CS, GS and AS) was very high (Table 1).

Results of repeated measures ANOVA showed a significant difference in the kinetic and kinematic variables recorded across the three stag ring leap modes (Table 2). A pairwise comparison between the three execution modes (i.e., CS, GS and AS) is presented in Table 3.

Kinetic variables

There is significant difference in the kinetic variables of stag ring leap ($p < 0.01$) (Table 2). The three techniques had varying impact on the vertical ground reaction force (GRF) the time at which the force is applied (i.e., rate of force development, RFD) and the time to reach the max GRF (TMF), according to pairwise comparison (i.e., the Bonferroni post-hoc test) (Table 3).

The ground reaction force (GRF) was considerably increased in GS technique with respect to the other techniques (i.e., by 83.77% CS vs. GS, with $p < 0.001$ and by 20.17% GS vs. AS with $p < 0.01$), the same was confirmed for AS, which is significantly better than the CS technique (i.e., by 46.69% CS vs. AS with $p < 0.01$), while the rate of force development (RFD) increased in both AS and GS compared to CS

Table 1. Statistical analysis of the absolute and relative reliability of vertical ground reaction force measured during the three stag ring leap modes

R_1 vs. R_2	Mean ± SD GRF [%BW]	T-test (p)	TEM	$TEM_{(\%)}$	$MDC_{(95\%)}$	$SWC_{(0.2)}$	ICC $_{(95\%\ CI)}$	d
CS	3.010 ± 0.279 2.988 ± 0.260	0.160	0.002	0.076	0.006	0.052	0.996 (0.974–0.999)	0.08
GS	5.519 ± 0.709 5.499 ± 0.688	0.290	0.001	0.026	0.004	0.134	0.999 (0.994–1.000)	0.03
AS	4.407 ± 0.764 4.384 ± 0.753	0.175	0.001	0.028	0.003	0.146	0.999 (0.995–1.000)	0.02

R_1 – first repetition, R_2 – second repetition, GRF – ground reaction force, TEM – typical error of measurement, MDC – minimal detectable change, SWC – smallest worthwhile change, ICC – intraclass correlation coefficient, d – effect size, CS – chassé and Stag ring leap, GS – glissade stag ring leap, AS – assemblé stag ring leap.

Table 2. ANOVA repeated measures of the three-stag ring leap execution modes

Variables		df	Mean square	F	Sig.	Effect size	Power
Kinetic	GRF [%BW)	2	11.076	55.651	0.000	6.102	1.000
	RFD [%BW/s)	2	0.707	34.363	0.000	4.779	1.000
	TMF [s)	2	0.007	12.103	0.001	2.843	0.978
Linear Kinematic	dx_{COM} [m]	2	0.285	28.768	0.002	4.372	0.993
	dy_{COM} [m]	2	0.003	5.832	0.052	1.972	0.526
	dx_{toe} [m]	2	0.123	7.708	0.032	2.265	0.641
	Vx_{COM} [m]	2	0.335	51.595	0.000	5.870	1.000
	Vy_{COM} [m]	2	0.982	47.654	0.000	5.631	1.000
Angular Kinematic	$AngS_{leg}$ [°]	2	1080.643	30.178	0.002	4.482	0.994
	$AngT/L_{left}$ [°]	2	644.643	29.334	0.002	4.419	0.993
	$VangK_{right}$ [°/s]	2	383882.694	31.293	0.001	4.565	0.996

GRF – ground reaction force, RFD – rate of force development, TMF – time to reach the max GRF, dx_{COM} – horizontal displacement of the centre of mass, dy_{COM} – vertical displacement of the centre of mass; dx_{toe} – horizontal displacement of the toe, Vx_{COM} – horizontal velocity of the centre of mass, Vy_{COM} – vertical velocity of the centre of mass; $AngS_{leg}$ – angle of split legs, $AngT/L_{left}$ – angle trunk left leg, $VangK_{right}$ – angular velocity of the right knee.

Table 3. Post-hoc comparative study between the three-stag ring leap execution modes

Variables			Mean ± SD		Mean diff.	Std. error	Sig.	Effect size
Kinetic	GRF [%BW]	CS vs. GS	2.988 ± 0.260	5.499 ± 0.688	–2.510	0.207	0.000	12.125
		CS vs. AS	2.988 ± 0.260	4.384 ± 0.753	–1.396	0.261	0.002	5.348
		GS vs. AS	5.499 ± 0.688	4.384 ± 0.753	1.114	0.243	0.004	4.584
	RFD [%BW/s]	CS vs. GS	1.320 ± 0.203	1.861 ± 0.315	–0.541	0.088	0.001	6.147
		CS vs. AS	1.320 ± 0.203	1.880 ± 0.201	–0.560	0.068	0.000	8.235
	TMF [s]	CS vs. GS	0.111 ± 0.031	0.137 ± 0.034	–0.026	0.004	0.000	6.499
		GS vs. AS	0.137 ± 0.034	0.090 ± 0.012	0.047	0.012	0.009	3.916
Linear Kinematic	dx_{COM} [m]	CS vs. AS	0.62 ± 0.07	0.34 ± 0.14	0.28	0.05	0.005	5.396
		GS vs. AS	0.60 ± 0.06	0.34 ± 0.14	0.26	0.06	0.026	3.826
	dy_{COM} [m]	GS vs. AS	0.299 ± 0.04	0.32 ± 0.04	–0.02	0.07	0.025	4.000
	dx_{toe} [m]	CS vs. AS	1.15 ± 0.24	0.559 ± 0.05	0.59	0.09	0.003	5.959
		GS vs. AS	1.01 ± 0.07	0.55 ± 0.05	0.45	0.03	0.000	14.774
	Vx_{COM} [m]	CS vs. AS	1.66 ± 0.18	1.37 ± 0.13	0.28	0.08	0.049	3.310
		GS vs. AS	1.79 ± 0.04	1.37 ± 0.13	0.41	0.04	0.000	9.581
	Vy_{COM} [m]	CS vs. GS	2.19 ± 0.14	1.97 ± 0.07	0.22	0.06	0.034	3.596
		CS vs. AS	2.19 ± 0.14	2.66 ± 0.24	–0.47	0.10	0.014	4.370
		GS vs. AS	1.97 ± 0.07	2.66 ± 0.24	–0.69	0.10	0.002	6.682

Table 3 continued

Angular Kinematic	$AngS_{leg}$ [°]	CS vs. AS	176.57 ± 11.26	194.142 ± 11.567	–17.57	3.19	0.005	5.492
		GS vs. AS	174.00 ± 6.13	194.142 ± 11.567	–20.14	4.04	0.007	4.980
	$AngT/L_{left}$ [°]	CS vs. AS	71.00 ± 5.56	57.42 ± 6.82	13.57	2.50	0.005	5.415
		GS vs. AS	69.42 ± 4.85	57.42 ± 6.82	12.00	2.52	0.009	4.750
	$VangK_{right}$ [°/s]	CS vs. AS	581.84 ± 35.22	913.02 ± 134.75	–331.18	59.20	0.004	5.593
		GS vs. AS	596.76 ± 45.65	913.02 ± 134.75	–316.25	49.82	0.002	6.347

GRF – ground reaction force, RFD – rate of force development, TMF – time to reach the max GRF, dx_{COM} – horizontal displacement of the centre of mass, dy_{COM} – vertical displacement of the centre of mass, dx_{toe} – horizontal displacement of the toe, Vx_{COM} – horizontal velocity of the centre of mass, Vy_{COM} – vertical velocity of the centre of mass, $AngS_{leg}$ – angle of split legs, $AngT/L_{left}$ – angle trunk left leg, $VangK_{right}$ – angular velocity of the right knee, CS – chassé and stag ring leap, GS – glissade stag ring leap, AS – assemblé stag ring leap.

($p < 0.01$), respectively, by 42.44% and by 40.34% (Fig. 3). In the same way, the time to reach the max GRF (TMF) is shortly in both AS and CS compared to GS ($p < 0.01$), respectively, by 52.38% and by 23.07%.

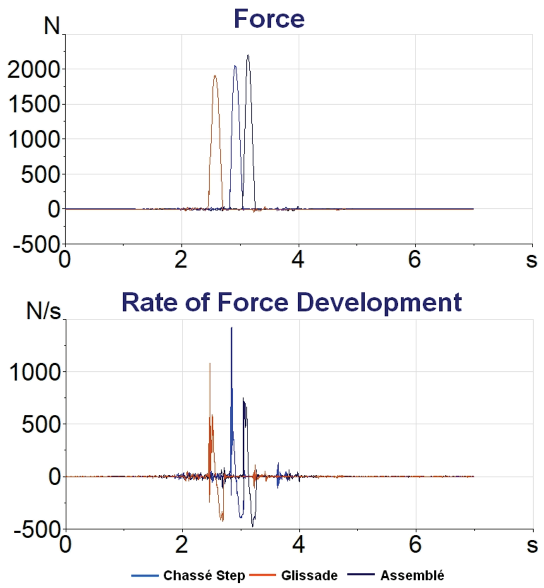

Fig. 3. Ground reaction force and rate of development force of the three run-up techniques

Linear kinematic variables

There is a significant statistical increase that was noticed in the horizontal displacement of the center of mass (dx_{COM}) in the CS (i.e., by 45.16% CSTBS vs. AS with $p < 0.01$ and by 43.33% GS vs. AS with $p < 0.05$). Likewise, the horizontal displacement toe (dx_{toe}) was increased by 51.30% in the CS technique compared to the AS technique ($p < 0.01$), and also, in the GS by 44.55% compared to the AS ($p < 0.01$).

In contrast, looking at the absolute data, the AS showed the highest level of vertical displacement of the center of mass (dy_{COM}) by 6.68% compared to the GS (0.32 ± 0.04 m and 0.29 ± 0.04, respectively).

Moreover, the horizontal component of velocity (Vx_{COM}) was increased in GS and CS with respect to AS technique (i.e., by 16.86% CS vs. AS with $p < 0.05$ and by 22.90% GS vs. AS with $p < 0.01$). In contrast to these findings, the AS developed more vertical velocity (Vy_{COM}) than the CS and the GS. It was increased by 20.54% compared to the CS ($p < 0.05$) and by 35.02% compared to the GS ($p < 0.01$). The same was observed for CS, which was increased by 10.04% compared to GS ($p < 0.05$).

Linear kinematic variables

The angle of split legs ($AngS_{leg}$) was better in AS with respect to the other techniques (i.e., by 9.95% CS vs. AS with $p < 0.01$ and by 11.57% AS vs. GS with $p < 0.01$).

The ANOVA repeated measures show that the trunk left leg angle ($AngT/L_{left}$) was increased in AS by 19.11% compared to CS ($p < 0.01$) and by 17.28% compared to GS ($p < 0.01$).

Lastly, the angular velocity of the right knee ($VangK_{rigth}$) was increased in AS with respect to the other techniques (i.e., by 56.91% CS vs. AS with $p < 0.01$) and by 52.99% GS vs. AS with $p < 0.01$).

4. Discussion

In order to accomplish a stag ring jump with a throw--catch of the ball, this study compared the kinetic and kinematic factors of three different run-up steps, two of which were for one leg take-off and one for two leg take-off. Although our gymnasts had performed the three different techniques throughout their careers, none could dispute the fact that they each favored one technique over the others. Further, each gymnast was given three chances to try each technique, with just the best effort being recorded for further analysis.

Based on the results, it is clear that various run-up step types significantly influence the kinetic data of the stag ring leap. When evaluating the kinetic study of the stag ring leap in rhythmic gymnastics, three important factors are taken into account: the vertical ground reaction force (GRF), the rate of force development (RFD) and the time to reach the max GRF (TMF).

Since the RFD is created using the force measured during explosive voluntary contraction [1], assembled with a better RFD, the assemblé technique can be considered as the more explosive as they can develop larger forces in a shorter period of time, which may improve their overall athletic performance.

According to Laffaye and Wagner [30], a higher RFD has been linked to a better jump. Furthermore, Rodríguez-Rosell et al. [37] suggested that having a greater RFD is important for being able to move quickly and forcefully.

The vertical GRF was significantly higher in GS than in AS and CS ($p < 0.01$), and the Fy in AS was more important than in CS.

Compared to the variation of the RFD, the force variation during the stag ring leap was different, wherein the glissade's RFD was lower than the assemblé's RFD. According to Jensen [27], a slower RFD would mean the individual must take more time to peak and to complete the acceleration phase of the movement. Indeed, TMF follow the same kinetics, it is shorter in the assemblé and slower in the glissage. Hence, in the assemblé, the gymnast can usually achieve a higher peak force. These findings are in agreement with those of Jensen [27], Gorwa et al. [21], [22], who showed that a quick jump (i.e., with a shorter TMF) produces higher RFD, while slower jumps (i.e., with a larger TMF) have lower RFD, which may explain the results.

As the gymnasts left the floor, we observed that the three run-up step techniques affected the linear kinematic variables of the stag ring leap. The horizontal displacement of COM and of toes varied significantly ($p < 0.01$), it was higher during CS and GS than AS.

As a result, we may deduce that the horizontal displacements of COM (dx_{COM}) and toe (dx_{toe}) are influenced by the initial run up step types used. Because the two techniques with one leg take-off have extremely near values compared to those with both leg take-off, which is proven by the obtained data, that the difference is between CS vs. AS and GS vs. AS. This variation of the horizontal displacement could be explained by the various run-up lengths. Thus, Nemtsev et al. [32] demonstrated that when the run-up was short, the horizontal displacement was substantially lower, and when the run-up was long, the horizontal displacement increased.

Furthermore, the essential requirement for jumping element eligibility is completing the movement by achieving an exact and fixed shape [15]. It is, therefore, difficult for a jump to attain a clearly defined form if it lacks sufficient height. Hence, in order to create a fixed form, vertical displacement is required. The greatest indices of vertical displacement of COM (dy_{COM}) were attained during the assemblé followed by the glissade technique. The reason could be that both legs together can generate greater joint angular impulse to lift the body higher than one leg only [40], which appears to be adequate to produce an important height.

Oddsson [33] has reported that the jumping height is determined by the vertical velocity of the COM at take-off. Their findings were in agreement with those of the current study, where the gymnasts achieved their highest velocity component during the run-up with both legs take-off "the assemblé". Vanrenterghem et al. [41] suggested that a strong relationship between the jump height (dy_{COM}) and the vertical velocity at take-off exists. According to their findings, the jump height increased as the vertical velocity during take-off. Increased findings could explain the highest values of the vertical velocity of the COM obtained during the assemblé (AS) followed by the glissade (GS) and the chassé step (CS).

On the other hand, horizontal velocity (Vx_{COM}) varied significantly, at $p < 0.05$, whereas the AS showed the lowest values, followed by the CS and GS.

In contrast to prior findings for vertical velocity, the AS values did not result in a significant amount of horizontal velocity. These statistics show that, first, the one-foot take-off allows for a greater Vx_{COM} than the two-foot take-off, as validated by Huang et al. [25] and second, the length of the run-up step technique may impact the Vx_{COM}, as suggested by Nemtsev et al. [32] a short run-up decreases the Vx_{COM}, whereas a long run-up increases it.

According to Aji-Putra et al. [2], the success of motions and the evolution of more complicated movements are both influenced by the flexibility variable. Furthermore, because this component is one of the fundamental physical abilities of gymnasts [26]. It is critical to study it depending on the result of leg flexibility, notably the angle of split legs ($\mathrm{AngS}_{\mathrm{leg}}$), which was substantially greater during the AS than during the GS and CS. In line with the findings of Aji-Putra et al. [2] that the split leap value is related to the height jump, as per the COP [18], a split position of 180° is required at the highest point of the leap, therefore, the gymnast should attain a substantial height to have a better angle of split leg, which is confirmed by the findings of the acquired data.

During the AS, the angle of the left trunk/leg, which is the ring position, was mainly closed, but the other two techniques restricted the leg's motion at an angle of roughly 70°. According to the COP [18], during the stag ring leap, the leg should be in a closed ring position. Touching any part of the head is required for the correct shape. As a result, smaller angles (i.e., closer circles) produce a clear image of a fixed and well-defined shape whereas bigger angles (i.e., opener circles) produce an incorrect shape with a large deviation.

According to the literature, performing beautiful motions at high angular velocities is one of the features of RG. In order to do this, athletes aim to enhance joint angular velocities. Indeed, Frutuoso et al. [19] indicated when accomplishing the stag ring leap with the assemblé technique, RG athletes had very high values of angular velocity of the right knee (front leg) as compared to the two other techniques. To the best of the gymnasts' jump, this leg should be maximally bent to be approved by the judges [18]. As a result, it appears that the two legs taking off allows for higher angular velocities, which facilitates the completion of movement and the creation of amplitude in the shape.

Limitations and future research perspectives

This study has some limitations that warrant discussion. First, the sample size is rather small. However, we recruited all the members of the Rhythmic Gymnastics Tunisian national team. Additionally, unlike team sports, the overall population in RG is rather reduced, making the procedure of recruiting a large sample size very challenging, particularly at the elite level. Nevertheless, future studies with larger sample sizes are needed to reinforce the findings of the current investigation. Second, the analysis system used in this study could represent a limitation. This is because it is a semi-automatic system and the force-plate is uniaxial. Upcoming studies should favor using a real-time motion analysis system (e.g., Vicon) coupled with triaxial force plates.

In perspective, it would be interesting to study these three take-off techniques with and without throwing the ball at different age groups and different jump difficulties (i.e., that involves bending the trunk backwards, such as the stag leap with back bend of the trunk or split leap with back bend of the trunk). Also, it would also be interesting to select a different apparatus (i.e., hoop, clubs, and ribbon) in order to learn more about the factors that cause the success of aerial challenges in RG. A following study on these areas may be appropriate.

5. Conclusions

The results of the current study's findings suggest that there is an effect of the three different run-up steps on the mechanical variables which, in turn, influences the performance of the stag ring leap with the throw-catch of the ball.

The AS appears to be the more explosive because it can generate more force in a shorter period of time due to a greater RFD, given a higher displacement of the COM, which can result in a clearly defined shape and, most importantly, a greater angle of split legs and closed ring position. Thus, the two legs take-off technique appears to promote the maximum vertical velocity of the COM and a very high value of angular velocity of the right knee.

Finally, this study shows that the AS approach is optimum for improving overall athletic performance, facilitating movement execution, and creating amplitude in the shape.

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