Original Article

Gold standard motion analysis system for evaluating jumping performance in rhythmic gymnastics

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ABSTRACT

The aim of this study is to investigate the effectiveness, not yet described in the literature, of the gold standard system for motion analysis, to analyse the kinematic and dynamic aspects of the split leap in rhythmic gymnastics performed with and without the ribbon. The sample consists of six top level gymnasts aged between 13 and 16 (mean 15.1 ± 0.94). The acquisitions were carried out with the integrated multifactorial optoelectronic system BTS Bioengineering. Fifteen passive markers, six BTS Smart-DX cameras, two cameras for video support and seven BTS-6000 force platforms were used. After the acquisition of the gymnasts' anthropometric measurements, a standardized and specific neuromuscular activation was carried out. The software SMART tracker and SMART analyser were used to process and analyse the dynamics and kinematics data. A questionnaire was administered to the gymnasts to collect information regarding training. The results showed no major differences in force impulse, jump amplitude, elevation and flight time between the trials performed with and without ribbon. The experiment conducted demonstrates the effectiveness of using the integrated multifactor optoelectronic system to carry out the kinematic and dynamic analysis of a highly complex sports technique.

Keywords: Performance analysis of sport, Gold standard system, Sport performance, Gymnasts, Biomechanical evaluation.

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INTRODUCTION

Rhythmic gymnastics is a sport characterized by fluid and harmonious movements. It involves the execution of both individual and team exercises accompanied by a musical base. The performances can be carried out both free-body and with the use of small tools: rope, hoop, ball, clubs and ribbon.

The jury, to evaluate the exercises during competitions, uses a Code of Points (CoP) which is a federal document drawn up by the International Gymnastics Federation after each Olympics. The current one is the 2022-2024 CoP. Among the various sections into which the code is divided, there is the part dedicated to body difficulties (DB) in which the judging parameters, values and penalties are described in terms of scores for jumps, balances and rotations (Code of Points, 2022). The increase of the gymnasts involved, in the last years, in this sport has aroused the interest of researchers. As can be observed from the literature on the argument the studies carried out mainly focus on aspects of a pedagogic and didactic nature (Coppola & Vastola, 2019); on contribution of physical fitness to the technical execution (Donti et al., 2016); on the quality of difficulty judging in rhythmic gymnastics at different levels of performance (Leandro et al., 2017); on the experimentation of technological systems to support the judges for the evaluation of the performances (Díaz-Pereira et al., 2014); and on the health promotion of gymnasts (Coppola et al., 2015).

This study is focused on the assessment of technical aspects of jumping, in particular, the DB of the split jump performed free body and with the ribbon. This DB involves a sagittal split in flight bringing the dominant leg forward and the non-dominant one back, reaching an amplitude of at least 180°. During the flight phase, the shape must be fixed and well defined and the elevation must allow the desired shape to be achieved (Di Cagno et al., 2008). As reported in the CoP, this jump has a value of 0.30 points. It requires great skills of quickness, explosive strength, body control and coordination. To reach the maximum width of the legs during the jump, it is essential to have good mobility skills of the coxo-femoral joint (Aparo et al., 1999).

Equally important is the landing phase from the jump since, as pointed out in the study conducted by Błażkiewicz et al. (2019), the hip and knee joints are the most vulnerable to pain and injuries if you do not land properly after the flight phase.

Rhythmic gymnastics is defined as a "*high leap demanding sport*" (Polat, 2018) and, for this reason, jumps and their biomechanical components have been extensively analysed in the literature. Christoforidou et al. (2017) has investigated the aspects related to biomechanical and neuromuscular strategies in trained gymnasts and untrained prepubescent girls. The study conducted by Gittoes et al. (2012) investigated the biomechanical approaches to understanding the potentially injurious demands of gymnastic-style impact landings. The aim of the study conducted by Mills et al. (2009) was to determine landing strategies that minimise ground reaction forces (GRF) and internal forces. A review carried out by Farana and colleagues, in 2023, had the aim of exploring biomechanics and motor control research in skill development and technique selection in artistic gymnastics with a focus on the underlying concepts and scientific principles that allow performance enhancement, skill development and injury risk reduction.

Jumping difficulties are among the most used elements but also the most complex since they require: ability to balance in flight, good elevation, amplitude, coordination, body control, power, explosive strength, speed, and muscle elasticity (Marcolin et al., 2019).

Hutchinson et al. (1998), in their studies, define jumps as fundamental movements that involve a complex motor coordination between upper and lower limbs.

Studies of the kinematic and biomechanical nature of jumps in rhythmic gymnastics represent a fundamental element both from an analytical point of view of basic research for understanding the force and kinematic components that occur during performances, and from a of applied research concerning the methodological field of sports training. In fact, through this research with gold standard technologies, it is possible to study and analyse various aspects concerning the training of female athletes and the performance of high-level gymnasts to make, where necessary, adjustments or modifications to the methodologies and training protocols used. The studies in the scientific literature on jumps in rhythmic gymnastics, as described below, were mainly conducted with technologies that do not represent the gold standard for motion analysis. Therefore, the aim of this study was to investigate the effectiveness of using the gold standard systems for motion analysis, i.e., the integrated multifactor optoelectronic motion capture system, for the kinematic and dynamic analysis of the technical difficulties of jump in rhythmic gymnastics with and without apparatus.

Some studies published in scientific literature that have investigated different aspects of jumping performance in rhythmic gymnastics are presented below.

In a recent study, Akkari-Ghazouani et al. (2022) compared the execution of the biche a boucle jump with and without the ball toss, using the glissade-step technique (using the glissade-step as a preparatory phase for take-off with one-leg). Two cameras and a force platform were used for the 2D acquisitions. Some jumping tests were performed without the ball, others with the launch during the glissade and, lastly, with the launch of the ball during the execution of the jump. The parameters investigated were the vertical force, the speed and the horizontal and vertical displacements. The results showed that all three jumps had significant impacts on performance variables, especially strength, speed and flexibility.

Aji-Putra et al. (2021) examined how lower limb flexibility and length affect jumping performance and judging scores. Fifty-two gymnasts, divided into two groups based on age and technical level, were subjected to a series of tests of flexibility and explosive strength of the lower limbs. Through the use of a body scale and the UNG (Real Image Size) software for postural analysis, the anthropometric measurements of the athletes were taken (height, leg length and body weight). Furthermore, with the *"Kinovea"* software, the angle of flexibility (ROM-Range of Motion) of the hip joint was measured. Subsequently, two international judges evaluated the split jump tests, attributing the scores and the relative penalties according to the CoP. It has been found that the athlete's body composition, flexibility and explosive strength of the lower limbs contribute to the success of the jump difficulty.

Örs & Turşak (2020) also studied the correlation between static leg flexibility and the kinematic components of the straight jump. To do this, they used a camera positioned perpendicular to the plane in which the jump is performed and passive markers applied to different anatomical points. It emerged that the flexibility of the dominant limb, which lies forward during the straight jump, is significantly correlated to the flexibility of the hind limb which, in turn, is positively correlated to the flexion-extension angle of the hind leg joint hip during the flight phase.

Coppola et al. (2020) performed a case study of two types of run-ups to be performed before the split jump, a simple run and the chasse step. For the kinematic analysis, the gold standard system was used, in particular six video cameras and two force platforms. The motor task was divided into three phases: run-up, take-off and flight, in which position, speed, linear acceleration of the sacrum and jump amplitude were examined. From the collected data it emerged that, during the run-up and take-off phases, the height of the sacrum is greater using the run, while the maximum elevation and a greater angle of flexion-extension of the hip joint are obtained with the chasse. Therefore, it is believed that the momentum of the lower limbs is greater when using chasse than when running and this, consequently, also determines a better execution of the jump.

Johnson et al. (2018) conducted a study on the split jump performed after static stretching and vibration stretching sessions. Video analysis software and the *"Vibeplate"* vibrating platform were used, with which the gymnasts stretched the back muscles of the legs and the hip flexors. Both stretching with and without vibrations negatively affect the performance of jumping straight but, in particular, with vibrations the flexibility of the lower limbs was markedly reduced compared to stretching without vibrations. Instead, jump height was similar across all trials.

Polat (2018) analysed the flight time, height, speed and power of two jumps in rhythmic gymnastics, the enjambée and the biche a boucle. The OptoJump system and the "*Gyko Inertial System*" were used for the study. The jumps were performed with two different take-off phases, first with one foot and then with two feet. The data obtained demonstrates that gymnasts performed better with the single foot take-off.

Mkaouer et al. (2012), using a 2D motion analysis system, studied the variation of strength, speed and flexibility parameters during the execution of the split jump with and without apparatus (in this case the ball was chosen). When the gear is introduced, the results show a significant change in muzzle velocity, time of flight, vertical displacement, and angular velocity. In particular, there is a decrease in flight time and initial speed, while there is an increase in vertical displacement, acceleration and angular speed.

Cicchella (2009) used a Vicon 460 motion analysis system to compare the split with three other jumps, based on the kinematic analysis of several parameters, including: the length of the last stride, the knee angle before the jump, the thrust time and that of flight. All jumps showed a similar flight time, despite the different movements performed. The highest variable, on the other hand, is represented by the length of the last stride especially during the execution of the enjambée.

Already Sousa & Lebre (1998) studied different techniques used by the gymnast to perform four jumps, including split leap. Using video analysis software, the kinematic parameters of the jump were analysed, in particular: the flight time, the distance covered in the horizontal direction, the speed, the height of the centre of mass and the joint angles at take-off. This last parameter has proved to be the most influential in the performance of the gymnasts.

In the literature there are no studies that have used the integrated multifactorial optoelectronic system for the analysis of the jumping performance performed with the handling of the ribbon (5 metres) in rhythmic gymnastics.

This study made it possible to investigate the "*effectiveness*" and potential of the use of gold standard technologies for motion analysis, i.e. the BTS Bioengineering integrated multifactor optoelectronic motion capture system, which allow for the study of some characteristics in a more analytical and objective way kinematics and dynamics of the motor task of the split performed with and without the ribbon. In particular, the amplitude and height of the jump, the flight time and the force impulse were analysed.

METHODS AND MATERIALS

Participants

The sample of this study consists of six competitive gymnasts aged between 13 and 16 years. The mean age is 15.1 years with a standard deviation of 0.94.

Five out of six athletes train three hours a day for five days a week and compete at regional, interregional and national level in gold sector competitions. A gymnast, on the other hand, falls into the silver sector and trains three times a week for two hours.

The parents of the gymnasts signed an informed consent form authorizing their participation in the study.

The study was conducted at the Laboratory for the Analysis of Innovative Didactics and Sports Performance of the University of Salerno, in June 2022.

Statement of human and animal rights

This trial is conducted in accordance with ethical principles of the Declaration of Helsinki. Declaration of Helsinki Ethical Principles for Medical Research involving human subjects (WMA, 2013).

Data availability statement

Data are available from the corresponding author upon request.

Survey

Before carrying out the acquisitions in the laboratory, a questionnaire was administered to the gymnasts to collect information regarding anthropometric measurements (weight, height and BMI), years of sport practice, weekly training days and hours, years of use of the ribbon and, on the basis of previous experience, their considerations on the execution of the split jump with and without a ribbon and with the chosen handling (serpentines above and behind the head).

Instruments: the integrated multifactor optoelectronic system

BTS Bioengineering gold standard equipment was used. In particular, six BTS Smart-DX video cameras, three of which are placed in front and three behind the acquisition volume; two cameras for video support; seven BTS-6000 force platforms to detect the contact of the feet on the ground and the resultant of the forces and fifteen passive markers.

Procedure: acquisition protocol

First, the system was calibrated through a sequence of axes. The triad of laboratory reference axes was placed in the centre of the acquisition volume, so that the cameras had an origin and axes to refer to (axes sequence). Subsequently, the position of the force platforms was identified using two axes (platform sequence). Finally, an axis formed by markers was moved in the acquisition volume to facilitate the recognition of the markers by the cameras during dynamic acquisitions and to delimit the boundaries of the work volume (wand sequence).

For the preparation of the athletes, the following anthropometric measurements were taken: body weight, height, leg length (measuring the distance between the anterior superior iliac spine and the medial malleolus), pelvis width (measuring the distance between the anterior superior iliac spines with a pelvimeter), height of the pelvis (taking the measurement perpendicular to a ruler placed parallel to the table passing through the greater trochanter and the anterior superior iliac spine), the diameter of the knee (measuring the distance between the femoral condyles of the knee) and the diameter of the ankle (measuring the distance between the medial and lateral malleoli) (Vastola, 2018).

Before acquiring the motor task, each gymnast performed a standardized and specific neuromuscular activation with warm-up and joint mobility exercises of the lower limbs and the muscles involved.

Subsequently, fifteen passive markers were applied to the landmarks of the athletes' bodies following the Helen Hayes protocol: one on the sacrum, one on the right and left anterior-superior iliac spines, one on the lateral epicondyles, one on the lateral malleoli, one on the heels and one on the second metatarsal heads. Additionally, four marker rods were used: two on the thighs in alignment with the greater trochanter of the femur and epicondyle markers, and two on the legs in alignment with the epicondyle and lateral malleolus markers (Kadaba et al., 1990).

Before the motor gesture tests, a static acquisition of the subjects in orthostasis was performed to identify the initial position of the markers with respect to the biomechanical model. Subsequently, we moved on to the dynamic acquisitions of the motor task: the split jump performed first with free body and then with the ribbon. The handling of the chosen tool consists of coils above and behind the head. The athletes performed five free body jump tests and five with the apparatus.

Data processing and analysis

The SMART tracker and SMART analyser software were used to process the dynamics and kinematics data.

SMART tracker made it possible to reconstruct the movement of the selected motor task in 3D using the positioning model of the markers on the body (Helen Hayes protocol) and to identify the ground reaction forces at the moment of foot contact with the force platforms.

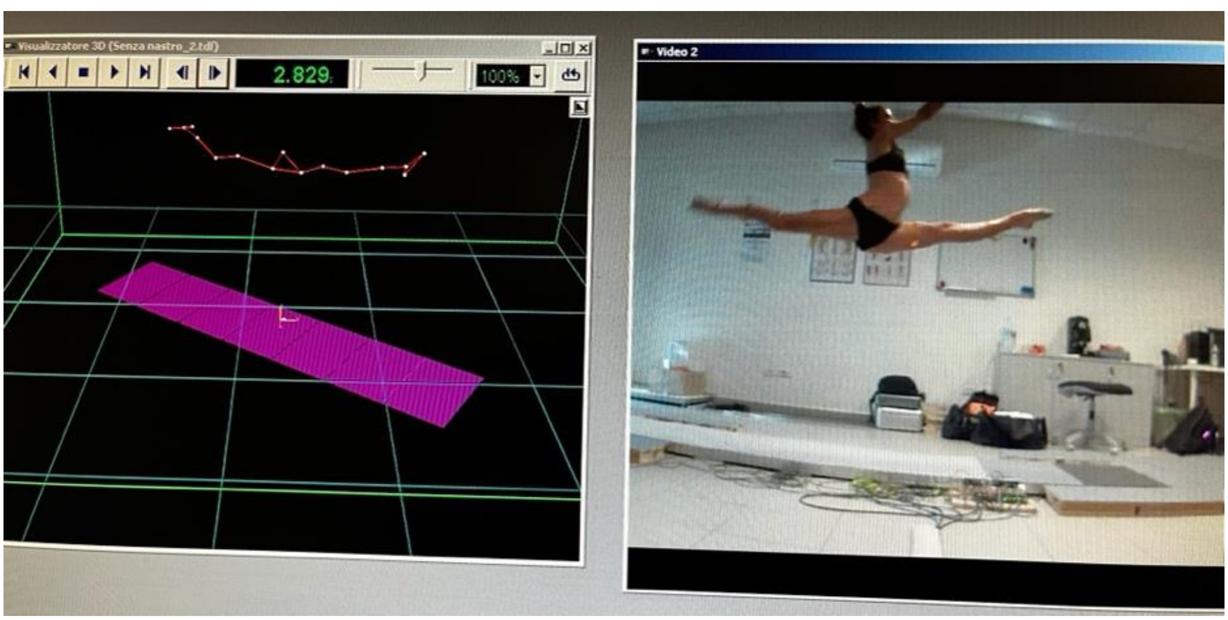

Figure 1. Representation on the SMART tracker software of the free-body leap.

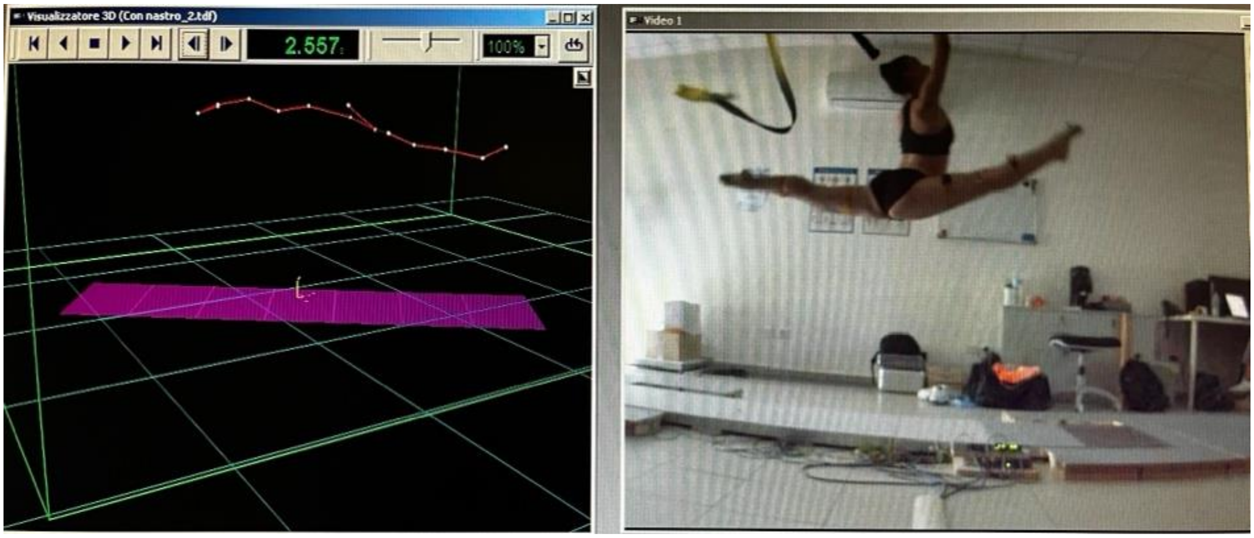

Figure 2. SMART tracker software depiction of enjambée jump performed with ribbon.

Subsequently, with SMART analyser, using the static test, the anthropometric measurements and the three best dynamic tests chosen among those carried out on the basis of the technical execution and the quality of the optoelectronic system acquisitions, two events were identified: a frame prior to contact of the non-dominant foot on the power platform, before the take-off phase of the jump, and one frame prior to contact of the dominant foot on the power platform after the jump.

From this procedure, the kinematic data relating to the time of flight, the maximum elevation and the maximum amplitude of the split jump performed with and without the ribbon and the dynamic data relating to the force impulse were obtained.

All the data obtained from the software and those emerging from the answers to the questionnaire administered before carrying out the acquisitions were entered in Excel tables for the descriptive statistical analysis.

RESULTS

Table 1 shows the mean, the standard deviation, the minimum and maximum values of age, BMI, years of sports practice and weekly training hours of the six gymnasts obtained from the answers to the questionnaire administered before the laboratory acquisitions. The athletes are between the ages of 13 and 16. The mean age is 15.1 years, the standard deviation is 0.94, the minimum value is 13.8 years and the maximum value is 16.1 years.

Table 1. Data on age, BMI, years of competitive practice and weekly training hours of gymnasts.

	Age	BMI	Years of agonistic practice	Hours of training for week
Mean	15.1	19.23	6	14.5
Standard deviation	0.94	1.96	2.76	4.81
Minimum value	13.8	15.43	3	6
Maximum value	16.1	20.69	10	18

The mean BMI value is 19.23 with a standard deviation of 1.96. The minimum value is 15.43, while the maximum value is 20.69.

The athletes performed an average of 6 years of competitive activity with a standard deviation of 2.76. The minimum value is 3 years of competitive practice, while the maximum is 10 years.

Gymnasts train on average 14.5 hours a week. The standard deviation is 4.81. The minimum weekly training hours are 6, while the maximum value is 18 hours.

Kinematic data

Table 2 and figures 3-4 report the data of the maximum height of the sacrum during the maximum amplitude of the jump performed with and without ribbon. The mean total maximum height of the sacrum in ribbon jumping is 1.154 m above the ground with a standard deviation of 0.034. The mean value without ribbon is 1.176 m with a standard deviation of 0.015.

Table 2. Data relating to the maximum height (MH) of the sacrum during jumping with and without five meters ribbon.

	With ribbon	**No ribbon**	**With ribbon**	**No ribbon**
	MH sacred in fullest extent	MH sacred in fullest extent	Standard deviation	Standard deviation
Gymnast 1	1.118	1.109	0.008	0.013
Gymnast 2	1.232	1.238	0.014	0.02
Gymnast 3	1.138	1.164	0.008	0.005
Gymnast 4	1.105	1.111	0.014	0.005
Gymnast 5	1.184	1.286	0.142	0.015
Gymnast 6	1.149	1.149	0.02	0.03
Mean value (m)	1.154	1.176	0.034	0.015

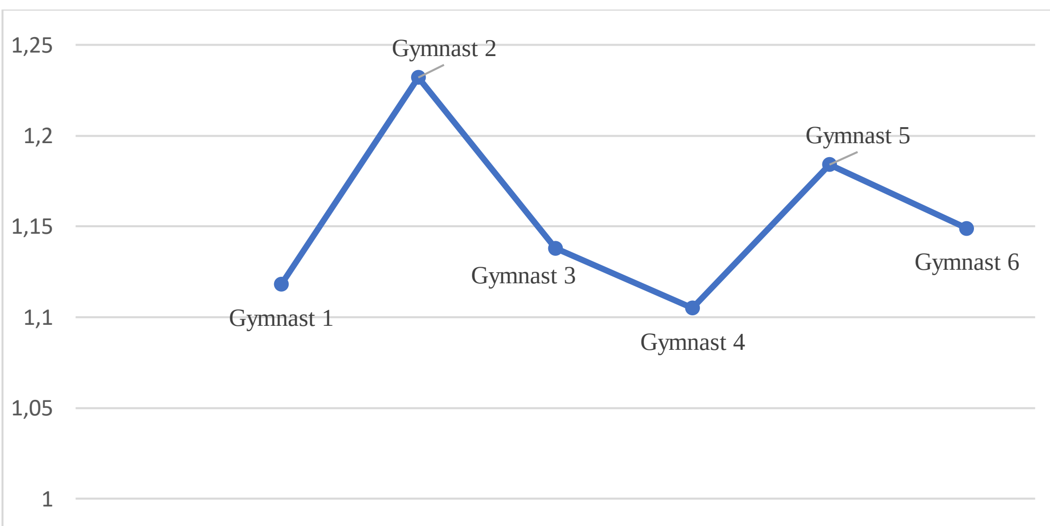

Figure 3. Values of maximum sacrum height in maximum amplitude with ribbon.

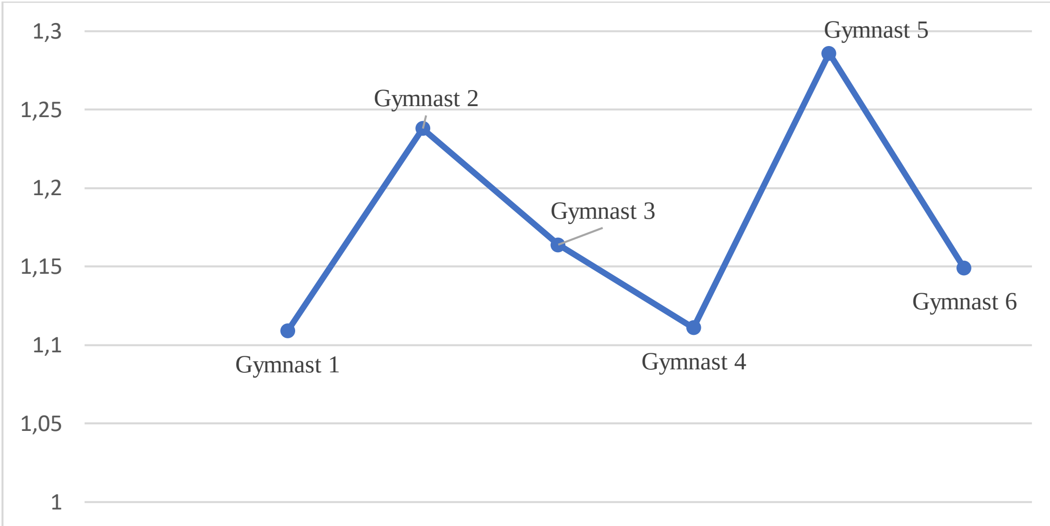

Figure 4. Values of maximum sacrum height in maximum amplitude without ribbon.

Table 3. Data relating to the maximum amplitude (MA) of the jump performed with and without ribbon.

	With ribbon	**No ribbon**	**With ribbon**	**No ribbon**
	Max jump amplitude (MA)	Max jump amplitude (MA)	Standard Deviation	Standard Deviation
Gymnast 1	148.067	140.133	2.614	1.268
Gymnast 2	187.933	181.167	5.39	2.659
Gymnast 3	155.967	155.967	4.328	0.685
Gymnast 4	155.533	157.067	3.675	1.987
Gymnast 5	165.9	151.967	7.976	0.665
Gymnast 6	183.175	170.033	1.75	8.351
Mean value (degrees)	165.763	159.389	4.289	2.603

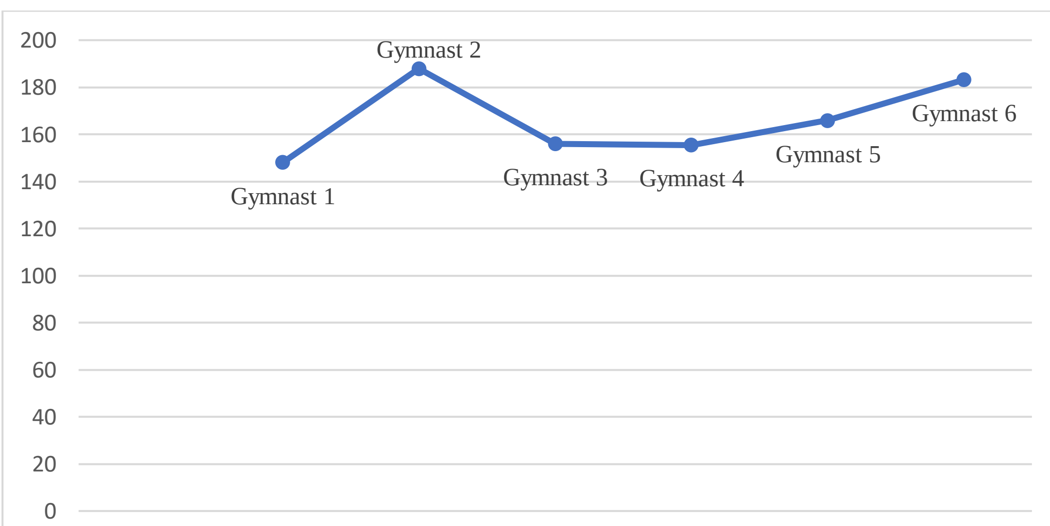

Figure 5. Maximum jump amplitude values with ribbon.

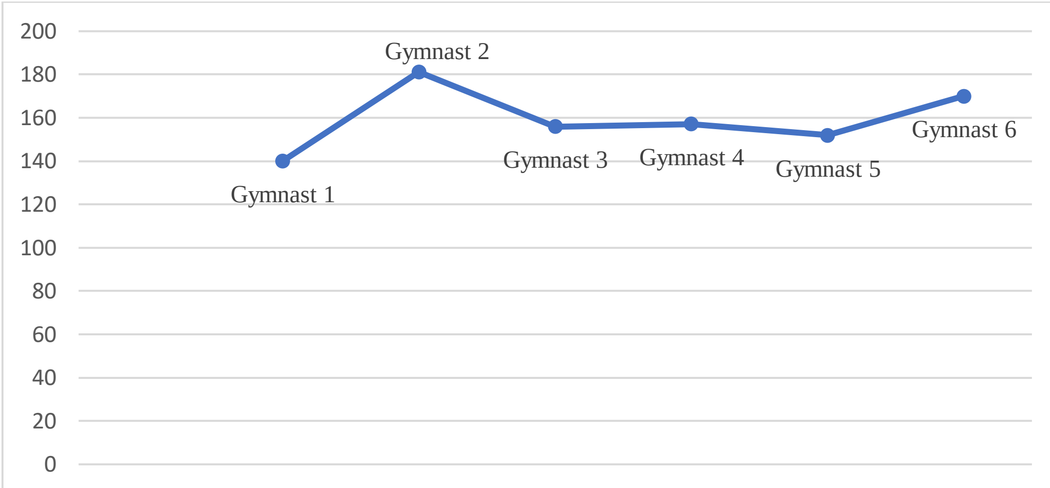

Figure 6. Maximum jump amplitude values without ribbon.

From the data collected in table 3 and in graphs 5-6 it emerges that the average value of the maximum amplitude of the jump with the ribbon is 165.763° with a standard deviation of 4.289, while the average value of the maximum amplitude without using the ribbon is 159.389° with a standard deviation of 2.603.

Table 4. Flight time data of jump with and without ribbon.

	With ribbon	**No ribbon**	**With ribbon**	**No ribbon**
	MT Flight	MT Flight	Standard Deviation	Standard Deviation
Gymnast 1	0.548	0.538	0.007	0.007
Gymnast 2	0.638	0.638	0.018	0.018
Gymnast 3	0.624	0.638	0.007	0.07
Gymnast 4	0.571	0.581	0.02	0.013
Gymnast 5	0.671	0.667	0.012	0.007
Gymnast 6	0.579	0.614	0.014	0.02
Mean value (seconds)	0.605	0.613	0.013	0.012

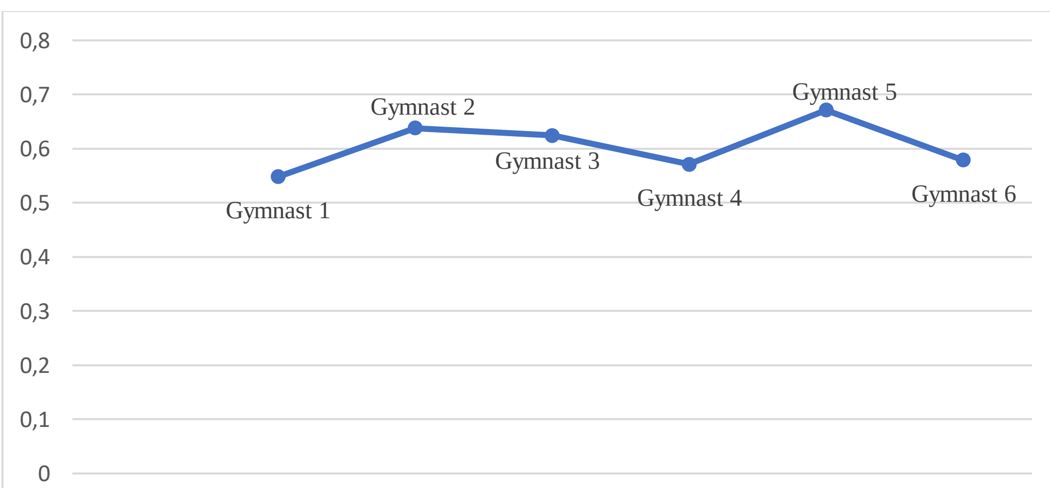

Figure 7. Time of flight values of jump with ribbon.

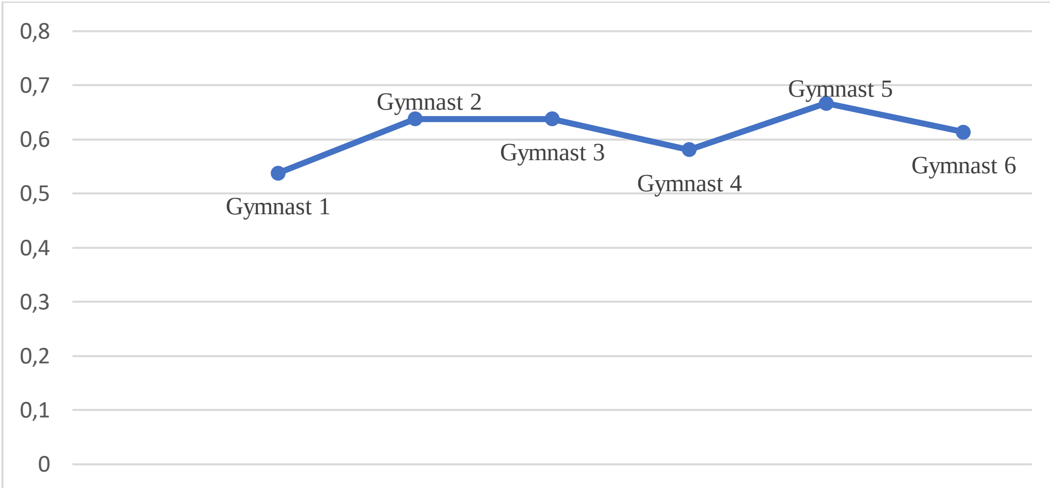

Figure 8. Time of flight values of jump without ribbon.

Table 4 and figures 7-8 show the data relating to the flight time of the jump with and without ribbon. The mean value of the flight time (MT) of the ribbon jump is 0.605 s with a standard deviation of 0.013, while for the no-ribbon jump the mean value is 0.613 s with a standard deviation of 0.012.

Dynamic data

Table 5. Force impulse data.

	With ribbon	**No ribbon**
Gymnast 1	3.581 Nsec	4.197 Nsec
Gymnast 2	4.458 Nsec	4.833 Nsec
Gymnast 3	4.314 Nsec	4.619 Nsec
Gymnast 4	4.585 Nsec	5.103 Nsec
Gymnast 5	4.258 Nsec	3.982 Nsec
Gymnast 6	4.32 Nsec	3.907 Nsec

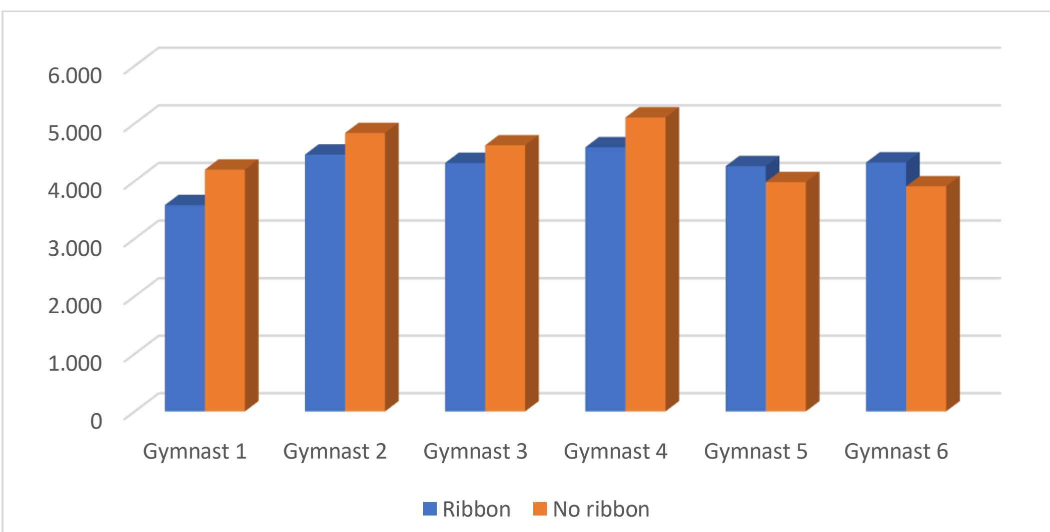

Figure 9. Impulse force values of jump take-off with and without ribbon.

From table 5 and from graph 9 it can be seen that for four gymnasts the force impulse value is greater in the tests performed with floor exercise (4.197 Nsec, 4.833 Nsec, 4.619 Nsec, 5.103 Nsec), while for two athletes this value is greater for ribbon performances (4.258 Nsec, 4.32 Nsec).

Table 6. Comparison of Elevation Amplitude and Flight Time data between experienced and novice gymnasts in ribbon handling.

	Elevation without ribbon (m)	Elevation with ribbon (m)	Amplitude without ribbon (degrees)	Amplitude with ribbon (degrees)	Time Flight without ribbon (s)	Time Flight with ribbon (s)
Expert gymnasts with the ribbon	1.238	1.232	140.133	148.067	0.538	0.548
	1.109	1.118	181.167	187.933	0.638	0.638
	1.164	1.138	155.967	155.967	0.638	0.624
	1.111	1.105	157.067	155.533	0.581	0.571
No Expert gymnasts with the ribbon	1.286	1.184	151.967	165.9	0.667	0.671
	1.149	1.149	170.033	183.175	0.614	0.579

Table 6 shows that there are no important differences in terms of elevation, amplitude and flight time between the exercises carried out with bodyweight and with ribbon for both expert and less expert gymnasts in handling the apparatus.

In particular, for three experienced gymnasts' data of a higher jump elevation was recorded in the trials without a ribbon (1.238 m, 1.164 m, 1.111 m), while only one athlete had a higher elevation during the ribbon jump (1.118 m). Regarding the amplitude of the jump, two expert gymnasts reached maximum values in the tests with the ribbon (148.067°, 187.933°). A gymnast recorded the maximum amplitude in the trials without a ribbon (157.067°) and, instead, another athlete reported equal values in both the free body and apparatus trials (155.967°).

One experienced gymnast recorded longer airtime in ribbon executions (0.548 s); for an athlete not experienced with ribbon, the greatest flight time was identified in the trials with the apparatus (0.671 s) and, finally, another gymnast reported the same data in both trials (0.638 s).

An important fact concerns the amplitude of the jump performed with the ribbon by less expert gymnasts in handling this piece of equipment. In fact, although in the questionnaire the athletes stated that the chosen handling (serpentines above and behind the head) did not help them in the momentum of the legs, higher values were recorded precisely in the amplitude of the jump with the ribbon compared to executions without apparatus (165.9°, 183.175°).

DISCUSSION AND CONCLUSIONS

The results obtained in this study, in relation to the size of the sample and the impossibility of carrying out the surveys on a more representative sample of the population of gymnasts, are mainly suggestive rather than conclusive.

A result of particular scientific interest concerns the fact that, despite the technologies used in this study, i.e. the gold standard for the analysis of human movement, they have not previously been used for such complex motor tasks as the free-body split jump and with the handling of the ribbon, they proved to be equally valid and made it possible to analyse the biomechanical and dynamic characteristics of the jump in a quantitative, as well as qualitative, highly analytical way. The same can also be said for the movement analysis protocol used (Helen-Hayes) which was specifically chosen according to the motor task and the anatomical positioning of the markers which reduces the risk of loss and detachment of the same during the execution of the jump.

The questionnaire administered to the gymnasts was also a valid and useful tool for research purposes since it allowed us to understand and deepen the data obtained from the biomechanical and dynamic analysis. It has proven to be easy to use to carry out an initial anamnesis on the anthropometric measurements of the athletes, on the years of experience using the ribbon and, on the hours, and days of training for week.

The data collected, all treated anonymously, proved to be useful but, since there are no specific studies on this motor task in the literature with the use of these specific gold standard technologies and the use of ribbon, it was not possible to compare the data directly.

Furthermore, the marker positioned on the sacrum was not always visible to the cameras, since, despite these having been positioned in the best possible way to carry out these acquisitions, during the swing of the rear leg the marker was covered by the limb and, consequently, the video cameras were not always able to follow it in the phases of maximum elevation and maximum amplitude of the jump.

The split, being a very fast motor task that causes high muscle vibrations, required great attention in positioning the markers on the anatomical landmarks and, in some cases, it was necessary to further block the markers by applying adhesive tape around them.

As for the use of the ribbon, given the size of the laboratory, it could have led to several problems both in terms of space and in terms of coverage of the markers positioned on the body during the jump tests, but this did not happen.

From the kinematic data collected, it can be seen that there are no important differences in terms of jump amplitude, elevation and flight time between the split performed free body and with the ribbon. An important fact to underline concerns the amplitude of the jump performed with the ribbon by the two less experienced gymnasts in handling this piece of equipment. In fact, contrary to what the athletes stated in the answers to the questionnaire, i.e. that the chosen handling (serpentines above and behind the head) did not help them in the momentum of their legs, higher values were recorded precisely in the amplitude of the jump with the ribbon compared to the designs without tool (with ribbon 165.9°, without ribbon 151.967°; with ribbon 183.175°, without ribbon 170.033°). This can probably be due to the fact that the athletes, already during the run-up phase of the jump, had their dominant arm extended upwards to handle the apparatus and therefore all the masses of the body segments were projected upwards favouring the thrust of the lower limbs more and, consequently, also a greater amplitude of the jump.

Even the dynamic data, concerning the force impulse at the moment of the take-off before the jump, do not show large differences between the tests with and without ribbon. From the values obtained, it emerges that half of the athletes have an impulse of greater force in the execution of the split without the ribbon.

The study conducted and the data collected can lead to suggestions regarding the reasons for the slight differences in the execution of the motor task with and without the tool, also due to factors related to daily experience in the field, but it is not possible to draw standardized conclusions also due to the limited sample and the impossibility of repeating the acquisitions over time.

Finally, although the data obtained are not conclusive and representative of the population of gymnasts, this study allowed us to investigate the effectiveness, not yet described in the literature, of using the gold standard systems for movement analysis, i.e. the integrated multifactorial optoelectronic motion capture system, to analyse the kinematic and dynamic aspects of the split leap in rhythmic gymnastics performed with and without the apparatus.

AUTHOR CONTRIBUTIONS

Coppola S. and Costa C. designed and performed the experiments, derived the models, and analysed the data. Vastola R. worked out almost all of the technical details and performed the numerical calculations for the suggested experiment. Coppola S. and Costa C. wrote the manuscript in consultation with Vastola R. Vastola R. supervised the project research.

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DISCLOSURE STATEMENT

No potential conflict of interest were reported by the authors.

STATEMENT OF INFORMED CONSENT

The parents of the gymnasts signed an informed consent form authorizing their participation in the study. The informed consent forms are available from the corresponding author upon request.

STATEMENT OF HUMAN AND ANIMAL RIGHTS

This trial is conducted in accordance with ethical principles of the Declaration of Helsinki. Declaration of Helsinki Ethical Principles for Medical Research involving human subjects (WMA, 2013).

DATA AVAILABILITY STATEMENT

Data are available from the corresponding author upon request.

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