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KINEMATICS OF THE DELIVERY PHASE AND RELEASE PARAMETERS OF TOP FEMALE JAVELIN THROWERS

KINEMATIČNI PARAMETRI FAZE META IN IZMETA PRI VRHUNSKIH METALKAH KOPJA

ABSTRACT

The introduction of the new-rules javelin for female athletes in 1999 was thought to be a cause of increased demand for excellence in the throwing technique and that a greater demand for biomechanical analysis was stressed. The purpose of the study was to investigate the kinematical parameters of the delivery phase and the release parameters of contemporary top female javelin throwers in order to support the above mentioned suggestion. Twenty-six throws performed during competitions by 16 right-handed top athletes (age: 28.5 years ± 4.3; body height: 1.75 m ± 0.05; body mass: 73.8 kg ± 6.3; average ± standard deviation, respectively) were recorded with a digital video camera (sampling frequency: 50fps). The delivery and release phases were examined with a 2D-DLT analysis method. The relationship of the extracted spatio-temporal, kinematical and release parameters with the official throwing distance was examined with a two-tailed Pearson correlation. The results indicated that the official distance (59.22 m ± 4.42) was strongly correlated ($r = .909$, $p < .001$) with the release velocity (22.9 m/sec ± 1.6) and negatively correlated ($r = -.608$, $p < .05$) with the knee angle of the right leg at its last touchdown (142.2° ± 13.1). The temporal parameters of the delivery phase were significantly ($p < .05$) correlated spatial parameters such as the delivery stride length, the inclination of the torso, the elbow angle of the throwing arm and the knee angle of the braking leg. Emphasis should be given in these parameters to ensure an improvement in female javelin performance.

Key words: javelin, female, throwing technique, biomechanics, kinematical parameters

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IZVLEČEK

Uvedba novih pravil za ženski met kopja leta 1999 naj bi povzročila vse več zahtev po odličnosti tehnike meta, obenem pa so se povečale tudi potrebe po biomehanskih analizah. Namen raziskave je bil preučiti kinematične parametre faze meta in parametre izmeta pri vrhunskih metalkah kopja v sodobnem času, da bi lahko podprli zgornji predlog. Šestindvajset metov kopja, ki jih je na tekmovanjih izvedlo 16 elitnih športnic, desničark (starost: 28,5 let ± 4,3; telesna višina: 1,75 m ± 0,05; telesna teža: 73,8 kg ± 6,3; kar pomeni povprečje ± standardni odklon), smo posneli z digitalno video kamero (frekvenca zajemanja slik: 50 fps). Fazi meta in izmeta smo preučili z analitično metodo 2D-DLT. Odnos med ekstrahiranimi prostorsko-časovnimi, kinematičnimi in izmetnimi parametri ter uradno doseženo razdaljo metov smo preučili z dvostranskim testom Pearsonove korelacije. Rezultati so pokazali močno pozitivno korelacijo ($r = ,909$, $p < ,001$) med uradno doseženo razdaljo (59,22 m ± 4,42) in hitrostjo izmeta (22,9 m/sek ± 1,6) in negativno korelacijo ($r = -,608$, $p < ,05$) s kotom desnega kolenskega sklepa v trenutku zadnjega dotika tal (142,2° ± 13,1). Časovni parametri faze meta so značilno ($p < ,05$) korelirali s prostorskimi parametri, kot so dolžina koraka med metom, naklon trupa, kot v komolčnem sklepu izmetne roke in kot v kolenu zavirajoče noge. Za izboljšanje ženskega meta kopja je treba poudarek nameniti tem parametrom.

Ključne besede: kopje, ženske, tehnika meta, biomehanika, kinematični parametri

INTRODUCTION

After being introduced at the 1932 Olympic Games, the performance in female javelin throwing saw constant improvements in the past century (Bartonietz, 2000; Dyer, 1989; Jokl, 1984; Tsarouchas & Giavroglou, 1986). It is believed that it represents the most highly evolved throwing event in track and field since performances improved by 80% in the time span between 1932–1992 (Tipton, 1997) and the large throwing distances marked (≈ 80 m) were actually achieved about 15 years earlier than predicted (Jokl, 1984). The International Amateur Athletics Federation (IAAF) altered its rules concerning the specifications of the positioning of the centre of gravity in women's javelin in 1999, a fact suggested as being to be the cause of increased demand for excellence in the throwing technique (Bartonietz, 2000). Given the release parameters of the implement, the new-rules javelin starts to decelerate earlier in the flight due to the shorter maintenance of the angle of attack and the decreased lift of the implement, which eventually results in a 10% smaller range than the old-rules javelin (White, 2011). The increased demand for biomechanical analysis of female javelin throwers with the new-rules implement in order to redefine the recommendations for optimising the release parameters has been noted (Bartonietz, 2000).

Studies generally conclude that release velocity is the single most important factor regarding the official throwing distance based on the existence of a strong correlation between them (Bartlett & Best, 1988; Bartonietz, Best, & Borgström, 1996; Bartonietz, 2000; Hay, 1985; Lehmann, 2010; Maier, Wank, Bartonietz, & Blickhan, 2000; Mero, Komi, Korjus, Navarro, & Gregor, 1994; Murakami, Tanabe, Ishikawa, Isolehto, Komi, & Ito, 2006; Viitasalo, Mononen, & Norvapalo, 2003). The velocity of the javelin is generated through its acceleration path during the delivery phase (Bartlett & Best, 1988; Morriss, 1995). It is suggested that further development of the javelin's velocity should be conducted through elongation of the acceleration path by keeping a relatively extended elbow (i.e. "straight throwing arm") during the early parts of the delivery phase (Morriss, 1995).

The majority of information concerning women's javelin throw has been retreated from studies investigating the old-rules implement (Bartonietz et al., 1996; Menzel, 1986; Menzel, 1998; Mero et al., 1994; Shi & Tong, 2000; Tsarouchas & Giavroglou, 1986; Viitasalo et al., 2003; Xu & Nelson, 1988). The literature indicates that a limited number of biomechanical studies have analysed various aspects of the technique of female javelin throwers since the new-rules javelin was introduced (Jung et al., 2012; Kumar, 2005; LeBlanc & Mooney, 2004; Lehmann, 2010; Leigh, Liu, & Yu, 2010). A review of the above studies suggests that quantitative differences exist between the javelin technique with the previous (i.e. before 1999) and the current specifications concerning the spatio-temporal, kinematical and release parameters of the release. In detail, it seems that the current elite javelin release technique is characterised by an increased average release velocity (over 24 m/sec versus past reported values of 21–24 m/sec) and larger average angles of attitude (over instead of less than 40 degrees). These findings lead to the conclusion that further thoroughly inspected in order to establish the magnitude of the relationship of the key release and kinematical parameters with the throwing performance among contemporary top female javelin throwers.

Based on the above, the primary purpose of the present study was to quantify the spatio-temporal and kinematical parameters of the delivery phase and the release parameters of the javelin throw executed by top female athletes in competition. The secondary aim of the study was to investigate the relationship of the examined parameters with the official throwing distance in order to establish the effect of those parameters on the throwing performance.

MATERIALS AND METHODS

Subject sample. Sixteen (n = 16) right-handed, top-level female javelin throwers (age: 28.5 years ± 4.3; body height: 1.75 m ± 0.05; body mass: 73.8 kg ± 6.3; average ± standard deviation, respectively) were examined during several major IAAF competitions held in Greece between 2006 and 2009. With the exception of one, all participants had competed at least once in the three most recent Olympic Games. The study was conducted in accordance with the Institutional Research Committee's Guidelines for the use of human subjects.

Data acquisition. All trials of the participants were recorded from the right side of the athletes during the examined competitions. The recordings were acquired with a stationary JVC GR-D720E digital video camera (Victor Co., Japan), operating with a sampling frequency of 50fps and a shutter speed of 1/4000. A single camera set-up was selected since two-dimensional methods have been found to be adequate for evaluating basic javelin release parameters (Best, Bartlett, & Sawyer, 1995; Viitasalo et al., 2003). The camera was positioned on a fixed tripod in the stands at a distance of about 32 m from the middle of the runway and about 4 m before the foul line.

The recorded area was calibrated by consecutively placing a 0.02 m × 0.02 m × 2.5 m pole in several predefined spots within the filming view following the guidelines suggested by Gervais et al. (1989) and Kollias (1997). This procedure was conducted in order to produce two-dimensional

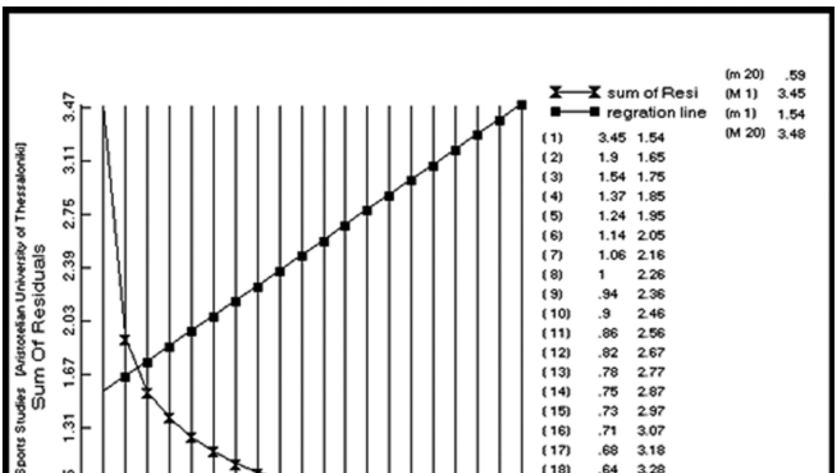

Figure 1. Determination of the cut-off frequency, based on the residual analysis method proposed by Winter (1990), using the SIDES2® (©: Iraklis A. Kollias) software (m: minimum value; M: maximum value).

coordinates with the use of the 2D-DLT kinematic analysis method, where the X-axis was parallel to the javelin throw runway and the Y-axis was perpendicular and vertical to the X-axis.

Data analysis. From all the recorded videos only the best attempt regarding the official throwing distance (S_{OFF}) marked for the participants in each competition was selected for further analysis. In all, 26 throws of the 16 participants were analysed. Twenty-two anatomical points of the body (tip of the toe, 5_{th} metatarsal, heel, ankle, knee, hip, shoulder, elbow, wrist and 5_{th} metacarpal on both sides of the body, 7_{th} cervical vertebra and the top of the head), the grip and both ends of the javelin were manually digitised in each field. The coordinates of the body centre of mass (BCM) were calculated for every field using the segmentational data proposed by Dempster (1955). A second-order low-pass Butterworth filter with a cut-off frequency ranging from 3.5 to 6 Hz, based on the noise calculated with residual analysis (Winter, 1990), was selected for smoothing (see the example in Figure 1). The digitisation, smoothing and analysis were conducted using the DIASDIG® and SIDES2® software (©: Iraklis A. Kollias). The accuracy of the 2D reconstruction was determined by Root Mean Square error, after randomly re-digitising 5% of the captured frames. An error of 0.4 cm and 0.3 cm was found for the X- and Y-axes, respectively.

The coordinates of the digitised points were used to calculate the kinematical parameters presented in this study. The extracted parameters were examined regarding three key instants of the delivery phase: the last right foot touchdown (T1), the last left foot touchdown (T2) and the release of the javelin (T3) and were defined as illustrated in Figure 2 and described below.

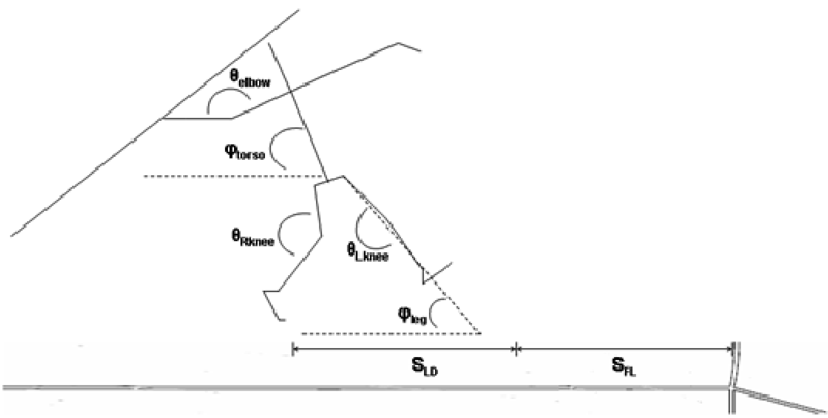

Figure 2. Definition of the spatial parameters of the delivery phase which were examined in the present study (see text for the abbreviations displayed).

- Delivery stride length (S_{LD}): the horizontal distance between the toes of the right foot at T1 and the toes of the left foot at T2
- Distance from foul line (S_{FL}): the horizontal distance between the toes of the left leg and the middle of the foul line at T2
- Javelin acceleration path ($S\gamma$): the two-dimensional displacement of the javelin's grip
- Knee angle: the angle formed by the longitudinal axes of the thigh and the shank of the right (θ_{Rknee}) and left (θ_{Lknee}) leg
- Elbow angle (θ_{elbow}): the angle formed by the longitudinal axes of the arm and the forearm of the throwing side

- Torso inclination (φ_{torso}): the angle between the horizontal level and the line connecting the midpoints of the hips and shoulder joints' axis
- Leg inclination (φ_{leg}): the angle between the horizontal level and the line connecting the hip and ankle joints
- Release velocity (V_0): the resultant velocity of the javelin's centre of mass at the instant of release
- Height of release (h_0): the vertical distance between the ground and the javelin's mass centre at the instant of release
- Release angle (θ_0): the angle between the direction of the vector of the release velocity and the horizontal level
- Angle of attitude (θ_α): the angle between the horizontal level and the longitudinal axis of the javelin
- Angle of attack (θβ): the angle between the javelin's longitudinal axis and the direction of the vector of the release velocity

S_{LD}, Sγ and h_0 were also expressed relatively to body height in order to normalise data by excluding the effect of the anthropometric factors. To fulfil the descriptive nature of the present study, the researchers also obtained the number of the strides of the running and the acyclic parts of the approach by visual observation.

Statistical Analysis. Results are provided for the group of the analysed throws in the form of basic descriptive statistics (mean ± standard deviation). After testing the normality of the distribution for each parameter with the Kolmogorov-Smirnov test, a two-tailed Pearson correlation analysis was used to investigate possible correlations between the examined spatio-temporal and release parameters and the official throwing distance, along with the intercorrelation among the examined parameters. All statistical procedures were conducted using the SPSS 10.0.1 software (SPSS Inc., Chicago, IL), with the level of statistical significance set at $p = 0.05$ for all analyses.

RESULTS

The average S_{OFF} of the analysed throws was 59.22 m ± 4.42 (range: 49.78 m – 67.78), which corresponded to 93.2% of the participants' season best. 26.1% of the attempted throws were fouls. On average, the approach consisted of 7.7 running strides, followed by the acyclic part which was accomplished with 7 strides by all the participants. The values of the parameters extracted for the instants of the last right foot touchdown (T1), last left foot touchdown (T2) and javelin release (T3) are presented in Table 1. The delivery phase (T1→T3) had a duration of 0.335 sec ± 0.033, in which the ratio between the single-support phase (T1→T2) and the double-support phase (T2→T3) was approximately 60%:40% (± 6.2).

S_{LD} was about 80% (± 7.8) of the body height and was correlated with the time interval between T1 and T2 ($r = .495$, $p < .05$), with φ_{torso} at T1 ($r = .508$, $p < .05$) and with θ_{elbow} at T1 ($r = -.489$, $p < .05$). θ_{elbow} at T1 was also negatively correlated with φ_{torso} ($r = -.616$, $p < .01$) and the duration of the double-support phase ($r = .636$, $p < .01$). The duration of the single support was related with θ_{Lknee} at the instant of release of the javelin ($r = .539$, $p < .05$). S_{OFF} was negatively correlated ($r = -.608$, $p < .05$) with θ_{Rknee} at T1. Sγ from T2 to T3 was about 108.5% ± 15.5 of body height.

Table 1. Values of the spatio-temporal parameters at the last right foot touchdown (T1), at the last left foot touchdown (T2) and at the release of the javelin (T3) and the respective correlation coefficient (r) with the official throwing distance for the analysed attempts ($n = 26$)

Parameter	**Mean**	**SD**	**r**	**sig**
Duration of delivery stride (sec) – T1→T2	0.201	0.031	-.196	ns
Duration of release (sec) – T2→T3	0.134	0.018	-.286	ns
Duration of delivery phase (sec) – T1→T3	0.335	0.033	-.284	ns
Delivery stride length (S_{LD}, m) – T1→T2	1.40	0.14	.428	ns
Distance from foul line (S_{FL}, m) – T2	2.27	0.70	.172	ns
Javelin acceleration path ($S\gamma$, m) – T2→T3	1.92	0.27	.293	ns
Support leg knee angle (θ_{Rknee}, °) – T1	142.2	13.1	-.608	*
Throwing arm elbow angle (θ_{elbow}, °) - T1	156.2	15.5	.075	ns
Torso inclination (φ_{torso}, °) – T1	69.6	5.4	.240	ns
Braking leg knee angle (θ_{Lknee}, °) – T2	164.6	3.9	-.002	ns
Braking leg inclination (φ_{leg}, °) – T2	50.6	5.0	.138	ns
Braking leg knee angle (θ_{Lknee}, °) – T3	155.0	17.6	.097	ns

Legend: The data on the parameters are expressed as mean values and standard deviation (SD). Figure 2 provides an illustrated description of the definition of the parameters. An asterisk indicates a significant correlation (sig = *: $p < 0.05$); ns: non-significant.

The release parameters are presented in Table 2. h_0 was equal to 103.3% ± 5.4 of the participants' body height. V_0 was strongly correlated with S_{OFF} ($r = .909$, $p < .001$) and with θ_{Rknee} at T1 ($r = -.543$, $p < .05$).

Table 2. Values of the 2D release parameters of the analysed attempts ($n = 26$) and the respective correlation coefficient with the official throwing distance (sig = ***: $p < .001$).

Parameter	**Mean**	**SD**	**r**	**sig**
Velocity of release (V_0, m/sec)	22.0	0.8	.909	***
Height of release (h_0, m)	1.80	0.08	.225	ns
Angle of release (θ_0, °)	36.0	3.9	-.231	ns
Angle of attitude ($\theta\alpha$, °)	41.0	5.2	-.020	ns
Angle of attack ($\theta\beta$, °)	5.0	6.7	.116	ns

Legend. The data on the 2D release parameters are expressed as mean values and standard deviation (SD). An asterisk indicates a significant correlation (sig = ***: $p < 0.001$); ns: non-significant.

θ_{Lknee} at T3 was found to be the most variable parameter. A detailed examination of θ_{Lknee} and θ_{Rknee} revealed differences concerning the function of the lower extremities during the entire delivery phase. Figures 2 and 3 present two distinct patterns: a constant flexion of both knees during the double support of the delivery phase (Figure 3), and a flexion-extension function of both knees in the same time period (Figure 4).

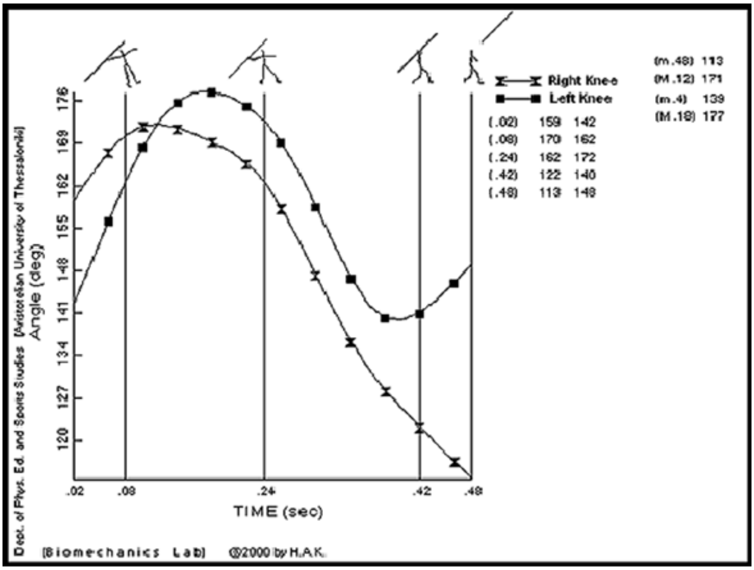

Figure 3. Javelin throwing pattern with the knees of both legs continuously flexing during the double support of the delivery phase (m: minimum value; M: maximum value). From left to right, the three vertical axis represent the instances of last right foot touchdown, the last left foot touchdown and the release of the javelin, as indicated by the respective stick figure at the top of the plot.

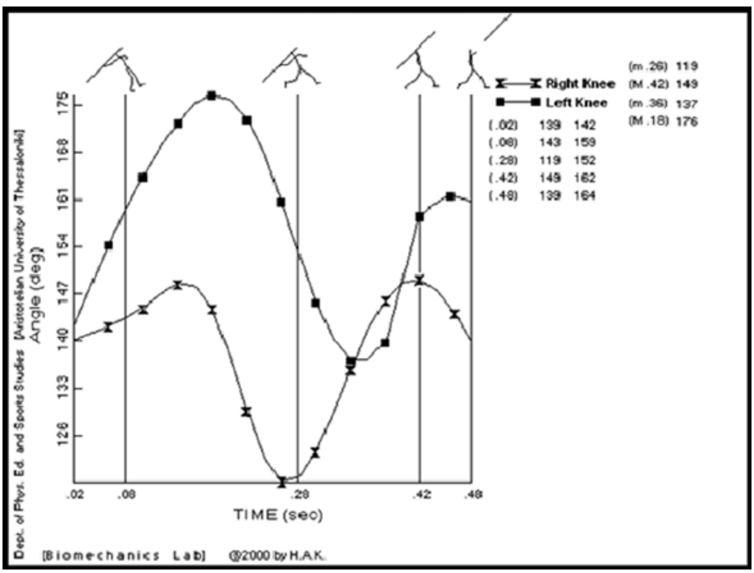

Figure 4. Javelin throwing pattern with a stretch-shortening function of the knee extensor muscles of both legs during the double support of the delivery phase (m: minimum value; M: maximum value). From left to right, the three vertical axis represent the instances of last right foot touchdown, the last left foot touchdown and the release of the javelin, as indicated by the respective stick figure at the top of the plot.

DISCUSSION AND CONCLUSIONS

Based on the results of the correlation analysis, S_{LD}, φ_{torso}, θ_{Lknee}, θ_{Rknee} and θ_{elbow} were established as important technique elements for top female javelin throw performance. It was confirmed that V_0 was the single most important factor for S_{OFF} since a strong correlation was revealed as previously noted (Bartlett & Best, 1988; Bartonietz, 2000; Bartonietz et al., 1996; Hay, 1985; Lehmann, 2010; Mero et al., 1994; Murakami et al., 2006; Viitasalo et al., 2003). In addition, the other release parameters (h_0, θ_0, θ_α, $\theta\beta$) were in reasonable agreement with findings noted in recent literature (Bartonietz, 2000; Jung et al., 2012; LeBlanc & Mooney, 2004; Lehmann, 2010).

S_{OFF} of the examined female throwers was in line with the distances reported in similar studies concerning the new-rules implement (Jung et al., 2012; Lehmann, 2010; Liu et al., 2010). However, a low percentage of the analysed throws with respect to the season bests was observed. This can be attributed either to the fact that a small share of throwers achieve their personal best in major competitions or to the large seasonal variations noted in throwing performances (Bartonietz & Larsen, 1997).

The duration of the delivery phase observed in the present study was quite a lot shorter than noted in previous studies (Jung et al., 2012; Liu et al., 2010; Mero et al., 1994), mainly because of the faster final left foot touchdown. The faster planting of the left foot is a requirement of efficiency of the throwing movement and depends on its position during the single-support phase and the function of the right leg (Bartonietz, 2000). However, S_{LD} was smaller than past findings (Jung et al., 2012; Lehmann 2010; Menzel, 1986; Mero et al., 1994; Xu & Nelson, 1988) and its correlation with the duration of the single-support delivery phase may indicate the inefficient activity of the rear leg (Bartonietz, 2000). Nevertheless, the 60%:40% ratio between the single-support (T1→T2) and the double-support phase (T2→T3) was approximately in agreement with other studies (Jung et al., 2012; Liu et al., 2010; Mero et al., 1994), indicating the existence of an appropriate movement pattern for the execution of the throw.

φ_{torso} at T1 was found not to agree with previous observations (LeBlanc & Mooney, 2004; Menzel, 1986; Shi & Tong, 2000) since the examined throwers had their body in a more upright position. Although the backward lay of the body during a throw is thought to have a limited influence on the throwing performance (Bartonietz, 2000; Lawler, 1993), the revealed significant relationship of φ_{torso} with other key technique elements such as θ_{elbow} indicates that it is a noteworthy parameter. Nevertheless, the large lean of the trunk backwards has being suggested to favour an increase of the acceleration path since the thrower has additional time to exert force on the javelin (Hay, 1985; Morriss & Bartlett, 1996; Tidow, 1996). The limited backward lean at T1 combined with the shorter duration of each part of the delivery phase than reported elsewhere could be the reasons for observing lower values of V_0 in the present study.

The extension of the throwing arm's elbow at the beginning of the delivery phase is believed to put the javelin in a proper position in order to achieve a more efficient performance (Tidow, 1996) and is associated with greater throwing distances (Leigh et al., 2010). At T1, θ_{elbow} of the examined throwers was on average more extended than the proposed angle of 140° (Morriss, 1995) and previous findings (Kumar, 2005; Liu, Leigh, & Yu, 2009). The extended throwing arm, in combination with the position of the body, results in a beneficial carrying position of the javelin that contributes to better application of the thrower's capabilities during the release phase, more effective release conditions and eventually to better flight conditions for the implement

(Morriss & Bartlett, 1996; Tazuke, 2009). The above description could provide explanations about the existence of the revealed significant correlations among θ_{elbow}, φ_{torso} and the duration of the double-support delivery phase found in the present study.

θ_{Lknee} is thought to be a sign of the thrower's braking ability (Bartonietz, 2000; Maximov, 1979; Morriss, 1995; Morriss et al., 2001) and it is suggested that it should not be less than 150-160° during the entire double-support delivery phase (Lehmann, 2010; Menzel, 1986; Tidow, 1996). The average θ_{Lknee} recorded for the examined athletes, although more flexed than previously reported (Shi & Tong, 2000), was within the suggested values. Moreover, the braking leg's planting φ_{leg} was executed according to recommendations (Bartonietz, 2000). This was important since the actions of the braking leg during the delivery phase contribute to the backward lean of the torso and to the sustained application of the forces on the javelin and thus a larger S_{γ} is achieved (Dyson, 1977). As noted elsewhere (Menzel, 1998), two distinct patterns were revealed concerning the actions of the knee joints. In the first one (Figure 4), both knees were flexed at the beginning with their contact with the ground and then extended until the instant of release. This sequencing enables the stretch-shortening muscle function that, in the case of the rear leg, aides the acceleration of the body and enables the correct segmental sequencing of the throwing movement by properly activating the hip joint axis (Bartionietz, 2000; Liu et al., 2010; Schmolinski, 1983). In addition, the extension of the braking leg contributes to a higher h_0 and a longer S_{γ}, with both parameters believed to eventually result in a larger V_0 and θ_0 (Hay, 1985; Ogiolda, 1993; Schmolinski, 1983). In the other pattern (Figure 3), the knees of both legs were constantly flexing during the double support of the delivery phase. This function was characterised by a slight flexion of the rear leg's knee at touchdown, followed by a further flexion during the pivoting on the foot. A flexed knee of the braking leg is believed to be an indicator of the insufficient application of muscular strength during the delivery phase (Maximov, 1979). Such inadequate braking, accompanied by a short S_{LD} and weak arm and shoulder muscles, could cause the rear leg to take-off before the release of the javelin (Dyson, 1977) and is considered to be a serious technique error (Tidow, 1996). This chain of events was partly verified by the significant correlations observed among the duration of the sub-phases of the delivery and the angles of the examined joints.

Even though the release parameters found were in agreement with previous findings, their use as input variables in a typical projectile equation leads to a deviation between the actual and calculated S_{OFF} of about 9–10 m, which seems to be a typical error in this circumstance (White, 2011). The aerodynamic and environmental factors affecting the flight of the javelin are not determined in kinematical analyses. Although three-dimensional optimisation models have addressed this issue (Best et al., 1995; Maier et al., 2000), knowledge of the landing parameters and a javelin-referenced monitoring of the flight could provide data to enhance the estimation of the impact of the two-dimensional release parameters extracted from a planar kinematical analysis.

In conclusion, the top female athletes presented a typical temporal structure of the delivery phase of their javelin throwing technique since a slight dominance of the single support over double support was noticed. The findings suggest that the distance of the throw is highly correlated with the speed of the javelin upon its release. There were indications that the examined athletes performed the throw by either combining an inadequate braking of the lead leg and an ineffective action of the rear leg or with a proper sequencing of the utilisation of the stretch-shortening function of the muscles around both knee joints. Indications were revealed concerning the importance of the actions of the rear leg on the speed of the implement at its release and eventually for the throwing distance. Another important factor for elite female javelin performance seems to be the existence of a large backward lean of the body with a concurrent mostly extended throwing arm's elbow joint at the beginning of the delivery phase.

It is suggested that female athletes should perform the final stages of the javelin throw focusing on the above mentioned technique elements. However, additional research is needed in order to study the impact of the interaction of the above mentioned parameters when manipulating them so as to achieve optimum release parameters of the javelin and the enhancement of their effect on the throwing distance through training.

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