Acta of Bioengineering and Biomechanics
Vol. 21, No. 1, 2019

Original paper
DOI: 10.5277/ABB-01215-2018-02

Mechanical energy flows between body segments in ballistic track-and-field movements (shot put, discus, javelin) as a performance evaluation method

MICHALINA BŁAŻKIEWICZ*, BARBARA ŁYSOŃ, ANDRZEJ WIT

Józef Piłsudski University of Physical Education, Faculty of Rehabilitation, Warsaw, Poland.

Purpose: Seeking a method to evaluate and monitor the performance of the shot put, discus and javelin throw, we analyzed the transfer of mechanical energy between body segments. *Methods*: The study was conducted on groups consisting of elite throwers on the Polish National Team for each of the aforementioned sport disciplines. The movements of each throw were recorded using Vicon system and Kistler plates. The power and energy fluctuations were computed for the final acceleration phase of each throw. *Results*: In all three disciplines studied, we found an average energy loss of 1.63 J/kg generated from shoulder to wrist. The value of generated energy from ankle to torso initially increased in all disciplines, followed by a descent – with the exception of the javelin throw, where there was an average 27% decrease in both hip joints. We found strong correlations between relative amplitude values of energy and the athlete's personal performance records: –0.8226 (shot put), 0.6008 (discus) and 0.7273 (javelin). *Conclusions*: Measuring the transfer of mechanical energy between body segments offers a useful method for evaluating the technique of ballistic movements and for monitoring training progress.

Key words: *biomechanics, mechanical energy, track and filed*

1. Introduction

The goal of a throwing movement in sports will generally be distance, accuracy or some combination of the two. The shot put, javelin throw, discus throw and other track-and-field throwing disciplines involve no accuracy requirements, so it is the distance of the throw that is the predominant objective. Typically, therefore, the performance of individual athletes in such disciplines is evaluated, and their training progress is monitored, in terms of such easily-measurable physical variables as release velocity, angle, height of release and speed.

The three track-and-field disciplines we examined differ in terms of the type of throwing movements involved. Throwing movements are often classified as underarm, overarm or sidearm [8], with the latter two dominating in track and field throwing events [12], [19]. In an overarm throw, the trunk flexes laterally away from the throwing arm, while in a sidearm throw the trunk flexes laterally towards that arm. The over arm throw has one of the fastest joint rotations in the human body [4]. In a right-handed thrower, for instance, it includes pelvic and trunk rotation to the right, horizontal extension and lateral rotation at the shoulder, elbow flexion and wrist hyperextension. Javelin throwing is a classic example of an overarm throw, the shot put, in turn, combines overarm throwing with a pushing movement, while the discus throw is a sidearm throw, mainly through restricted movement at the shoulder joint, where frontal plane movements dominate. These ballistic sport movements incorporate balance, coordination, central nervous system programming, momentum and generating mechanical energy from the musculoskeletal system.

* Corresponding author: Michalina Błażkiewicz, Józef Piłsudski University of Physical Education, Marymoncka 34, 00-968, Warsaw, Poland. Phone: +48503121114, e-mail: michalinablazkiewicz@gmail.com

Received: September 24th 2018
Accepted for publication: January 29th 2019

The coordination of joint and muscle actions is often considered to be crucial to the successful execution of throwing movements. Mechanical energy is a single variable that encompasses information relating to the mass, moment of inertia, linear velocity, angular velocity and force. Therefore, the transfer of mechanical energy between body segments is proposed as a feature of vigorous sports movements, including throws [2], [6], [19]. Mechanical power is what causes the flow of energy through the body [1]. In a discrete system, power is transferred through joints by joint torques and through reaction forces. Mechanical power represents the rate of passive transfer of mechanical energy into or out of a segment from an adjacent segment, but it carries no information about which force or torque was responsible for the energy transfer. Therefore, the segmental power technique does not enable one to directly determine the effect of a joint torque on the energy level of anatomically remote segments. However, despite this limitation, some researchers have successfully used segmental power analysis to make inferences about mechanical energy flow [13]. Their techniques are based on the assumption that an increase in segmental energy can occur only if joint power is positive.

To date, however, no published study has examined mechanical energy flow during the motions involved in the glide shot put, discus throw or javelin throw. Therefore, the purpose of the present study was to use a segmental power analysis technique to evaluate the transfer of mechanical energy through all leg segments to the trunk and upper limb during throwing motions in these three track-and-field disciplines. Overall, we sought to identify how the analysis of mechanical energy flows between body segments in ballistic track-and-field movements might be used as a better tool for evaluation and monitoring of athletes' performance than the physical variables traditionally used, as mentioned above.

2. Material and Methods

2.1. Participants

The study evaluated groups of athletes from the Polish National Team in each of the three disciplines. All members of the Polish National Team competing in the given discipline were asked to participate, and those who were able to comply were qualified for the groups. Parameters describing the groups of athletes in each discipline are presented in Table 1.

The study was conducted in accordance with the ethical guidelines and principles of the Declaration of Helsinki. All study participants provided written consent to participate in the experimental procedures, which were approved by the local ethics committee.

2.2. Measures and data analysis

Before the experiment, anthropometric measurements were taken for each participant. Next, thirty-four spherical markers were placed at anatomical landmarks according to the biomechanical model PlugInGait standards for the motion capture system (Vicon Motion Systems Ltd, Oxford, UK). Three force plates (Kistler Holding AG, Winterthur, Switzerland) embedded into the floor were used to measure ground reaction force (GRF) data at a sampling rate of 1000 Hz. The motion capture system consisting of nine infra-red cameras was employed to collect kinematic data at a sampling rate of 100 Hz. The force plates were synchronized with the motion capture system. Before the trials were conducted, both systems were calibrated according to the manufacturers' recommendations.

The experiment was conducted in an indoor gym adapted to perform biomechanical tests of shot put, discus and javelin throws. All subjects were right-

Table 1. Parameters of groups of athletes in the shot put, discus and javelin throw

Group [*n* = 8]	Age [years]	Body mass [kg]	Body Height [cm]	Throwing implement [kg]	Personal record [m]*
Shot put	22.3 ± 4.1	105.6 ± 10.5	194.9 ± 4.7	7.26	16.06 ± 4.05
Discus throw	22 ± 4.48	99 ± 8.3	189.6 ± 7.3	2	54.3 ± 12.95
Javelin throw	21.7 ± 2.6	82.6 ± 6.1	182.3 ± 4.8	0.8	57.06 ± 24.3

Note: * http://www.domtel-sport.pl/statystykaLA/

handed throwers and performed three trials. The shot putters used a glide technique and threw a special 7.26 kg ball made of durable flexible polyvinyl chloride (PVC) and filled with pellets. A net was suspended at a distance of 6 meters from the platforms to catch the shot put ball, discus or javelin after each throw was executed. The further analysis was performed based only on those trials which did not involve any random mistakes, with the individual performing the task naturally. A coach was on hand to assess each trial and ensure it had been performed correctly.

2.3. Data analysis

Phase detection

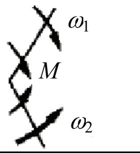
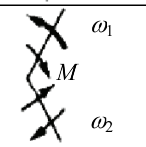
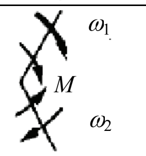
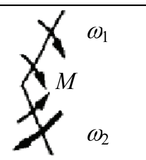
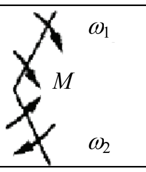
The Vicon system was used to record the kinetics data for each throw. The final acceleration phase was analysed for each discipline [19]. For the shot put and javelin throw, this was determined by the first foot contact with the Kistler platform immediately after the glide, adopted as the beginning of the movement during the shot put, and immediately after the cross-over stride for the javelin throw. For the discus throw, given the lack of a clear impulse of ground reaction forces, the beginning of the analysed movement was determined by the position of the marker located on the right wrist. The end of each movement was determined as the moment at which the projectile left the athlete's hand.

Inverse dynamics, joint power and energy flow

For further analysis muscle torques in each joint were taken into account, based on which the joint power was calculated. Muscle torques were calculated using inverse dynamics method (ID). This task is part of the Vicon system. In practice, inverse dynamics determines the generalized forces (e.g., net forces and torques) at each joint responsible for a given movement. Given the kinematics (motion) describing the movement of a model and a portion of the kinetics (e.g., ground reaction forces) applied to the model, the ID uses these data to yield the net forces and torques at each joint which produce the movement.

A detailed motion analysis was performed on mechanical energy. The evaluation of mechanical energy generation and absorption between body segments required an analysis of the actual sources of mechanical power. Thus, mechanical energy was calculated using the following formula: $E_j = \int_{t_1}^{t_2} \sum_{i=1}^{n} (P_{M(j,n,m)})$, where:

Table 2. Mechanical energy generation, absorption and transfer [19]

Segment rotation	Muscle action	Angular velocity	Muscle function	Amount and direction of power flow		
				Segment 1	Segment 2	Joint torque M
In opposite directions, joint angle decreasing	Concentric		Mechanical energy generation	Receives energy generated by M at the rate: $M_{\omega 1}$	Receives energy generated by M at the rate: $M_{\omega 2}$	Generates energy at the rate: $M(\omega_1 + \omega_2)$
In opposite directions, joint angle increasing	Eccentric		Mechanical energy absorption	Gives off energy at the rate: $M_{\omega 1}$	Gives off energy at the rate: $M_{\omega 2}$	Absorbs energy at the rate: $M(\omega_1 + \omega_2)$
In same directions, joint angle decreasing	Concentric		Mechanical energy generation and transfer	Receives energy at the rate: $M_{\omega 1}$	Gives off energy at the rate: $M_{\omega 2}$	Generates energy at the rate: $M(\omega_1+\omega_2)$ and transfers from segment 2 to segment 1 at the rate: $M_{\omega 2}$
In same directions, joint angle increasing	Eccentric		Mechanical energy absorption and transfer	Receives energy at the rate: $M_{\omega 1}$	Gives off energy at the rate: $M_{\omega 2}$	Absorbs energy at the rate: $M(\omega_1-\omega_2)$ and transfers from segment 2 to segment 1 at the rate: $M_{\omega 1}$
In same directions, joint angle constant	Isometric		Mechanical energy transfer	Receives energy at the rate: $M_{\omega 1}$	Gives off energy at the rate: $M_{\omega 2}$	Transfers the energy from segment 2 to segment 1 at the rate: $M_{\omega 2}$

$P_{M(j,n,m)} = M_{(j,n)}(\omega_{(n)} - \omega_{(m)})\cdot$ $M_{(j,n)}$ is the muscle torque generated by muscles during j-joint movement and, $\omega_{(n)}$, $\omega_{(m)}$, is the angular velocity of the n-th and m-th segment, respectively. Moreover, positive muscle power indicated that the muscle torque and joint angular velocity were moving toward the same direction, and the muscle was doing concentric contraction. In contrast, negative muscle power indicated eccentric contraction of the muscle (Table 2).

Total energy of athlete's center of body mass

For each athlete, potential (E_p) and kinetic (E_k) energy fluctuations of CoM were calculated according to the equations: $E_p = mgz$; $E_k = E_{kx} + E_{ky} + E_{kz} = 0.5m[(\dot{x})^2 + (\dot{y})^2 + (\dot{z})^2]$, where m is the athlete's body mass, g is the acceleration due to gravity (9.81 m/s^2), z is the vertical displacement of CoM, E_{kx} is the lateral kinetic energy, E_{ky} is the horizontal and E_{kz} is the vertical kinetic energy. Total energy was calculated according to the following formula: $E_{\text{tot}} = E_p + E_k$ [7]. The possibility of energy transfer depends not only on the shape of the E_p and E_k curves, but also on their relative magnitude and phase relationship [3]. Energy exchange is optimal when both curves show equal amplitudes. Therefore, their relative amplitudes (RA) were calculated using the following formula: $RA = \dfrac{\max(E_p) - \min(E_p)}{\max(E_k) - \min(E_k)}$. Next, the Spearman correlation was calculated between RA values and the athlete's personal performance records in each discipline using Statistica software (StatSoft Inc., Tulsa, USA). Significance level was set at $p < 0.05$ for all statistical analysis.

3. Results

For each of the groups of athletes (eight in each discipline) tested in our laboratory, in Table 3, median values for generated (positive values) and absorbed energy (negative values) from the distal to the proximal segments respectively for the right and left sides of the body for each discipline were collected, for the mean duration of the final acceleration phase for shot put 0.47 ± 0.06 s, discus 0.59 ± 0.11 s and javelin 0.58 ± 0.05 s.

These energy values indicate that for the entire duration of the final acceleration phase, the discus and javelin throwers showed an increase in energy in the segment between the right lower limb and the right upper limb, with the most energy generated in the hip joint in the case of discus throwers, and in the torso for the javelin group. In contrast, in the shot put group, higher energy values were generated for the ankle and knee on the left side of the body, with the maximum value obtained at the hip joint, similarly to the discus group. For all disciplines, there was an average energy loss of 1.63 J/kg between the upper limb segments from the shoulder to the wrist. It should be noted that in all disciplines the value of generated energy from the ankle to the torso initially rises, followed by a decline, except for the javelin group, which experienced an average 27% decrease in energy at the hip joints.

However, because the possibility of energy transfer depends not only on the shape of the potential energy and kinetic energy but also on their relative magnitude, their relative amplitudes (RA) were cal-

Table 3. Positive and negative median energy values in each group from the distal to the proximal joints

Discipline	Positive	Median energy values [J/kg]						
		Ankle	Knee	Hip	Torso	Shoulder	Elbow	Wrist
Shot put (n = 8)	Left	0.51	0.91	0.48	1.92	0.96	0.2	0.01
	Right	0.34	0.27	1.33		0.22	0	0.01
Discus (n = 8)	Left	0.11	0.41	0.5	1.96	0.46	0.09	0
	Right	0.77	0.77	2.16		0.05	0.01	0.01
Javelin (n = 8)	Left	0.13	0.69	0.37	1.46	0.40	0.05	0
	Right	0.56	0.96	0.88		0.22	0.26	0.03
	Negative	Ankle	Knee	Hip	Torso	Shoulder	Elbow	Wrist
Shot put (n = 8)	Left	–0.1	–0.29	–0.19	–0.86	–0.05	–0.02	–0.01
	Right	–0.07	–0.42	–0.64		–0.14	–0.41	–0.06
Discus (n = 8)	Left	–0.06	–0.48	–0.23	–0.3	–0.01	–0.02	0
	Right	–0.12	–0.12	–0.24		–0.6	–0.02	0
Javelin (n = 8)	Left	–0.03	–0.24	–0.29	–0.7	0	–0.01	0
	Right	–0.57	–0.9	–0.4		–0.2	–0.03	0

culated for all the individual athletes in the groups. This showed that the energy exchange is most optimal when both curves show equal amplitudes. This is true for shot putters, for whom the value of the index is 0.91 J. Significantly worse values of 1.82 J and 0.31 J are observed in the discus and javelin throwers.

The last step in the analysis was to calculate the Spearman correlation between RA values and personal performance records in each discipline. There are strong statistically significant ($p < 0.05$) correlations in each of the disciplines: –0.8226 for the shot put, 0.6008 for the discus and 0.7273 for the javelin.

4. Discussion

The main criteria traditionally used for evaluation of the quality of a track-and-field throwing performance include the variables of release velocity, angle and height of release. During athletic events, special reports [10] are prepared that provide a detailed analysis of the best athletes in every discipline in terms of these variables, which have the advantage of being easy to measure, even during a live performance. The research presented in this paper, however, explored other criteria for evaluating such throwing movements, including power, work and the energy generated, absorbed or passed between body segments. In contrast to kinematic parameters, such energetic variables cannot simply be observed and require special equipment to be calculated. Therefore, the results presented herein offer new insights into athletic throwing techniques.

Differences in energy flow were observed in the analysed throws. The javelin throw is classic example of an overarm throw, which is one of the fastest joint rotations in the human body [5], whereas the shot put combines overarm throwing with a pushing movement and the discus throw is a sidearm throw, mainly through restricted action at the shoulder joint, where frontal plane movements dominate. Median energy values allowed us to differentiate between the three different types of throws, showing that the torso plays a key role in the generation and transfer of energy during the shot put and javelin throw, whereas in discus throwing it is the power of the hip joints that is most important. It has long been known [16]–[18] that the energy transfer between two segments occurs when both segments are rotating in the same direction (Table 2), and when there is a net moment of force acting across the joint. This kind of energy transfer related to the work of muscles in the analysed throws showed much higher values for the lower body, compared to upper extremities. We noted, however, that the flow of mechanical energy also occurs when there is a translational movement of the joint. This suggests that in movements requiring high speed generation, such as the shot put, discus and javelin throw, the lower body along with the torso are responsible for generating power, while the other segments convey the energy towards the projectile. The joint translational power, however, was not included in the current study and is therefore a subject worth exploring in future research.

The differences in release parameters in shot putting are inevitably caused by the limitations of the geometry and musculoskeletal structure, and the athletic ability of the thrower [11]. Analysing the data from the 12th IAAF World Championships in Athletics in Berlin in 2009 [10], for instance, one can observe large differences in release parameters for the two best shot putters. This suggests that even among the very top world athletes there are certain significant variations in technique. Therefore, averaging the values of energy transfer for throwers having different heights, weights, strengths and skills may be a certain limitation when comparing the three throwing disciplines.

In the analysed throws, the athletes groups showed varied energy flow patterns. However, absorption of energy was observed in all of them. In the case of the shot putter, it took place mainly in the torso, while the discus and javelin throwers spread the absorption more evenly between segments. The use of the prestretch is one of principle relating to the stretch, which is the shortening of the muscular contraction cycle [9], [15]. In most throws, a segment moves in the opposite direction to the one intended. This initial countermovement is necessary to allow the subsequent movement to occur, for the increased acceleration path, storage of elastic energy, and stretching of the muscle to the optimal length for forceful contraction. Therefore, the presented energy values enable one to determine the body segment locations in which absorption and eccentric work of muscles took place.

Ballistic movements are generally fast and can be subdivided biomechanically into three phases: preparation, action and recovery or follow-through [19]. Each of these phases has specific biomechanical functions. Subsequent phases depend on the previous phases. The final acceleration phase, being a part of the action phase, was analysed in the presented research. It was not possible for the athletes to perform the entire shooting/pushing motion in each discipline. The shot put using the glide technique allowed an athlete to perform the throw using all the described phases. In the case of the discus throw, however, in order to properly record the final acceleration phase, the athlete had to shoot from a standing position, with no turns leading up to the throw. This may explain why the duration of the shooting motion was the longest for the discus throwers, since they was not able to generate enough speed. It may also explain why the energy generation and transfer values were the lowest for the discus throw, which may not occur in real conditions.

Our main finding in this study is that RA values correlate with athletes' personal best performances. This is important because it means this index allows the athletes to be evaluated in terms of energy expenditure based on the sporting results achieved. It may also provide a useful criterion of evaluation for throwing technique in various stages of athlete training. Moreover, our finding that RA values correlate with the athletes' personal best performances may lead to another important conclusion. Although the RA was close to 1 only in shot putting, the indicator could still be significant. Cavagna G.A., Thys H. [3] stated that energy exchange is optimal when the E_k and E_p curves show equal amplitude. However, this claim pertained to gait, treating the human body as a reverse pendulum.

5. Conclusion

Therefore, new possibilities of evaluating the athletic throws were demonstrated in the research described herein: based on energy-flow analysis (the energy transfer pattern and the RA indicator), we were able to differentiate not only the throwing disciplines, but also the relative skill level of the throwers. Despite testing almost all the javelin throwers, discus throwers and shot putters on the Polish National Team, the study was limited by the relatively small numbers of participants in the groups (eight each), and the variation seen among them. Additionally, even though the presented research was conducted using projectiles of real size and weight, it was still performed under training conditions. Therefore, we propose that the presented parameters should be studied in future biomechanics analyses conducted during actual athletic events.

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