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The Relationship between Approach Run Kinematics and Javelin Throwing Performance

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Abstract

Purpose: The present study aimed to clarify the kinematic characteristics of effective throwing movements, including the approach run movements, which may help improve javelin performance and coaching methods. Methods: Javelin throw movements were collected from 57 male javelin throwers during several competitive events (including the gold medallist at the 2005 IAAF World Championships in Helsinki). Approach and delivery velocities were calculated using the thrower's centre of gravity. The excellent throwers' (EG group, throws of $\geq$ 70 m) and other throwers' (OG group) average maximum angular velocities of the support and blocking legs' knee flexion were also calculated during the delivery phase. Results: The overall throw performances ranged from 45.25 m to 87.17 m. Significant positive correlations were observed between the initial velocity and approach velocity (r = .657, p < .001) and between the approach velocity and delivery velocity (r = .925, p < .001). Compared to the OG group (-10.86 $\pm$ 3.82 rad/s), the EG group (-9.03 $\pm$ 2.05 rad/s; p < .05) exhibited a significantly lower angular velocity of the support leg's knee flexion. The knee extension angular velocities in the support leg were 7.46 $\pm$ 2.26 rad/s in the EG group and 10.91 $\pm$ 3.30 rad/s

in the OG group, which indicated a significantly lower angular velocity ($p < .05$). Conclusions: We suggest that a high initial javelin velocity can be achieved by converting the rotational velocity of the trunk, which can generate a high arm swing velocity. We also suggest that a kick movement may be needed to maintain a high horizontal velocity at the centre of gravity, until the moment of the final front foot contact, similar to the movements of elite sprinters.

Keywords: javelin throw, performance, kinematic characteristics, approach run, correlation

Introduction

During high-performance javelin competitions, throwers start their run-up during the approach run (approximately 30 m) before the final phase of the throwing movement (Miller & Munro, 1983). Unlike other competitions, javelin competitions permit an isolated approach run, and the javelin is lighter than other thrown items, such as the shot, discus, and hammer. These distinct characteristics of javelin throwing have led to 98.48 m being the current world record for a javelin throw. Therefore, the current objectives of javelin training are to develop high approach run speed and explosive power.

Biomechanical studies of javelin throws have mainly focused on release parameters, such as initial velocity, release angle, attitude angle, attack angle, and release height (Bartlett, Muller, Lindinger, Brunner, & Morris, 1996; Hubbard & Always, 1987; Komi & Mero, 1985; Miller & Munro, 1983). These studies found that a high release velocity was the key factor for achieving top performance. Furthermore, other researchers evaluated data from the 1992 Olympic Games (Mero, Komi, Korjus, Navarro, & Gregor, 1994), and suggested that the upper body contributes to javelin throws, based on the mean intra-group differences in several kinematic parameters from the throws of male and female finalists. Moreover, Whiting, Gregor, and Halushka (1991) have investigated the movement characteristics that are necessary to optimize the approach, transition, release, and flight phases. Murakami et al. (2006) have also confirmed the importance of release velocity, and identified specific throwing movement characteristics that enabled finalists at world championships to achieve higher velocities, compared to other competitors. These characteristics include a higher approach-run velocity and maintaining an extended front knee angle during the final phase of the throw, which helps convert the approach run velocity into forward trunk rotation. Hay (1985) has also suggested that throwers transition from a straight run-up to the final front foot contact (FFC), while Tauchi, Murakami, Endo, Takesako, and Gomi (2009) demonstrated that more successful javelin throwers exhibited a greater right knee angle, which helped maintain a high velocity at the body's centre of gravity during the preparatory phase. However, despite the findings of these many studies, the relationship between the approach run and javelin performance remains unclear. Therefore, the present study aimed to clarify the kinematic characteristics of effective throwing movements, including the approach run movements, which may help improve javelin performance.

Methods

Subjects

Javelin throw movements were collected from 57 male javelin throwers during several competitive events (including the gold medallist at the 2005 IAAF World Championships in Helsinki). The overall throw performances ranged from 45.25 m to 87.17 m, and we created a group of 16 excellent throwers (the EG group) using a performance cut-off of 70 m (41 throwers were included in the other group [the OG group]).

Materials

The throwing movements and approach run were separately recorded using two 200-fps video cameras (Memrecam C^{2}S, NAC, Japan) in the Japanese stadiums and using two 60-fps cameras (DCR-VX2000, SONY, Japan) in the Finnish stadiums. Twenty-four anatomical locations and three javelin locations (Figure 1) were digitized (Frame-dias 2 and 3; DKH,

Japan). The three-dimensional coordinates were calculated using the direct linear transformation method (Abdel-Aziz & Karara, 2015). Kinematic data were smoothed using a fourth-order low-pass Butterworth digital filter with cut-off frequencies of 4.5–20.5 Hz, which were calculated using a residual analysis method (Yokoi & McNitty-Gray, 1990).

Analysis Method

We defined the three phases (Figure 2) of a javelin throw for right-handed athletes according to the methods of Payne (1985): (1) the approach phase before the final rear foot contact (RFC), (2) the delivery phase between the RFC and the FFC, and (3) the release phase between the FFC and the javelin release (JRL). The JRL parameters (initial velocity, release angle, attitude angle, attack angle, and release height) and throwing movements are shown in Table 1. A previous study regarding attitude angle (Komi & Mero, 1985) calculated the angle based on the tip to tail of the javelin. However, in this present study, the attitude angle was calculated using the vector connecting the
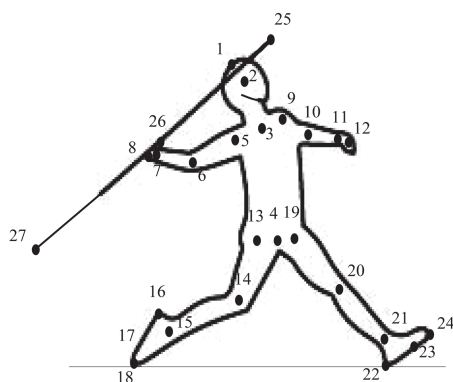
1. vertex of head
2. center of head
3. chest; midpoint of straight line connecting the center of shoulder joints
4. midpoint of straight line connecting the center of hip joints
5.9. center of shoulder joint
6.10. center of elbow joint
7.11. center of wrist joint
8.12. head of the third metacarpal for right/left hand
13.19. center of hip joint
14.20. center of knee joint
15.21. center of ankle joint
16.22. heel
17.23. ball of the pollex
18.24. toe
25. tip of javelin
26. grip of javelin
27. tail of javelin

Figure 1. Digitizing points on the body and javelin.

javelin's grip and tip, in order to exclude vibration in the javelin's tail (Tauchi et al., 2009). The throwing movement characteristics during the delivery phase were defined as horizontal approach and delivery velocity, knee angle, angular velocity, and step length and time; the characteristics during the release phase were the deceleration of the body's centre of gravity's horizontal velocity (V_{dec}), maximum horizontal chest velocity (V_{cst}), maximum hip flexion velocity, and maximum horizontal arm velocity (V_{arm}). The chest was defined as the midpoint of a straight line connecting the centers of the shoulder joints.

Statistical Analysis

The relationships between the variables were evaluated using Pearson's correlation coefficient. The probability level for statistical significance was set at $\alpha = .05$. Inter-group comparisons were performed using the t-test.

Results

Release Parameters

Table 2 shows that the javelin's initial velocity was significantly correlated with throw distance ($r = .889$, $p < .001$) and the attack angle was negatively and significantly correlated with throw distance ($r = -.303$, $p < .05$), but not with release height or release attitude.

Approach, Delivery, and Initial Velocities

Approach velocity and delivery velocity were calculated using the thrower's centre of gravity. Significant positive correlations were observed between the initial velocity and approach velocity ($r = .657$, $p < .001$; Figure 3a) and between the approach velocity and delivery velocity ($r = .925$, $p < .001$; Figure 3b).

Kinematics of Step Movement during the Delivery Phase

Figure 4a shows the EG and OG groups' average maximum angular velocities of their support leg's knee flexion during the delivery phase. Compared to the OG group (-10.86 ± 3.82 rad/s), the EG group (-9.03 ± 2.05 rad/s; $p < .05$) exhibited a significantly lower angular velocity. The knee extension angular velocities in the support leg (Figure 4b) were 7.46 ± 2.26
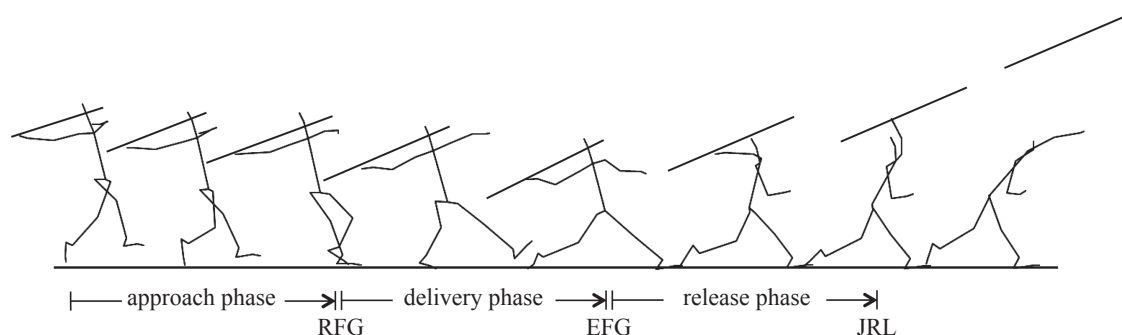

Figure 2. Definition of throwing movement for three phases. Approach phase means between started the approach run and before the rear foot contact (RFC). Delivery phase means between RFC and the front foot contact (FFC). Release phase means between FFC and the javelin release (JRL).

Table 1
Operational Definition

Parameters	Definition
Initial velocity (m/s)	The resultant velocity of the grip, which averaged about 0.03 s after the JRL
Release angle (deg)	The acute angle between the initial velocity of vector and horizontal line, which averaged about 0.03 s after the JRL
Attitude angle (deg)	The acute angle between the vector of tip to the grip of javelin and the horizontal line, which averaged about 0.03 s after the JRL
Attack angle (deg)	The difference between the attitude angle and the release angle, which averaged about 0.03 s after the JRL
Release height (m)	The vertical length between the grip of javelin and ground at the moment of JRL
Approach velocity (m/s)	The horizontal velocity of BCG at the moment of RFC
Delivery velocity (m/s)	The horizontal velocity of BCG at the moment of FFC
V_{cst} (m/s)	The relative horizontal velocity of the chest to the front heel
V_{arm} (m/s)	The relative horizontal velocity of the right hand to right shoulder
V_{dec} (m/s)	The subtraction of the delivery velocity and velocity of BCG at the monument of JRL (horizontal velocity)
Front leg's knee angle (deg)	The intersegment angle of the front leg's knee
Angular velocity of rear leg's knee (rad/s)	The angular velocity of the rear leg's knee
Angular flexion velocity of hip (rad/s)	The angular flexion velocity of the left hip
Step length (m)	The horizontal distance from rear foot toe to front foot heel
Step time (s)	Duration of the step (rear foot toe contact to front foot heel contact)

Note. JRL = javelin release; BCG = body's center of gravity; RFC = rear foot contact; FFC = front foot contact.

Table 2
A Correlation Coefficient of the Distance and Release Parameters of the Javelin

	EG ($n = 16$)	OG ($n = 41$)	CC	S
Distance thrown (m)	76.06 ± 5.62	59.75 ± 6.58	—	—
Initial velocity (m/s)	27.75 ± 1.42	23.49 ± 1.79	0.904	$p < .001$
Release angle (deg)	34.46 ± 2.97	33.88 ± 3.05	0.082	n.s.
Attitude angle (deg)	37.42 ± 3.00	38.81 ± 4.06	-0.252	n.s.
Attack angle (deg)	2.77 ± 3.97	4.92 ± 3.88	-0.303	$p < .05$
Release height (m)	1.73 ± 0.16	1.69 ± 0.11	0.000	n.s.

Note. EG = excellent throwers group; OG = other throwers group; CC = correlation coefficients; S = significance level; n.s. = not significant.
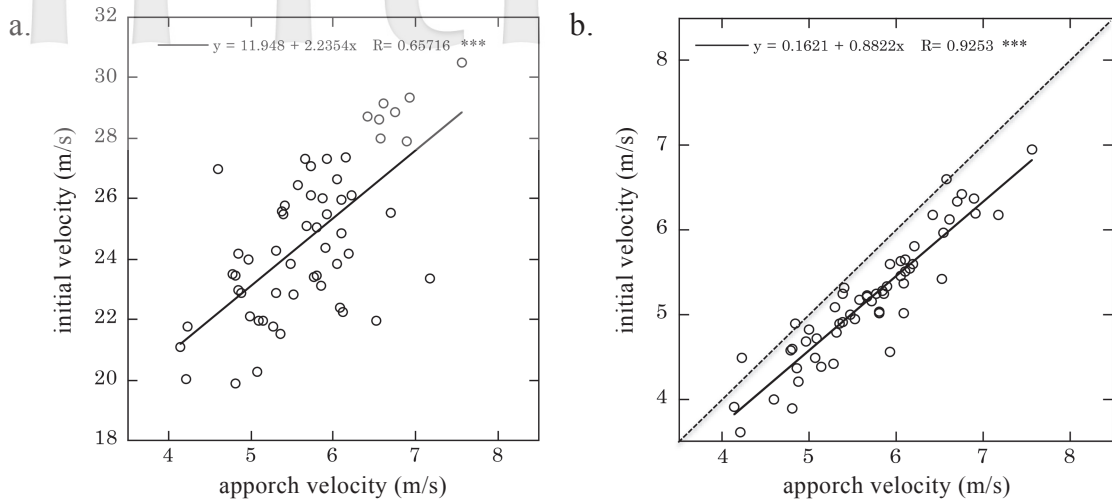
Figure 3. The left figure (a) shows that relationship between initial velocity and approach velocity. The right figure (b) shows that relationship between approach velocity and delivery velocity. A dotted line was indicated a correlation coefficient R equal 1.
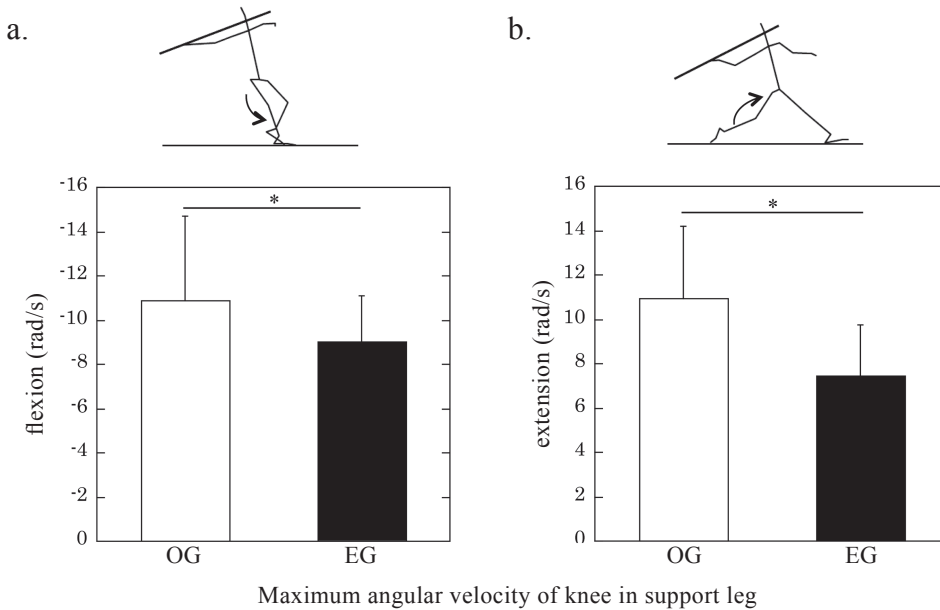
***$p < .001$.

Maximum angular velocity of knee in support leg

Figure 4. The figure compares excellent throwers (EG) with other throwers (OG) for maximum angular velocity of knee flexion (a) and extension (b) in the support leg during DP.

*$p < .05$.

rad/s in the EG group and 10.91 ± 3.30 rad/s in the OG group, which indicated a significantly lower angular velocity ($p < .05$). Step length was calculated using the positions of the left heel and right toes during the delivery phase, and a significant positive correlation was observed between the delivery velocity and step length ($r = .604$, $p < .001$; Figure 5a). A significant negative correlation was observed between the delivery velocity and step time ($r = -.435$, $p < .01$; Figure 5b). We also calculated the deceleration in the delivery velocity to clarify V_{dec} during the release phase, and found a significant positive correlation between Vdec and the delivery velocity ($r = .435$, $p < .01$; Figure 6).
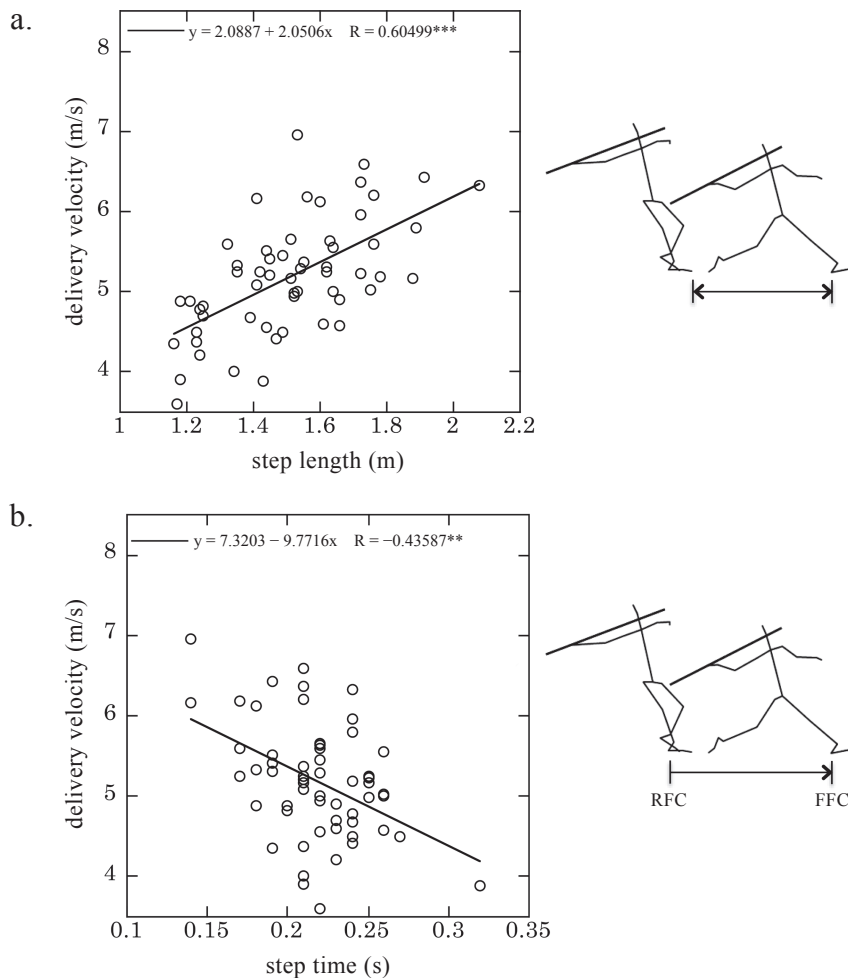

Figure 5. The upper figure (a) shows the relationship between the step length and delivery velocity. The bottom figure (b) shows the relationship between the step time and delivery velocity.
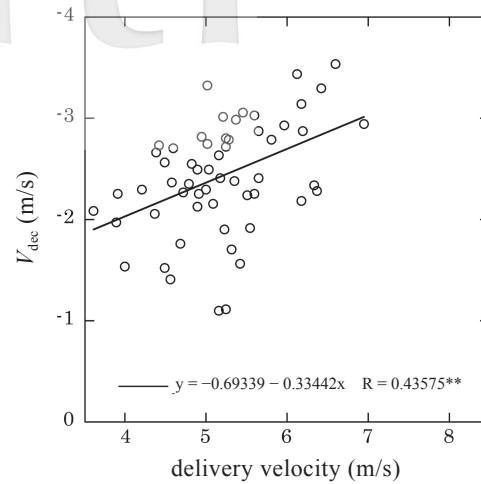
***$p < .001$, **$p < .01$.

Figure 6. The figure shows the relationship between the delivery velocity and deceleration velocity during delivery phase.

**$p < .01$.

Kinematics of Throwing Movement during the Release Phase

We clarified the difference in the tangential maximum chest velocity (V_{cst}) and calculated the left-hip flexion angular velocity to evaluate the forward rotation of the whole body or hip. Figure 7b shows the significant positive correlation between V_{dec} and V_{cst} ($r = .548$, $p < .001$), although Figure 7a shows that there was no significant correlation between V_{dec} and the left-hip flexion angular velocity. Therefore, we measured the influence of whole-body forward rotation on the flexion angle of the blocking leg's knee. Figure 8 shows the significant positive correlation between the maximum flexion angle of the blocking leg's knee and V_{cst} ($r = .359$, $p < .05$). To calculate the forward rotation velocity of the whole body (V_{cst}), we needed to maintain extension of the blocking leg's knee. Thus, we evaluated the relationship between V_{cst} and the arm velocity (V_{arm}), and Figure 9a shows the significant positive

correlation between V_{cst} and V_{arm} ($r = .661$, $p < .001$). The blocking leg's knee angle was 154.66 ± 16.99° for the EG group and 141.05 ± 25.54° for the OG group (p < 0.05; Figure 9b). Figure 10 shows the significant positive correlation between V_{arm} and the initial release velocity ($r = .714$, $p < .001$).

Discussion

Unlike other throwing competitions that only allow a short run-up, javelin competitions allow an approach run. Therefore, we aimed to clarify the kinematic characteristics of the approach run during javelin throwing. Based on the work of Payne (1985), we characterized three phases of the throwing movement (Figure 2): the approach phase, the delivery phase, and the release phase. These phases allowed us to investigate the relationship of javelin performance with the approach velocity and delivery velocity, using the thrower's centre of gravity. The JRL parameters from the
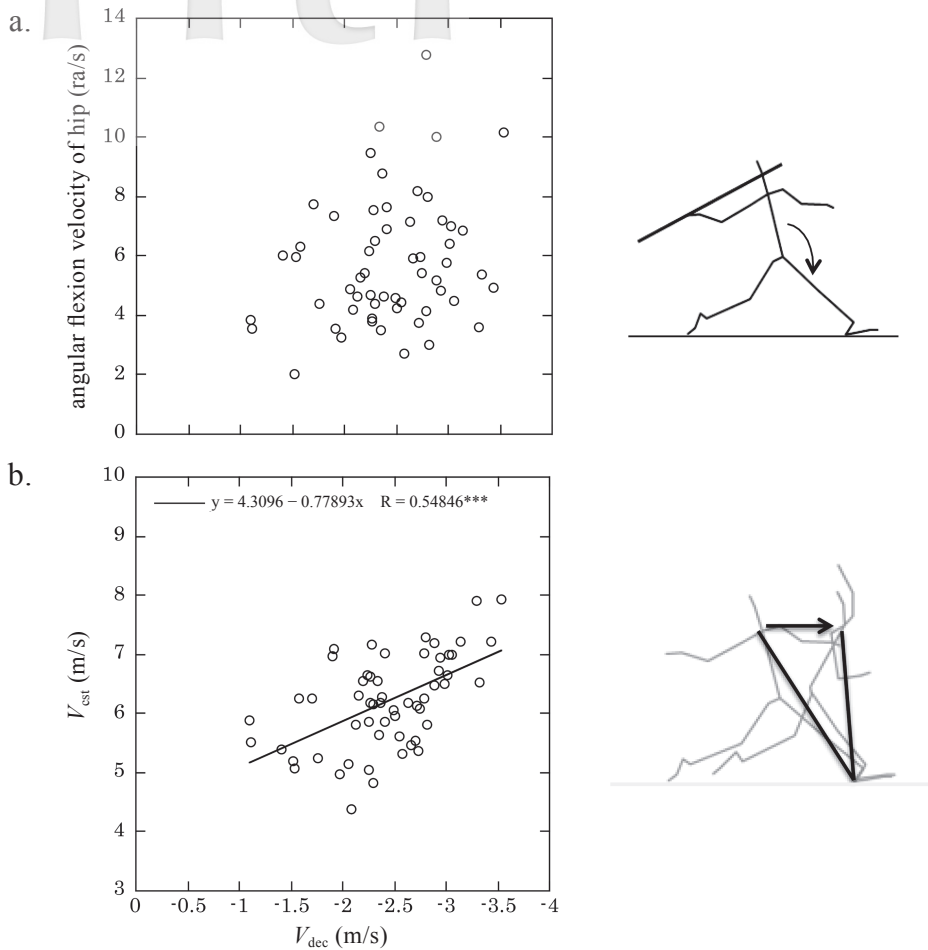
Figure 7. The upper figure (a) shows the relationship between the deceleration velocity of body's center of gravity and angular velocity of hip joint. The Bottom figure (b) shows the relationship between deceleration velocity of body's center of gravity and maximum chest horizontal velocity. **$p < .01$.

present study were consistent with those from previous studies (Bartlett et al., 1996; Hubbard & Always, 1987; Komi & Mero, 1985; Miller & Munro, 1983). Those studies found that initial velocity and reactions to environmental factors were significantly correlated with the distance that the javelin was thrown. In the present study, initial velocity was very significantly correlated with distance thrown (r = .904, $p < .001$), and the attack angle was also negatively correlated with distance thrown (r = -.303, $p < .05$). Distance was not correlated with release angle, attitude angle, or release height. The lift force is critical during a javelin throw, although the results of Lehmann (2014) indicated that the attack angle tends to decrease among excellent throwers (throws of > 87 m) who achieve greater distances. According to the study of Hubbard and Always (1987), the attack angle in the simulation has a tendency
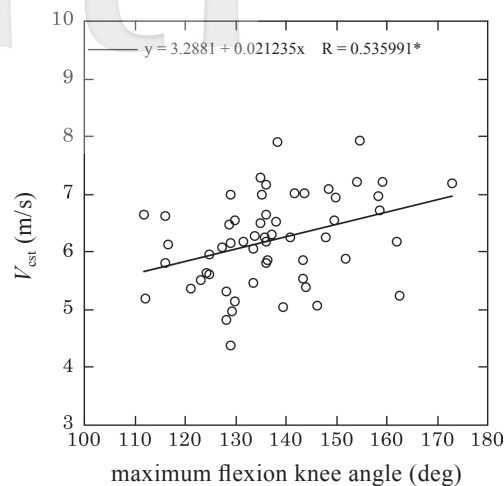
Figure 8. The figure shows the relationship between the maximum chest velocity and maximum flexion angle of front knee during release phase.

**$p < .05$.

to decrease from 0º to -2.5º when it reaches the javelin's nominal velocity of 23–35 m/s. Thus, we found that reducing the attack angle is necessary to obtain a longer throwing distance. Although this present study revealed a negative correlation between the attack angle and throw distance, these results are consistent with the previous finding that a javelin's initial velocity is the most important factor in improving performance.

In the present study, we also investigated the correlations of the approach, delivery, and initial velocities. Significant positive correlations were observed between the initial velocity and approach velocity ($r = .657$) and between the approach velocity and delivery velocity ($r = .925$). Lehmann (2014) had reported that the javelin's velocity was approximately 10 m/s at the FFC and this velocity was about 30% of the javelin's initial velocity. These results suggest that high approach and delivery velocities should be maintained until the FFC in order to generate

the optimal initial velocity. We also evaluated the movement of the support leg's knee during the delivery phase, and found that the EG group exhibited a significantly lower knee flexion angular velocity, compared to the OG group. In addition, the knee extension angular velocity in the EG group was significantly lower than that in the OG group. Furthermore, we observed a significant positive correlation between step length and delivery velocity ($r = .604$) and a significant negative correlation between step time and delivery velocity ($r = -.435$).

Ito et al. (1998) have reported that the elite sprinters did not extend their knee to transfer the hip extension velocity effectively to the leg swing velocity during the supported leg's contact. Thus, elite sprinters obtain a high running velocity using less extension movement in the knee of the support leg. This directs the hip joint's movement towards the ground and increases the swing velocity of the whole support leg, which extends the forward movement. In contrast, a lower running velocity
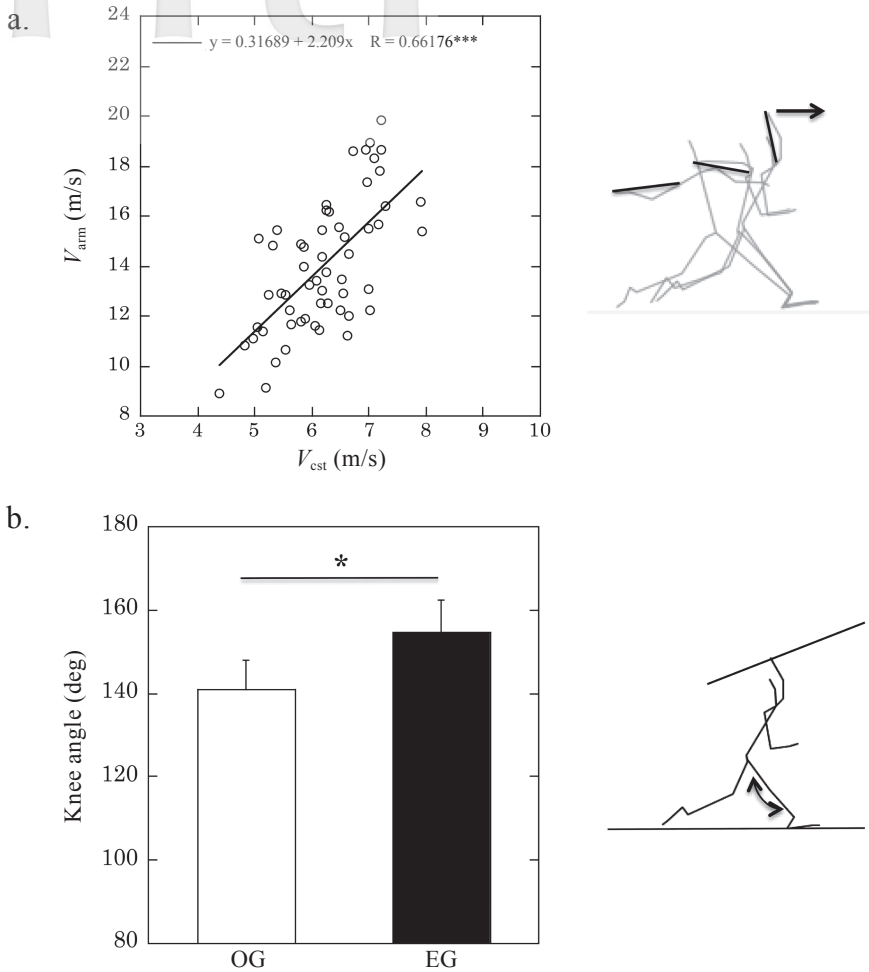
Figure 9. The upper figure (a) shows the relationship between maximum chest horizontal velocity and arm swing velocity. The bottom figure (b) compares the maximum angle of knee extension during the release phase between excellent throwers (EG) and that of other throwers (OG). ***p < .001, *p < .05.

was caused by absorbing the reactionary force from the ground through greater extension movement in the knee of the support leg.

A similar mechanism may also contribute to javelin throwing, as it would allow the thrower to maintain a high delivery velocity using less knee movement and to achieve a longer stride in less time (Figure 11). Moreover, Lehmann (2014) had reported that the forward translation of the hip on the support leg side induces tension in the trunk. Thus, performing an intentional kick movement of the support legs may prepare a wide basal plane for both legs while maintaining a high delivery velocity, and also prepare for the throwing movement of the upper body in the subsequent release phase. These findings suggest that specific lower-body movements during javelin throwing are
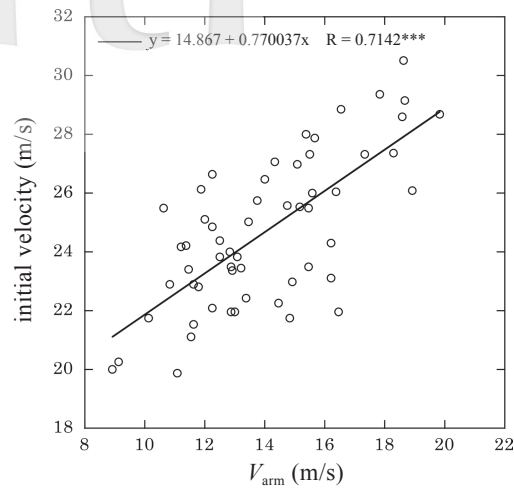
Figure 10. The figure shows the relationship between the initial velocity and arm swing velocity. ****p* < .001.
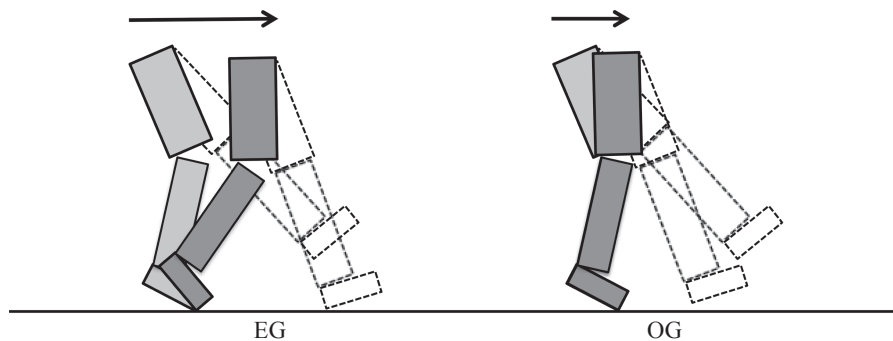

Figure 11. The figure shows the modified kick movement exhibited by excellent javelin throwers (EG) compared with other throwers (OG) during the delivery phase.

necessary to achieve high performance in the delivery phase.

We also evaluated the correlation of delivery velocity with V_{dec}, and found that delivery velocity was correlated with V_{dec} (r = .435). Therefore, we investigated the change in delivery velocity during the release phase, based on the correlation of V_{dec} with V_{cst}. There was a significant positive correlation between V_{dec} and V_{cst} (r = .548), but no significant correlation between V_{dec} and the hip flexion angular

velocity. In this context, Murakami et al. (2006) have reported that elite throwers exhibit a high angular velocity during forward trunk rotation at the moment of the JRL. Thus, these results suggest that excellent throwers generate a high forward rotation velocity using their whole body, and maintain this velocity at the moment of the JRL.

In the present study, we evaluated how the blocking leg movement during the release phase helped achieve a high V_{cst}. We observed

a significant positive correlation between the maximum knee flexion angle and V_{cst} ($r = .359$), which suggests that a more extended knee angle in the blocking leg can promote a high V_{cst} during the release phase. We also found that effective support leg movement helped promote excellent throws, as a high delivery velocity was achieved by converting whole-body forward rotation by extending the knee of the blocking leg throughout the throwing motion. Furthermore, we observed a significant positive correlation between V_{cst} and V_{arm} ($r = .661$). Previous baseball pitching studies (Feltner & Dapena, 1986; Fleisig, Chu, & Weber, 2009) have been able to identify the optimal throwing arm movement for that sport, and we hoped that it would be theoretically possible to identify the optimal throwing arm movement for the javelin in the present study using the internal and external rotation of the shoulder joint. However, even though we measured the tangential velocity of the right arm (V_{arm}), the internal and external rotation angles were difficult to digitize based on the intersegment angle of the extended elbow.

We compared the EG and OG groups to evaluate the knee angle at the moment of the JRL, and observed a significantly greater extension in the EG, compared to the OG. Mero et al. (1994) and Murakami et al. (2006) have reported that gold medallists exhibit a large extension in their front leg's knee at the FFC, which suggests that excellent throwers tend to execute stronger blocking movements, compared to less effective throwers (Lehmann, 2014; Morris, Bartlett, & Navarro, 2001). Thus, excellent throwers appear to maintain a more extended knee angle by swinging the throwing arm until the moment of the JRL. Finally, we investigated the correlation of V_{arm} and the javelin's initial velocity, and the results suggest

that excellent throwers tend to achieve high initial velocities using a high V_{arm}.

Conclusions

The present study revealed several new technical details related to javelin throwing, which can help improving javelin performance. First, it is necessary to effectively convert the horizontal velocity of the center of mass to rotational velocity of the trunk, while keeping an extended position in the blocking leg. Thus, a high arm swing speed may be achieved by converting the rotational velocity of the trunk, which may help provide a high initial velocity. We also suggest that a kick movement during the delivery phase is needed to maintain a high horizontal velocity at the center of gravity, until the moment of the FFC, similar to the movements of elite sprinters.

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