Three-dimensional kinetic analysis of the throwing arm and torso motion for elite male javelin throwers

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Abstract

There is little three-dimensional kinetic information of elite javelin throwers during real competition. The purpose of this study was to investigate and describe three-dimensional kinetics of the throwing arm and torso for elite male javelin throwers, i.e. a world record holder and a Japanese record holder. The javelin throwing motion of the two elite throwers was videotaped with two high-speed video cameras operating at 200Hz in official competitions. The three-dimensional direct linear transformation (DLT) method was applied to calculate the joint torques, joint forces and joint torque powers for the throwing arm and torso joints by an inverse dynamics approach. The major conclusions were as follows. 1) Elite male javelin throwers generated the great torque at the torso joint. 2) Although the abduction and internal rotation torques of the shoulder joint and the varus torque of the elbow joint were common in both throwers, the joint torques were used in two different ways. 3) The work done by the joint forces at the distal joints was much greater than that done by joint torques, but in the torso this was not the case. 4) Body rotation during the delivery phase is necessary for effectively transferring the mechanical energy generated by the joint torques and will be induced by the body position during the last stride or transition phase.

Key words: javelin throwing, videography, kinetics, DLT method, three-dimensional motion analysis

1. Introduction

Javelin throwing is one of the most subtle events in athletics because the throwing techniques and aerodynamic factors influence the performance much more than in other throwing events and because this event is less influenced by the physique of athletes. The javelin throwing technique can be divided into the run-up, cross-steps, and the delivery and follow-through phases. The most important phase is the delivery phase, which begins with the left foot strike and ends with the release of the javelin in the case of a right-handed thrower. Since investigations of the techniques of elite javelin throwers provide us with better understanding of the throwing techniques, biomechanical analyses of elite javelin throwers, especially three-dimensional analyses of their techniques in real competitions, have been carried out, and research findings have been accumulated by the contribution of sport biomechanists (Komi and Mero,[6)], Gregor and Pink,[5)], Mero et al.,[7)], Wakayama et al.,[13)], Bartlett et al.,[3)], Morriss et al.,[8)], Böettcher and Küehl,[4)], Ae et al.,[2)], Murakami et al.[9)]).

Most of these investigations have analyzed kinematic aspects of the techniques and attempted to determine factors influencing the performance with statistical methods, mostly testing significant differences between excellent and less proficient groups, the correlation coefficient between some kinematic variables and the record in competition. This is one of the most effective approaches to resolving research problems of javelin throwing, i.e. what technique is better, or the best techniques to

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obtain longer throwing distances. Böettcher and Küehl[4] described the throwing techniques for female throwers as, "There are many fewer differences between the techniques demonstrated by the top throwers than expected." However, Morriss et al.[8] pointed out, "Interestingly, each of the athletes had a markedly different way of generating the release speed. Zelezny and Henry appeared to use shoulder medial rotation and elbow extension to provide the force necessary to accelerate the javelin. Backly, however, used rapid shoulder extension and horizontal flexion as primary movements." Their statements imply that another possible approach to understanding javelin throwing techniques would be to investigate a single athlete or a small number of excellent athletes in detail, which is sometimes called a case study. Although Gregor and Pink[5] reported a case study that analyzed the release parameters of Petranoff's world record (99.72m in 1983) with two-dimensional analysis, the number of case studies is still small. Furthermore, the kinetic information such as joint force and joint torque exerted by excellent throwers is essential in understanding their techniques and to determine guidance in the training of javelin throwing. However, there is little three-dimensional kinetic information of elite javelin throwers during real competitions.

The purpose of this study was to investigate and describe three-dimensional kinetics of the throwing arm and torso for elite male javelin throwers, i.e. a world record holder and a Japanese record holder, by using joint torque and joint torque power as primary variables.

2. Methods

2.1 Subjects

The subjects were a world record holder (J. Zelezny, Czech Republic, height 1.88m, body weight 77kg, personal best 98.48m, 1996) and a Japanese record holder (K. Mizoguchi, height 1.81m, body weight 88kg, personal best 87.60m, 1986).

2.2 Data collection and data processing

The throwing motion of the subjects was videotaped with two high-speed video cameras (HSV-500, NAC Co., Japan) operating at 250Hz in the 1995 Japanese Championships in Athletics for Mizoguchi, and the 1996 IAAF Grand Prix in Osaka for Zelezny. The videotaping was done as a research activity of the scientific committee of The Japanese Association of Athletic Federations.

The throwing motion of the best performance in the competition for each subject was chosen as the trial to be analyzed. Their records in the analyzed competitions were 76.60m for Mizoguchi and 90.60m for Zelezny. The three-dimensional DLT method was applied to collect three-dimensional coordinate data of the endpoints of fifteen segments, i.e. both hands, forearms, upper arms, feet, shanks, thighs, head, and upper and lower torso. Digitizing was carried out in every frame from the tenth frame before the moment of touchdown of the right foot (R-on) to the tenth frame after the release of the javelin. The root mean squares of the differences in the three-dimensional coordinates between the measured and estimated calibration points were 0.01m in x (transverse to the throwing direction), 0.009m in y (throwing direction) and 0.007m in z (vertical) for the Japanese Championships in 1995, and 0.015m, 0.011m and 0.008m for the 1996 IAAF Grand Prix. The coordinate data were smoothed by a Butterworth low-pass digital filter with a cutoff frequency at 7 to 12Hz.

The locations of the center of mass and the moments of inertia for the three- dimensional segment link model of the body were estimated from the body segment parameters developed by Ae et al.[1]. Since we were not able to obtain information on the inertia properties of the javelins that the two throwers used in the competitions, the inertia properties input to the equations of motion of a javelin were obtained by measuring an officially approved javelin of the varsity athletics club, University of Tsukuba, with a weight scale for the mass and a pendulum method for the moment of inertia. The inertia properties used for the calculation of the force and moment of the javelin were 0.808kg for the mass and 0.399kgm^2 for the moment of inertia about the transverse axes (x and y axes), assuming the javelin as a thin rod whose moment of inertia about the longitudinal axis was zero.

In calculating the joint force and torque of the hand, it was assumed that the force and torque from the javelin were applied to the hand at the third metacarpal caput. The three-dimensional inverse dynamics approach based on Shimada[11] was applied to calculate the joint torques, joint forces, and joint torque powers for the throwing arm and torso joints, and work done by the joint torques and joint forces. Tang's method[12] was applied to calculate the effective moment, differentiating the angular momentum of the javelin. The joint torque power was calculated as a scalar product of the joint torque and the joint angular velocity obtained as the difference in segment angular velocity between two adjacent segments by subtracting the proximal segment angular velocity from the distal one.

2.3 Definition of the joint coordinates of the throwing arm and upper torso

Figure 1 defines the joint coordinates of the throwing arm and upper torso. For the right wrist joint, the origin of the coordinates was set at the center of the wrist and the z axis was set along the hand and defined as the pronation (+)/spination (-) axis, the x axis was set perpendicular to the plane made by the hand and the forearm and defined as the palmar (+)/ dorsi (-) flexion axis, and the y axis was set as a vector product of the x and z axes and defined as the ulnar (+)/radial (-) flexion axis.

For the elbow joint, the z axis was set along the forearm and defined as the pronation (+)/spination (-) axis, the y axis was set perpendicular to the plane made by the forearm and the upper arm and defined as the extension (+)/flexion (-) axis, and the x axis was set as a vector product of the y and z axes and defined as the varus(+)/valgus(-) axis.

For the shoulder joint, the z axis was set along the upper arm and defined as the internal (+)/external (-) rotation axis. The y axis was assigned as the adduction (+)/abduction (-) axis and was defined as a vector product of the z axis and the interim vector connecting the right bottom edge of the rib cage and the right shoulder joint center. The x axis was defined as the vector product of the y and z axes and considered the horizontal adduction (+)/abduction (-) axis.

For the upper torso, the origin was set at the intersection of the right and left bottom edges of the rib cage. The z axis was set as a vector connecting the intersection of both bottom edges of the rib cage and the suprasternale and was defined as the forward (+)/backward (-) rotation axis. The x axis was set as a vector connecting the left and right bottom edges of

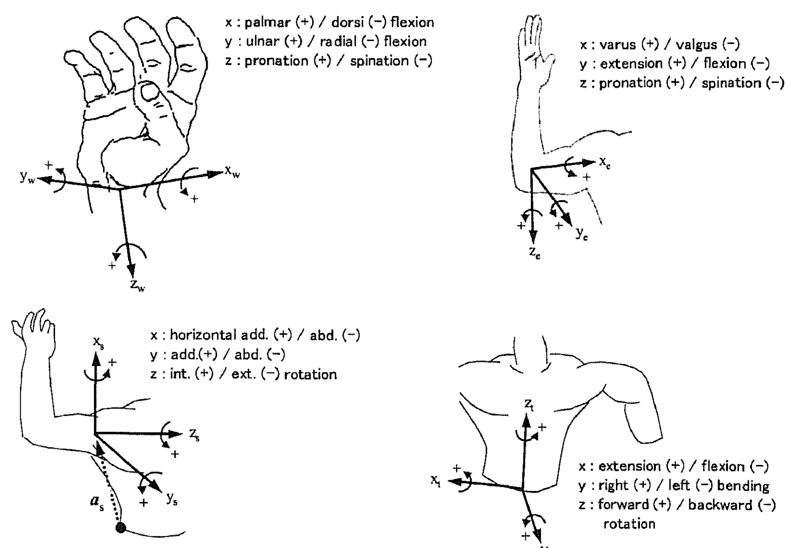

Figure 1 Definition of the joint coordinates of the throwing arm and upper torso.

the rib cage and defined as the extension (+)/flexion (-) axis; the y axis was set as a vector product of the z and x axes and defined as the right (+)/left (-) flexion axis.

3. Results and discussion

Due to the limitaion of official competitions, we were not able to obtain enough information to discuss various factors influencing differences in kinetics between two throwers. There is no doubt that the kinetic parameters of the throwing motion are influenced by the subjects' characteristics such as anthropometric factors, strength, and power. However, we were unable to refer to effects of the subjects' characteristics on the kinetics of their throwing motions, which is a limitation of this study.

3.1 Throwing motions of Mizoguchi and Zelezny

Figures 2 and 3 present a series of stick pictures from the lateral and frontal views during the last stride (R-on to L-on) and delivery phase (L-on to Release) for Mizoguchi and Zelezny. The javelin-throwing motion of Mizoguchi (Figure 2) was characterized by the great backward inclination of the body at R-on, the long last step by the great extension of the right thigh and hip during the last stride, the elevated throwing arm at release, and the small lower torso rotation during the delivery phase.

The motion of world record holder Zelezny in Figure 3 seems to be slightly different from that of Mizoguchi. Compared with Mizoguchi's motion, his throwing motion was characterized by less backward inclination and higher position of the body at R-on, the lack of heel contact with the ground at R-on, the short and quick last step with less extension of the right thigh, the throwing arm kept in the lower position relative to the torso, and less shoulder abduction at release, which seemed more like he had thrown a discus rather than a javelin.

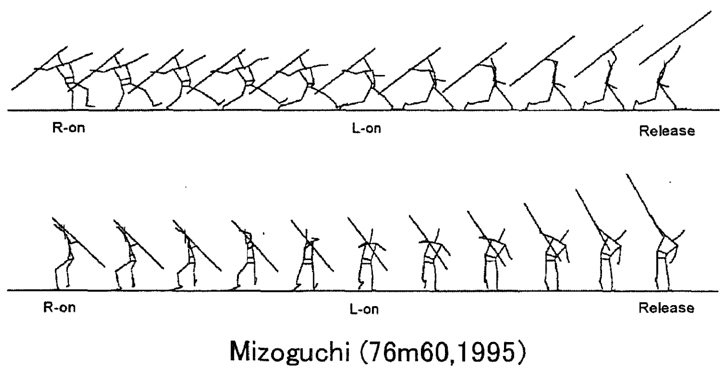

Figure 2 Series of stick pictures depicting the last stride (R-on to L-on) and delivery (L-on to Release) phases for Mizoguchi. Top, lateral view; Bottom, frontal view.

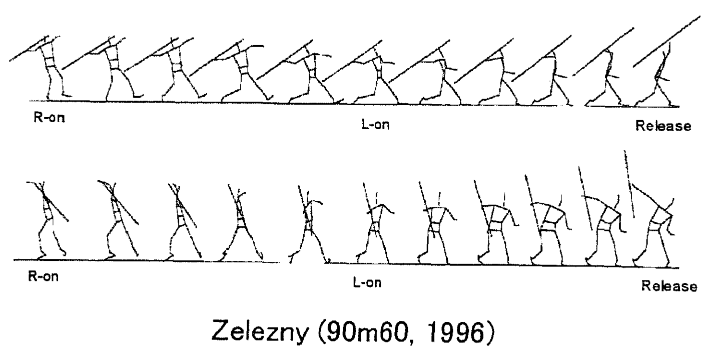

Figure 3 Series of stick pictures depicting the last stride (R-on to L-on) and delivery (L-on to Release) phases for Zelezny. Top, lateral view; Bottom, frontal view.

As mentioned in the Introduction, since the delivery phase is the most important phase in javelin throwing, we focused our attention on the delivery phase for the two record holders and tried to obtain findings to help understand javelin throwing techniques.

3.2 Joint torque, angular velocity and torque power of the throwing arm and upper torso

Since the maximum joint torque of the wrist exerted by the palmar flexion or ulnar flexion was less than 70Nm and much smaller than that of the other joints for both throwers, we excluded the wrist joint from the following discussion.

Figures 4 to 9 illustrate changes in the joint torque, angular velocity and torque power of the throwing arm and upper torso during the delivery phase for Mizoguchi and Zelezny. The top figures depict joint torque; the middle ones, angular velocity; and the bottom ones, joint torque power. It should be kept in mind that scales of the vertical axes in these figures differ from figure to figure.

3.2.1 Upper torso (Figures 4 and 5)

For Mizoguchi (Figure 4), the greatest torque was exerted at the torso joint. The dominant torques were the right flexion and forward rotation torques in the first half of the delivery phase and the left and forward rotation torques in the second half. The angular velocity indicates that the torso rotated forward and then to the left in the first phase and flexed in the second half. Great positive power was generated by the forward rotation torque, and great negative power was generated by the left flexion torque in the first half but the joint torque power was low in the second half. These results indicate that Mizoguchi generated great power of the torso in the first half.

For Zelezny (Figure 5), the dominant torque of the torso was similar to that of Mizoguchi, but he exerted much greater torso torque than Mizoguchi. His torque pattern was characterized by much greater and continuous forward rotation torque and extremely greater left flexion torque before release. The pattern of the angular velocity of Zelezny was very different from that of Mizoguchi in that he extended his torso from the L-on, then rotated to the left and rotated forward in the middle part of the delivery phase. As a result, compared to Mizoguchi, he generated much greater negative power by the flexion torque and right flexion torque, which were followed by the great

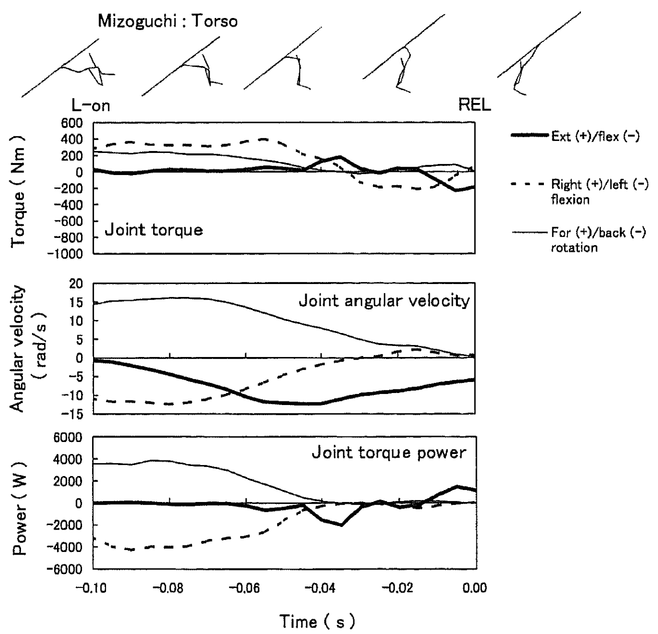

Figure 4 Changes in the joint torque, angular velocity and torque power at the upper torso during the delivery phase for Mizoguchi.

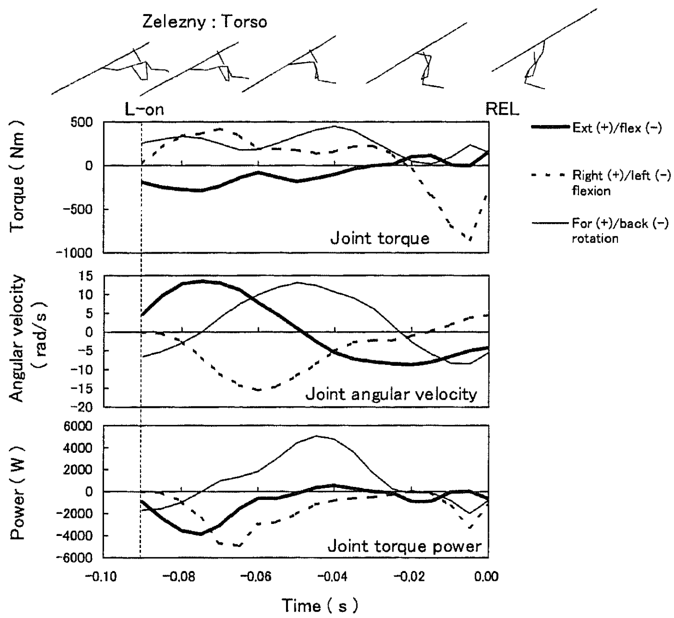

Figure 5 Changes in the joint torque, angular velocity and torque power at the upper torso during the delivery phase for Zelezny.

positive power from the forward rotation torque. This means that his power source from the torso was the great forward rotation torque and velocity during the delivery phase.

Both throwers generated negative power by the right flexion torque at the torso in the first half of the delivery phase, which was contrary to our expectation. Since they flexed the torso to the left side with high angular velocity at or after L-on, the right flexion torque exerted in the first half appeared to inhibit excess left flexion and to stabilize the position of the upper torso.

3.2.2 The shoulder (Figures 6 and 7)

For Mizoguchi (Figure 6), the horizontal adduction and internal rotation torques were almost equal in magnitude, and the abduction torque was exerted during most of the delivery phase. The shoulder abduction torque during the delivery phase helped lift the right upper arm toward the release point. Instead of the relatively low angular velocity of the abduction and horizontal adduction, the internal rotation velocity for Mizoguchi abruptly increased before release and became quite large at release. The internal rotation torque generated negative power in the first half and positive power before release. These results indicated that Mizoguchi largely relied on the shoulder internal rotation to provide the velocity of the javelin.

Zelezny (Figure 7) exerted much greater torques in the shoulder than Mizoguchi. His torque pattern was characterized by greater horizontal adduction and abduction torques at the shoulder. While the changes in the shoulder torques were dynamic, the shoulder angular velocities were relatively flat in that there was no abrupt change in the internal rotation angular velocity before release, even though external rotation angular velocity was observed. He generated much greater positive power by the horizontal adduction torque in the second half and by the abduction torque near release. These power generation patterns indicate that his power generation greatly relied on the abduction torque before release. It is interesting that his internal rotation power was very large but negative, although internal torque was exerted. This pattern was very different from that of Mizoguchi. It can be inferred from the motion of the throwing arm in Figure. 3 and the great abduction and horizontal adduction of the shoulder torques and abrupt increase

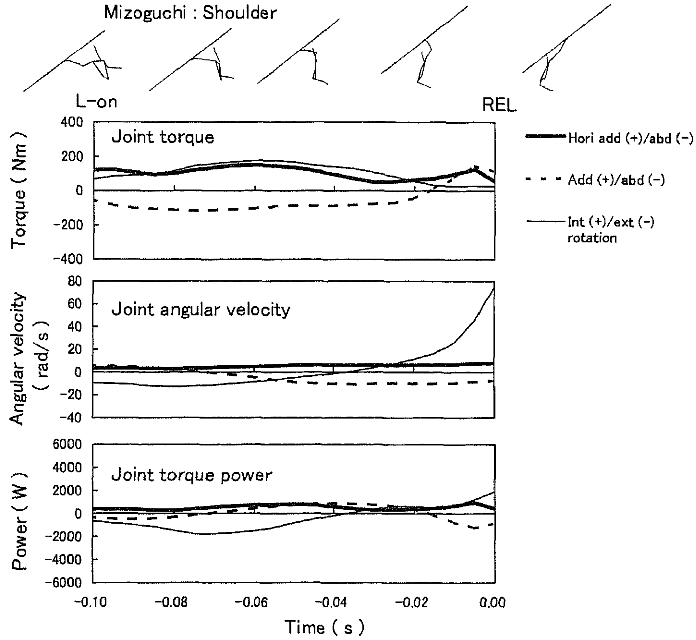

Figure 6 Changes in the joint torque, angular velocity and torque power at the throwing shoulder during the delivery phase for Mizoguchi.

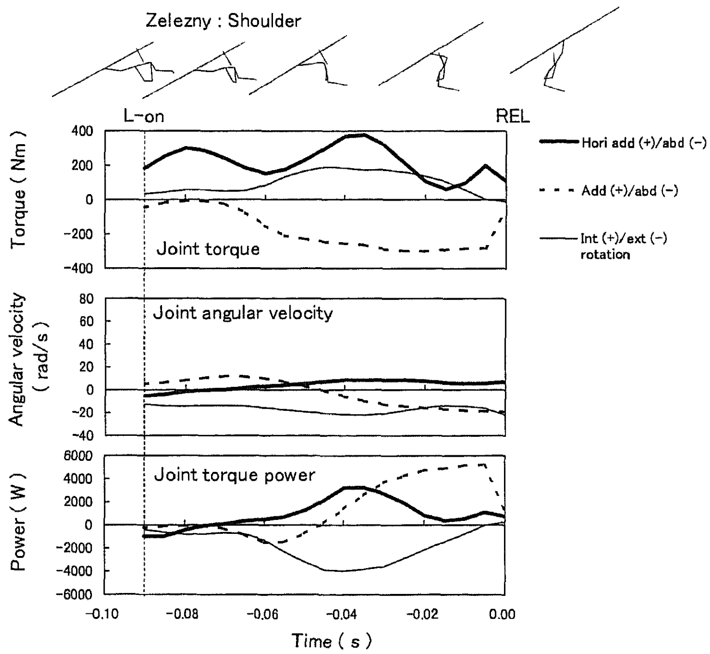

Figure 7 Changes in the joint torque, angular velocity and torque power at the throwing shoulder during the delivery phase for Zelezny.

in the torso left flexion torque that the external rotation moment produced by upward motion-dependent force at the elbow joint was great enough to overcome the internal rotation torque and resulted in the external rotation. It is noteworthy that his shoulder abduction torque was much greater than that of Mizoguchi, although his abduction of the shoulder joint was small. This reveals that Zelezny may have intended to lift his upper arm during the delivery phase but was unable to complete this task. One of the reasons why he was not able to lift up his throwing arm by the release of the javelin may be the limited delivery time due to his fast throwing motion. These power generation patterns at the shoulder joint appear to characterize Zelezny's throwing motion.

3.2.3 The elbow joint (Figures 8 and 9)

For Mizoguchi (Figure 8), the varus torque at the elbow joint was greater during the whole delivery phase than the extension torque, which changed to flexion torque. Since the varus torque pattern was almost synchronized with the pattern of the shoulder internal rotation torque, the varus torque at the elbow joint was likely to be exerted through the shoulder internal rotation torque. His elbow extension angular velocity was so great in the second half that his elbow flexors generated great negative power before the release, in which the elbow flexors helped to prevent hyper-extension of the elbow joint.

Zelezny (Figure 9) exerted much greater elbow extension torque and larger continuous varus torque than Mizoguchi. For the varus torque, a reason similar to the case of Mizoguchi can be applied. His elbow joint angular velocity was still increasing at release. Unlike Mizoguchi, Zelezny generated great positive elbow extension power, but the negative power generated by the elbow flexors was very small. Considering the kinetics of his shoulder joint, these results partially support the statement of Morriss et al.[8] that Zelezny appeared to use the shoulder medial rotation and elbow extension to provide the force necessary to accelerate the javelin.

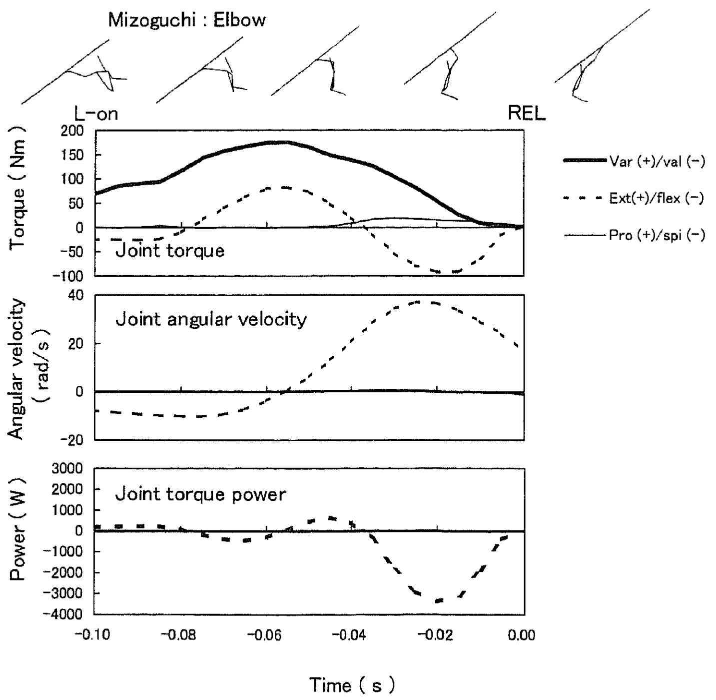

Figure 8 Changes in the joint torque, angular velocity and torque power at the throwing elbow during the delivery phase for Mizoguchi.

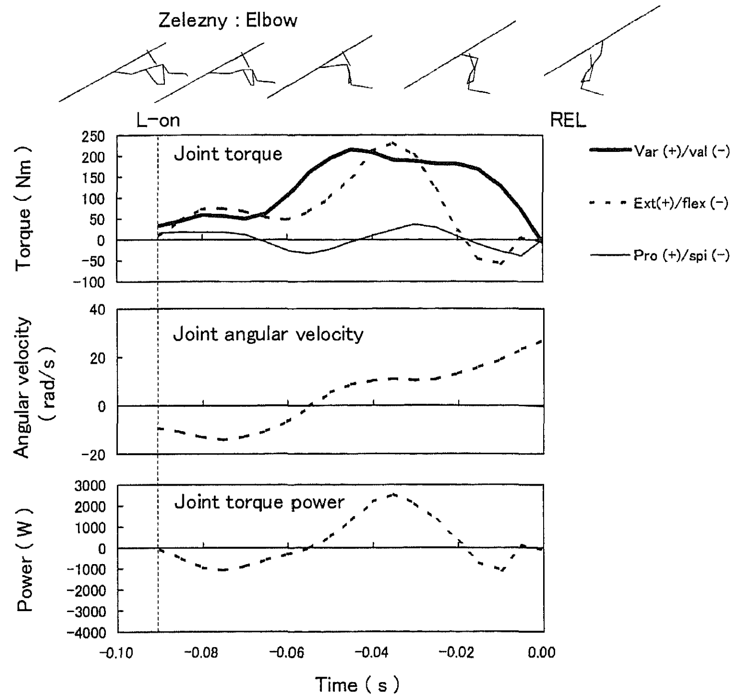

Figure 9 Changes in the joint torque, angular velocity and torque power at the throwing elbow during the delivery phase for Zelezny.

3.3 Work done by the joint torque and joint force

Figure 10 illustrates the positive, negative and total work done by the joint torque and joint force at the throwing arm and torso joints. As a result of the remarkably large joint force power, the positive and total work done by the joint force was much greater than that of the joint torques. It is noteworthy that Zelezny's positive and total work done by the shoulder, elbow, and wrist joint forces was much greater than those of Mizoguchi. Since the wrist joint torque was very small in both throwers, the great amount of positive and total work done by the wrist joint can be attributed to the motion-dependent force at the wrist joint. As the joint force power is considered to be an index of a mechanical energy flow, the great joint force power and the total work done by the joint forces clearly indicates that excellent javelin throwers transfer mechanical energy from the proximal to the distal segments.

Another remarkable difference between Mizoguchi and Zelezny was in the work done by the torso joint torque. As mentioned previously, the joint torque power generated by the forward rotation torque for Zelezny was greater in the middle part of the delivery phase. This result suggests that the most typical technique of Zelezny lies in his torso motion.

3.4 Effects of torso motion on javelin throwing

Figure 11 plots the change in angular velocity of the upper and lower torsos during the delivery phase for Mizoguchi and Zelezny. Although there was some difference in the magnitude of the angular velocity of the upper torso and Zelezny maintained his greater angular velocity a little longer, no remarkable difference was found in the pattern between the two throwers. However, the angular velocity of the lower torso was very different in both the pattern and magnitude. Great double peaks were observed for Zelezny, while Mizoguchi exhibited very small and flat changes in the angular velocity of the lower torso. It appears that Zelezny's first peak contributed to the backward twisting of the upper torso, which would

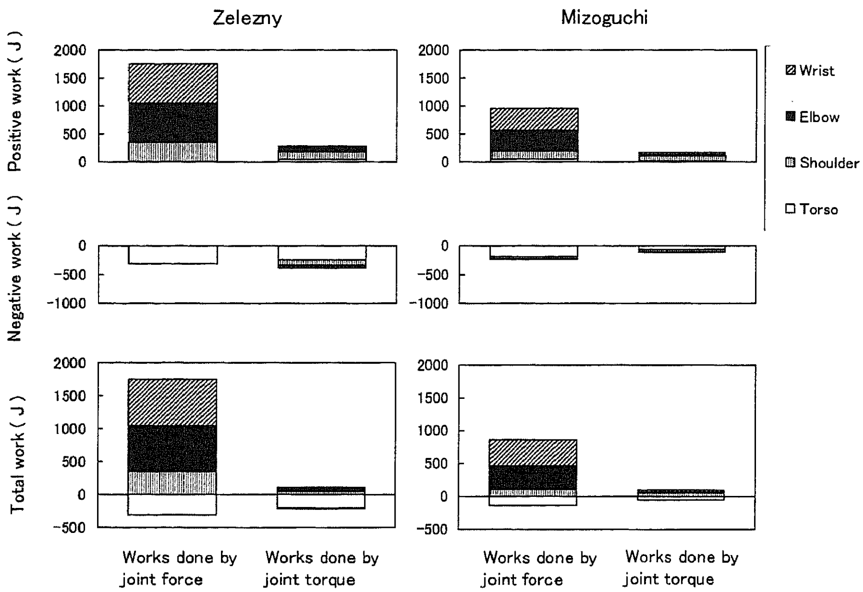

Figure 10 Work done by the joint torque and joint force at the throwing arm and torso during the delivery phase for Mizoguchi and Zelezny.

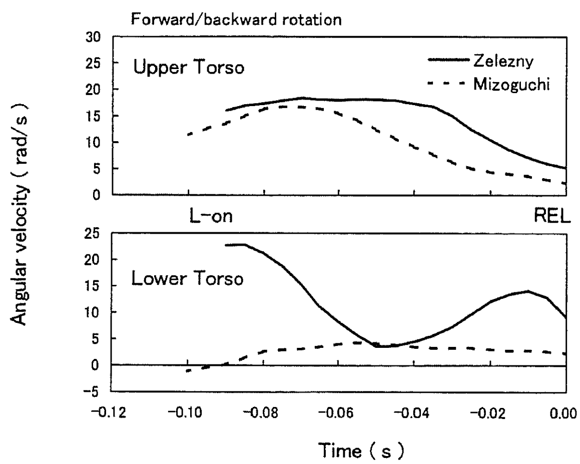

Figure 11 Change in the angular velocity of the upper and lower torso during the delivery phase for Mizoguchi and Zelezny.

cause a stretch-shortening cycle in the torso muscles. Since the second peak magnitude was similar to that of the upper torso, the upper and lower torso rotated together even before release. This rotation may serve to increase the velocities of the shoulder and distal joints. How could Zelezny keep rotating his trunk? In investigating the pathways of the center of gravity (CG) and left foot for Mizoguchi and Zelezny during the penultimate and delivery phases, Ae et al.[2)] found that Zelezny's CG, viewed from the top, proceeded forward a short distance from the left foot while Mizoguchi's CG passed just over the left foot, and suggested that this distance functioned as a moment arm and resulted in the moment about the left foot, which would rotate his hip and trunk. This relationship between the CG and the left foot can be observed in

Figure. 3 in which Zelezny positioned his left foot laterally to land on the left heel during the last stride. The results on the torso motion revealed that a key factor of good javelin throwing techniques, in which mechanical energy must be transferred from the proximal to the distal segments, is an effective use of the torso, and the effective rotation of the torso will be induced by the body position during the last stride or transition phase.

4. Conclusions

The following conclusions can be drawn based on the results and discussion of the throwing arm and torso kinetics during the delivery phase and some kinematics for two excellent male javelin throwers.

1) The elite male javelin throwers generated great torque at the torso joint. In particular, the world record holder continued to exert great forward rotation torque of the torso during the delivery phase.
2) Although the abduction and internal rotation torques of the shoulder joint and the varus torque of the elbow joint were common in both throwers, the joint torques were used in two different ways. One thrower dominantly used the shoulder horizontal adduction torque and elbow extension torque, while the other thrower dominantly used the shoulder abduction and internal rotation torques.
3) The work done by the joint forces at the distal joints was much greater than that done by joint torques, but this was not the case for the torso.
4) These results suggest that good javelin throwing techniques incorporated transfer of mechanical energy from the proximal to the distal segments.
5) The body must be rotated during the delivery phase to effectively transfer the mechanical energy generated by the joint torques; such rotation will be induced by the body position during the last stride or transition phase.

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