RELATIONSHIPS BETWEEN MOTION OF THE SHOULDER JOINT AND THE MAXIMAL HEIGHT OF VAULTERS' CENTRE OF GRAVITY

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The purpose of this study was to clarify the effect of the shoulder joint motion during vaulting on the maximal height of vaulters' centre of gravity (CGv). Eight male vaulters (personal best record: 4 m 60 to 5 m 77) vaulted over a cross bar with run-ups and pole in the same set up as competitions. Three-dimensional coordinates of the body were collected using a motion capture system (250 Hz). The angular displacement of the shoulder joint on the lower grip side between take-off and swing and on the upper grip side between rock back and pole straight showed high correlations with the maximal height of the CGv (r = 0.78 and -0.91, respectively). These results suggest that the shoulder joint motions because this motion could make it easy for vaulters and poles to rotate around the lower tip and possible for them to receive the recoil force of the poles effectively.

KEYWORDS: motion analysis, pole vault, shoulder joint motion

INTRODUCTION: Pole vault is an event in which vaulters compete for the vault height of the cross bar with the pole. In other word, the fundamental principle of pole vaulting is the interaction between vaulters and the pole to convert kinetic energy to potential energy through the strain energy of the pole (Frère et al., 2010). In order to convert the energies effectively, previous studies have shown the importance of shoulder joints and shoulder girdle muscles, which produce major joint torques and gained mechanical energy during vaulting (Frère et al., 2012a; Hubbard, 1980; McGinnis and Bergman, 1986). Thus, the motion of the shoulder joints will effect on the improvement in the maximal height of vaulters' centre of gravity (CGv). However, the effective motion of the shoulder joints for the improvement has not been clarified. Its clarification will provide beneficial information for vaulters and coaches.
Thus, the purpose of this study was to clarify the effect of the shoulder joint motion during vaulting on the maximal height of the CGv.

METHODS: Eight experienced Japanese male vaulters (mass: 69.6±4.53 kg; height: 1.78±0.04 m; season's best vault height: 5.32±0.36 m) participated in this study. This experiment was conducted as an applied research project for athletics managed by the department of Sport Science in Japan Institute of Sport Sciences and approved by the Japan Institute of Sport Sciences Ethics Committee.
After warm-up, the participants undertook trials with run-up steps and poles identical to those in competitions. For each participant, the trial in which the highest maximal CGv height was recorded was analysed. The vaulters' motion from the instant of touchdown (TD) to the time of reaching the peak height of the CGv was investigated. TD was defined as the instant at which the TO foot came in contact with the ground; pole plant (PP), as the instant at which the lower tip of the pole hit the back of the planting box; TO, as the instant at which the TO foot left the ground; swing (SW), as the instant at which the peak angular momentum of the lower limbs around the hip-joint centre was observed; maximal pole bending (MPB), as the instant at which the bending rate reached its maximal; rock back (RB), as the instant at which the trunk angle [angle between the Z axis and the segment connecting the midpoint of both shoulder joint centres and the midpoint of both hip joint centres; Figure 1] reached 90°; inverted position (IP), as the instant at which both hip joints switched from flexion to extension; pole straight (PS), as the instant at which the pole fully extended [Figure 2].

Three-dimensional coordinates of 56 reflective markers attached on specific body landmarks and the pole were collected using a motion capture system (Vicon Motion System Ltd., Oxford, UK) and analysed using the Nexus software (Vicon Motion System Ltd.). The obtained three-dimensional coordinates were smoothed using a fourth-order Butterworth digital filter at optimum cut-off frequencies (15 - 20 Hz), which were determined using the residual analysis methods (Wells and Winter, 1980). The vaulters' body was constructed using a 15-segment model (Winter, 1990) on the basis of the the three-dimensional coordinates.

The shoulder joint angle was defined as the flexion-extension angle within the sagittal plane [Figure 3].

To consider the relationship between the shoulder joint angles and the maximal height of the CGv, the maximal Pearson's product-moment correlation coefficients were used, and their 90% confidence intervals (90%CI) were calculated after the normality test of all variable was performed. Further, the magnitude of the correlation coefficients was assessed on the basis of the definition (Hopkins et al., 2009). Only the variables with 0.7 < r were discussed.

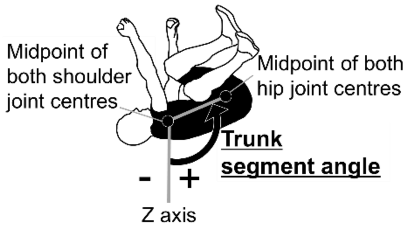

Figure 1: Definition of trunk segment angle.

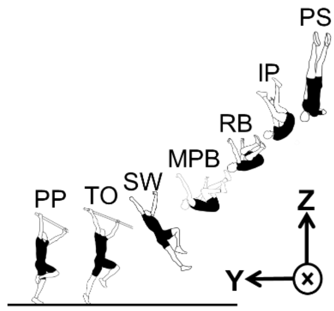

Figure 2: Events during vaulting.

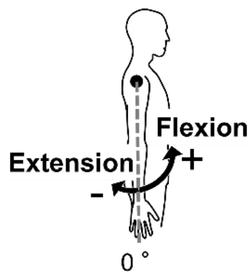

Figure 3: Definition of shoulder joint angle.

RESULTS: The mean maximal height of the CGv of the participants was 5.03±0.29 m.

The time course of the shoulder joint and trunk segment angles between PP to PS was shown in Figure 4. Both shoulder joint angles flexed temporarily after PP. Thereafter, the both sides continued to extend; however, the lower side turned to flex earlier than the other side. The trunk segment angle increased between PP to PS and decreased thereafter.

The means and standard deviations (SDs) of both shoulder joint angles in each event were shown in Table 1.

The correlation coefficients between the maximal height of the CGv and the angular displacement of the shoulder joint angles between each event were shown in Table 2. On the upper grip side, the angular displacement between MPB to PS and RB to PS showed large correlations with the maximal height of the CGv (r = -0.71 and -0.91, respectively). On the lower grip side, the angular displacement between TO to SW showed large correlations with the maximal height of the CGv (r = 0.78).

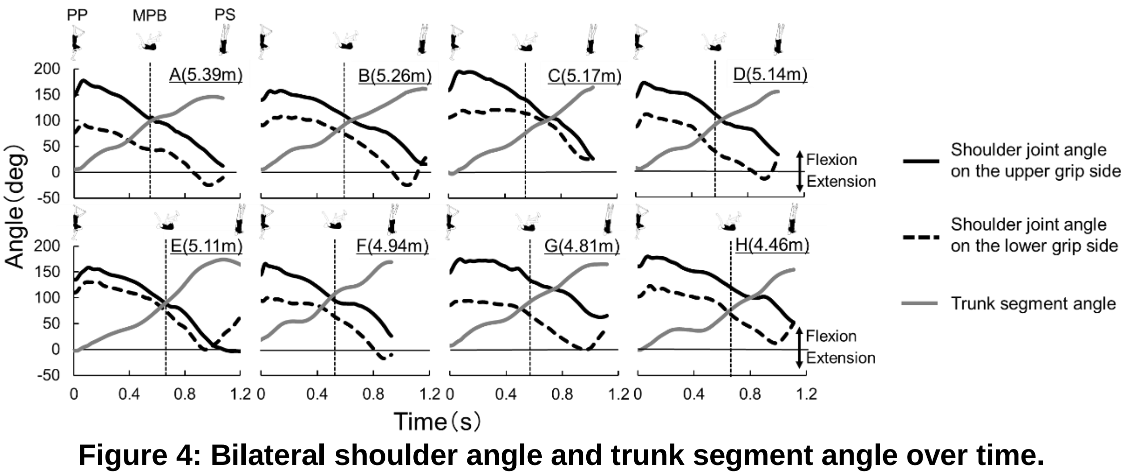

Figure 4: Bilateral shoulder angle and trunk segment angle over time.

Table 1: Time from PP to each event and both shoulder joint angles at each event.

	Lower		Upper	
Event	Mean	±SD (°)	Mean	±SD (°)
PP	91.3	±11.6	143.5	±8.0
TO	98.0	±14.6	158.8	±17.2
SW	94.2	±13.6	147.8	±13.0
MPB	65.8	±22.6	109.9	±16.4
RB	63.2	±20.3	106.3	±11.5
IP	52.2	±22.7	95.1	±14.3
PS	26.1	±26.3	26.8	±21.1

Table 2: Correlations between the maximal height of the CGv and the angular displacement of the bilateral shoulder joint between each event.
(a) Upper grip side (b) Lower grip side

(a)

From	Event	TO	SW	MPB	RB	IP	PS
	PP	-0.29 - 0.78 – 0.41	0.27 -0.43 – 0.77	-0.01 -0.63 – 0.62	0.13 -0.54 – 0.70	-0.24 -0.75 – 0.45	-0.64 -0.90 – -0.02
	TO	-	0.52 -0.16 – 0.86	0.30 -0.40 – 0.78	0.35 -0.35 – 0.80	0.02 -0.61 – 0.64	-0.34 -0.80 – 0.60
	SW	-	-	-0.17 -0.72 – 0.51	-0.20 -0.73 – 0.49	-0.57 -0.88 – 0.09	-0.53 -0.87 – 0.14
	MPB	-	-	-	0.16 -0.52 – 0.71	-0.26 -0.76 – 0.44	-0.71 -0.98 – -0.15
	RB	-	-	-	-	-0.56 -0.88 – 0.10	-0.91 -0.98 – -0.66
	IP	-	-	-	-	-	-0.61 -0.89 – 0.03

(b)

From	Event	TO	SW	MPB	RB	IP	PS
	PP	-0.58 - 0.88 – 0.07	0.38 -0.32 – 0.81	0.14 -0.53 – 0.70	0.30 -0.40 – 0.78	0.14 -0.53 – 0.70	-0.37 -0.81 – -0.33
	TO	-	0.78 0.30 – 0.94	0.38 -0.32 – 0.81	0.51 -0.17 – 0.86	0.39 -0.31 – 0.82	-0.21 -0.74 – 0.48
	SW	-	-	-0.01 -0.63 – 0.62	0.16 -0.52 – 0.71	0.03 -0.61 – 0.64	-0.49 -0.85 – 0.20
	MPB	-	-	-	0.35 -0.35 – 0.80	0.06 -0.59 – 0.66	-0.35 -0.80 – 0.35
	RB	-	-	-	-	-0.19 -0.73 – 0.50	-0.41 -0.82 – 0.29
	IP	-	-	-	-	-	-0.38 -0.81 – 0.32

DISCUSSION: The pole bends by application of the compression force and bending moment; the contribution of the former is larger (Arampatazis et al., 2004). However, the compression force was more forward than upward at the beginning of vaulting (Frère et al., 2010). Moreover, the reaction of the compression force acts on the grips to rotate the CGv around the grips immediately after TO because there is a distance between the grips and the CGv. Therefore, the compression force makes for the vaulter to cause easier the passive swing between TO to SW. Additionally, the passive swing between TO to SW decreases the horizontal velocity of the entire system because the velocity vector of the CGv becomes more vertically upward by the rotation of the CGv around the grips. Thereby the passive swing makes it difficult for the entire system to rotate around the lower tip of the pole. Thus, it is important that the moment of inertia of the vaulter around the grips increases so as to not cause passive swing. In addition, pole vault has been referred to as a double pendulum of the vaulter and pole (Hay, 1993). As the moment of inertia of the vaulter around the grips increases, the moment of inertia of the entire system around the lower tip decrease, making it easy for the vaulter and pole to rotate around the lower tip and enabling the vaulter to vault with longer poles. One method to increase the moment of inertia of the vaulter around the grips is to keep the shoulder joints flexed position after TO because this motion can make the distance between the grips and the CGv larger. In this study, the angular displacement of the shoulder joint on the lower grip side between TO to SW showed large correlations with the maximal height of the CGv [Table2(b)]. The result suggests that keeping the shoulder joint on the lower grip side flexed position

between TO to SW is effective for facilitating rotation of the whole system around the lower tip of the pole and effects on the maximal height of the CGv. The “penetration”, namely the generic term of follow-through motion after TO, has been recognised as the effective vaulting motion in practice (Petrov, 2004). However, the effectiveness of the penetration has not been clarified biomechanically. Thus, the shoulder joint motion on the lower grip side between TO to SW will be one of the technical viewpoints to perform the effective penetration.
The maximal vertical velocity of the CGv affects the catapult effect and maximal height of the CGv because the trajectory of the CGv after PR draws a parabola. Further, Angulo-Kinzler et al. (1994) have shown that the maximal vertical velocity of the CGv appears around PS. Thus, in order to vault higher, it is necessary for the vaulter to receive recoil of the poles. To achieve such, it is necessary to bring the CGv on the line where the recoil force of the pole acts on. The vaulter needs to extend the shoulder joints and keep the CGv close to the grips and pole during pull up because the recoil force acts on the grips. Therefore, the angular displacement of the shoulder joint on the upper grip side between RB and PS showed a very large correlation with the maximal height of the CGv [table 2(a)]. During such, the shoulder joint angle on the upper grip side continued to extend [Figure 4]. Simultaneously, the trunk segment angle continued to increase [Figure 4]. The motion of extending the shoulder joint and taking the trunk vertically, as if dropping the shoulder down, can make it possible for the vaulter to keep close the CGv and the line where the recoil force of the pole acts on. Thus, these results indicate that the motion of dropping the shoulder down effects on the maximal height of the CGv because the vaulter can receive the recoil of the poles. It has been mentioned that the maximal height of CGv depended mainly on vaulters’ motions before PS (Frère et al., 2012b), although the kinematic analysis of the body motion itself has not been conducted in detail. Accordingly, present study showed one of the effective motions for improvement the maximal height of CGv.

CONCLUSION: In this study, the shoulder joint motion within the sagittal plane was shown during vaulting. As a result, it was suggested that keeping the shoulder joint on the lower grip side flexed position between TO to SW and the extension of the shoulder joint on the upper grip side between RB to PS effected on the maximal height of the CGv. These results showed biomechanically and concretely the techniques that has been recognised effective for improvement the maximal height of CGv.

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