BEHAVIOUR OF THE POLE IN POLE VAULTING

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This study clarified behavior of the pole during vaulting. Eight male vaulters (4.60 m-5.77 m: personal best record) vaulted over a closs bar with run-up and pole in the same set up as competitions. Three-dimensional coordinates of reflective markers attached on body and the pole were collected by a motion capture system (250Hz). The results showed: (1) the height of the upper tip of the pole was temporarily lower than the instant of pole plant (PP) between PP and maximum pole bending (MPB) for the top three participants who recorded the highest maximum height; (2) the turning angle at MPB showed positive values (35.2 ± 9.21°) for all participants. The results of this study suggested that participants vaulted with individual vaulting styles and it was effective to rotate the pole around the vertical axis, in order to move vaulter‘s body more vertically between MPB and pole straight (PS) and prevent the body from getting too close the bar at PS.

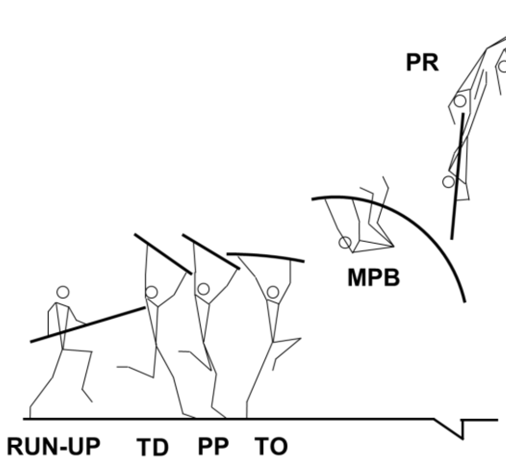
KEYWORDS: pole bending, behaviour of the pole, turning angle.

INTRODUCTION: The pole used in pole vaulting may be of any material or combination of materials and of any length or diameter, but the basic surface must be smooth (IAAF, 2017). Elastic poles are most commonly used as vaulters can use a higher grip point compared with inelastic poles (Hay, 1993). Bending the pole reduces the moment of inertia of the vaulter–pole system around the lower tip of the pole, thereby making it easier for the vaulter and pole to rotate around the lower tip of the pole. Previous studies have used the bending rate (Gudelj et al., 2015; Schade et al., 2004) and the elastic energy in the pole (Arampatzis et al., 2004; Schade et al., 2006) to evaluate pole bending. However, the behaviour of the pole, relating to how the pole bends and recoils in relation to the bending rate and elastic energy storage, has yet to be clarified. After take-off, the vaulter swings the body quickly and widely, while also rotating the body around its long axis while moving into an inverted posture. By applying the force and bending moment to the pole connected to the ground, the vaulter is able to perform these motions. The purpose of this study was to clarify the behaviour of the pole during vaulting with respect to an effective vaulting technique.

METHODS: Eight experienced Japanese male vaulters (69.6 ± 4.53 kg; 1.78±0.04 m; 2015 season best vault height = 5.32±0.36 m), from the top international level to the intercollegiate entry level, participated in this study. This experiment was conducted as an applied research project for Athletics, managed by the Department of Sport Sciences, Japan Institute of Sport Sciences. Following warming up, the participants undertook trials using a run-up and pole selection that replicated competition performance. For each participant, the trial that achieved the highest maximum CGv height (vaulter's centre of gravity) was analysed. The motion from the instant of touchdown to the time of the peak height of CGv was analysed (Figure 1).
The three-dimensional coordinates of 56 reflective markers attached to specific body landmarks, and 18 reflective markers attached on the pole (Figure 2), were collected by a motion capture system operating at 250 Hz (Vicon Motion System Ltd., Oxford, UK; three MX-Giganet, four T40 cameras, 16 T20 cameras and four T10 cameras) and analysed using Nexus software (Vicon Motion System Ltd., Oxford, UK). The global coordinate system was defined as the Y axis in the opposite direction to the run-up, the Z axis in the vertical upward direction, and the X axis as the cross product of the Y axis and Z axis. 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 residual analysis methods (Wells and Winter, 1980). The vaulter's body and the pole were constructed using a 15-segment model (Winter, 1990) and 8-segment model, respectively, from the three-dimensional coordinates. In order to clarify the behaviour of the pole in the Y-Z plane, the ratio of the vertical and horizontal change of the upper tip of the pole (UTP) were calculated from the coordinates of UTP relative to PP, with respect to the vertical and horizontal displacement of UTP between PP and PS. Also, to clarify the behaviour of the pole in X-Y plane, the angle formed by the end segment which includes the upper tip of the pole and Y axis was calculated and termed a 'turning angle' (Figure 3).The trajectories of the upper tip of the pole in the Y-Z and X-Y plane are presented over the time period from PP to PS.

Figure 1: Pole vault model (adapted from Frère (2010))
TD: last touchdown; PP: pole plant; TO: last take-off; MPB: maximum pole bending;
PS: pole straight; PR: pole release; and HP: peak height of CGv.



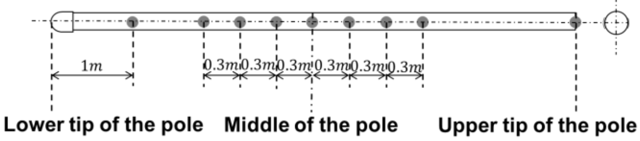


Figure 2: Reflective markers attached to the pole

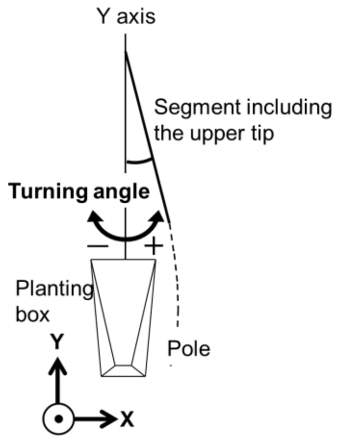


Figure 3: Definition of the turning angle

RESULTS: The mean maximum height of CGv of the participants was 5.03 ± 0.29 m, with the maximum height of CGv and the characteristic of pole for each participant presented in Table 1. The trajectory of the UTP projected to Y-Z plane is shown in Figure 4. Unsurprisingly, the UTP trajectory rose from PP to PS for all participants. Closer inspection revealed that the height of the UTP was temporarily lower than at the instant of PP between PP and MPB for participant A, B, C and F. The trajectory of the turning angle is shown in Figure 5. The turning angle at MPB was positive and increased after MPB across all participants.

Table 1: The maximum height of CGv and the characteristic of pole for each participant.

Participant	Maximum height of CG (m)	Grip height (m)	Ratio of the vertical change of UTP at MPB (%)	Turning angle at MPB (deg)
A	5.39	4.77	11.6	49.4
B	5.26	4.85	25.4	29.1
C	5.17	4.50	18.8	18.6
D	5.14	4.54	24.3	42.0
E	5.11	4.71	25.3	37.6
F	4.94	4.53	21.9	39.0
G	4.81	4.55	28.1	31.9
H	4.46	4.36	46.9	33.7
Mean ± SD	5.03 ± 0.29	4.60 ± 0.16	25.3 ± 10.1	35.2 ± 9.21

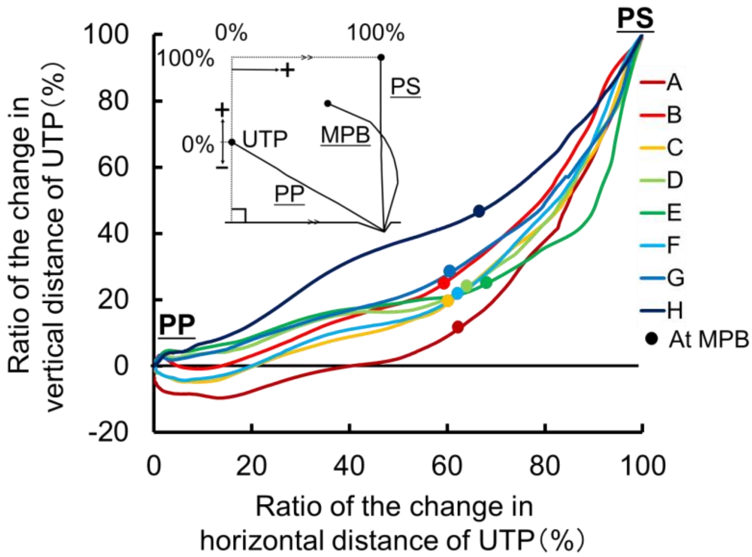


Figure 3: Trajectory of the UTP in Y-Z plane.

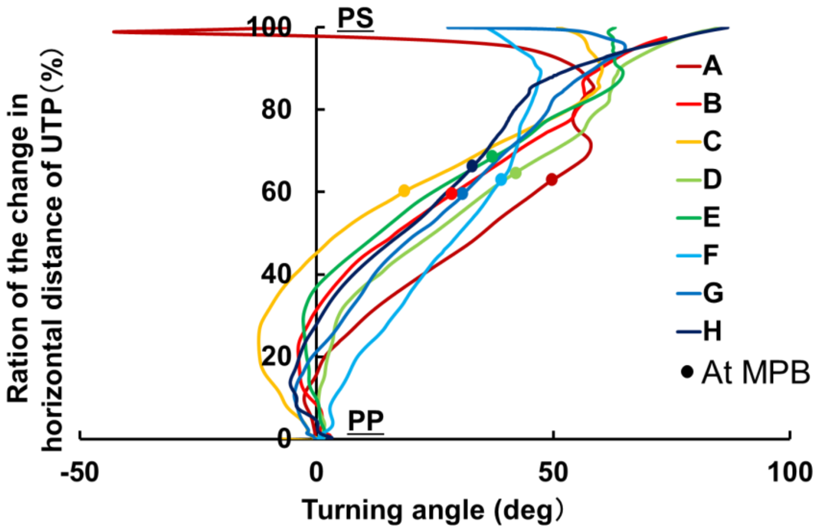


Figure 4: Trajectory of the turning angle in X-Y plane.

DISCUSSION: For participant A, B, C and F, the height of the UTP was lower than at the instant of PP, between PP and MPB (Figure 4). Especially, participant A, B and C who were the top three participants recording the highest maximum height of CGv. In pole vault, to increase effective vault height the athlete must increase the maximum vertical CGv velocity achieved, as the trajectory of CGv becomes a parabola path after pole release. To increase the maximum vertical CGv velocity, the vaulter must obtain effective recoil of the pole. Motion

of the UTP is reflected by more vertical movement from MPB to PS. However, effective UTP vertical increase from MPB to PS, where the UTP does not move vertically between PP and MPB. For the top three vaulters, the height of the UTP was lower than the instant of PP between PP and MPB. This suggests that the amount of pole recoiling effectively becomes the vertical displacement of the UTP by decreasing the upward vertical change in UTP from PP to MPB. In contrast, for participant H who recorded the lowest maximum height of CGv, the ratio of change in vertical distance of UTP had already exceeded 40% at MPB (Figure 4). Thus, the ratio of change in vertical distance of the UTP at MPB different across participants, who displayed a wide variety vaulting styles.
The turning angle at MPB showed positive value in all participants (Figure 5). In addition, the turning angle increased after MPB. If the turning angle does not increase after MPB, the pole segment, inclusive of the UTP, moves primarily within the Y-Z plane. So, the horizontal distance that the UTP moves from MPB to PS increases. It is possible that the horizontal distance between the UTP and the cross bar is too close at PS. Conversely, if the turning angle increases after MPB, the plane that the segment, inclusive of the UTP is rotated around is the Z axis. The horizontal distance that the UTP moves from MPB to PS can be controlled by increasing the turning angle, given that the UTP moves within not only Y-Z plane but X-Z plane. In other words, it is possible to prevent the horizontal distance between the UTP and the cross bar from being too close at PS. The pole will be extended relatively more upward within the Y-Z plane by increasing the turning angle following the MPB. Subsequently, for achieving higher clearances it is important that the UTP moves more vertically from MPB to PS. To do so, it is effective to reduce the vertical change of UTP between PP and MPB. On the other hand, the possibility that the pole is too close to the bar at PS may occur, so by rotation the pole around the Z axis, the vaulters could prevent their body from getting too close to the bar, and may move in the more desirable vertical direction at PS.

CONCLUSION: In this study, the behaviour of the pole during vaulting was analysed. The results suggest that there are various vaulting styles, since the trajectory of the upper tip of the pole from PP to MPB varied greatly across participants. Athletes also position the pole so as to extend relatively more upward within the Y-Z plane, given the turning angle showed positive values at MPB and increased after MPB, in all participants.

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