Measurement of 3-dimensional pole plant forces in an elite pole-vaulter over various approach distances

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Abstract

This paper presents pilot data derived from a newly installed 3-dimensional instrumented pole plant box and offers comparisons between the forces produced in vaults performed over three difference approach distances. Data was collected from an elite male pole vaulter performing 2-step, 4-step and 8-step approaches, with the resulting force profiles compared to determine differences in forces produced during the vaults. Utilising the force data a typical vault was characterised into four phases. Noticeable force increases were observed in the two horizontal planes as the approach distance increased, especially in the first and third phases of the vault. Timing changes in the phases of the vault were also observed, with the second phase of the vault decreasing in time and the third phase increasing in duration as the approach distance increased. Further investigation is required, however it appears the middle two phases are the most likely to change with different vaults, and therefore may be crucial to the execution of successful jumps in pole vault.

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1. Introduction

The pole vault event has been a success story in Australian track and field. To maintain a competitive edge in the area of elite sport, it is essential to provide innovative and world leading information to our
elite athletes. This paper aims to present pilot data derived from a newly installed 3-dimensional instrumented pole plant box and compare the forces produced in vaults performed over three different approach distances.

Current biomechanical analysis in the area of pole vault in Australia rely on quantification of approach velocity, stride analysis, temporal analyses of the vaulting action and a gross measurement of energy flow using kinematic analysis. While this provides important monitoring information on the performance state of the vaulters at any given time, the level of information is insufficient to optimise the vaulting mechanics or investigate the potential effectiveness of new techniques.

Research over the last decade from investigators in Cologne, Germany have pioneered the development of an energy-orientated approach in their analysis of pole vault, which crossed the bridge between abstract considerations concerning the energy exchange and the actual movements of the athletes [1,2,3,4]. This has been typically limited to analysis of the energy change at discrete phases of the vault, rather than an understanding of the energy flow into and out of the vaulter’s pole. In a recently published review of pole vaulting literature [5] a new model was proposed that takes into account the energy exchange between the athlete and pole. Schade et al. [6], has previously published a dynamometric investigation which has displayed sample curves for sub-elite vaulters, in which the three dimensional pole kinetics were used to validate the energy analysis techniques used by these authors, rather than to differentiate technical points within the vaulters technique.

To this end, the Western Australian Institute of Sport has installed a 3-dimensional instrumented pole plant box (built to IAAF regulations) in a dedicated pole vault testing pit. This box enables the 3-dimensional pole forces to be registered during the vault to provide a greater level of understanding of the pole vault mechanics. Understanding the mechanics of pole vaulting is fundamental to performance and our aim is to utilise information from a 3D instrumented plant box to help understand these mechanics and distinguish critical features associated with successful and unsuccessful jumps.

2. Methods

2.1. Data collection

The data presented in this paper was obtained from an individual male pole vaulter, who is the current World and Olympic champion. All data was collected during a single, typical training session for the participant, who received no instruction throughout the session, except the normal feedback provided from his coach.

The participant performed a number of vaults utilising three different run-up distances, namely a 2-step, 4-step or 8-step approach. These are typical approach distances used by vaulters as they progress through to full approach jumps. Three-dimensional force data at the pole plant was collected using the instrumented pole plant box during these trials.

2.2. Apparatus

The instrumented pole plant box used in this investigation is a specially constructed box adhering to IAAF specifications. It consists of a separated back portion mounted independently on a 3-dimensional load cell (ATI Theta-S1-2500-400; ATI Industrial Automation, Apex, USA). Figure 1 shows a picture of the separated front section of the instrumented pole plant box as well as the pole plant box in situ. This arrangement allows the forces acting on the pole throughout the vault to be measured in an environment which is consistent with the athlete’s daily training environment. The collected forces were defined in 3
axes; horizontal and parallel to the runway (x), horizontal and perpendicular to the runway (y) and vertical (z). Positive directions for these forces are also outlined in Figure 1.

Fig 1. (a) Front section of pole plant box on load cell, with positive axis directions; (b) pole plant box in-situ, with positive axis directions

All output from the load cell was passed through a signal conditioning box where the data was amplified and manufacturer's calibration factors were applied. Data was then collected at 500Hz using custom designed software. High speed (500 Hz) video was taken from the side aspect and normal (50Hz) video was taken of the plant box to allow visualisation of the vault when examining the force data.

2.3. Load cell calibration

The load cell was calibrated both statically, to determine the load cell’s response to a steadily applied force, and dynamically, to determine the frequency response to an impact type force. All calibration was conducted in the Physics Laboratory at The University of Western Australia. Static calibration was conducted by placing known masses on the load cell from 0kg up to a total of 140 kg for the vertical direction with the load cell’s measurement recorded. The x-horizontal direction was also calibrated however only up to a total of 20 kg weight due to the difficulty of applying large loads when mounted sideways.

Fig. 2. (a) Static calibration of the load cell in the z-direction; (b) static calibration of the load cell in the x-direction

Each applied load was measured twice for a 5 second period on the load cell. This data was then loaded into a computer software program (IGOR Pro) where the mean of the 5s period was calculated.
The load cell output was then plotted against the known weight to calibrate the load cell. This was repeated for the x- horizontal direction where the load cell was mounted on its side and masses could be applied vertically. It can be seen (Figure 2) that the load cell response exhibited very good correlation with the applied loads in both directions (b = 0.998 and 1.05) and excellent linearity ($R^2 = 0.999$ and 0.999) over the range of measurement.

The dynamic calibration examined the response of the load cell to a short impulse applied with a soft hammer. The load cell was calibrated with the plant box attached. The effect of adding the pole plant box to the load cell was to reduce the resonant frequency of the load cell from the manufacturer's quoted frequency of 820 Hz (vertical) and 680 Hz (horizontal). Repeated five second trials were recorded and the data transferred into IGOR Pro software to be analysed. The load cell behaves like a damped mass-spring system which can be well characterised by the resonate frequency ($f_o$) and mechanical Q (quality factor). The load cell frequency-response is shown in figure 3. It can be seen that two resonant frequencies were observed in the load cell-plant box assembly. The higher frequency ($f_o = 170$ Hz, $Q = 9$) is that of the vertical plane, while the lower frequency ($f_o = 25$ Hz, $Q = 8$) is in the horizontal planes.

![Fig. 3. Load cell dynamic response characterisation](image)

In the horizontal planes (x, y) limited effect on the load cell response will occur at loading frequencies below approximately 10 Hz, after which the resonant characteristics will affect the signal according to the transfer function shown. Similarly, in the vertical plane (z) the load cell response will be stable at loading below approximately 30 Hz.

2.4. Data analysis

Due to the limited number of attempts recorded in this pilot session, it was decided to examine a representative vault for each of the three approach strategies. Examination of the force profiles and associated footage revealed five important occurrences throughout the vault:

1. Contact: The time when the plug contacts the back face of the box, beginning of pole bend.
2. Plug movement: Pole plug contacts with bottom surface of the pole plant box.
3. Beginning of lateral forces: The end of the pole has shifted into the corner of the box; sides of the box providing increase lateral forces coinciding with the beginning of active work by the vaulter.
4. Start of pole extension: Return of energy from the pole to the vaulter.
5. End of pole work: The time when the vaulter releases the pole.
Four phases of the vault were characterised, delineated by the previous points;
A. Early Pole Bend/Hang Phase
B. Mid Pole Bend/Swing Phase
C. Late Pole Bend/Rock-back Phase
D. Pole Extension/Inverted Phase

Examples of these points and phases are outlined in Figure 4, along with representative images of the vaulter.

Time spent and impulse produced in each of the phases was determined from the force curve for each of the approach strategies.

3. Results and Discussion

The force curves for the three approach strategies are shown in Figure 5. It can be seen that the three strategies demonstrate distinct differences from one another. The results will be presented and discussed by phase of the vault.
Overall time for the vault was similar for all three approaches (Table 1) with the 2-step vault occurring over a slightly shorter time (1000 ms) than the 4-step (1046 ms) and 8-step (1072 ms) approaches. Examination of the impulses derived from the force profiles (Table 2) outline the major differences observed in the force profiles. Total impulse in the x-direction changed considerably from the 2-step (52.6 N.ms) to the 4-step (194.2 N.ms) and again in the 8-step (369.1 N.ms), while total y-direction impulse more than doubled between the 2-step and 4-step vaults (176.2 N.ms to 406.9 N.ms) and again rose to 454.3 N.ms in the 8-step approach. The total vault impulses were similar in the z-direction for all three vaults.

These results demonstrate that while the overall time taken for the vault did not change considerably for the different step approaches, the kinetics within the vault did change, predominantly in the x and y direction, which is most likely due to increased velocity into the box and the resultant higher forces of the bottom of the pole against the vertical walls of the box. Forces in the z-direction did not alter to the same extent, due to the need for the athlete to exert similar vertical forces (ie body weight and extension) no matter which approach was utilised.

Table 1. Phase times and total time for the three approach distances

<table>
<thead>
<tr>
<th>Time in each phase (ms)</th>
<th>Phase A (ms)</th>
<th>Phase B (ms)</th>
<th>Phase C (ms)</th>
<th>Phase D (ms)</th>
<th>Total (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 step approach</td>
<td>330</td>
<td>206</td>
<td>64</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>4 step approach</td>
<td>402</td>
<td>134</td>
<td>104</td>
<td>406</td>
<td>1046</td>
</tr>
<tr>
<td>8 step approach</td>
<td>388</td>
<td>98</td>
<td>246</td>
<td>340</td>
<td>1072</td>
</tr>
</tbody>
</table>

3.1. Phase A: Early pole bend/hang phase

There was some difference in the time period of phase A (Table 1) but no distinct trend was observed. Impulses in this phase (Table 2) increased considerably between the 2-step and 4-step approaches in both the x (17.3 N.ms to 96.4 N.ms) and y (102.6 N.ms to 250.3 N.ms) directions. A similar change was not seen between the 4-step and 8-step approaches. It appears that the increased velocity from the 4-step approach is enough to exert noticeably greater forces to the vertical wall of the box, while the corresponding increase to 8-steps does not further increase these forces.

3.2. Phase B: Mid pole bend/swing phase

The timing of phase B can be seen (Table 1) to reduce greatly from 2-steps (206 ms) to 4-steps (134 ms) and again to 8-steps (98 ms). This is accompanied by a noticeable increase in both the x and y forces (Figure 5) but not impulse, due to the reduced time in the phase. These results are most likely due to more
rapid loading of the pole during this phase from the increased momentum of the athlete as the run-up increases in length. The reduced impulse in the z-direction as run-up increases (188.9 N.ms: 135.9 N.ms: 102.5 N.ms) is due to the reduced time in the phase, and not decreased force along this axis).

Table 2. Phase and total impulse for the three approach distances.

<table>
<thead>
<tr>
<th>Impulse in each phase (N.ms)</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Phase D</th>
<th>Total</th>
</tr>
</thead>
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<tr>
<td>2 step approach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ix</td>
<td>17.3</td>
<td>12.4</td>
<td>7.2</td>
<td>15.8</td>
<td>52.6</td>
</tr>
<tr>
<td>ly</td>
<td>102.6</td>
<td>48.4</td>
<td>16.4</td>
<td>8.8</td>
<td>176.2</td>
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<tr>
<td>Iz</td>
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<td>188.9</td>
<td>78.6</td>
<td>392.4</td>
<td>905.5</td>
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<tr>
<td>4 step approach</td>
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<td></td>
</tr>
<tr>
<td>Ix</td>
<td>96.4</td>
<td>11.2</td>
<td>43.1</td>
<td>43.6</td>
<td>194.2</td>
</tr>
<tr>
<td>ly</td>
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<td>64.4</td>
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<td>406.9</td>
</tr>
<tr>
<td>Iz</td>
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<td>135.9</td>
<td>139.4</td>
<td>490.1</td>
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<td>8 step approach</td>
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<td></td>
</tr>
<tr>
<td>Ix</td>
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<td>13.7</td>
<td>236.3</td>
<td>41.7</td>
<td>369.1</td>
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<tr>
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<td>200.3</td>
<td>8.6</td>
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</tr>
<tr>
<td>Iz</td>
<td>252.3</td>
<td>102.5</td>
<td>322.5</td>
<td>368.8</td>
<td>1046.0</td>
</tr>
</tbody>
</table>

3.3. Phase C: Late pole bend/rock-back phase

The timing of phase C shows an increase in time in the phase as the run-up increases in length. The time almost doubles from 2 to 4-steps (64 ms to 104 ms) and then again to 8-steps (246 ms). This is accompanied by a marked increase in both force and impulse in both the x (7.2 N.ms: 43.1 N.ms: 236.3 N.ms) and y (16.4 N.ms: 64.4 N.ms: 200.3 N.ms) directions as the number of steps increase. The reduced times and increased forces are most likely due to a more rapid initial pole bend (phase B) allowing a longer period for the vaulter to apply more active work to the pole in this phase. While the z-forces do not change considerably during this phase, the increased time creates much larger impulses as step number increases.

3.4. Phase D: Pole extension/inverted phase

Timing of phase D shows little difference between 2 and 4-steps (400 vs. 406 ms), with a small change to 8-steps (340 ms). This may be due to increased active work allowing more body speed into the phase, thus reducing the time spent with the pole extending. Examination of the impulses reveals some change between the 2-step and 4-step approaches in the x (15.8 N.ms vs. 43.6 N.ms) and y (8.8 N.ms vs. 41.6 N.ms) directions, which is not repeated in the change to the 8-step run-up. It appears that the final phase of the vault is not as dissimilar between approaches as phases B and C, as the predominant movement is extension of the pole and vertical extension of the athlete, which are quite consistent despite run-up length.

4. Conclusions

The instrumented pole plant box was shown to be able to accurately measure forces exerted in the pole vault action at a sampling rate high enough to record distinct phase changes in the force profiles of the vault. Feedback from the elite athlete was very positive in regards to the manner in which the instrumentation reproduced the feel of a normal pole plant box.
It was found that increasing number of steps in the run-up to the vault led to distinct changes in the forces produced during the vault, predominantly in the two horizontal planes, and largely during the Mid Pole Bend/Swing Phase and Late Pole Bend/Rock-back Phase. Further investigation is required, but it appears these two phases are the most likely to change with different vaults, and therefore may be crucial to the execution of successful jumps in pole vault.

References


