EFFECTS OF SEGMENTAL ROTATIONS ON VERTICAL AND HORIZONTAL ENERGIES DURING TAKE-OFF OF A LONG JUMP

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This study aimed to reveal the effect of segmental rotation on the generation of vertical velocity and loss of horizontal velocity during take-off of a long jump. 3D motion capture system and force plates were used to capture the long jumps by nine male athletes with an approach running distance of approximately 20 m. Forward rotations of the shank and thigh of the stance leg increased vertical energy (E_{vert}) and decreased horizontal energy (E_{hori}); however, elevation of the free leg side of the pelvis increased E_{vert} (0.53 ± 0.16 J/kg), although pelvic elevation did not decrease E_{hori} (0.01 ± 0.02 J/kg). It was revealed that although shank and thigh movements involved the loss of horizontal velocity, elevation of the free leg side of the pelvis generated vertical velocity without the loss of horizontal velocity. This study provides evidence for a new technical approach for a long jump.

KEYWORDS: frontal plane, vertical velocity, trade-off relationship

INTRODUCTION: The generation of vertical velocity, while minimising the loss of horizontal velocity, is required for an effective long jump (Hay, 1993), where the two parameters are believed to act in a trade-off. This trade-off relationship was suggested by the finding that the loss of horizontal velocity during take-off fitted well ($r^2 = 0.94$) with regression analyses of the take-off angle and horizontal velocity before take-off (Willwacher et al., 2017). Therefore, the generation of sufficient vertical velocity, without the loss of horizontal velocity, is important but difficult to achieve.

It has been observed that the free leg side of the pelvis was elevated during a long jump (Graham-Smith and Lees, 2005; Panoutsakopoulos and Papaiakovou, 2010), which resulted in the upward movement of body segments higher than the pelvis and free leg. This meant that elevating the free leg side of the pelvis also involved moving the centre of mass (CoM) upwards, thereby generating vertical velocity. Pelvic elevation constitutes movement in the vertical–lateral (frontal) plane, and we hypothesised that pelvic elevation generates vertical velocity without the loss of horizontal velocity. However, to our knowledge, the effect of segmental movement on the vertical velocity and horizontal velocity has not been examined. If our hypothesis is correct, long-jump athletes and their coaches should pay close attention to frontal plane movement during training sessions, which would provide valuable practical information. This study aimed to investigate the rotational effect of each body segment on both vertical velocity and horizontal velocity of the long jump.

METHODS: Experiments were conducted in an outdoor athletic field. Nine male long jumpers (mean age, 22.6 ± 4.2 years; mean height, 1.75 ± 0.04 m; mean weight, 65.8 ± 1.9 kg), with personal best distance records of 6.53–7.28 m, performed three long jumps toward high-jump mat with an approach running distance of approximately 20 m. We analysed a trial in which take-off was performed on a force platform. For participant who performed multiple successful trials, the trial, having larger generation of vertical CoM velocity relative to loss of horizontal velocity, was chosen. A three-dimensional (3D) motion capture system consisting of 14 cameras (Motion Analysis Corporation, Santa Rosa, CA, USA) and four force platforms (Force Plate 9281E, Kistler, Winterthur, Switzerland) were used to record both kinematic and ground reaction force (GRF) data. We used the whole-body marker set with 47 markers (Sado et al. 2017). The position coordinates of the markers were smoothed using a Butterworth, low-pass, digital filter with a cut-off frequency of 15 Hz. To prevent introducing artefacts soon after contact, the GRF data were also smoothed with a cut-off frequency of 15 Hz, which was identical to that used to filter the marker position data (Bisseling and Hof, 2006). The CoM position was calculated using human anthropometric data (Dumas et al., 2015, 2007), with the whole body velocity vector being calculated by differentiating the position vector of the CoM. The mathematical relationships between vertical and horizontal external powers (P_{vert} and P_{hori}) as well as the rates of change of vertical energy (E_{vert}: sum of the gravitational potential energy and vertical kinetic energy) and horizontal kinetic energy (E_{hori}) are respectively given as follow:

$$P_{vert} = f_z \dot{z}_{body} \text{ and } P_{hori} = f_y \dot{y}_{body} \quad (1)$$

where f_z and f_y are vertical and horizontal GRFs, respectively, and $\dot{z}_{body}$ and $\dot{y}_{body}$ are vertical and horizontal velocities of the CoM for the whole body, respectively. The change of E_{vert} and E_{hori} were calculated as integrals of P_{vert} and P_{hori}.

$\dot{z}_{body}$ and $\dot{y}_{body}$ due to each segment rotation can be calculated using the velocities of the proximal joint and CoM of the segment relative to that of the distal joint of the segment (Figure 1). Firstly, we separated the $\dot{z}_{body}$ and $\dot{y}_{body}$ into components due to segmental rotations. Then, we separated the change of E_{vert} and E_{hori} into components based on segmental movements. In this study, the decomposition of the E_{vert} component is shown for example; however, segmental E_{hori} components were also determined in the same manner.

$\dot{z}_{body}$ can be calculated as follows:

$$\dot{z}_{body} = \sum \left(\frac{m_s}{m_{body}} \dot{z}_s \right) \quad (2)$$

where m_s is the mass of s, and $\dot{z}_s$ is the CoM vertical velocity of s.

As shown in Figure 1, $\dot{z}_{body}$ was separated into components due to segment s ($\dot{z}^s_{body}$). For example, $\dot{z}^{SLthigh}_{body}$ was calculated as follows:

$$\dot{z}^{SLthigh}_{body} = \frac{m_{SLthigh}}{m_{body}} \left(\dot{z}_{SLthigh} - \dot{z}_{SLknee} \right) + \frac{m_{body} - (m_{thigh} + m_{shank} + m_{foot})}{m_{body}} \left(\dot{z}_{SLhip} - \dot{z}_{SLknee} \right) \quad (3)$$

where the first term $\left[\frac{m_{SLthigh}}{m_{body}} \left(\dot{z}_{SLthigh} - \dot{z}_{SLknee} \right) \right]$ shows the $\dot{z}_{body}$ component due to the vertical velocity of the thigh CoM generated by its own rotation, and the second term $\left[\frac{m_{body} - (m_{thigh} + m_{shank} + m_{foot})}{m_{body}} \left(\dot{z}_{SLhip} - \dot{z}_{SLknee} \right) \right]$ shows the component due to the vertical velocity of more proximal segmental CoMs elevated by thigh rotation. The segmental components of other than thigh were calculated in the same manner.

The substitution of equation 3 into equation 1 yields P^s_{vert} (P_{vert} component due to segment s):

$$P_{vert} = \sum (P^s_{vert}), \text{ where } P^s_{vert} = f_z \dot{z}^s_{body} \quad (4)$$

Segmental components of E_{vert} and E_{hori} were calculated as the integrals of P_{vert-s}.

The velocity components of segment CoM and proximal end due to segment s can also be calculated using segment angular velocity and relative positional vectors. Using these, we calculated each rotational axis component.

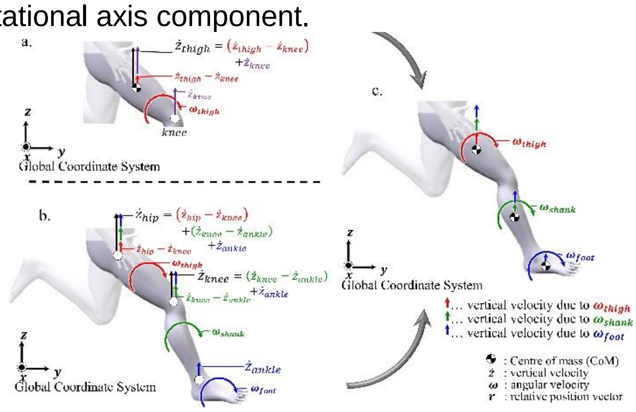

Figure 1: Determination of the sources of the vertical velocity of centre of mass (CoM).

RESULTS: $\dot{z}_{body}$ was −0.589 ± 0.206 m/s at touch-down and 3.157 ± 0.182 m/s at toe-off (Figure 2b). $\dot{y}_{body}$ was 7.724 ± 0.410 m/s at touch-down and 6.374 ± 0.428 m/s at toe-off (Figure 2b). In almost all phases, E_{hori} decreased (Figure 2d), whereas E_{vert} for height increased during take-off phase, except 0%–10% (Figure 2d). The change of E_{vert} and E_{hori} were 5.71 ± 0.69 J/kg and −9.43 ± 1.71 J/kg, respectively.

Pelvic movement increased E_{vert} during approximately 30%–100% of the take-off phase (Figure 3a), which was primarily due to pelvic elevation during movement (Figure 3a2; 0.53 ± 0.16 J/kg). Pelvic movement decreased E_{hori}; the reduction was due to pelvic axial rotation (Figure 3a3; −0.54 ± 0.23 J/kg), and pelvic elevation caused a little change in E_{hori} (Figure 3a2; 0.01 ± 0.02 J/kg).
Forward rotation of the thigh increased E_{vert} during most of the take-off phase (Figure 3c, 4.35 ± 0.56 J/kg), while decreasing E_{hori} (−1.15 ± 0.28 J/kg). Forward rotation of the shank increased E_{vert} during approximately 0%–30% of the take-off phase (Figure 3d) and decreased E_{hori} during the majority of the take-off phase (Figure 3d; −5.32 ± 0.75 J/kg).

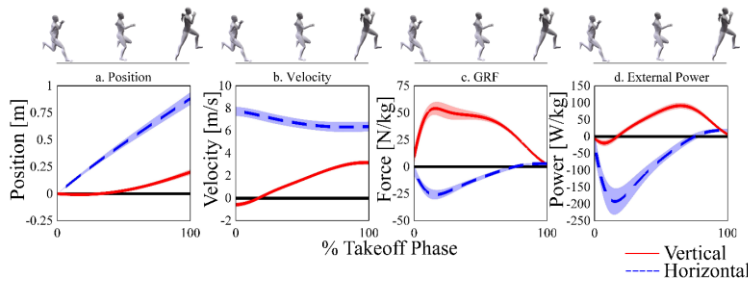

Figure 2: Ensemble averages of the centre of mass (CoM) position relative to touch down, CoM velocity, ground reaction force (GRF) and external power.

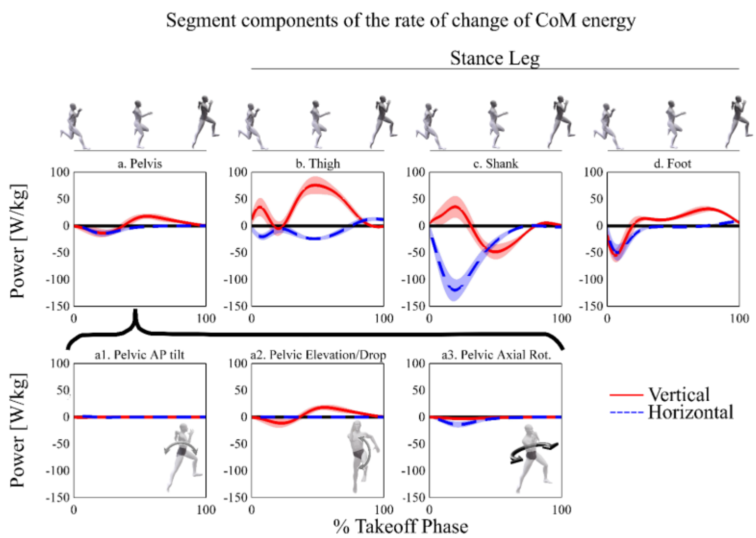

Figure 3: Ensemble averages of the sources of rates of changes in effective energies for height (red) and horizontal moving (blue) due to selected segments.

DISCUSSION: To the best of our knowledge, this is the first study to quantify the effect of segmental rotation on both the vertical and horizontal velocities of a long jump. We hypothesised that the frontal movement of the pelvis generates vertical velocity, without the loss of the horizontal velocity. The data supported our hypothesis, thereby demonstrating the uniqueness of this study.
In the early phase of take-off, the forward rotation of the shank increased E_{vert} and decreased E_{hori} (Figure 3d). Similarly, the forward rotation of the thigh also increased E_{vert}; however, E_{hori} decreased (Figure 3c). These results suggested that E_{hori} is transformed into E_{vert} via forward rotational movements of the shank and thigh. A previous study showed that the generation of E_{vert} due to rotations of the shank and thigh were dependent on their angle about the vertical axis (Bobbert and van Ingen Schenau, 1988).
As such, larger backward leans of shank and thigh makes the velocities of their CoMs and their proximal joints due to their forward rotation closer to vertical, leading the increase in the E_{vert} due to the shank and thigh; however, a large backward lean would place the whole-body CoM further behind the point of support and increase the backward force, resulting in a greater loss of E_{hori}. Therefore, the generation of a greater E_{vert} due to the angle of the shank and

thigh would cause a large decrease in E_{hori}, which will not necessarily lead to an improvement in long-jump performance.

Previous studies have observed that the free leg side of the pelvis is elevated during long jump (Graham-Smith and Lees, 2005; Panoutsakopoulos and Papaiakovou, 2010). The present study found that pelvic elevation generated E_{vert} (0.53 ± 0.16 J/kg) with minimal effect on E_{hori} (0.01 ± 0.02 J/kg), thereby indicating that elevation of the free leg side of the pelvis is capable of generating vertical velocity without the influence of the horizontal velocity. Although it is ideal to generate the vertical velocity without loss of horizontal velocity in long jump (Hay, 1993), it is believed that the two parameters compete with each other (i.e. a trade-off) (Willwacher et al., 2017). The results for the shank and thigh in this study supported this trade-off relationship. Therefore, the results presented here imply that elevation of the free leg side of the pelvis is maybe an important technical consideration with regard to long-jump performance.

This study had some limitations. First, we could not collect the data of long jump with full approach, which may have effect on the results. Second, we analysed the long jump toward high-jump mat, and actual jumping distances could not be measured.

A practical suggestion is that long jump athletes and their coaches should pay close attention not only to sagittal movement but also to frontal movement. Long-jump techniques are frequently discussed in terms of the sagittal plane; however, this study showed that pelvic movement in the frontal plane generated E_{vert} without the loss of E_{hori}. Our findings, therefore, suggested that strengthening the musculature controlling the frontal movement of the pelvis, such as the hip abductor and lumbar lateral–flexor muscles towards the free leg side, would critically improve long-jump performance. In technical training sessions, it would be important to ensure that the free leg side of the pelvis is highly elevated during the take-off phase.

CONCLUSION: This study examined the effect of each segmental movement on both vertical velocity and horizontal velocity during a long jump. We found that elevation of the free leg side of the pelvis generated vertical velocity without the loss of horizontal velocity, although the stance leg movement in the sagittal plane caused the generation of vertical velocity and the loss of horizontal velocity. Therefore, we suggest that long jump athletes and their coaches pay special attention to pelvic movements in the frontal plane, even though the focus of long-jump technique is frequently limited to the sagittal plane.

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