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Trade-offs between horizontal and vertical velocities during triple jumping and the effect on phase distances

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ABSTRACT

The triple jump is an athletic event involving three ground contact phases during which athletes must trade off the maintenance of horizontal velocity against the generation of vertical velocity. Previous studies have indicated that individual athletes have a linear relationship between the loss in horizontal velocity and the gain in vertical velocity during each phase. This study used computer simulation to investigate the effects of constraining the takeoff velocities in the hop phase on the velocity trade-offs in this and subsequent phases. Kinematic data were obtained from an entire triple jump using a Vicon automatic motion capture system, and strength and anthropometric data were collected from the triple jumper. A planar 13-segment torque-driven subject-specific computer simulation model was used to maximise the distance of each phase by varying torque generator activation timings using a genetic algorithm. Vertical takeoff velocities in the hop phase were constrained to be 100%, ±10%, ±20%, and ±30% of the performance velocity, and subsequent phases were optimised with initial conditions calculated from the takeoff of the previous phase and with no constraints on takeoff velocity. The results showed that the loss in horizontal velocity during each contact phase was strongly related to the vertical takeoff velocity (R^2=0.83) in that phase rather than the overall gain in vertical velocity as found in previous studies. Maximum overall distances were achieved with step phases which were 30% of the total distance of the triple jump confirming the results of experimental studies on elite triple jumpers.

1. Introduction

The triple jump is an athletic event involving three ground contact phases during which athletes must trade off a loss in horizontal velocity of the centre of mass (COM) against the generation of vertical velocity of the COM. Studies on the triple jump have investigated the relationship between the gain in vertical velocity and the consequent loss in horizontal velocity during each of the ground contact phases and its effect on the 'phase ratio' of the three phase distances expressed as three percentages of the total distance jumped (Yu and Hay, 1996; Yu, 1999). These studies found that individual athletes had a linear relationship between the gain in vertical velocity and the loss in horizontal velocity in each of the three phases, which they termed the 'horizontal-to-vertical velocity conversion factor'. Perhaps surprisingly the athletes with the highest horizontal-to-vertical velocity conversion factor (those that lost the most horizontal velocity for a unit gain in vertical velocity) were those that jumped the furthest overall (Yu and Hay, 1996). These investigations did not consider the effects of initial velocities at the touchdown of each phase on the subsequent velocity trade-offs.

Assuming that landing and takeoff positions remain constant, the trade-offs between horizontal and vertical velocities determine the phase ratio. Hay (1992) stated that the identification of the optimum phase ratio for an athlete, "should take priority over all other problems of triple jump technique because, without a solution to this problem, all others must be considered in ignorance". Hay (1992) defined three triple jump techniques with respect to phase ratio as being: (1) hop-dominated – where the hop percentage is at least 2% greater than the next largest phase percentage; (2) jump-dominated – where the jump percentage is at least 2% greater than the next largest phase percentage; and (3) balanced – where the largest phase percentage is less than 2% greater than the next largest phase percentage. In world record performances from 1911 to 1985 a move away from a hop-dominated technique with a small step phase (40–41%:22%:36–38%), towards a hop-dominated technique with a larger step phase (37–39%:28–30%:31–33%), and latterly towards a jump-dominated technique (34–35%:28–30%:36–37%) was seen (Hay, 1993). Hay (1993) noted that world record advances over the last three decades considered in the analysis seemed to have involved a search for the ideal hop and jump percentages to go with a step of approximately 30%. Hay (1999) observed that roughly half the

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competitors in the final of the 1996 Olympic Games employed hop-dominated techniques and half employed other techniques. Therefore, despite a number of studies in this area, these results indicate that no consensus has been reached either in the scientific community or in the athletic community as to whether optimum phase ratios for triple jumping exist, and if so, what they are.

The aims of this study are to investigate the relationships between horizontal and vertical velocities during takeoff, and to determine how this affects the ratio of each phase distance to the total distance jumped.

2. Methods

Kinematic and force data were gathered at the Loughborough University indoor High Performance Athletics Centre (HiPAC) from a male triple jumper of national standard (age: 22 years; mass: 72.6 kg; height: 1.82 m; best performance: 14.35 m). The study was carried out in accordance with the Loughborough University Ethical Advisory Committee guidelines. Forty-five 25 mm retroreflective markers were placed in positions on the jumper's body in order that locations of joint centres could be calculated. Eighteen Vicon MX cameras covered a volume of 18 m $\times$ 2 m $\times$ 2.5 m spanning the last stride of the approach and the full triple jump. Data were captured at 240 Hz during a single triple jump performance of 13.00 m. In addition to this the subject was asked to perform the ground contact of each phase of the triple jump from a single force plate for parameter determination, necessitating three trials. Orientation, defined as the angle of the trunk in a global reference frame, and configuration angles were calculated by considering the joint centre coordinates in the sagittal plane. Quintic splines (Wood and Jennings, 1979) were fitted to the time histories of these angles for input to the simulation model.

A 13-segment planar torque-driven computer simulation model (Fig. 1) was developed to investigate triple jumping technique (Allen et al., 2010, 2012). The 13 segments comprised: head+trunk, two upper arms, two forearms and hands, two thighs, two shanks, two 2-segment feet, with wobbling masses within the shanks, thighs, and torso. Non-linear spring-dampers connected the ends of the wobbling and fixed elements (Pain and Challis, 2001). Each foot had three points of contact with the ground at the heel, ball (metatarsophalangeal joint), and toe. The foot–ground interface was modelled using horizontal and vertical non-linear spring-dampers situated at the heel, ball, and toe of each foot (Allen et al., 2012).

Subject-specific torque and inertia parameters were calculated from measurements taken from an elite triple jumper. Maximal voluntary joint torque data were obtained assuming bilateral symmetry using an Isocom isovelocity dynamometer for flexion and extension of the ankle, knee, hip, and shoulder on the right hand side of the body (King et al., 2006). Ninety-five anthropometric measurements were taken and used as input to the inertia model of Yeadon (1990) in order to calculate subject-specific segmental inertia parameters.

Optimisation was used in three different ways: simulation ground reaction forces (GRFs) were matched to performance GRFs in order to obtain viscoelastic parameters governing the foot–ground interface; simulation kinematics were matched to performance kinematics in order to assess the accuracy of the model; seven hop phases were optimised with constraints ensuring a range of vertical takeoff velocities in order to investigate the effect on the loss of horizontal velocity in this and subsequent phases.

A set of viscoelastic parameters was obtained using the torque-driven model to minimise the difference between simulation and performance GRFs using all three phases to ensure that the parameter set was robust (Wilson et al., 2006). Wobbling mass parameters were taken from Allen et al. (2012). Ground reaction forces were found to be relatively insensitive to wobbling mass parameters, so only the viscoelastic parameters representing the springs at the foot were included in the optimisation. In order to do this a genetic algorithm (GA) (Carroll, 1996) minimised an objective function by varying 264 parameters: 12 stiffness and damping coefficients at the foot; 21 initial kinematic conditions comprising the orientation angle and angular velocity, configuration angles at the ankle, knee, and hip, and the horizontal and vertical COM velocities in each of the three phases; and 231 parameters comprising 77 torque generator parameters in each of the three phases. The objective function was composed of the percentage RMS differences between simulation and performance in: takeoff velocity, time of contact, time to peak force, magnitude of peak force, and overall RMS differences between the orientation, configuration, and force time histories (Allen et al., 2012).

The torque-driven model was evaluated by assessing how accurately a simulation could match performance data for each phase individually. This simulation was found by varying 77 torque generator parameters and seven initial kinematic conditions in order to minimise a difference function between simulation and performance data using a GA. The objective function for each

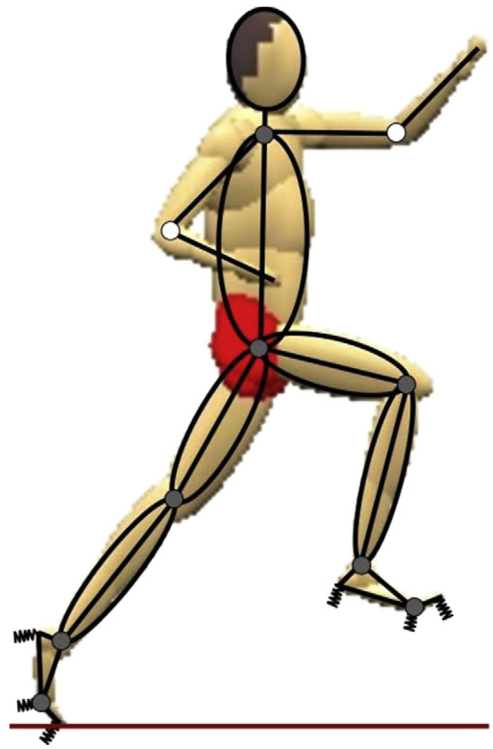

Fig. 1. Thirteen-segment simulation model with wobbling masses within the shank, thigh, and trunk segments, torque drivers at the ball, ankle, knee, hip, and shoulder joints (grey circles), angle drivers at the elbow joints (white circles), and spring-dampers at three points on each foot.

matched torque-driven simulation was the RMS of six parts (Allen et al., 2010): percentage difference in horizontal velocity of COM at takeoff; percentage difference in vertical velocity of COM at takeoff; overall RMS difference in (trunk) orientation in degrees during ground contact; overall RMS difference in whole-body configuration in degrees during ground contact; percentage absolute difference in time of contact; absolute difference in orientation at touchdown of the subsequent phase in degrees calculated as described by Allen et al. (2010). In all cases 1° was considered to be equivalent to 1% and objective difference function values are reported as percentages (Allen et al., 2010).

A GA was used to maximise phase distance by varying 77 torque generator parameters, and four initial angles: orientation angle, and the hip, knee, and ankle angles of the stance leg. Each phase distance (d_{phase}) comprised three components (Fig. 2): the takeoff distance (d_{takeoff}), the flight distance (d_{flight}), and the landing distance (d_{landing}). A range of vertical velocity changes during the hop phase was obtained by using penalties to constrain vertical COM velocity at takeoff to be within $\pm 1\%$ of 100%, $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$ of the performance velocity, leading to seven optimisations in total. The horizontal and vertical COM position and velocity and whole body angular momentum at takeoff from each optimisation were used in order to calculate the linear COM velocities and whole body angular velocity at the touchdown of the subsequent phase. Optimisations of the step and jump phases were performed by varying the equivalent parameters to the hop phase but involved maximising the sum of the distances of the phases preceding and following ground contact, with no constraints on takeoff velocities. The sum of two phases was used because varying the initial orientation and configuration angles altered the COM position and hence the d_{landing} of the previous phase (Fig. 2).

The initial orientation and configuration angles were allowed to vary in each phase. In the airborne phase orientation changes were estimated as described by Allen et al. (2010). The calculated orientation angle at landing of the subsequent ground contact was constrained (using penalties) to be within $\pm 1^\circ$ of the matched orientation. The initial orientation angles were allowed to vary in each phase, since it was assumed that different takeoff configurations and airborne motions could lead to altered orientation changes in the air. The initial orientation of the hop phase was permitted to vary between $\pm 10^\circ$ from the matched performance, since it was assumed that the athlete could alter his orientation substantially during the approach run. The bounds on the variations in initial orientation angle in the step and jump phases were based on the magnitude of the changes in orientation angle that performance configuration changes effected in the previous flight phase, with larger changes associated with increased bounds. This led to bounds of $\pm 5^\circ$, and $\pm 2^\circ$ respectively from the landing orientations of the step and jump phases calculated from the previous phases. The initial ankle, knee, and hip angles were each allowed to vary by up to $\pm 5^\circ$ from the matched simulation.