PERFORMANCE SENSITIVITY TO PERTURBATIONS IN ACTIVATION TIMING

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This study investigated the sensitivity of optimum jumping performances to perturbations in activation timing. A planar eight-segment computer simulation model was used to simulate the takeoff phase in a high jumping performance. The model was evaluated and subsequently used to produce an optimum performance with a jump height of 2.63 m. The muscle activation onset timings at the knee were then varied by ± 5 ms and the effect on the simulated performance was determined. By simply varying the knee activation onset timings the performance did not change in terms of jump height, but the simulations included penalties which indicated that anatomical constraints had been violated. Re-optimisation with a measure of robustness included resulted in an optimum simulated jump of 2.32 m with no penalties which was unaffected by 5 ms perturbations.

KEY WORDS: sensitivity, robustness, evaluation, optimisation

INTRODUCTION: The development of computer simulations models in the field of sport has allowed optimum solutions of performances to be determined. The robustness of these optimised performances to perturbations in activation timing is crucial if they are to be achievable in practice. If these optimal solutions are sensitive to small changes in parameter values then they are not robust. For a solution to be considered robust, small perturbations in parameter values, which result in an "optimal performance", should result in a near optimal performance. Harris and Wolpert (1998) presented a minimum-variance theory which proposed that the time profile of the neural command is selected so as to minimise the endpoint error in targeted movements. The aim of this study was to investigate the sensitivity of performance to perturbations in the muscle activation timings during a high jump in order to determine the robustness of an optimised jump and to subsequently re-optimise performance to be robust to timing perturbations.

METHODS: A computer simulation model of the contact phase in high jumping was developed and customised to an elite high jumper through the determination of subject-specific inertia, strength and elastic parameters. The simulation model was evaluated and was then used to optimise performance. Following this process the muscle activation timings were perturbed by small amounts and the effect of these perturbations on optimal performance was investigated. Performance was then re-optimised using a measure of robustness. One running jump for maximum height was recorded at an athletics track using two 50 Hz cameras and a 200 Hz camera to collect the kinematic data. Fifteen body landmarks (wrist, elbow, shoulder, hip, knee, ankle and toe on each side of the body plus the centre of the head) were digitised in each field of the movement sequence from each of the three camera views. The 11 Direct Linear Transform (DLT) parameters and a central lens distortion parameter were calculated for each camera, and these parameters along with the synchronised digitised co-ordinates of the movement data were used to reconstruct the 3D locations of each digitised point using the method of Karara (1980). The coordinate data were then used to calculate the athlete's orientation and configuration angles throughout each movement, along with the mass centre velocity and whole-body angular momentum about the mass centre (Yeadon, 1990a; Yeadon, 1990c). The time histories of the orientation and configuration angles were fitted using quintic splines (Wood and Jennings, 1979) in order to obtain angle and angular velocity estimates throughout the movement.
A planar eight-segment torque-driven forward dynamics computer simulation model was developed for the foot contact phase in running jumps (Figure 1). The model comprised foot, calf, and thigh of the takeoff leg; shank and thigh of the free leg; trunk + head; upper arm and

lower arm with torque generators situated at five of the joints (ankle, knee and hip of the takeoff leg; hip of the free leg and shoulder). Wobbling masses represented as non-linear spring-damper systems were included in the shank and thigh segments of the takeoff leg and in the trunk segment. The foot-ground interface was modeled in a similar way with vertical and horizontal non-linear stiffness and damping components situated at the toe and the heel. Ten torque generators acting around the five joints were used to represent the extensor and flexor muscle groups. Each muscle group was represented by a rotational elastic element in series with a rotational contractile element. The torque produced by the contractile element was modeled using a nine parameter surface fit (Equation (1)). The torque produced by the series elastic element was modeled as a linear function of the joint angle θ_{see} (Equation (2)).

$$T_{cc} = A(t)F(\theta_{cc}, \dot{\theta}_{cc}) \tag{1}$$

where: T_{cc} = torque produced by contractile element at time t, θ_{cc} =angle of the contractile element, $A(t)$ = muscle activation function, F = nine parameter function.

$$T_{sec} = K\theta_{sec} \tag{2}$$

where: T_{sec} = torque produced by the series elastic element at time t, K = series elastic stiffness parameter, θ_{sec} = angle of the series elastic element.

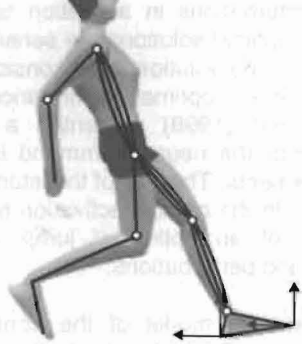

Figure 1 Eight-segment simulation model of the foot contact phase in running jumps.

The maximum voluntary torque capable of being produced by each torque generator was determined using the nine parameter function. The actual torque produced was then calculated by multiplying this maximum torque value by an activation profile. Two different profiles were used to represent the activation time histories of the agonist and antagonist muscle groups. Six parameters were needed to define the activation time histories of the agonists and five parameters were needed to define the activation time histories of the antagonists. The six parameters for each of the agonists defined two quintic functions representing the ramp up to maximum activation and the ramp back down. The five parameters for the antagonists also defined two quintic functions representing the ramp down from maximum to minimum activation and then back up.

Subject-specific model parameters comprising inertia, strength and spring-damper parameters were used in the model. The inertia parameters were determined using the anthropometric measurements taken on the subject and the model of Yeadon (1990b). The strength parameters were determined from isovelocity data collected on the subject. The visco-elastic parameters were determined using a kinematically driven model.

The model evaluation procedure involved using the Simulated Annealing optimisation algorithm (Corana et al, 1987) to minimise the difference between performance and simulation by varying the torque generator activation time histories. Optimisation involved varying the torque generator activation time histories, the initial configuration conditions and the approach velocity in order to maximise the height reached by the centre of mass during the flight phase again using Simulated Annealing. In order that the simulated movements were realistic, constraints on the knee and ankle joints at takeoff and in flight were imposed. The knee and ankle joint angles were not allowed to exceed 180° and 160° respectively either at takeoff or during the flight phase. If the simulation resulted in any of the constraints being violated a penalty was subtracted from the simulation height in the optimisation. For the obtained optimum solution, the activation onset timings of the knee joint were perturbed by ±5 ms to produce two new simulations. The performance was then re-optimised, including perturbations of 5 ms in knee activation timings, with the minimum height reached in a group of perturbed simulations being maximised.

RESULTS AND DISCUSSION: Close agreement was obtained between simulation and performance, with a difference 9.5%, providing confidence in the model's ability to simulate running jumps. The height reached by the centre of mass in the optimised solution was 2.63 m. When the knee activation onset timings were varied by ±5ms the peak jump height reached in the solutions did not change. Both these solutions, however, included penalties resulting from the constraints on the ankle and knee joints being violated, meaning the performances were not anatomically possible. Re-optimisation with a measure of robustness included resulted in a solution with a jump height of 2.32 m with no constraints being violated. When this optimised simulation was perturbed by 5 ms there was no reduction in jump height. The results highlight that the original optimal solution obtained was sensitive to perturbations in muscle activation timings, with small perturbations resulting in performances which were anatomically impossible. The final optimised height of 2.32 m was very close to the subject's personal best of 2.31 m. Since the effects of timing perturbations at the ankle and hip joints as well as at the knee joint will have an influence the magnitude of such perturbations will have to be less than 5 ms. This suggests that high jumpers are able to time their muscle activations to better than 5 ms.

CONCLUSION: This study has highlighted that when optimising performances it is necessary to include anatomical constraints and a measure of robustness in order to obtain realistic performances.

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