COMPUTER SIMULATION IN SPORTS BIOMECHANICS

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INTRODUCTION: Experimental studies of sports technique are inherently problematical. In competitive situations biomechanical variables are constrained to lie near optimal values and this results in a small range of values for each variable. For example in a high jump competition a competitor may have approach speeds that vary between 7.0 and 7.3 ms^{-1} (Greig, 1998). As a consequence there is often no statistically significant relationship between predictor and performance variables. In the training environment intervention is possible and the ranges of variable values can be increased. During high jump training, the approach speed may be varied from 5.7 to 7.2 ms^{-1} (Greig, 1998). It is difficult, however, to change just one technique variable without affecting others, and with intervention there is the possibility that technique becomes so perturbed that it is no longer representative of an unconstrained performance.
Theoretical studies employing linked segment models of the human body do not suffer from these experimental difficulties. With such models it is a simple matter to determine the influence of just one variable on performance. The difficulty is in developing a sufficiently detailed model that will represent the key features of the sports movement. The complexity of a model depends on the application. If the aim is to gain basic insights into the mechanics of the movement then a rather simple model may be sufficient. If the aim is to determine optimum technique then a more complex subject-specific model will be required. Models of increasing complexity of various sporting activities will be considered in this paper with a view to understanding the underlying mechanics, analysing performances, determining optimum techniques, and providing a simulated environment to assist in the learning of complex control.

Throwing

A simple model of the shot put event may be constructed by assuming that the release height is a constant two metres above ground level and that the release speed is a constant 14 ms^{-1}. For different release angles the horizontal range from the point of release may be calculated using the equations for constant acceleration with g = -9.81 ms^{-2}. Under these assumptions the optimum angle of release is 42.4^{o} as shown in Figure 1.

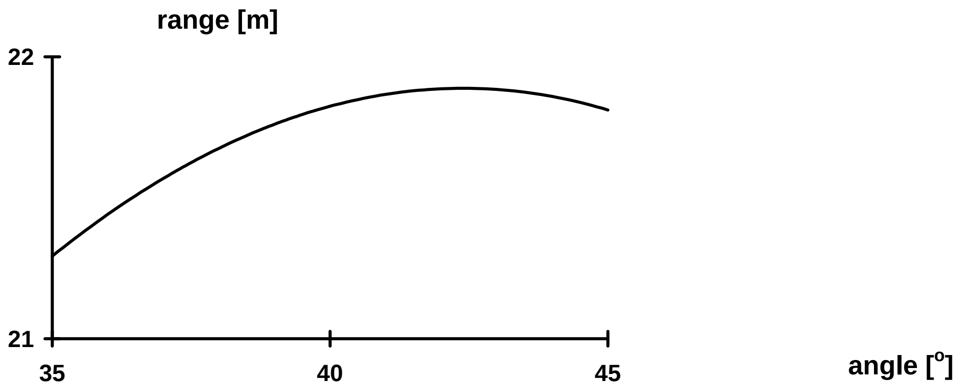


Figure 1. Horizontal range when release speed is held constant.

This model, however, does not account for the varying ability of the athlete to generate speed of the shot for different release angles. For lower release angles the possible release speed will be higher. If this relationship is represented by the equation $\boldsymbol{v = 15.6 - 0.04\theta}$ the optimum release angle becomes 37.4^o as shown in Figure 2.

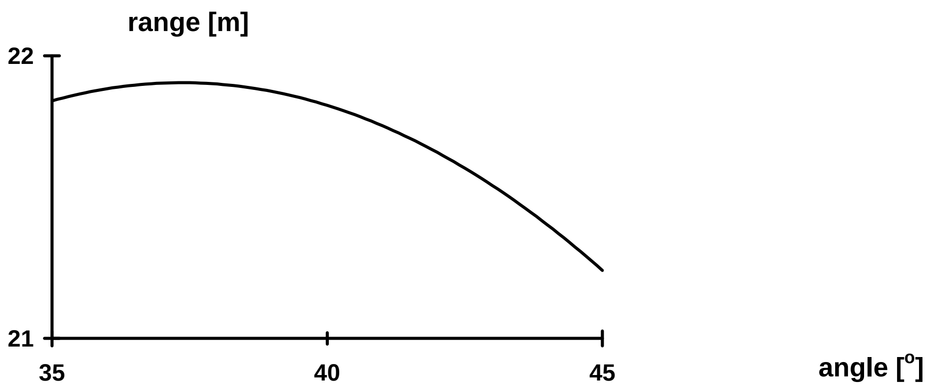


Figure 2. Horizontal range when release speed is a function of release angle.

Of course this model itself assumes that the release height of 2 m is independent of release angle and allowance for this factor will again change the optimum release angle. It may be concluded that a model must reflect any interdependencies of the variables that are used. It is difficult for a simple model to do this without using some experimentally determined relationships (e.g. Red and Zogaib, 1977).

Jumping

In high jumping there is experimental evidence that there is an optimum approach speed and an optimum plant angle of the takeoff leg (Greig, 1998). Alexander (1990) investigated the influence of approach speed and plant angle using a simple two segment model of jumping comprising a point mass, two massless thigh and shank segments, and a knee extensor torque dependent on knee angular velocity (Figure 3).

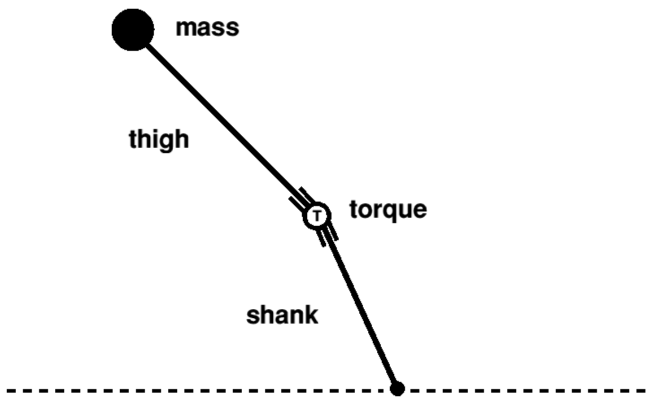


Figure 3. A two segment model of jumping (Alexander, 1990).

Such a model may be tuned to mean performance data for an individual by choosing the strength of the knee extensor so that the simulated jump height matches the experimental jump height at the given approach speed and plant angle (Greig, 1998). With this approach a two segment model was indeed able to match the performance conditions at the end of the takeoff phase but at the expense of an overly strong knee extensor. The corresponding optimum approach speed for the model, however, was 10.2 ms^{-1} with a corresponding jump height of 2.70 m (Figure 4). Since the fastest approach speed and greatest height of the mass centre in ten competitive jumps by this athlete were 7.5 ms^{-1} and 2.35 m it is clear that the model optima are not realistic.

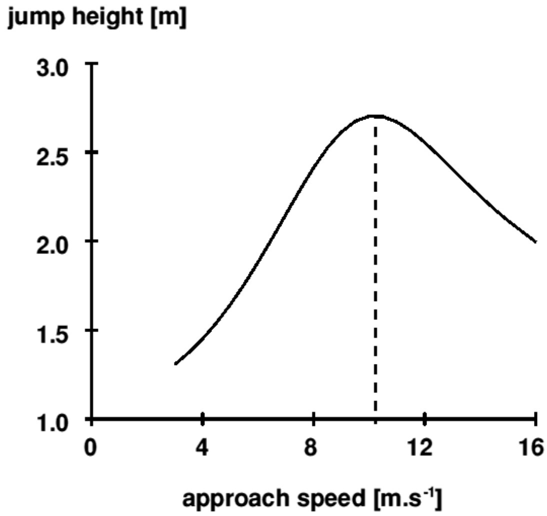


Figure 4. Jump height as a function of approach speed for a two segment model.

More realism may be introduced into the model by giving mass and moment of inertia to each segment and increasing the thigh length (to the distance from the knee to the mass centre of everything above the knee) and increasing the shank length (to the knee to ground contact distance). This resulted in some improvement with an optimum approach speed of 9.4 ms^{-1}. Introducing an impact phase with an elastic ground-foot interface produced a more realistic maximum knee torque value, more realistic ground reaction forces, and a more realistic ground contact time but resulted in a more unrealistic optimum performance (Greig, 1998) as shown in Figure 5.

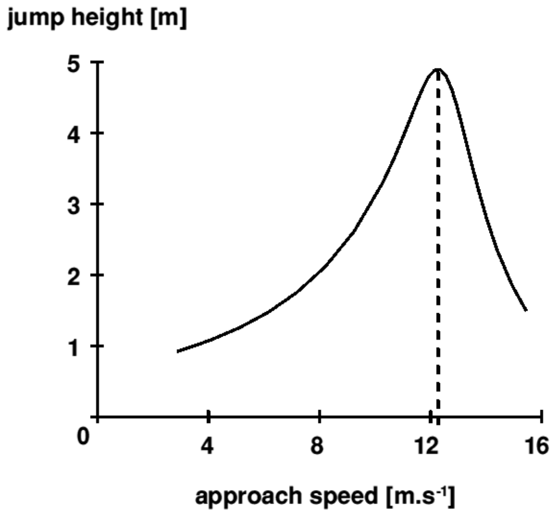


Figure 5. Jump height as a function of approach speed for a sprung model.

It must be concluded that the takeoff in high jumping is a complex coordinated skill which cannot be represented accurately using a simple two segment model.

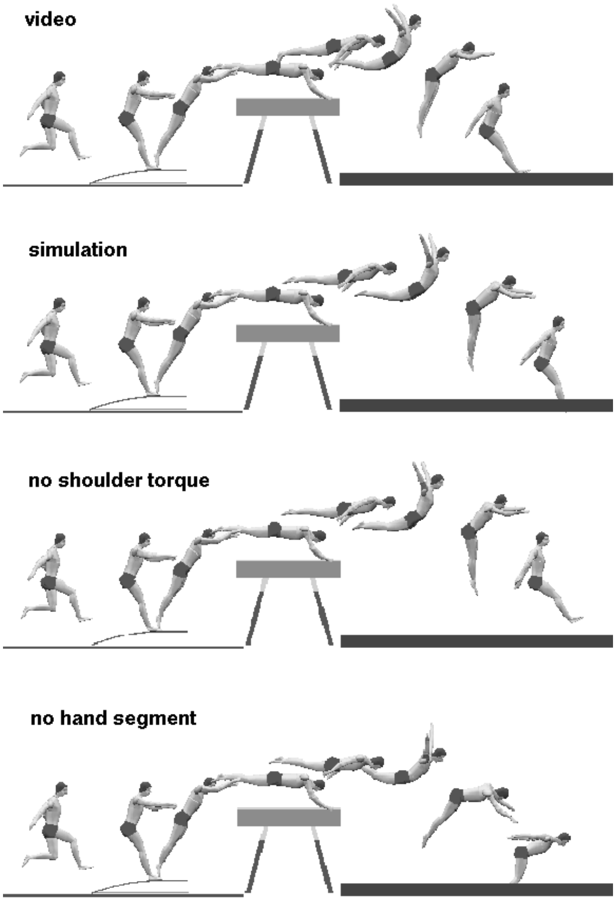
Vaulting

A two segment model with a torque at the shoulder and springs at the hand and shoulder may be expected to be more successful in modelling the Hecht vault in gymnastics since movement occurs primarily only at the shoulder joint during horse contact. The spring representing the hand changed its natural length and stiffness at maximum depression so as to maintain contact with the horse until the wrist was the required distance above the horse. Figures 6a and 6b compare an actual performance recorded on video with the simulated performance based on the same initial conditions prior to impact with the horse using subject-specific inertia and muscle parameters (King, 1998). Such an evaluation which demonstrates the close agreement between the model and reality is necessary before there can be confidence in the results obtained using the model in other situations. In order to determine the contribution of shoulder torque to performance in the Hecht vault a modified simulation was carried out in which the shoulder torque was set to zero during horse contact (Figure 6c). It can be seen that shoulder torque has little effect on the performance which is primarily a consequence of an appropriate preflight onto the horse and a passive impact with the horse (King, 1998). The effect of having no hand segment was simulated by using the same spring characteristics for the repulsion phase as for the compression phase. This reduced the horse contact time and resulted in insufficient rotation as shown in Figure 6d. It may be concluded that the two segment model provides an accurate representation of the Hecht vault and that the preflight, shoulder elasticity, and the hand segment are crucial determinants of performance whereas shoulder torque during horse contact has only a small effect (King, 1998).

Figure 6. Simulation of the Hecht vault: (a) actual performance obtained from video analysis, (b) simulated performance, (c) simulated performance without shoulder torque and (d) simulated performance without a hand segment.

Tumbling

A five segment subject-specific simulation model comprising foot, shank, thigh, trunk and arm segments with torque generators at ankle, knee, hip and shoulder and with springs at heel and toe may be used to model the takeoff phase of tumbling (King, 1998). The postflight aerial phase was simulated using the 11 segment model of Yeadon *et al.* (1990). For suitable timing of the onset of torque activations, reasonable agreement was obtained between the performance and simulation of a double layout somersault (Figures 7a, 7b). To determine the influence of the joint torques an attempt was made to produce a single layout somersault from the same initial touchdown conditions by modifying the joint torque activation times (Figure 7c). Without any torque activations the model did not manage to takeoff at all. To determine the influence of the preflight an attempt was made to produce a single layout somersault using the same activations as for the



simulated double layout (Figure 7b) by modifying the preflight touchdown conditions (Figure 7d). It may be concluded that a five segment model provides an adequate representation of tumbling takeoffs and that the preflight and torque activations are important contributors to performance.

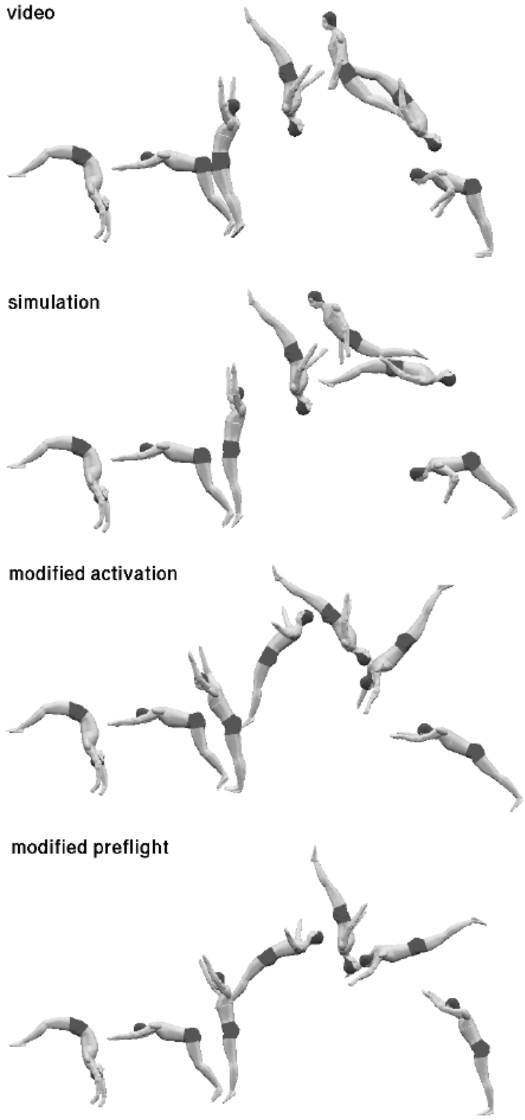


Figure 7. Simulation of a tumbling takeoff: (a) an actual performance of a double layout somersault obtained from video analysis, (b) simulated performance, (c) simulation with modified activation and (d) simulation with modified preflight.

Swinging

A four segment model comprising arm, trunk, thigh and shank segments with springs at the hand and shoulder driven by joint angles may be used to simulate giant circles on the high bar (Hiley, 1998). For suitable stiffness and damping parameters of the springs there is close agreement between an actual performance and simulated performance (Figure 8).

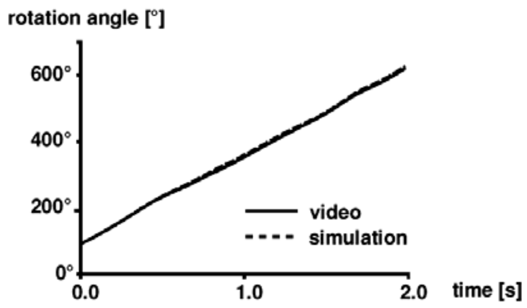


Figure 8. Comparison of rotation angles for actual and simulated performances of accelerated giant circles.

There are two techniques used by gymnasts to accelerate backward giant circles prior to a double layout somersault dismount. In the “traditional” technique the gymnast extends close to the vertical at the end of the penultimate giant circle (Figure 9a.9) whereas in the “scooped” technique the gymnast does not reach full extension until much later (Figure 9b.11). In order to determine which of the two techniques was better at producing high angular momentum at release the timing of the flexion and extension movements was optimised using a Simulated Annealing algorithm (Goffe *et al.*, 1994) subject to torque limits determined from dynamometer measurements. It was found that there was a global optimum which used the traditional technique (Figure 9a) but that there was also a local optimum (Figure 9b) which used the scooped technique and reached 98% of the angular momentum achieved at the global optimum. When the torque limits were decreased to 75% of the dynamometer determined limits, the global optimum was achieved using the scooped technique while there was a local optimum which used the traditional technique. This explains why there are two techniques in use and indicates that the best technique for a particular gymnast will depend on his strength or on how close to his strength limits he is able to work at the end of a high bar routine.

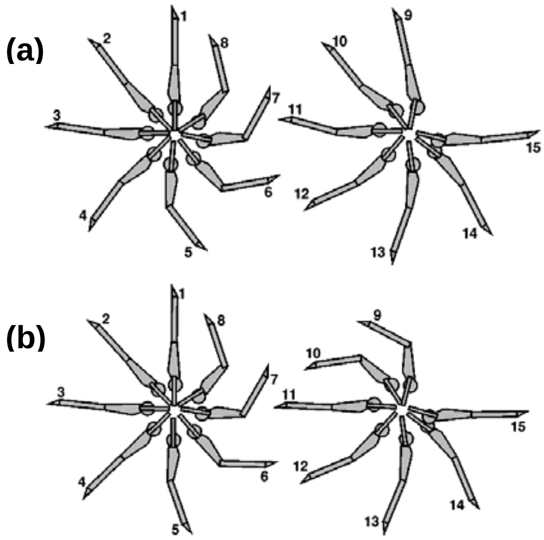


Figure 9. Accelerated giant circles prior to a dismount: (a) traditional technique and (b) scooped technique.

Control

Aircraft simulators are routinely used to train pilots to operate new types of aircraft in a safe but realistic environment. It is likely that the same kind of approach may be used to provide a virtual environment in which the athlete can learn certain aspects of control for sporting movements. Huffman *et al.* (1996) developed a bobsled simulator which was used by the US Bobsled Team as a training device. In the realm of twisting somersaults a virtual environment in the form of visual feedback via a headset should be able to train the ability to view the landing area during multiple somersaults with and without twists. The development of this ability is a key to producing accurate and stable landings. In addition sensors may be used to detect arm and leg movements and drive a simulation in real-time again with feedback via a stereo headset. This will permit the interactive learning of how to produce and control twist during simulated somersaults.

CONCLUSION: A drawback of very simple models is that they cannot match actual performances with great accuracy. As a consequence there is the possibility that a key element will have been omitted from the model and the insights gained into the sports movement may be erroneous. For complex models of the human body there are the problems of obtaining accurate representations of joint constraints, segmental inertias, muscle performance, and elastic structures within the body. Evaluating a model using actual performance data is a non-trivial necessity if there is to be confidence in the model predictions.
The application of simulation models to sports movements gives a means of understanding the underlying mechanics, analysing competitive performances, determining optimum techniques, and providing a simulated performance environment to assist in the learning of complex control.

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