OPTIMISATION OF TAKEOFF TECHNIQUE FOR MAXIMUM FORWARD ROTATION IN SPRINGBOARD DIVING

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The aim of this study was to optimise springboard diving takeoff technique for maximum forward rotation using a computer simulation model. A planar eight-segment model of a diver with torque generators together with a springboard model was developed. The model was evaluated by comparing simulation output with an elite diver's performance. The model was then used to optimise takeoff techniques for maximum rotational potential in the forward dive group by varying the activation timings of the torque-generators. There was a 20% increase in rotational potential in the optimised simulation compared to a performance of a forward two and one-half somersault pike (105 B) dive. The results highlight the importance of technique in springboard diving since by changing only the activation timing alone the diver can generate substantially more forward rotation.

KEY WORDS: torque, activation, evaluation, perturbation, robustness

INTRODUCTION: In competitive diving, the score of a dive comprises two parts: the judges' score and the degree of difficulty (DD) of the dive performed. The DD of a dive increases with somersault rotation and therefore it is beneficial to use a difficult dive with a high rotational requirement. Since the linear and angular momentum that the diver possesses in the air are determined by the end of the takeoff phase, it is crucial to understand the mechanics of the takeoff in terms of generating angular momentum, gaining dive height and keeping a safe distance from the board. The aim of this study was to optimise springboard diving takeoff technique for maximum forward rotation using a computer simulation model.

METHODS: A planar simulation model of a springboard and a diver (Figure 1) was developed using the Autolev 3.4^{TM} software package based on Kane's method of formulating equations of motion (Kane and Levinson, 1985). The springboard was modelled as a uniform rod allowing vertical, horizontal and rotational movements (Kong et al., 2004). The diver was represented by an eight-segment linked system with extensor and flexor torque generators acting at the metatarsal-phalangeal, ankle, knee, hip and shoulder joints. Wobbling masses were included within the trunk, thigh and shank segments to represent soft tissue movement during takeoff. The foot-springboard interface was modelled using three pairs of parallel and perpendicular damped springs acting at the toes, ball and heel.

Figure 1 A planar eight-segment model of a diver and a springboard.

Each torque generator was modelled using a rotational muscle-tendon complex comprising a contractile component (CON) and a series elastic component (SEC) based on the model of Alexander (1990). The stiffness of SEC was calculated based on muscle lengths and moment arms scaled from the literature to the diver and a 5% stretch at maximum torque (Muramatsu et al., 2001). The torque at time t was the product of an activation level and a maximum voluntary torque function of joint angle and angular velocity (see Equation (1)).

$$TOR(t) = A(t) \cdot T(\theta,\omega) \qquad (1)$$

where TOR(t) = torque at time t, A(t) = activation level at time t, $T(\theta,\omega)$ = maximum torque calculated from a torque / angle / angular velocity function.

Subject-specific model parameters were required to customise the model to a diver so that simulation output could be compared with the diver's own performance. An elite female diver competing at junior international level (mass = 64.1 kg, height = 1.68 m) participated in this study as approved by the Loughborough University Ethical Advisory Committee. Diving performance from a one-metre springboard was recorded using a high speed video camera operating at 200 Hz. Ten body landmarks (wrist, elbow, shoulder, hip, knee, ankle, heel, ball, toes, and the centre of the head) and the tip of the springboard were digitised and the diver's orientation, joint angle time histories, mass centre (CM) velocity and whole-body angular momentum were then calculated. Anthropometric measurements of the diver were taken to calculate segmental inertias using a mathematical inertia model (Yeadon, 1990). Visco-elastic parameters of the springboard and the diver were determined either directly from experiments or indirectly using optimisation (Kong et al., 2005). Maximum isometric and isovelocity torques that the diver could produce at the shoulder, hip, knee and ankle were measured on an isovelocity dynamometer (Cybex Norm) to obtain a joint torque / angle / angular velocity relationship.

Input to the model included initial conditions at touchdown obtained using high speed video together with activation time histories throughout the simulation. Output of the model comprised time histories of the springboard displacement, the diver's joint angle and angular velocity at each joint, body orientation, CM velocity and whole-body angular momentum. The model was evaluated by comparing the simulation outputs to the performance of a forward dive pike (101B) and a forward two and one-half somersault pike (105B). This was achieved by using a root mean squared (RMS) difference score which calculated the difference between the simulation and the performance in terms of S_1: joint angles, S_2: orientation, S_3: linear momentum, S_4: angular momentum, S_5: springboard characteristics (see Equation (2)). Penalty scores were used to limit the joint angles during takeoff and the joint angular velocities at takeoff to prevent hyper-extension in flight. Sixty muscle activation parameters plus the initial trunk orientation (±1°) and angular velocity (±1 rad s^{-1}) were varied to minimise the score S using the Simulated Annealing optimisation algorithm (Corana et al., 1987).

$$S = \sqrt{\frac{1}{5}\sum_{i=1}^{5} S_i^{\,2}} + \text{penalties} \qquad (2)$$

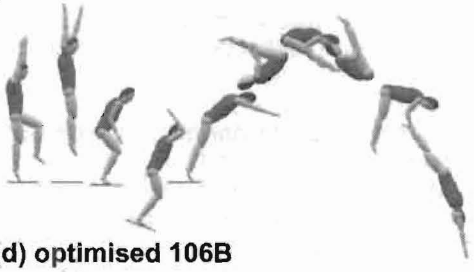
After satisfactory evaluation, the model was used to optimise takeoff techniques for maximum rotational potential in the forward dive group. The rotational potential was calculated as a product of the angular momentum and flight time. The minimum dive height and maximum horizontal travel constraints were based on the 105B performed by the diver. The sixty muscle activation parameters were re-optimised to maximise the rotational potential. Penalty scores were again used to prevent joint hyper-extension. The sensitivity of the simulation was investigated by activating the hip flexor 5 ms and 10 ms earlier and later.

RESULTS: The two simulations matched the performance very well with a score of 6 % for 101B and 7% for 105B. Graphical comparison of the simulation and the performance of 105 B is shown in Figure 2. The flight phase performance was predicted using an angle-driven simulation model of aerial movement (Yeadon et al., 1990) based on the takeoff characteristics of the simulation comprising body orientation and CM linear and angular momentum, together with joint angle time histories obtained from the video data. In the optimisation for maximum rotational potential, there was a 19.9% increase in rotational potential in the optimised simulation compared to the 105B dive. The optimised takeoff technique was characterised by a faster knee extension, a faster and increased hip extension before a rapid hip flexion towards the end of the takeoff phase. Using the optimised takeoff technique, the model can perform an improved 105 B with sufficient time to come out and prepare for the entry (see Figure 2c). Based on the same takeoff conditions, a forward triple somersault pike (106B) dive can be performed by modifying the come-out technique for the entry (see Figure 2d). The effect of early and late activation timing of the hip flexor to the optimised simulation is tabulated in Table 1.

(a) 105B performance

(b) matching 105B

(c) optimised 105B



(d) optimised 106B

Figure 2 Graphical comparison of the (a): performance of a forward two and one-half somersault pike (105B); (b): matching simulation of 105B; (c): optimised simulation of 105B and (d): forward triple somersault pike (106B) using the takeoff techniques for maximum forward rotational potential simulation (with additional 0.6 m horizontal spacing between contact phase and 0.4 m between flight phase figures).

Table 1 Sensitivity of the Optimised Simulation to Hip Flexor Activation Timing.

Hip flexor activation	Rotational potential (SS)*	Penalties
Matching simulation	1.07	no
Optimised simulation	1.28	no
10 ms earlier	1.24	no
5 ms earlier	1.26	no
5 ms later	1.31	knee, metatarsal-phalangeal
10 ms later	1.33	knee, metatarsal-phalangeal

*The rotational potential was normalised to the number of straight somersaults (SS).

DISCUSSION: The good match between the simulation and the performance suggests that the model successfully reproduces realistic springboard diving takeoff movements. The optimisation result shows a substantial increase in rotational potential by changing the activation alone without any increase in strength. This highlights the importance of technique in springboard diving. In order to generate more forward rotation, the diver should push the board harder with increased knee and hip extension during the board depression phase, followed by a fast hip flexion towards the end of the board recoil phase to generate forward angular momentum. This fast hip flexion from a more extended hip position requires a larger hip torque compared to the matching simulation but this torque is within the strength capability of the diver as measured using the isovelocity dynamometer.

The optimised simulation is, however, sensitive to activation timing since early activation of the hip flexor resulted in a progressive decrease in rotational potential whilst late activation resulted in an increase in rotational potential but with violation of the joint angle constraints. Any violation in joint angle constraints suggests that the activation timing will cause injury and is therefore unlikely used by a diver in practice. Less rotational potential may be expected with a robust solution that is insensitive to small perturbations in activation timing.

CONCLUSION: This study highlighted the importance of technique in springboard diving since by changing the activation alone the diver can generate substantially more forward rotation. In future robustness to activation timing perturbations should be included in the optimisation procedure in order to ensure that performances can be consistent.

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