# CONSTRAINTS AND ROBUSTNESS CONSIDERATIONS IN THE OPTIMISATION OF SPRINGBOARD DIVING TAKEOFF TECHNIQUE: A SIMULATION STUDY

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The aim of this study was to investigate the effects of imposing anatomical constraints and robustness requirements on the optimisation of springboard diving takeoff technique. A planar eight-segment model of a diver with torque generators together with a springboard model was used to optimise takeoff techniques for maximum rotational potential in the forward dive group by varying the activation timings of the torque-generators. Optimisation 1 imposed no constraints or robustness requirements. Optimisation 2 imposed anatomical constraints. Optimisation 3 imposed anatomical constraints and a requirement of robustness to perturbations in activation timing. The results showed that imposing both anatomical constraints and robustness requirements have a substantial effect on optimum simulated performance.

**KEY WORDS:** model, anatomical, perturbation, activation, sensitivity.

**INTRODUCTION:** Computer simulation models have been used to investigate springboard diving takeoff techniques with an aim to enhance performance (e.g. Cheng & Hubbard, 2004; Sprigings & Miller, 2004). For a model to predict realistic human movement, constraints must be identified and incorporated into the optimisation procedures. This may be achieved by introducing a penalty into the optimisation score once a constraint in violated. In springboard diving constraints should be applied to give realistic joint movement and performance characteristics such as dive height and distance travelled. In addition to constraints, the robustness of an optimisation solution to perturbations should also be incorporated to ensure that performance is consistent (King & Yeadon, 2003). The aim of this study was to investigate the effects of imposing anatomical constraints and robustness requirements on the optimisation of a forward dive with maximum somersault rotation from a one-metre springboard.

**METHOD:** A planar simulation model of a springboard and a diver (Figure 1) was developed using the Autolev 3.4™ software package based on Kane's method of formulating the equations of motion (Kane & 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 (MP), ankle, knee, hip and shoulder joints. Each torque generator was modelled using a rotational muscle-tendon complex comprising a contractile component and a series elastic component based on the model of Alexander (1990). The torque of each contractile component was the product of an activation level and a maximum voluntary torque function of joint angle and angular velocity. Subject-specific model parameters were determined from 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

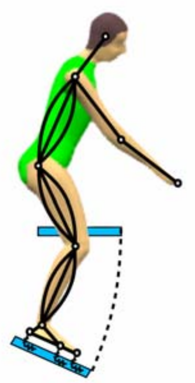

Figure 1: A planar eight-segment model of a diver and a springboard.

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., 2005a). Joint torque parameters were determined from the maximum joint torques at the shoulder, hip, knee and ankle measured using an isovelocity dynamometer (Cybex Norm).

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 angle and angular velocity at each joint, trunk orientation, CM velocity and whole-body angular momentum.

This simulation model has been evaluated previously by comparing simulations with diving performances in terms of joint angles and orientation time histories, linear and angular momentum at takeoff, springboard depression and takeoff time. Close agreement between the matching simulation and the performance of a forward two and one-half somersault pike (105B) dive was demonstrated (Kong et al., 2005b). After satisfactory evaluation, the model was used to optimise takeoff techniques for maximum rotational potential in the forward dive group. Rotational potential was calculated as the product of the angular momentum and flight time normalised to give the equivalent number of straight somersaults (SS). In order to assess the effects of imposing constraints and robustness on optimisation results, three different optimisation procedures were used: Optimisation 1 imposed no constraints or robustness; Optimisation 2 imposed anatomical constraints; and Optimisation 3 imposed both anatomical constraints and a requirement of robustness to perturbations in activation timing. Each optimisation was carried out by varying 60 torque activation parameters to search for a simulation that produced maximum rotation potential using the Simulated Annealing optimisation algorithm (Corana et al., 1987). To ensure that the optimised simulation corresponded to a good performance, constraints on minimum dive height and maximum horizontal travel were imposed in all three optimisations based upon the 105B matching simulation results.

In Optimisation 2 and Optimisation 3, anatomical constraints were used to limit the joint angles during takeoff and the joint angular velocities at takeoff to prevent unrealistic hyper-extension during takeoff and in the early part of flight. To achieve this, the joint angles 0.1 s after takeoff were calculated using Equation (1):

$$\theta_2 = \theta + \omega\,(0.1) \qquad (1)$$

where $\theta_2$ = predicted joint angle 0.1 s after takeoff, $\theta$ = joint angle at takeoff, $\omega$ = angular velocity at takeoff. Both the joint angles $\theta$ and the predicted joint angles $\theta_2$ were limited to the range observed in video recordings of diving performances (Table 1). Penalty scores were imposed once the angles exceeded this range. In Optimisation 3 perturbations of ±10 ms were introduced into the activation timing of the hip and knee torque generators and the score was taken to be the minimum rotation potential of four perturbed simulations. The sensitivities of Optimisation 2 and Optimisation 3 to perturbations of ±10 ms were determined.

Table 1 Anatomical constraints observed from video recordings of diving performances

| **joints** | **$\theta$ during takeoff** | | **$\theta_2$ after takeoff** | |
|---|---|---|---|---|
| | **minimum** | **maximum** | **minimum** | **maximum** |
| MP | 85° | 190° | 85° | 190° |
| ankle | 85° | 180° | 85° | 180° |
| knee | / | 180° | 110° | 180° |
| hip | / | 220° | / | 220° |
| shoulder | / | 195° | / | 195° |

**RESULTS:** The optimised rotational potential was 1.76 SS in Optimisation 1 without constraints or robustness, 1.32 SS in Optimisation 2 with anatomical constraints and 1.06 SS in Optimisation 3 with anatomical constraints and robustness requirements compared to 1.08 SS in the 105B matching simulation. Table 2 compares the kinematics of the three optimised and the 105B matching simulation. The sensitivity of Optimisation 2 and Optimisation 3 to perturbations in activation timing of ±10 ms at the hip and knee are shown in Table 3.

Table 2 Kinematic comparison of the optimised and matching simulations

| kinematics | matching | opt 1 | opt 2 | opt 3 |
|---|---|---|---|---|
| dive height (m) | 2.90 | 2.90 | 2.93 | 2.80 |
| distance travelled (m) | 1.58 | 1.53 | 1.49 | 1.59 |
| angular momentum (kg $m^2$ $s^{-1}$) | 58.8 | 101.3 | 73.0 | 59.7 |
| rotation (SS) | 1.08 | 1.76 | 1.32 | 1.06 |
| takeoff angle (°) | 25.7 | 30.6 | 33.6 | 31.1 |
| takeoff time (s) | 0.41 | 0.41 | 0.40 | 0.40 |

**DISCUSSION:** In Optimisation 1 where no constraints or robustness were imposed, there was a substantial increase (63%) in rotation potential in the optimised simulation compared to the matching simulation. When anatomical constraints were used in Optimisation 2, the optimised rotation potential decreased to 1.32 SS which was 22% higher than the matching simulation. The results of Optimisation 2 are more reasonable than those in Optimisation 1 since the elite diver should have been performing close to her maximum capability and it is unlikely that minor changes in techniques would increase the rotation potential by as much as 63%. These results show that imposing anatomical constraints in the optimisation procedures has a significant influence to the results obtained. Table 3 shows that the simulation obtained in Optimisation 2 is sensitive to perturbations in hip and knee activation timings. Early activation tends to decrease rotational potential and delayed activation tends to increase rotational potential. Most perturbations, except for early hip activation, lead to violations of anatomical ranges. During the takeoff phase only the knee angle range is violated. This shows that the knee angle in the optimised solution is close to the pre-set anatomical limit. The flight angle $\theta_2$ predicted by the final takeoff angle and angular velocities is more sensitive to perturbations and there are violations in both knee and MP joints.
The rotational potential (1.06 SS) in optimisation 3 is closer to that of the matching simulation (1.08 SS) and the solution is robust to perturbations of ±10 ms in hip and knee activation timings without any joint constraint violations (Table 3). This indicates that the achievement level in the actual performance can be accounted for by constraint and robustness considerations.

Table 3. Effects of hip and knee timing perturbations in Optimisation 2 and Optimisation 3

| perturbation | rotation (SS) | dive height (m) | distance (m) | joint angle violation | |
|---|---|---|---|---|---|
| | | | | $\theta$ | $\theta_2$ |
| opt 2 | 1.32 | 2.93 | 1.49 | -- | -- |
| knee -10 ms | 1.27 | 2.93 | 1.53 | -- | MP |
| knee +10 ms | 1.36 | 2.94 | 1.45 | knee | knee |
| hip -10 ms | 1.18 | 2.88 | 1.54 | -- | -- |
| hip +10 ms | 1.43 | 2.88 | 1.28 | knee | MP, knee |
| | | | | | |
| opt 3 | 1.06 | 2.80 | 1.59 | -- | -- |
| knee -10 ms | 1.01 | 2.79 | 1.62 | -- | -- |
| knee +10 ms | 1.09 | 2.80 | 1.56 | -- | -- |
| hip -10 ms | 1.03 | 2.65 | 1.32 | -- | -- |
| hip +10 ms | 1.14 | 2.89 | 1.71 | -- | -- |

**CONCLUSION:** This study shows that 1) imposing anatomical constraints is important for the realistic optimisation of performance; 2) robustness to activation timing perturbations should be included in optimisation procedures in order to ensure some consistency of performance; and 3) the achievement level in the actual performance can be accounted for by constraint and robustness considerations.

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