Portuguese Journal of Sport Sciences
11 (Suppl. 2), 2011

COMPUTER SIMULATION MODELLING IN SPORTS BIOMECHANICS

Mark King

School of Sport, Exercise and Health Sciences, Loughborough University, UK

Theoretical analysis using computer simulation is a powerful tool in sports biomechanics that helps understand the factors that limit optimal performance or factors that might affect loading on the body. This paper considers a number of the main issues that face sports biomechanists when developing computer simulation models such as model complexity, computer software, subject-specific parameters, model evaluation and optimisation. In particular: two examples of whole body torque-driven forward dynamics computer simulation models of the takeoff phase in tumbling and springboard diving are used to investigate optimum performance; a model of one-handed backhand strokes in tennis to investigate loading at the elbow. Subject-specific parameters are determined for each model based upon experimental data on each elite athlete and the models are evaluated by comparing simulations with performances. Simulations and optimisations are then used to investigate specific questions for each activity.

KEY WORDS: computer simulation, optimisation, subject-specific, evaluation.

INTRODUCTION: Theoretical approaches to answering a research question in sports biomechanics typically employ a simulation model that gives a simplified representation of the physical system under study. With the human body being very complex any simulation model is a simplification of reality, with the specific complexity of the simulation model dependent on the activity being simulated and the purpose of the study. The advantage of a theoretical approach is that an ideal experiment can be conducted with one variable altered at a time. Whole body forward dynamics computer simulation models can be used to gain an understanding of the factors that have the most influence on optimum performance. The ability to run thousands of simulations in a single day allows investigations into optimum performance by characterising the technique used in a sports movement using a number of parameters and then optimising to find the best set of parameter values that maximises or minimises a performance score.

Typically a large number of parameters are required to characterise the technique used in a sports movement and this is often done using profiles which define the general shape of the activation time history for each actuator in the model. The parameters which define the shape of each profile are then varied using an optimisation routine in order to determine optimum performance. The performance score that is optimised could simply be the distance thrown, the height jumped or the amount of rotation produced. Although using a simple performance score will find an optimum solution, it may not be a realistic optimum as the solution could be very sensitive to small variations in technique and therefore result in an inconsistent performance. This problem can be overcome by incorporating perturbations of the technique parameters within the optimisation procedure.

The aim of this study was to use examples of torque-driven computer simulation models to consider a number of the main issues that face sports biomechanists when developing computer simulation models to investigate optimum performance and loading on the body for dynamic sports movements.

METHODS: Subject-specific torque-driven computer simulation models were developed for the takeoff phase of tumbling and springboard diving along with a torque-driven simulation model of one-handed backhand groundstrokes in tennis (Figure 1). The equations of motion for the two jumping models of varying complexity were developed using the Autolev software package (Kane and Levinson, 1985) while the model of one handed backhand groundstrokes was developed using MSC.ADAMS (MSC.Software Corp, California, USA).

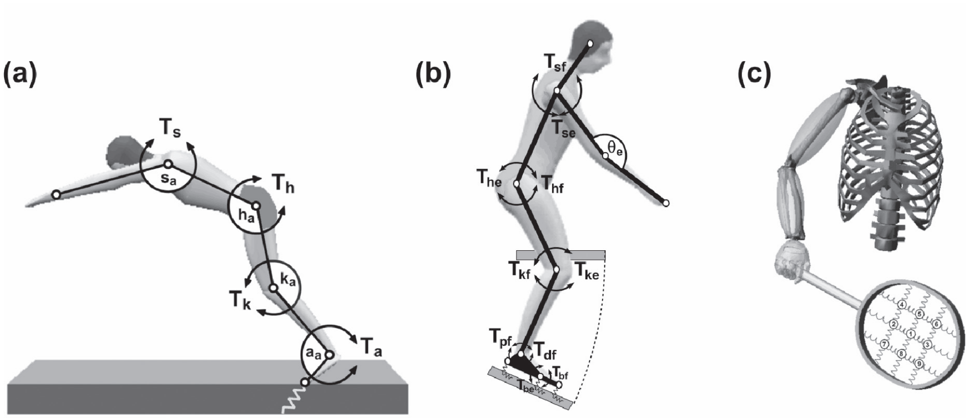

Figure 1: Computer simulation models of (a) the takeoff phase in tumbling, (b) the takeoff phase in springboard diving and (c) one handed backhand ground strokes in tennis.

Each simulation model was customised to an elite athlete based upon measurements taken on the subject. Inertia parameters (segmental length, mass, mass centre location and moment of inertia) for each rigid segment were determined from 95 anthropometric measurements on each elite athlete using the inertia model of Yeadon (1990). Strength measurements on each elite athlete using an isovelocity dynamometer (King and Yeadon, 2002) were used to determine the maximum voluntary torque that could be produced at each joint as a function of angle and angular velocity. Visco-elastic parameters for the springboard model were determined from experimental tests on the springboard (Yeadon et al., 2006), visco-elastic parameters for the tumbling track / model interface and springboard / model interface were determined using an optimisation procedure (Yeadon and King, 2002; Yeadon et al., 2006) and racket, stringbed and ball properties were deteremind from experimental tests on the equipment (Glynn, et al., 2011).

Each simulation model was evaluated by comparing simulations to performances of each activity by an elite subject. The activation profiles corresponding to each torque generator were varied using the simulated annealing optimisation algorithm (Corana et al., 1987) in order to obtain the best match to the performance of each activity in terms of joint angle changes and mass centre velocity / whole body angular momentum at takeoff.

The tumbling model was used to investigate how to maximise somersault rotation using technique changes during the final takeoff phase; the springboard diving model was used to maximise height and rotation from the 1 m springboard for forward dives and the tennis model was used to investigate under what conditions there are higher levels of eccentric contraction of the wrist extensors during one-handed tennis backhand ground strokes and potentially tennis elbow. With both jumping models the performance in flight was calculated using a simulation model for aerial motion (Yeadon et al., 1990) which used the linear and angular momentum at takeoff along with the configuration changes during flight as input.

RESULTS: All three subject-specific simulation models were successfully evaluated with good agreement obtained between performance and simulation (e.g. Figure 2). This is an important step in the modelling process as without this the wrong results may be obtained in simulations.

Optimising performance using the tumbling model showed that producing a triple layout somersault was only possible if the model's initial horizontal velocity was increased by 50% to 7.0 m/s (Figure 3a). However, this optimum triple layout somersault was very sensitive to the activation profiles used with a small change in the profile resulting in a substantial decrease in performance (Figure 3b). When perturbations to the activation profiles were included within the optimisation process a new optimum was found which was robust to 50 ms perturbations of the activation profiles (Figure 3c).

Optimising the height reached during flight for a forward dive piked resulted in a realistic increase in dive height of 65 mm when compared with the elite divers performance. This small increase in dive height supports the model evaluation and suggests that the strength parameters used in the springboard diving model are about right. However when the model was optimised for rotation (with initial conditions for the elite divers maximal dive; a forward two and a half piked) the resulting simulation had sufficient rotation potential at takeoff (angular momentum at takeoff × flight time) to give 63% more rotation during flight. This increase in rotation was unrealistic and was due to the knee angle exceeding its anatomical range of motion at takeoff and during early flight (20° hyperextension at takeoff increasing to

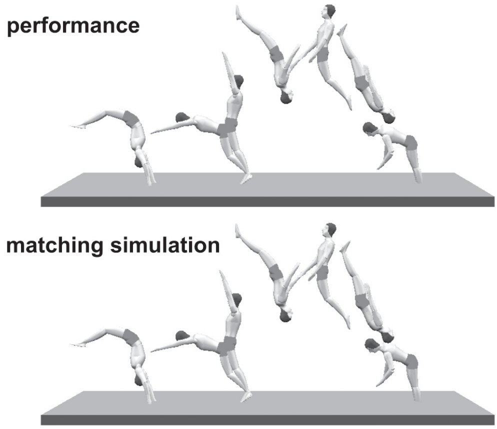

Figure 2: Performance and matching simulation of a double layout somersault.

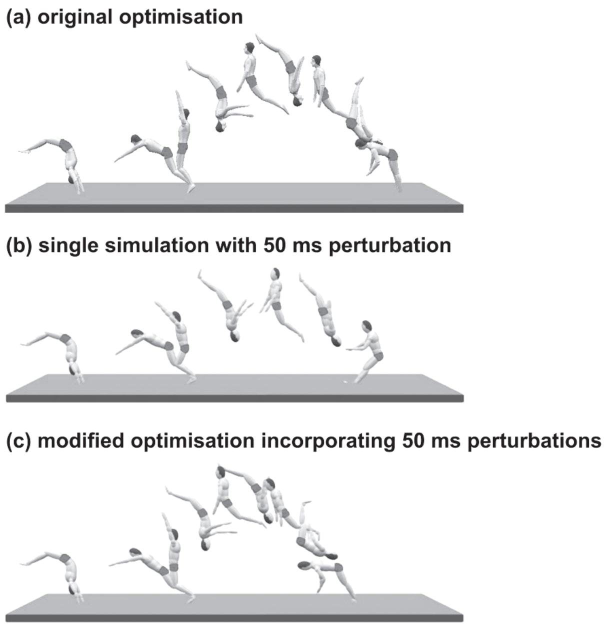

Figure 3: Tumbling optimisations.

50° during flight). As a consequence a penalty function was incorporated within the optimisation routine to prevent simulations which exceeded anatomical ranges of motion. This resulted in a more realistic increase in rotation of 22% and demonstrated the dangers of using a simple performance score.
Simulations at the nine impact locations on the stringbed (Figure 1) showed that the major kinematic change with respect to a centre impact simulation was observed in the racket rotation about its longitudinal axis relative to the hand and the wrist flexion / extension angle. Off-centre impacts on the longitudinal axis of the racket had small effects while impact locations above and below the longitudinal axis caused considerable increases in wrist extension and flexion, respectively. In particular during off-centre impacts below the longitudinal axis of the racket, the wrist was forced to flex up to 16° more with up to six times more wrist extension torque when compared to a centre impact simulation.

CONCLUSION: The importance of developing a subject-specific computer simulation model which can be evaluated by comparing simulations with performances has been demonstrated. Optimising performance using a simple performance score may lead to unrealistic optimum solutions, as a consequence robustness to timing perturbations and anatomical constraints should be taken into account. Using a subject-specific simulation model allows an ideal experiment to be run with one variable being perturbed so that the effect of a specific variable can be established.

REFERENCES:

Corana, A., Marchesi, M., Martini, C., & Ridella, S., (1987). Minimising multimodal functions of continuous variables with the "simulated annealing" algorithm. *ACM Transactions on Mathematical Software*, 13, 262-280.

Glynn, J.A., King, M.A., & Mitchell, S.R. (2011). A computer simulation model of tennis racket/ball impacts. *Sports Engineering*, 13, 65-72.

Kane, T.R. & Levinson, D.A. (1985). *Dynamics: Theory and applications*. New York: McGraw-Hill Book Company.

King, M.A. & Yeadon, M.R. (2002). Determining subject-specific torque parameters for use in a torque-driven simulation model of dynamic jumping. *Journal of Applied Biomechanics,* 18, 207-217.

Yeadon, M.R. (1990). The simulation of aerial movement - II: A mathematical inertia model of the human body. *Journal of Biomechanics,* 23, 67-74.

Yeadon, M.R., Atha, J. & Hales, F.D. (1990). The simulation of aerial movement – IV: A computer simulation model. *Journal of Biomechanics*, 23: 85-89.

Yeadon. M.R., King, M.A. & Wilson, C. (2006). Modelling the maximum voluntary joint torque / angular velocity relationship in human movement. *Journal of Biomechanics,.* 39, 476-482.

Yeadon, M.R., Kong, P.W. & King, M.A. (2006). Parameter determination for a computer simulation model of a diver and a springboard. *Journal of Applied Biomechanics*, 22, 167-176.

Acknowledgement

Co-workers: Jonathan Glynn, Behzat Kentel, Veni Kong and Fred Yeadon.