Yeadon, M.R. and King, M.A. 2008. Computer simulation modelling in sport. In Biomechanical Analysis of Movement in Sport & Exercise (Eds C.J. Payton and R.M. Bartlett), pp. 176-205. London: Routledge.

This chapter describes the process of building a mathematical model using rigid bodies and elastic structures to represent body segments and various ways of representing the force generating capabilities of muscle. Direct and indirect methods of determining the physical parameters associated with these elements are described. Before using a model to answer a research question it is first necessary to establish that the model is an adequate representation of the real physical system. This process of model evaluation by comparing model output with real data is discussed. Examples of applications of both forward dynamics and inverse dynamics computer modelling are given.

Computer Simulation Modelling in Sport

M.R. Yeadon and M.A. King

Introduction

Experimental Science aims to answer research questions by

of the human body may adequately represent the aerial phase of a straight dive but a model with two or three segments would be required for a piked dive to give an adequate representation. As a consequence a single model cannot be used to simulate all activities and so specific simulation models are built for particular tasks. As a general rule the model should be as simple as possible, while being sufficiently complex to address the questions set. This simple rule of thumb can be quite difficult to implement since the level of complexity needed is not always obvious.

Essentially forward dynamics simulation models can either be: [1] angle-driven where the joint angle time histories are input to the model and the resulting whole body orientation and mass centre position are calculated (along with the required jointm w 117( )231(w)5r

Model Components

The following section will discuss the various components that are used to build a typical simulation model.

Linked segment models

Most of the whole body simulation models in sports biomechanics are based on a collection of rigid bodies (segments) linked together, and are generically called ‘linked segment systems’. The rigid bodies are the principal building blocks of simulation models and can be thought of as representing the basic structure and inertia of the human body. For each rigid segment in a planar model four parameters are usually required: length, mass, mass centre location, and moment of inertia. The number of segments used depends on the aim of the study and the activity being modelle

Interface with external surface

The simplest way to model contact between a human body model and an external surface, such as the ground or sports equipment, is to use a 'joint' so that the model rotates about a fixed point on the external surface (Bobbert et al., 2002). The disadvantage of this method is that it does not allow the model to translate relative to the point of contact or allow for a collision with the external surface since for an impact to occur the velocity of the point contacting the surface has to be non-zero initially. Alternatively forces can be applied at a finite number of locations using visco-elastic elements at the interface with the forces determined by the displacements and velocities of the points in contact. The visco-elastic elements can be used to represent specific elastic structures within the body such as the heel pad (Pain and Challis, 2001b) or sports equipment such as the high bar (Hiley and Yeadon, 2003b) or tumble track / foot interface (King and Yeadon, 2004). The equations used for the visco-elastic elements have varied in complexity from simple damped linear representations (King and Yeadon, 2004) through to highly non-linear equations (Wright et al., 1998). The number of points of contact varies but it is typically less than three (Yeadon and King, 2002) although 66 points of contact were used to simulate heel-toe running (Wright

within realistic limits in order to define the activation time history used for each muscle during a specific simulation.

Series elastic element

The series elastic element represents the connective tissue in series with the contractile element (tendon and aponeurosis). The force produced by the series elastic element is typically expressed as an increasing function of its length with a slack length below which no force

Model construction

The following sections will discuss the process of building a simulation model and running simulations using the components described in the previous section.

Free body diagram of the model

A free-body diagram of a simulation model gives all the necessary information required to build the computer simulation model. The free-body diagram should include the segments, the forces and torques and the nomenclature for lengths (Figure 1). In the system shown there are two degrees of freedom since the two angles θ_a and θ_b define the orientation and

For more complex models a computer package is recommended, as it can take a long time to generate the equations of motion by hand and the likelihood of making errors is high. There are a number of commercially available software packages (e.g. DADS, ADAMS, AUTOLEV and SD Fast) that can generate equations of motion for a user defined system of rigid and elastic elements. Each package allows the user to input a relatively simple description of the model and the equations of motion are then automatically generated, solved and integrated. Note, with all packages that automatically generate equations of motion it is important to learn how to use the specific software by building simple models and performing checks to ensure that the results are correct. Some packages (e.g. AUTOLEV) generate computer

Integration

Running a simulation to calculate how a model moves requires a method for integrating the equations of motion over time. The simplest method to increment a set of equations of motion (ordinary differential equations) through a time interval dt is to use derivative information from the beginning of the interval. This is known as the ‘Euler method’ (Press et al., 1988):

$$x_{n\ 1} \quad x_{x} \quad x_{n}dt \quad \tfrac{1}{2}\ddot{x}_{n}dt^{2}$$

Optimisation

Simulation models can be used to find the optimum technique for a specific task by running many simulations with different inputs. To perform an optimisation is a three stage process. Firstly

- Decide whether to use a software package or to build the model from first principles

Parameter Determination

An alternative method which is worthy of mention is to use medical imaging techniques (Martin et al., 1989; Zatsiorsky et al., 1990) to determine segmental inertia parameters. With current technol dynamometer over a range of joint angular velocities and joint angles for the subject and so subject-specific parameters can be determined that define maximal voluntary torque as a function of muscle angle and velocity (King and Yeadon, 2002; Yeadon et al., 2006). With this approach it is still necessary to use data from the literature to determine the parameters for the series elastic element for each torque generator. In recent studies (King et al., 2006) it has been assumed that the series elastic element stretches by 5% of its resting length during isometric contractions (de Zee and Voigt, 2001; Muramatsu et al., 2001). Although it would be desirable to be a

assumptions are not erroneous and that there are no gross modelling defects or simulation software errors. Ideally the evaluation process should include all aspects of the model that are going to be used to make predictions. If a model is going to be used to investigate the effect of initial conditions on maximum jump height then the model should be evaluated quantitatively to show that for a given set of initial conditions the model can perform the movement in a similar way and produce a similar jump height. If a model is to be used to examine how the knee flexor and extensor muscles are used in jumping, the model should be evaluated to show that for a given jump the model uses similar muscle forces to the actual performance.

To evaluate a simulation model is challenging and may require a number of iterations of model development before the model is evaluated satisfactorily. Initially data must be collected on an actual performance by the sports participant. Ideally this should be an elite performer who is able to work maximally throughout the testing and produce a performance that is close to optimal. Time histories of kinematic variables (from video or an automatic system), kinetic variables (from force plate or force transducers) and EMG histories (if possible) should be obtained. Subject-specific model parameter values are then determined from the measurements taken on the subject (anthropometric, strength, etc) with as little reliance on data from the literature as possible (Yeadon et al., 2006; Wilson et al., 2006). The initial kinematic conditions (positions and velocities) for the model are then determined from the performance data and input to the model along with any other time histories that are required for the model to run a single simulation. If the model is kinetically driven this will consist of the activation time history for each actuator (Yeadon and King, 2002), while if the model is kinematically driven the time history of each joint angle will be required (Hiley and Yeadon, 2003a). Once a single simulation has been run a difference score should be calculated by quantitatively comparing the simulation with the actual performance. The formulation of the score depends on the activity being simulated, but it should include all features of the performance that the model should match (e.g. joint angle changes, linear and angular momentum, floor movement etc). The difficulty in combining severable variables into one score is that appropriate weightings need to be chosen for each part of the objective function. For example Yeadon and King (2002) assumed that a 1° difference in a joint angle at takeoff was equivalent to a 1% difference in mass centre velocity at takeoff. Furthermore, for variables that cannot be measured accurately (e.g. wobbling mass movement) it may be more appropriate to add a penalty to the difference score if too much movement occurs (King et al., 2006). Finally the input to the model is then varied until the best comparison is found (score minimised) using an optimisation routine. If the comparison between performance and simulation is close (Figure 2) then the model can be used to run simulations. If not then the model complexity or model parameters need to be modified and the model re-evaluated. If the comparison gives a percentage difference of less than 10% this is often sufficient for applications in sports biomechanics.

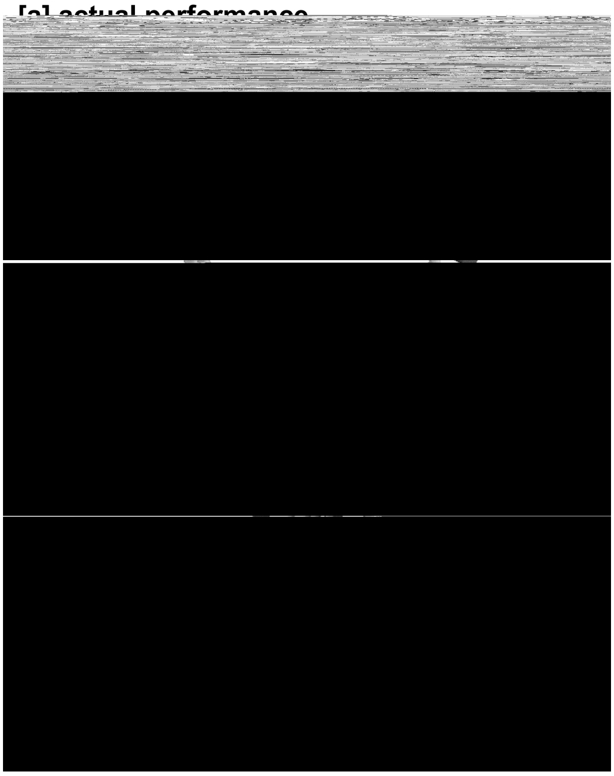


Figure 2. Comparison of performance and simulation graphics for the tumbling model of Yeadon and King (2002).

Issues in Model Design

The design of a partic4.33117(g)5.67433117(a)-4.33117(r)2.Tni474(f)-12.1715(65133117

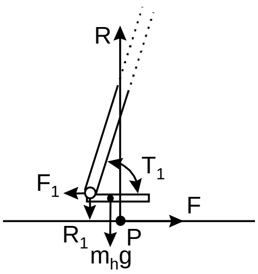
equations in the joint accelerations and joint torques by eliminating the six reaction forces. A knowledge of the segmental inertia parameters of a gymnast together with the time histories of the three joint angles during a handstand then permits the calculation of the joint torque time histories.

Nomenclature

H	:	hand segment
A	:	arm segment
B	:	body (trunk and head) segment
C	:	leg segment
J_1	:	wrist joint
J_2	:	shoulder joint
J_3	:	hip joint
(x_i, z_i)	:	joint centre coordinates (i = 1,3)
F_i	:	horizontal joint reaction forces (i = 1,3)
R_i	:	vertical joint reaction forces (i = 1,3)
P	:	centre of pressure
(x_j, z_j)	:	segment mass centre coordinates (j = h, a, b or c)
(x_p, z_p)	:	point of force application (z_p is assumed = 0)
x_j	:	horizontal linear accelerations of segment mass centres (j = h, a, b or c)
z_j	:	vertical linear accelerations of segment mass centres (j = h, a, b or c)
I_j		

Each of the four segments (H, A, B, C) produce three equations: one for resultant vertical force, one for resultant horizontal force, one for moments about the mass centre.

Hand (H) : (assumed stationary)



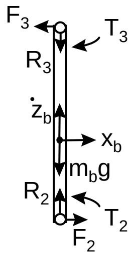
$\uparrow$: $R - R_1 - m_hg = 0$

- (1)

$\rightarrow$: $F - F_1 = 0$

- (2)

H : − + − + − +


F3
T3
R3
z_b
x_b
m_bg
R2
T2
F2

$$F(z_2 - z_p) - R(x_2 - x_p) + m_h g(x_2 - x_h) + m_a g(x_2 - x_a)$$

$$= T_2 + I_a \ddot{\phi}_a + m_a \ddot{x}_a (z_2 - z_a) - m_a \ddot{z}_a (x_2 - x_a) \qquad - (16)$$

Combining equations (16) and (9), substituting for R_3 and F_3 and taking moments about J_3 for H, A and B gives:

$$F(z_3 - z_p) - R(x_3 - x_p) + m_h g(x_3 - x_h) + m_a g(x_3 - x_a) + m_b g(x_3 - x_b)$$

$$= T_3 + I_a \ddot{\phi}_a + I_b \ddot{\phi}_b + m_a \ddot{x}_a (z_3 - z_a) + m_a \ddot{x}_b (z_3 - z_b) - m_a \ddot{z}_a (x_3 - x_a) - m_b \ddot{z}_b (x_3 - x_b) \qquad - (17)$$

Combining equations (17) and (12) is equivalent to taking moments about P for the whole system and gives:

$$=$$

$$x_a = x_1 + a_1\cos\phi_a \qquad \ddot{x}_a = -a_1\sin\phi_a\ddot{\phi}_a - a_1\cos\phi_a\dot{\phi}_a^2$$

$$z_a = z_1 + a_1\sin\phi_a \qquad \ddot{z}_a = -a_1\cos\phi_a\ddot{\phi}_a - a_1\sin\phi_a\dot{\phi}_a{}^2$$

$$x_b = x_1 + a_2\cos\phi_a + b_1\cos\phi_b \qquad \ddot{x}_b = -a_2\sin\phi_a\ddot{\phi}_a - a_2\cos\phi_a\dot{\phi}_a^2 - b_1\sin\phi_b\ddot{\phi}_b - b_1\cos\phi_b\dot{\phi}_b^2$$

$$z_b = z_1 + a_2\sin\phi_a + b_1\sin\phi_b \qquad \ddot{z}_b = a_2\cos\phi_a\ddot{\phi}_a - a_2\sin\phi_a\dot{\phi}_a^2 + b_1\cos\phi_b\ddot{\phi}_b - b_1\sin\phi_b\dot{\phi}_b^2$$

$$x_c = x_1 + a_2\cos\phi_a + b_2\cos\phi_b + c_1\cos\phi_c \qquad \ddot{x}_c = -a_2\sin\phi_a\ddot{\phi}_a - a_2\cos\phi_a\dot{\phi}_a^2 - b_2\sin\phi_b\ddot{\phi}_b - b_2\cos\phi_b\dot{\phi}_b^2$$

$$- c_1\sin\phi_c\ddot{\phi}_c - c_1\cos\phi_c\dot{\phi}_c^2$$

$$z_c = z_1 + a_2\sin\phi_a + b_2\sin\phi_b + c_1\sin\phi_c \qquad \ddot{z}_c = a_2\cos\phi_a\ddot{\phi}_a - a_2\sin\phi_a\dot{\phi}_a^2 + b_2\cos\phi_b\ddot{\phi}_b - b_2\sin\phi_b\dot{\phi}_b^2$$

$$+ c_1\cos\phi_c\ddot{\phi}_c - c_1\sin\phi_c\dot{\phi}_c^2$$

By substituting the geometric equivalents in place of the linear acceleration terms in equations (13)-(18) and re-arranging terms, we obtain six linear equations in the following form to solve for six unknowns (T_1, T_2, T_3, ϕ_a, ϕ_b, ϕ_c).

$$A_{11}T_1 + A_{12}T_2 + A_{13}T_3 + A_{14}\ddot{\phi}_a + A_{15}\ddot{\phi}_b + A_{16}\ddot{\phi}_c = B_1$$

$$A_{21}T_1 + A_{22}T_2 + A_{23}T_3 + A_{24}\ddot{\phi}_a + A_{25}\ddot{\phi}_b + A_{26}\ddot{\phi}_c = B_2$$

$$A_{31}T_1 + A_{32}T_2 + A_{33}T_3 + A_{34}\ddot{\phi}_a + A_{35}\ddot{\phi}_b + A_{36}\ddot{\phi}_c = B_3$$

$$A_{41}T_1 + A_{42}T_2 + A_{43}T_3 + A_{44}\ddot{\phi}_a + A_{45}\ddot{\phi}_b + A_{46}\ddot{\phi}_c = B_4$$

$$A_{51}T_1 + A_{52}T_2 + A_{53}T_3 + A_{54}\ddot{\phi}_a + A_{55}\ddot{\phi}_b + A_{56}\ddot{\phi}_c = B_5$$

$$A_{61}T_1 + A_{62}T_2 + A_{63}T_3 + A_{64}\ddot{\phi}_a + A_{65}\ddot{\phi}_b + A_{66}\ddot{\phi}_c = B_6$$

All of the terms held in the coefficients A_{11} through B_6 can be derived from video or force data at each instant in time. A linear equation solver is used to determine estimates for the six unknowns at each time instant.

However a number of the equation coefficients involve $\cos\phi_a$, $\cos\phi_b$, $\cos\phi_c$ which result in singularities in the calculated torques and angular accelerations around $\phi_j = 90^o$ (j = a, b, c). To avoid this problem a further three equations are added using video estimates e_1, e_2, e_3 of the angular accelerations $\ddot{\phi}_a, \ddot{\phi}_b, \ddot{\phi}_c$. These may be written as:

$$A_{44}\ddot{\phi}_a = A_{44}\, e_1$$

$$A_{55}\ddot{\phi}_b = A_{55}\, e_2$$

$$A_{66}\ddot{\phi}_c = A_{66}\, e_3$$

which match the coefficients of $\ddot{\phi}_a, \ddot{\phi}_b, \ddot{\phi}_c$

actual performance. In addition it is not possible to take advantage of an over-determined system and accurate acceleration values are needed which can be almost impossible to calculate during impacts.

Applications

twist angles produced by a number of techniques is likely to be greater than the twist resulting from the concurrent use of all the techniques. Additionally technique in the latter part of a twisting somersault may be primarily directed towards stopping the twist rather than producing the twist. Because of these effects Yeadon (1993d) used the maximum tilt angle as a measure of the twist potential in a movement. The tilt angles calculated in this way were additive situations it is important to take account of the inter-dependence of release parameters arising from the characteristics of the human participant (Hubbard et al., 2001).

More challenging are dynamic optimisations in which the time history of sports technique is optimised. Typically this requires a large number of parameters to characterise the technique used. In the case of angle-driven models it is a relatively simple matter to ensure that anatomical constraints at the joints are not violated (Hiley and Yeadon, 2003 correction to prevent drift away from the targeted performance. Variation in approach characteristics in tumbling may be compensated for by modifications in takeoff technique using feedforward control but only if such variation can be estimated in advance with sufficient accuracy (King and Yeadon, 2003).

Variation in technique can also be coped with by adopting a technique that is relatively insensitive (robust) to perturbations (van Soest et al., 1994; King and Yeadon, 2004). In cases where the limits of timing a movement are close to being reached, such considerations may be the main driver for selecting technique (Hiley and Yeadon, 2003b).

Conducting a Study

The main steps in conducting a study using a simulation model are as follows:-

- Identification of the research questions to be addressed
- Design of the model with these aims in mind
- Model construction
- Data collection for model input and parameter determination
- Parameter determination
- Model evaluation
- Experimental design of simulations to be run
- Results of simulations
- Conclusions: answering the research questions

Reporting on a Study

The format for reporting on a study will depend to some extent on the intended readership but should reflect the main steps listed in the previous section. Figures should be used when presenting a description of the model, performance data, simulation output, and model evaluation comparisons. The structure of a report or paper is usually along the following traditional lines:-

- Introduction: background, statement of aims
- Methods: model design, parameter determination, data collection, evaluation
- Results: simulation output, graphs, graphics, tables

- Discussion: addressing the aims, limitations, conclusions

Summary

The use of simulation models in sport can give insight into what is happening or in the case of a failing model what is not happening (Niklas, 1992). Models also provide a means for testing hypotheses generated from observations or measurements of performance. It should be remembered, however, that all models are simplifications and will not reflect all aspects of the real system. The strength of computer simulation modelling for sports science support is that it can provide general research results for the understanding of elite performance. While there is also the possibility of providing individual advice using personalised models, most sports biomechanics practitioners are a long way from realising this at present.

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