A COMPOSITE MODEL FOR THE SIMULATION OF SKIING TECHNIQUES

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INTRODUCTION

A mathematical model for the dynamic analysis and the simulation of skiing techniques has been recently developed by the authors.

It is composed of two sub-models: one for the human body, consisting of chains of rigid bodies, and one for the equipment consisting of flexible elements (beam elements); body segments and equipment (e.g. foot and ski) are linked by means of appropriate constraints, according with the chosen binding. The ski/snow contact model allows both edged skiing and skidding.

Such a model is the basis for a deeper understanding of the interaction between skier and equipment and its use will be profitable in various applications such as: equipment optimisation and technique improvement.

Due to the complexity of the problems involved, skier and equipment are generally studied separately, both experimentally and theoretically.

Regarding to downhill skiing and jumping, some papers deal with kinematic analysis of movement, or with aerodynamics, others analyse ski mechanical characteristics (stiffness, natural frequencies, vibration damping etc.), generally in a well defined environment; some others concern the measure of the action exchanged between ski and skier for safety aims but, on the other hand, only few papers deal with comprehensive models of the athlete with the equipment (e.g. Nachbauer 1994).

Skiing simulation may have several applications: for example in free-style jumps it allows to test a new exercise before its execution and to find the best conditions (velocity and momentum, as well as the limbs movements) required for reaching a good landing posture. It is also possible to predict the effects on skier performances of changes on ski mechanical and geometrical characteristics as well as on skier movements. At present the simulation of a whole race is not feasible because it requires the input of a huge amount of data such as the ones concerning the description of the race course; the simulation of a single phase is, on the contrary, affordable and profitable.

METHODS

To build our model we combined the methods used for multibody systems dynamic analysis (man model) with finite element techniques (ski model).

The human body model consists of 3D chains of rigid bodies: according to the "sophistication" of the simulation we use 16 segments, with 39 internal d.o.f (full man model), or 7 segments, with 6 internal d.o.f .

To describe rigid body dynamics and kinematics (man model) we adopt a method based on homogeneous matrices (Casolo 1996): both the absolute and the relative position, velocity and acceleration are described by 4x4 matrices, as well as the inertial properties and the external loads. This approach allows to embed both the linear and angular terms in the same formalism.

In order to evaluate, for each subject, the geometrical and inertial parameters required by the dynamic equations, a program, based on regression equations built on statistical bases, has been used (Zappa 1995).

To derive the equation of motion, a Lagrangian approach has been adopted, leading to a system of equation, which in matrix form can be written as follows:

$$\mathbf{M}\ddot{q} + \mathbf{C}(\dot{q},q) = \mathbf{F}_1(q,\dot{q},t) + \mathbf{F}_2(q)$$

where **M** is the mass matrix, **C** a vector holding the weight, the centrifugal and Coriolis action and **F** are the joint load components and q are the system d.o.f.

The model can be used to perform direct and inverse dynamics analysis of skiing, since it allows the input of joint torques and/or joint relative movements, which can be experimental data or can be generated by scratch, by using a law of motion pre-processor. If the joint acceleration are known the torques required for the movement can be easily obtained.

We implemented also a "mixed" approach: we model the muscles around a joint as a torque generator with a first order linear feedback to which is added a threshold for the maximum value of the resulting torque.

These procedures can obviously be combined, therefore some joints can be displacement driven, other torque driven and some other can have a linear feedback.

The action exchanged between equipment and skier depends on the relative motion allowed by the bindings. The constraints, simulated by stiff springs, exert actions preventing the relative motion between a body segment and the connected equipment: for example, downhill bindings and ski boots, in a simplified model, prevent both relative displacements and rotations between leg and ski (or, more into details, between the leg and a node of the ski model). Therefore 6 springs - 3 linear and 3 torsional - are introduced in order to constrain all the 6 relative d.o.f.

Skis are modelled with Finite Element techniques. The internal structure of a ski is quite complex: different material, with complex arrangement, are employed giving rise to properties (stiffness, damping and mass) which can be determined by experimental measures or by complex FE analysis. These properties can be quite well reproduced by means of a simplified model consisting of 3D beam elements . Some geometrical features, such as camber and sidecut, can be easily reproduced.

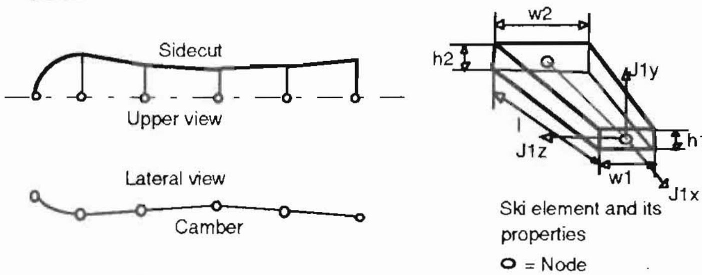

Fig. 1. An example of ski model with beam element properties

Ski equations of motion, in matrix form, are:

$$\mathbf{M}\ddot{q} + \mathbf{C}\dot{q}_{rel} + \mathbf{K}q_{def} = F_{ext} + F_{ski-man} + F_{ski-snow}$$

where **M**, **C**, **K** are, respectively, the ski mass, damping and stiffness matrices. The ski load consists of three terms: weight, action exerted by the skier through the bindings and the contact action exerted by the snow.

The equation of motion, both for the ski and for the man, are integrated with an implicit (Newmark) method.

Modelling the contact between ski and snow is not an easy task: snow is a very complex material and its properties are related to many factors such as the pressure exerted and the temperature. Moreover the behaviour of the ski on a particular kind of snow depends on other factors among which, for instance, the ski sole treatment and the edge sharpening are quite important.

Despite its simplicity, the ski model adopted for this work seems to be adequate to describe the phenomenon studied even if some details are neglected. For evaluating the contact forces we sampled the ski surface with a net of points lying on the lower ski surface: during time integration of the motion equations, the position of each of these points is computed and therefore the presence of contact between ski and snow can be detected.

Snow reacts, in different ways, both to ski deepening and to ski sliding and skidding. The action exchanged between ski and surface, preventing deepening, is directed upward (the surface can sustain only a compression load) and can be expressed as (DP_{ij} and VP_{ij} are the depth and deepening velocity of point P_{ij}):

$$F_{deep} = -k_{deep} DP_{ij} - c_{deep} VP_{ij-deep}$$

We suppose that the other two action components, which are parallel to the surface, could be originated by friction between ski and snow. We neglect the dependence of the coefficient of friction μ on velocity and pressure, but we consider it as a function of the local ski edging, i.e the angle between the local normals to the snow surface and to the ski lower surface.

$$F_{fric-slid} = -\mu_{slid} F_{Deep} \operatorname{atan}(k_1 VP_{ij-slid})$$

$$F_{fric-skid} = -\mu_{skid} (\vartheta_{edge}) F_{Deep} \operatorname{atan}(k_2 VP_{ij-skid})$$

The edging can vary along the ski due to ski deformation.

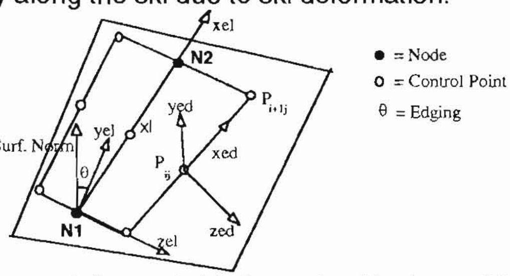

Fig. 2. A sketch of an undeformed ski element, with element frame (xel,yel,zel) and edge frame (xed,yed,zed).

PRELIMINARY RESULTS

To test the feasibility of the model for skiing simulation we performed some simple preliminary tests.

Some simulations have been performed to test model capabilities: we analysed the effect of ski torsional stiffness, as well as the amount of sidecut, on skier trajectory during traverse and turns.

We simulated the aerial phase of a free-style jump: appropriate initial condition on body position and velocity were given, together with the relative movements between body segments. Fig. 3 shows the output of this simulation.

With this kind of simulation the athlete, or the coach, can plan the exercise and then observe the resulting body motion, the landing position and check the joint loads. Modification to the exercises can be executed to improve the "score" of the jump and/or to reach a better (safe) landing posture.

Analyzing the landing phase (fig. 3b) is also possible to observe the ski deformation (and vibration).

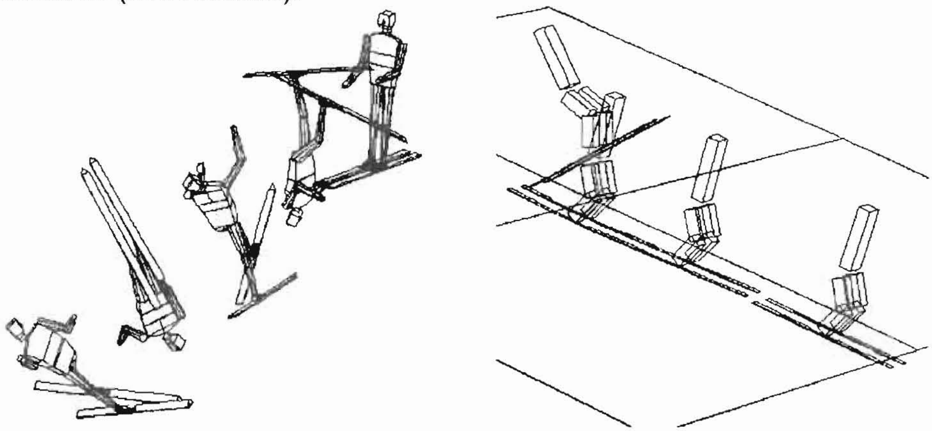

Fig. 3. Output of ski simulation

The preliminary tests of the system of programs based on the new model capable of simulating the aerial phase, the impact phase and the most important phase of skiing in which skis are on the snow, are very encouraging.

Movements of free style skiing, cross-country skiing and down hill skiing can be simulated taking into account for instance skis vibration, ski sinking into the snow and ski side cuts.

The model has been successfully validated for the aerial phase by means of experimental data currently available for some sports (for example diving, high jump and so on). Tests on the snow are under development in order to optimise and to validate the model in the other skiing phases. For these situation (turn and traverse, for example) the model can reproduce actual situations, pointing out the effect of some equipment characteristics.

We currently are working on the software to simplify the modification of the relative motion of the body segments, allowing also to stop and restart a simulation with corrected motion parameters.

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