Skier-ski system model and development of a computer simulation aiming to improve skier's performance and ski

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ABSTRACT

Background. Based on personal experience of ski teaching, ski training and ski competing, we have noticed that some gaps exist between classical models describing body-techniques and actual motor acts made by performing athletes. The evolution of new parabolic shaped skis with new mechanical and geometric characteristics increase these differences even more. Generally, scientific research focuses on situations where skiers are separated from their skis. Also, many specialized magazines, handbooks and papers print articles with similar epistemology. In this paper, we describe the development of a three-dimensional analysis to model the skier-skis' system. We subsequently used the model to propose an evaluation template to coaches that includes eight techniques and three observable consequences in order to make objective evaluations of their athletes' body-techniques. Once the system is modeled, we can develop a computer simulation in the form of a jumping jack, respecting degrees of freedom of the model. We can manipulate movement of each body segment or skis' gears' characteristics to detect performance variations. The purpose of this project is to elaborate assumptions to improve performance and propose experimental protocols to coaches to enable them to evaluate performance. This computer simulation also involves board and wheeled sports.

Methods. Eleven elite alpine skiers participated. Video cameras were used to observe motor acts in alpine skiers in two tasks: slalom and giant slalom turns. Kinematic data were input into the 3D Vision software. Two on-board balances were used to measure the six components of ski-boots→skis torques. All data sources were then synchronized.

Findings. We found correlations between force and torque measurements, the progression of center of pressure and the eight body-techniques. Based on these results, we created a technological model of the skier-ski system. Then, we have made a reading template and a model to coach young alpine skiers in clubs and world cup alpine skiers and, we have obtained results demonstrating the usefulness of our research.

Interpretation. These results suggest that it is now possible to create a three-dimensional simulator of an alpine skier. This tool is able to compare competitors' body-techniques to detect the most performing body-techniques. Additionally, it is potentially helpful to consider and evaluate new techniques and ski characteristics.

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Categories and Subject Descriptors
Measurement, Performance, Experimentation.

General Terms
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Keywords
Skier-ski system; Computer simulation; Techniques Reading template; Elite Skiing.

1. INTRODUCTION
There are gaps in research between classical models, describing body-techniques judged to be efficient and motor acts performed by athletes that we have observed during ski racing competition. Therefore, we decided to launch a research study on to analyse alpine skiing kinematics.

We believe that analysis of slalom or giant turn movement in alpine skiing are necessary to improve the current understanding of elite alpine skiing performance. Several studies have already been done on alpine skiing biomechanics: analysis of the carving turn with a combination of kinematics, electromyographic and pressure measurement method [1]; Analysis of the ski stiffness and snow conditions on the turn radius [2]. Research in ski racing used motion capture with inertial measurement units and GPS to collect biomechanical data and improve performance [3].

A three-dimensional movement analysis of the alpine skier while turning is a first step. The modeling of the skier and his/her technique will allow the development of a computer simulation in which every body segment will be modeled and potentially manipulated to interpret some parameters.

The last decade has seen the transformations of alpine skier equipment notably in terms of the geometrics and mechanical characteristics of skis due to new materials as well as the arrival of snowboarders. Research devices with micro computing and video cameras have also considerably improved.

On account of this evolution, we have developed a motion analysis system as a tool for alpine skiing research. The scientific literature is generally dedicated to the study of the alpine skier's body, independently from his equipment [2]. Our proposal is to consider skier and skis as a system divided into several sub-systems: skis, lower-limbs, trunk/head, upper-limbs which all interact with the coxal joint.

Modeling allows us to propose a reading template to coaches and instructors which can be potentially useful for champions' performance analysis and knowledge. It is made with eleven observation benchmarks, including eight specific ones for body-techniques and three with mechanical consequences. The goal is to simultaneously use and control these body-techniques to optimize efficiency according to the possible trajectory of the race's layout as well as the relief of the slope.

We assume that the simulator will be a tool for coaches to improve alpine skier performance and to improve new skis development.

The purpose of this article is three-fold. First a 3D analysis of eleven elite alpine skiers when performing a giant slalom turn or two slalom turns during a real skiing situation. We have done a tridimensional modeling of the skier, highlighting each body-segment. Second, a computer simulation in which we can manipulate movement of each body segment or skis' gears' characteristics to detect performance variations. Third, from the eight body-techniques (with their three consequences), as the reading template for coaches to improve skiers' efficiency, we have provided details of one, for an example.

2. SKIER-SKIS' SYSTEM MODELING

2.1 Methods

The first experiment took place in Les Saisies during an ISF (International Ski Federation) race, with nine skiers. The second experiment took place on the Grande Motte Glacier in Tignes, and the last one took place on the Mont de Lans Glacier in Les Deux-Alpes.
Eleven French elite alpine skiers (World Cup level) participated.

During the first experiment, we worked with the FFS (French Ski Federation) and videotaped nine athletes during a Giant Slalom ISF race. The French teams' director obtained the agreement from the referee of the race to put video cameras on the sides of the slope. The aim was to measure kinematic data of the skiers' techniques during a real race situation, to find out how alpine skiers start a turn and pilot for an efficient trajectory.

Distance between two Giant Slalom gates is 20 meters. We used two video cameras and oriented the optical field of the second camera in order to make a 30 degrees angle with the optical field of the first video camera. The common optical field of both video cameras was oriented according to the place where alpine skiers started to turn. The distance between the first camera and the slope was 20 meters, with maximal zoom lens while the distance of the second camera and the slope was 30 meters with maximal zoom lens. Data from the video were collected.

The second experiment involved one female alpine skier, performing the Giant Slalom. We created a mechanical model of skier-ski system thanks to Rossignol R&D who provided us with an on-board balance to measure ski boots→ski torques and snow→ski torques. The balance was inserted between the ski boot and the ski (figure 1). Skier had to carry herself units' data acquisition from the on-board balance (figure 1). Data was sampled at 936 Hz.
Six video cameras were located on the sides of the analyzed turn, three on the left side, and three on the right side.

Figure1. Unit data acquisition, focal points and on-board Balance

Nineteen focal points, made by fluorescent yellow and black squares tennis balls or scotch-tape, have been placed on the subject (anatomical landmarks) and skis on each side: one on the tip of the ski; one on the tail of the ski; one on the front binding; on the ski boot regarding the ankle; one on the knee; one on the hip; one on the elbow; one on the hand; one on the shoulder; one on the top of the helmet.
Data from the subject were input into 3D Vision software [4] and treated by a DLT (Direct Linear Transformation) algorithm [5].

Every 1/25th seconds, each position of each focal point located on subjects has been calculated. That way, the skier-ski system is located into the space of experiment.
The six video cameras were connected together to a synchronization device. To synchronize kinematic data (from video cameras) with on-board balance, we used a remote control which sent out a signal to units' data acquisition (on-board balance data) and which switched on a diode into the cameras' field of vision. The time-code value matching to the lighting of the diode is the time's origin of kinematic data. The signal recorded in units' data acquisition is the time's origin of torques' data. We made match the two origins (common event: remote control signal), and reduced the on-board balance frequency to 25Hz to synchronize all data.
We kept data when the subject skied through the experiment space: from the internal piquet of the upper gate to the internal piquet of the lower gate.
Data from focal points from the subject (on-board balance) was input into 3D Vision software and treated by a DLT algorithm.

Finally, for our last experiment, three male alpine skiers and one female alpine skier participated to the study. They skied on the Giant Slalom and Slalom.
Kinematic data were acquired the same way, except for video cameras. They were put on scaffolding to get rid of the spray snow, due to ski turns, which kept from seeing lower focal points.
We got two Kistler on-board force plates to measure ski-boots→ski torques and snow→ski torques. Force plates were inserted between the ski-boot and the ski. Skiers had to carry units' data acquisition of the on-board balance. Data was sampled at 936 Hz.
To collect 3D kinematic data, the measurement area was first calibrated. The area marking has been realized with focal points made by fluorescent yellow and black squares tennis balls impaled on a wood stick jabbed in the snow in the sight-line of video cameras. Focal points were also put on the bottom of the internal piquet of the upper gate, and on the bottom of the internal piquet of the lower gate.
Focal points data from the slalom gates and from the subjects were input into 3D Vision software and treated by a DLT algorithm.

We calculated both the position and the progression of the center of mass for each experiment. To determine the center of mass position, we had to calculate the weight, m_1, m_2, m_3… m_n, of each segment of the skier and of each ski gear, then determinate the position of the center of gravity M_1, M_2, M_3…M_n of each body segments and ski equipment in a space defined according to a frame. The position of the skier-ski system's center of gravity is calculated according to positions PM_1, PM_2, PM_3… PM_n of each center of gravity of body segments and ski equipment.

3. COMPUTER SIMULATOR

3.1 Tridimensional modeling

We consider skier-ski system as an articulated system divided in several sub-systems (figure 2). The first one, where the torque snow→skis is applied, is itself made by sub-systems skis and lower limbs. The second one, which it articulated with the previous one at each coxal joint, is constituted by the trunk, the head and upper limbs.

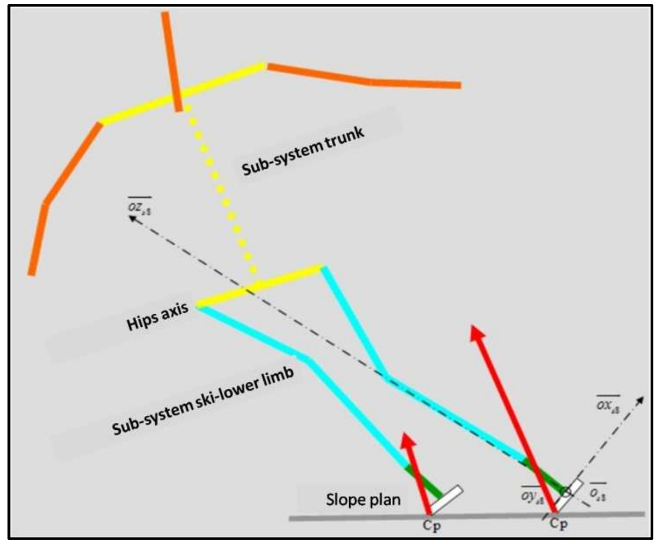

Figure 2. Skier-skis' system and sub-systems

We assume that we can better improve skis' development and training separating skier and skis, contrarily to a study about effects of ski and snow-cover on alpine skiing turn without studying the skier while using a sledge as the skier [2].

About the kinematic study, skier system is represented as a mechanical structure made by many stiff and rigid segments articulated with each other. Their moves are determined by degrees of freedom allowed by skeletal anatomy. The torques applied on joints have a muscular origin.

The ski-boot→ski torque is made up with three components of the support reaction (on the three axis) and with three torques compounding the resulting torque, results of the distance between the application point of the support reaction and the origin of the binding mounting mark (engraved on the topsheet by the ski constructor).

3.2 Computer representation

From the first model obtained with the 3D Vision software (figure 3), we have determined the position of some segmental centers of masses, using an anthropometric model [6] [7]. Then, we calculated the global center of mass. Those segments have been chosen because they can produce the eight fundamental techniques that the skier uses to control him/herself.

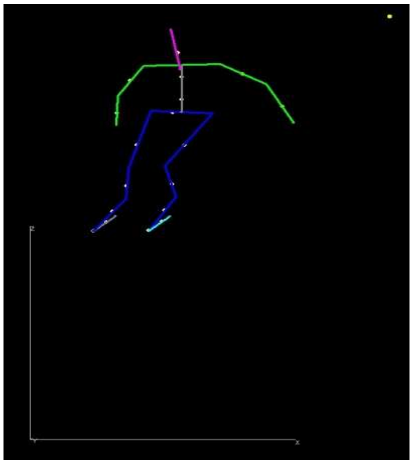

Figure 3. First modeling

Software works with a DLT algorithm ("Direct Linear Transformation"). It connects real coordinates (according to a known frame) of focal points which are in the common optical field of video cameras, with coordinates collected on the computer screen of each focal point recorded by each video camera. This calculation enables to rebuild the position of the moving point into the real space of experimentation. Then, the point which moves on the screen owns the 3D characteristics of the real moving point kinematic.

The 3D computer representation distinguishes each body segment, the coxal joint, the progression of center of gravity, feet trajectory, and each ski-boot→ski torque (represented by arrows, figure 4).

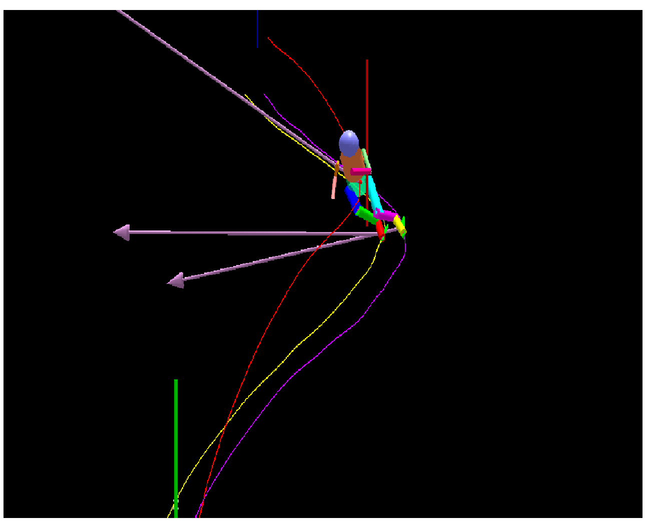

Figure 4. Jumping jack, computer simulator

The computer simulator makes the manipulation of the model possible to measure disturbances on the system: the trajectory changes; a joint order; a torque ski-boot→ski transformation which corresponds to a modification of a mechanical or geometric characteristics of a kind of ski. Thus, we will be able to discover, in a short term, new ways to improve performance.

With the new software ID3D (latest version of the 3D Vision software), we can pilot the progression of each segment of the jumping jack with captured kinematic of skier's movements' analysis. We can provide to the jumping jack anthropometrics characteristics modeled by Hanavan and apply context's torques that constrain the jumping jack. We can then measure data.

With the computer simulator, we aim two goals. The first is didactic, to show to coaches, trainees or athletes (beginners or experts) some biomechanical causes which affect the skier-skis' system and which the understanding is useful either to give instructions or to act. The second one is technological; it consists to impose technical instructions to the computer jumping jack, or modify some equipment characteristics, to measure their consequences. The goal is then to make assumptions about the evolution of techniques, skis modeling, and relations between the evolution of the ski structure and the torques produced during a specific situation.

4. RESULTS

The figure 4 shows the segmental modeling with resultant forces of ski→ski-boot torques, and also the direction of the global acceleration of the center of masses.

We calculated variations of joint angles to underline technique used by each subject to pilot himself. We made statistical comparisons which make objective our empirical model.

The two next graphics (figures 5 and 6) show in 2D variations of lateral knee inclination to the on-edge angle.

Graphics make appear a dispersion of size and timing but also a similar shape showing that the action is realized by every racer. So, it is a fundamental technique to make vary the on-edge angle and make our biomechanical and technological models.

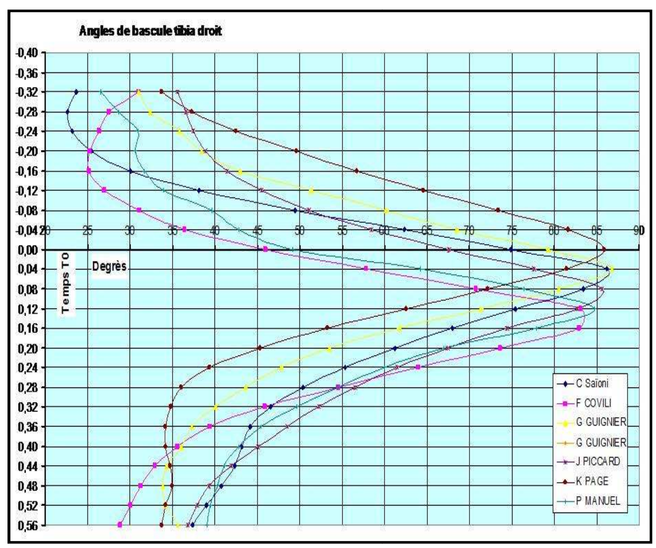

Figure 5. Angle right shin tip up

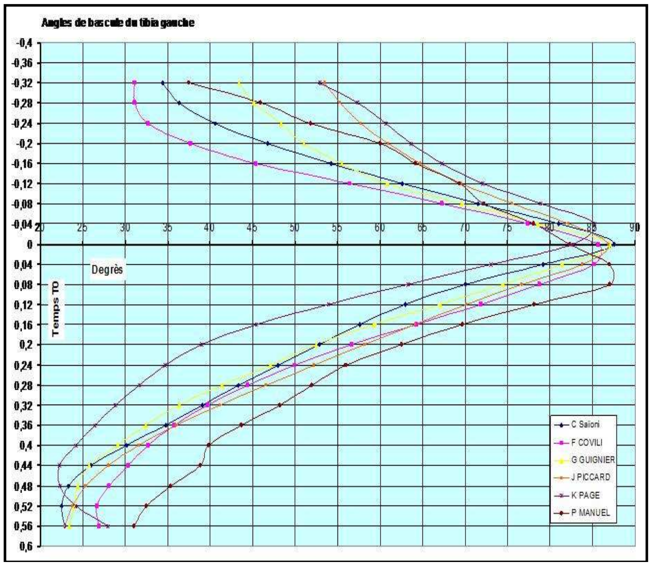

Figure 6. Angle left shin tip up

That way, contrarily to the classical model, and comparing our results with skeletal determinisms of our species described by physiologists [8], we have showed that the most performing skiers use the technique of the lower-limb's plane rotation, made by the axis middle of the ski boot – knee and knee -coxal joint around the axis middle of the ski boot to the coxal joint by a femoral adduction on the pelvis creating a lateral inclination of the outer knee. The aim is to make vary the on-edge angle without moving the center of mass on the inner foot in order to create a radial component to the contact snow→ski setting off the steering change the skier wants to make.

5. EXAMPLE OF A BODY-TECHNIQUE

Eight techniques have been highlighted with a ski motion analysis [9]. Because of their relevancy for world level coaches and physics theory, they have been defined according theses two points of view. For example, the body-technique told as "shin tip up" became for coaches "lateral knee inclination". The first definition respects physicians logical thought. The second one translates it as a useful technique to coaches because they can directly discernible, and described it, by words used in this professional field, biomechanical conceptions hold for the mathematical definition, keeping same body frames.

According to mechanics laws and because of mechanical and geometric characteristics of skis, three conditions are required to produce a directional effect: a sliding (skier's engine is the gravity); a ski loading (a deforming effort on the ski); an on-edge angle. To create and control this directional effect, skiers produce eight techniques (actually, nine: one of them is not an action, but a consequence: the lunge [9]). Theses eight techniques are three-aimed, but during skiing, they are constantly interacting and make a system. Following, we have focused on one technique: the lateral knee inclination.

5.1 Lateral knee inclination

This technique controls on-edge ski angle variations loading more the external foot leaning the ski. The observation will be done staring at the skier with a front or a rear view.

This technique is evaluated by the size of the angle formed between the axis middle of the ski-boot – knee and the slope's plane (figure 7). It is the only biomechanical way to increase the external on-edge ski angle without moving the center of gravity inwards. It creates a directional effect and the future upper ski. It is only possible when the external knee bending is about 120° [10].

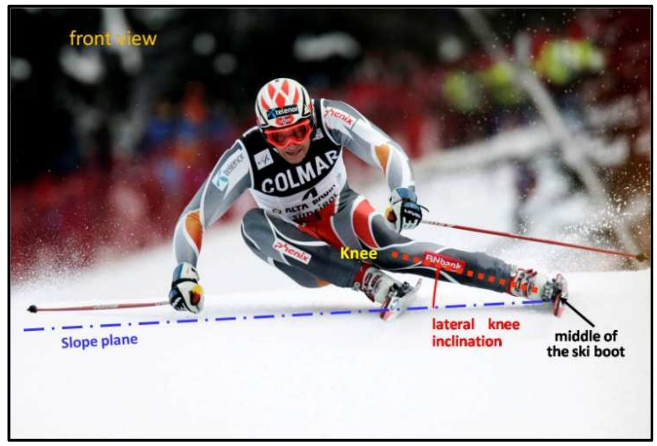

Figure 7. Lateral knee inclination

The variations of lateral knee inclination to the on-edge angle are measured into the moving frame o, $\vec{x}$, $\vec{y}$, $\vec{z}$ (figure 8). The binding mounting mark is the origin (O_{S1}) that the ski constructor skis designed, and which becomes the middle of the ski boot for the coach. This is a negligible approximation (for the one who observes): the ski boot is hold by ski bindings where the middle of the ski boot matches with the binding mounting mark, but separated by the thickness of the ski – ski-bindings interface.

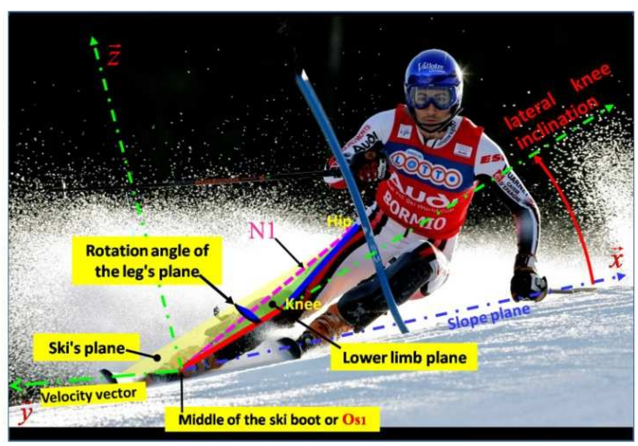

Figure 8. Variation knee inclination

5.2 Observation for coaches

We have transposed this biomechanical conception to the field of coaches completing the technique's description by a cause which makes sense to give an instruction: the lateral outer knee inclination is the only way to make vary, according to joints limits, the on-edge angle of the ski (the outer one) always keeping a predominant load on the outer ski in order to create a directional effect. This technique becomes possible when the skier's knee flexion is around 120° because it releases the second degree of freedom of his knee which allows the leg fixing [8] [10].
We propose below, two synchronized pictures (figures 9 and 10) illustrating the invented words to pass on our evaluations and our technological conceptions, comparing techniques used by the winner with one used by out athlete.

Figure 9. Picture of the winner

Figure 10. Picture of our athlete

We can notice that the weight, which can be measured by scales, changes if the skier does flexing, extension, and/or segmental movements. Those loads variations are due to skier's weight speed of altitude variations of the center of gravity or the moving body segments (accelerations).

It causes loads variations which deform skis and make change the trajectory radius depending on the race layout demands (interactions between loading, ski edge angle and skis' characteristics). The on-board balance inserted between the ski boot and the ski, to measure the torque ski→ski-boot highlights efforts applied on the articulated system which is the skier body. Those data are necessary to make calculation of dynamical modeling of the system skier and the system ski.
Plus, the forward-backward hip inclination with the knee bended about 120°, combined with the forward-backward trunk inclination, aims to keep the pressure on the bearings (ankle core) whatever the friction force between snow and skis.

The observation of this technique makes sense only if the coach is capable to connect them and think about the mechanical consequences (modeling). The amplitude, the rhythm and the timing causes the trajectory. The only goal is performance.

6. DISCUSSION

The system modeling, from this experimental method, seems now possible. This study went further than results obtained with a 3D motion analysis only [3] because it has highlighted some factors to improve performance. Nevertheless, it keeps pursuing the investigation of interactions of the mechanical and geometric skis' characteristics between the ski→ski-boot torque and the torque applied on ski by the snow cover. Snow cover properties change the on-edge angle on steering phase and loading on the ski [2].

Let's remind that the technique is defined according to articular or material marks taken from body or equipment. It corresponds to a technique seen as pertinent for the performance with current skis, and it also corresponds to a goal intended to vary ski-snow efforts or aerodynamic efforts characteristics.

This technical model of the skier is a tool for the coach and the skier to improve training. The body-technique described is referred to the middle of the ski-boot of the same side because the articulate skier-skis' system is mostly guided by each effort at the contact ski-snow cover. Mostly, because the aerodynamic strain, which depends on the speed and the skier's shape, also affects the system guiding but weaker than ski-snow efforts. It has also been showed that the saggital balance (that we call forward-backward inclination) is an important factor for performance [1].

It is still hard to predict loads on skis from the skier by electromyographic study, because estimations from EMG are barely reliable [11].

With the computer simulator, it is possible to apply on ski torques measured between the ski→ski-boot torque and the torque applied on ski by the snow cover. It is also possible to apply the on-edge angle measured. That way, the static load repartition is known. The computer simulator is capable to know the dynamic torques of skis and bindings (on-board balances measurements). Then, we can link loads applied on ski by the skier and by the snow to the ski materials and the ski structure. The simulator manipulates torques and skier-skis system characteristics. We can though find out what structure/material of the ski improves skier's performance

Avoiding replacing 3D skiers motion analysis, in their contexts, and measurement of external constraints applied on skiers, the computer simulator will allow to impose to the skier-ski system univocal constraints reducing experimental uncertainties, and to make assumptions easily. That way, with coaches, ski constructors, and researchers, studies will be lead to make and evaluate experimental protocols to improve ski development.

Let’s add that the computer simulator is not only thought for alpine skiing, but also for board and wheeled sports. We can manipulate movement of each body (on the jumping jack) or skis’ gears’ characteristics to detect and even simulate performance variations.

7. ACKNOWLEDGMENTS

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