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## Behaviour of an instrumented anthropomorphic dummy during full scale drop tests

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### Abstract

The aim of this work was to study the behaviour of an instrumented anthropomorphic dummy during full scale drop tests. The dummy presented triaxial accelerometers at head and chest and multiaxial load cells at the thighs. Drops were performed on a wooden floor inclined at 16° from horizontal. Kinematics of drop landing in sagittal plane was filmed with a high speed camera. Peak values of acceleration and thigh loads were recorded to provide a validation of a numerical model of the dummy including stiffness properties of the skis and boots.

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### 1. Introduction

Skiing injuries are mostly related to falls during slalom or collisions with other skiers and snowboarders. Among others, boot induced ACL injuries are related to the landing technique after a jump combined with the stiffness properties of boot & skis [1]. Direct measurements of kinetic biomechanical data during such events are almost impossible and are ethically unacceptable. As a result very few data are available in this field, and most of them are kinematic data extracted from video recordings of race events or test sessions when unexpected injuries occurred. Analysis of knee joint mechanics injuries during skiing requires the development of accurate numerical models. These simulations of full body motion therefore require the development of multi-body musculo-skeletal models of the skiers, with

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inverse or forward dynamics approach. A solution for passive structures loading, given a set of instantaneous joint loads and postures, requires a further detailed model which includes passive structures of the knee and involved active muscles.

The use of an instrumented full body dummy of known geometry and inertial properties can help the development of multi-body models, providing data for experimental validation of kinematic and kinetic values at important locations such as the head, trunk and knee joints.

In addition, the development of physical knee models with realistic materials simulating the presence and behaviour of passive structures and with sensorized devices for the dynamic measurement of strains and loads at the artificial ligaments or on the tibial plateaus during simulated injury events can improve the phenomena comprehension and orient the development of proper protective equipments.

Finally, the combination of a full body dummy with a realistic physical knee model, together with the application of artificial muscles of known line of action and mechanical active/passive properties could allow for a complete simulation of impacts and falls [2-3], thus enabling the evaluation of the degree of protection coming from equipment (boots, ski bindings, braces etc.) or the risk of certain manoeuvres.

The present work will focus on the results of full scale drop tests performed on a sloped plane using an instrumented anthropomorphic dummy wearing boots and skis of known stiffness.

## 2. Materials

An anthropomorphic instrumented dummy (total mass 76 kg) was used for the tests (Figure 1). The dummy presented a Hybrid III (50<sup>th</sup> percentile, male) neck-head assembly (78051-90 and 78051-61X, First Technology, 6.08 kg) as shown in Figure 1(a), a wooden CNC machined trunk with a cavity for housing the data acquisition system (34.6 kg, total), two thighs with fixed hips (30° flexed, 11 kg) and adjustable 1 DOF knees, two lower legs (4.5 kg) with 2 DOF ankle joints and foot prosthesis, enabling to wear ski-boots (4kg). Thighs of the dummy were made of high strength steel tubes and were machined in order to obtain two 6 channels sensing devices calibrated for measuring knee loads (Figure 2). The thigh reference system had the x-axis in the proximal-distal direction, the y-axis in the sagittal plane and the z-axis completing the frame. Each thigh load cell had six strain gauge full bridges obtained after application of HBM strain gauges to the cylindrical sensing area (Figure 2(b)). Two channels Fx and Mx were directly calibrated as Axial load (HBM 3/350XY41) and Torque (HBM 3/350 XY31) along the thigh axis, the other four (HBM 3/350DY41), two in the sagittal plane (BMzD, BMzP), two in the lateral plane (BMyD, BMyP), were calibrated as bending moments at proximal and distal sections in a lateral and sagittal plane.

Knees presented a single Flexion-Extension DOF, with the possibility of controlling knee resistance to flexion by means of a friction clamp, based on the tightening torque of the M16 bolt connecting knee hinge. Acceleration values at head and chest were measured by two triaxial piezoelectric accelerometers (SAPE-HLS-3010, SoMat) with a full scale of 500g, -3 dB range of 10 kHz [3]. Electro-goniometer sensors (Biometrics, UK) were applied to ankles, knees and head to record joint motion during impacts; an MTi IMU (Xsens, NL) sensor was applied to the trunk in order to obtain its absolute instantaneous orientation during the tests. By the measure of the limbs relative orientation to the trunk, the limbs absolute orientation could be evaluated after adding the absolute trunk orientation. Acceleration, orientation and strain signals were collected by a 24 channels system (eDAQ lite, Somat) programmed to collect acceleration, angle and strain signals at 50 kHz per channel (Figure 1(d)). The sloped plane consisted of a steel frame supporting a solid wooden plane (Figure (3)): plane inclination was set to 16° from horizontal. The drop surface hardness can be modified after application of foam panels of different stiffness [4], in order to better simulate the real presence of snow during landing and snow-ski interactions.

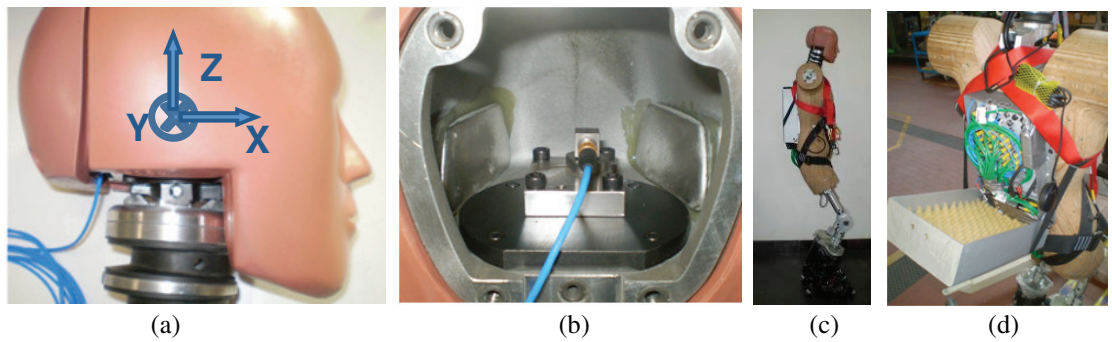


Fig. 1. The anthropomorphic dummy. (a) Hybrid III head and acceleration reference system. (b) Head accelerometer placement. (c) Full body view of the dummy, standing position. (d) Rear view of the onboard 24 channels data acquisition system.

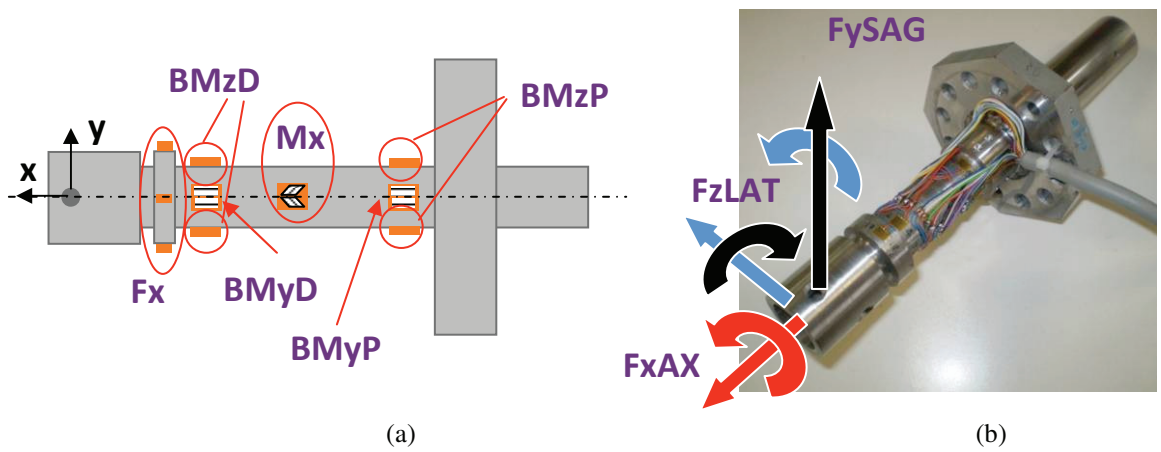


Fig. 2. Instrumented thighs. (a) Disposition of strain gauge full bridges. (b) View of the instrumented thigh with indication of measured knee loads.

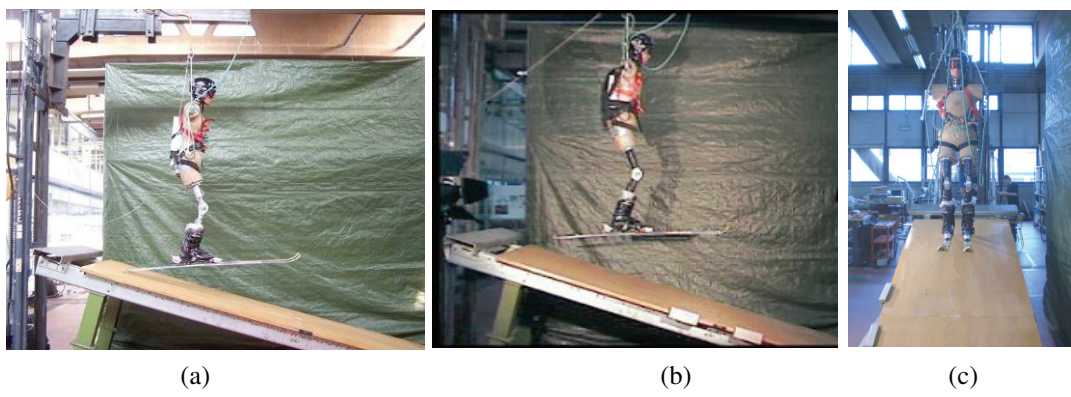


Fig. 3. (a) Drop height 0.3 m. (b) Drop height 0.5 m. (c) Front view of the dummy during the tests.

### 3. Methods

The dummy was equipped with the onboard crashworthy 24 channel data logger for fully unrestrained drops. It was wearing a climbing harness to control its orientation, and it was suspended by two hooks placed at the shoulders. A quick release karabiner, driven by a stiff cable, was used to support the dummy during the setup by means of a forklift and to release its support cable during data collection (Figure 3).

The drop tests were filmed by high speed video cameras (Motionblitz, DE) placed sideways to the sloped plane and collecting at 1000 fps. Drop heights were 0.3 m and 0.5 m, measured as the vertical distance between the boot mid center and the inclined floor.

Boots and skis of known stiffness were used in the tests. Boot stiffness was measured with a servocontrolled test bench at room temperature, with the boot wearing the same foot prosthesis used during the drop tests, following a standard measuring procedure. Boot bending stiffness resulted to be  $K = 11 \text{ Nm/deg}$ . Ski stiffness was measured at shovel and tail following ISO 5902 – 1980 recommendations.

### 4. Results and Discussion

Several drops were performed with the described setup at increasing drop height. The results here reported are those collected in the first two drops, with a drop height of 0.3 m, and two different tightening torques  $T_k$  at the knees: respectively Test 1,  $T_k = 140 \text{ Nm}$  and Test 2,  $T_k = 90 \text{ Nm}$ .

Kinematics of drop landing during the tests was obtained by the analysis of high speed video cameras (Figure 4). Five instants were introduced to help the interpretation of the impact dynamics: 1) 1<sup>st</sup> contact of the ski tail (Figure 4(a)); 2) contact at the rear binding (Figure 4(b)); 3) full boot contact (Figure 4(c)); 4) knee peak flexion; 5) beginning of forward sliding. In general, the first stage of the landing is the elastic deflection of the ski tail, when the ski stiffness properties play a major role; it is followed by a greater impact stage corresponding to the boot full landing, when the boot flexural stiffness is mostly involved. Further stage leads to the knee the peak flexion, when there is an influence of the knee tightening torque; afterwards, the ski will start sliding on the board.

Acceleration values of Test 1 at head are reported in Figure 5, together with trunk acceleration curves. After a 0.3 m drop height, peak resultant decelerations of 4.20 g and 4.23 g were recorded respectively at the head and the trunk of the dummy. Head peak followed slightly in delay the trunk peak. Right knee relative flexion during the impact was 9 degrees.

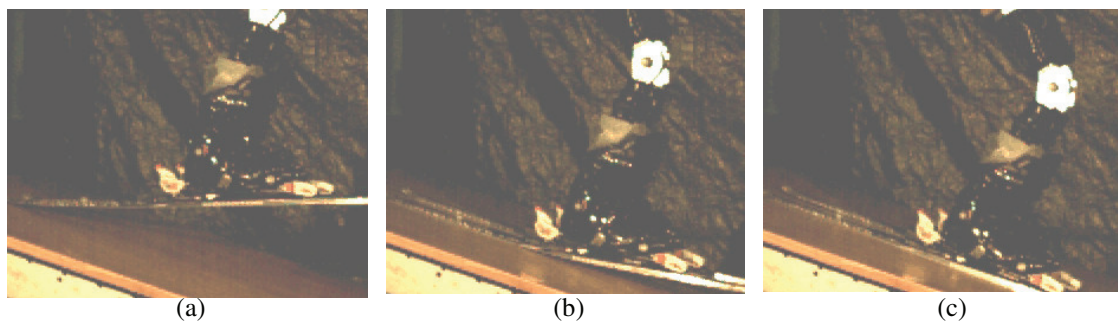


Fig. 4. Results of Drop Test 1. (a) Tail contact. (b) Rear binding contact. (c) Full boot contact.

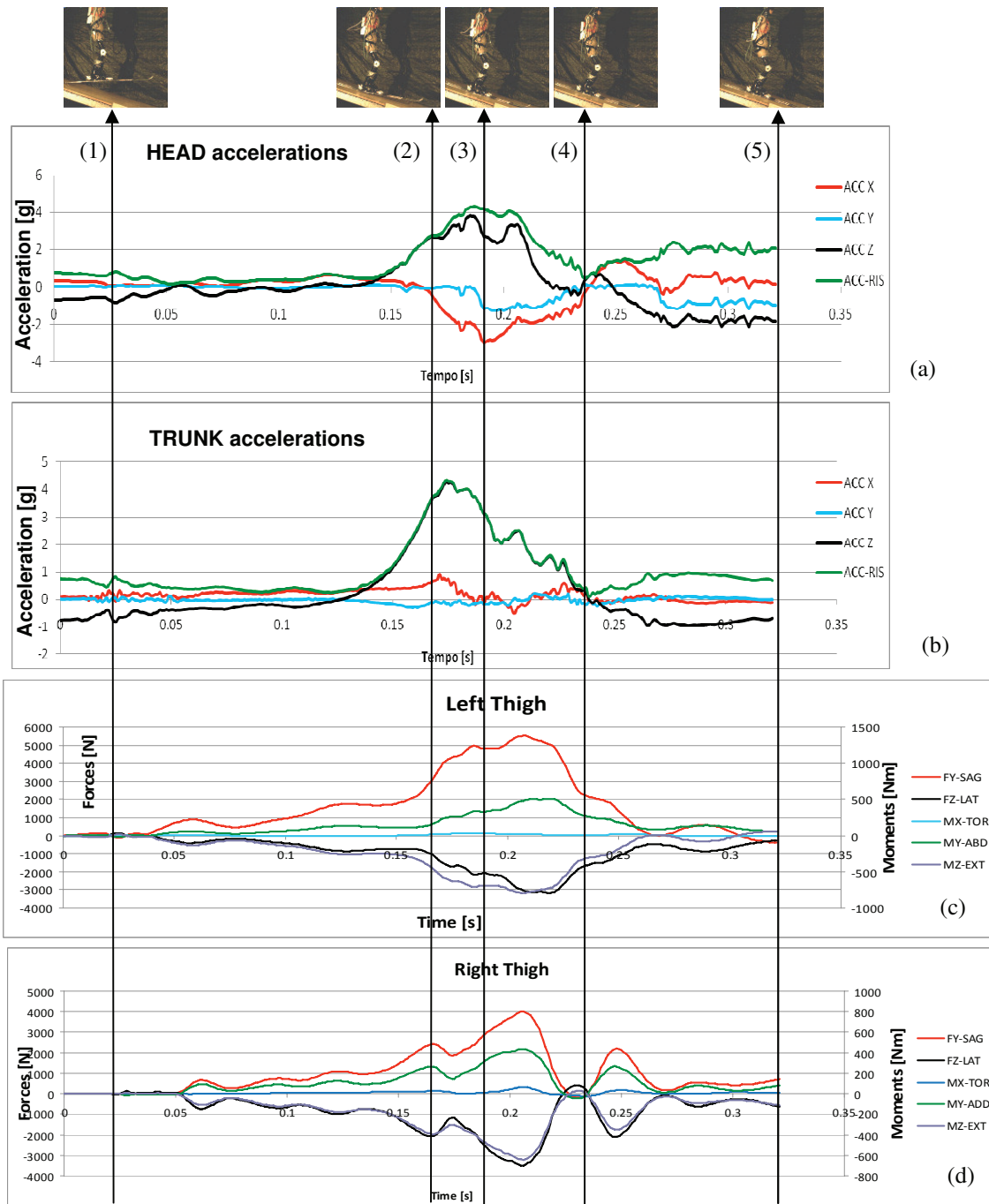


Fig. 5. Results of Drop Test 1. (a) Head acceleration values (b) Trunk acceleration values. (c) Left thigh measured load parameters. (d) Right thigh measured load parameters.



Shear loads at thigh in Y direction reached high peak values of about 6.5 B.W.: axial loads were not measured due to problems in the axial bridge connections. Despite the event was supposed to happen in the sagittal plane, considerable side loads and moments were recorded.

During Test 2 (0.3 m drop height,  $T_k = 90$  Nm), peak deceleration at head and trunk resulted of 3.93 g and 3.64 g respectively; shear peak loads at thigh in Y direction reached values of about 5 B.W. Right knee relative flexion during the impact was 19 degrees, further confirming the effect a lower knee friction limit torque in reducing structural loads transmitted to the upper body.

From a methodological point of view, several limitations of the present study should be addressed: first of all, the dummy had fixed hip angles of  $30^\circ$ , thus limiting the realistic dampening movement of the skier trunk during landing. Secondly, the eccentric contraction of antigravity muscles (glutei, quads, triceps surae) was absent in the dummy: the limit friction torque at the knee was the only preset damping parameter. Moreover, the drop direction was vertical, thus neglecting the horizontal component present in a real jump landing.

Nevertheless, the presented experience was helpful in the development of ongoing research regarding the study of indoor and outdoor tests on impacts and falls, oriented to the improvement of safety in skiing (SkiProTech, INTERREG IV, EU PROJECT). The dummy lifting, releasing, landing and restraining procedures were refined after tests: acceleration signals at head and trunk were made available for the development and validation of a multi-body model of the dummy, including ski and boot stiffness parameters.

Further development of the dummy will include the release of hips and the introduction of elastic/friction elements to simulate the presence of hip and knee extensor muscles.

## 5. Conclusions

The anthropomorphic instrumented dummy was used during simulated vertical 0.3m drop landings on inclined surfaces, in order to measure the accelerations at head and trunk and loads generated at knees. Peak values of 4.20 g and 4.23 g respectively at the head and trunk of the dummy resulted from the tests with fixed hips and friction tightened knees. Measured kinematic and kinetic data will be used for the validation of a corresponding multi-body numerical model.

## Acknowledgements

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