Margaret Estivalet
Pierre Brisson

The Engineering of Sport 7

Vol. 1

Springer
**ISEA 2008, just before the summer olympic games!**

What a fantastic opportunity to present a compilation of more than 160 articles talking about sports engineering, analysing the coefficients of friction between the balls and the rim and back-board for leather and synthetic basket balls, extracting the aerodynamic force data during real ski jumping flights, optimizing new prosthesis of the lower human leg, analysing the golf ball spin rate after impact, analysing the most common injury in sport climbing using eight fresh dozen cadaver fingers, describing the heat transfer in footwear using finite elements, measuring the aerodynamic performance of cycling time trial helmets, etc, …

What a challenge too to be honnest!

A huge diversity of articles, top level contributions to sports engineering.

Today the world is convinced sport is not only fun but economically a sector, a multi sector, which is not only growing if you only take into account the total turn over but is becoming one of the fast growing business.

Sport is not any more reserved for top sporters who want to maintain a certain level in some disciplines, it became a new philosophy of life, a new trend, a way to cope with aging population, with the reality of the society today.

Our every day life is concerned with sport or sport derived products or services, it is in our shoes, our suits, our car, our bike, at home, when we eat, when we drink, when we sleep, relax, when we look at TV for international events, when we listen, watch the news, for fun. The sports engineering community as it was noted two years ago keeps growing.

We have to admit it was a very difficult task to review all the contributions and to come down to 150 articles; It was very difficult too to allocate reviewers to contributions because a lot of articles were proposing not only scientific contributions but also engineering solutions and methodologies.

Some groups of articles could have been selected as a basis for a workshop in itself!

In front of such a diversity of contributions we have decided not to group the articles by families, by themas, by keywords, by branches, by sports, by subjects, by numbers of contributions but we decided to regroup it in two different volumes without any introduction which we thought would not bring anything to the readers, just proposing the articles in a natural order creating of course some surprises, but it was a choice!

Of course there is a table listing the articles with their authors and co-authors and the programme will indicate every time the article number.

Complex to read? Difficult to apprehend? We thought it would give the best way to understand the complexity of sports engineering today; An article about football in a ball section of proceedings, in the shoes section, in the field surface section, in the injury section, in the training part, in the video group, in the sliding effect paragraph, in the referee point of view chapter, in the leather section may be, why not the aerodynamics or the finite elements analysis, may be in the professional sports section or the leisure, the TV business, the star system, …

So many possibilities, we just did it in the way we were convinced would be the most open!
What we wanted to do is to provide the readers with the best sports engineering contributions in 2008, before the biggest sports event on earth, the Olympic games, in front of 5 billions telespectators who will enjoy the show and for many of them start again sporting, or just start a new sport, realising what they can do, discover a new passion, using in any case the brain storming of the world of engineering contributors to improve our everyday life.

This is the magic of sport

Margaret ESTIVALET & Pierre BRISSON
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Effects of Body Weight on Ski Jumping Performances under the New FIS Rules (P3)

Luca Oggiano¹, Lars Sætran²

Topics: Aerodynamics.
Abstract: Based on the results of several different experiments, it has been concluded that the weight of a ski jumper is crucial in performing a long ski jump. In response to this conclusion, many of the best ski jumpers in the world began dieting to reduce their weight, resulting in many underweight athletes and some incidents of anorexia. In order to deal with this problem the International Ski Federation (FIS) introduced a new rule where the ski length is determined by both the jumper’s height and weight. An athlete with a Body Mass Index (BMI) of less than 20 must reduce the length of his or her skis.
To evaluate the effect of the new rules a numerical and experimental investigation on the effects of the BMI on ski jumper’s performances has been done. A numerical model has been built in order to evaluate the effects of BMI on the final speed in the in-run path. The numerical results obtained from the model match experimental data present in the literature. Experiments in the wind tunnel have been made in order to evaluate the aerodynamic forces acting on the ski jumper and on the skis during the flight path according to the new FIS rules. Experiments have been carried out on a doll mounted on a 6 components balance and different positions and ski length have been tested. The data acquired have been introduced into a numerical model and the final jump length has been then estimated.
In conclusions it has been found out that the current FIS rules do reduce the problem addressed but experiments shows that it is still more advantageous to lose weight and consequently cut the skis, compared to gaining weight in order to keep the full ski length.
Keywords: Aerodynamic, Ski jumping, Drag, Lift.
1- Introduction

Ski Jumping is a sport discipline which involves different engineering fields. In this paper we will focus on the effect that BMI (and then the body weight) has on ski jumper’s performances and especially on the jump length.

The increase the BMI has 2 main effects on ski jumpers performances. It has a positive effect during the in-run (higher weight gives a higher speed at take-off) and it has a negative effect during the flight path (the higher the weight is, the shorter the jump is. The 2 effects are not balanced. The negative effect during the flight is much stronger than the positive one during the in run. The final effect of BMI increasing is a shorter jump length. [SM1].

Because of this advantage of being light in terms of jump length, athletes began to lose weight, and many cases of underweight and some of anorexia athletica [S] came up.

This alarming trend forced FIS to create new rules in order to reduce the problem with underweight ski jumpers.

Under the old rules, an athlete’s ski length was determined by the athlete’s height only but, in 2004, the rules changed, and today the ski length is determined by both height and BMI.

Under the new rules, an athlete with a BMI of less than 20 must reduce the length of his skis according to a table made by FIS. Any athlete who has a BMI below 17.5 is not allowed to participate in the competitions.

The rules change required underweight ski jumpers to use shorter skis than the jumpers' height had formerly allowed.

The intention was to reduce the positive lift forces acting on a ski jumper and his equipment during the flight, hence reducing the positive effect of being light.

When the new rules became operative, there was a general belief within the ski jumping community that it would be beneficial for the athletes to gain weight by building up their thigh muscles. The weight gained would cause an increase in BMI and the athletes could then keep their original ski length and, theoretically, increase the power generated at the jump.

The trend that the athletes followed it has not been the same that FIS expected. The average BMI among all the athletes present in the Olympic Games in Turin 2006 has been 19.41, 0.5 less than the average BMI measured in 2000 [SM1].

In order to determine whether the changes to the rules are justified, experiments have been conducted in a wind tunnel with 1:1 model of skis and ski jumper and a numerical model for In-run and Flying-path has been made and used to compute the final jump length.

Different positions and angles for both jumper and skis have been analyzed and tested. Experimental data from previously studies and wind tunnel experiments [SM2] have been used in order to determine the position of skis and body angle. An adaptive numerical model has been built trying to describe as close as possible the real flight path.
1.1 BMI

The BMI is a relation between a person’s weight and height. It’s defined as:

\[
BMI = \frac{\text{Mass}[Kg]}{\text{Height}^2[m^2]}
\]

Table 1 - BMI compared to weight status.

<table>
<thead>
<tr>
<th>BMI</th>
<th>Weight Status</th>
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<tbody>
<tr>
<td>&lt;15</td>
<td>Eating disorders</td>
</tr>
<tr>
<td>15 - 18.5</td>
<td>Underweight</td>
</tr>
<tr>
<td>18.6 - 25</td>
<td>Optimal Weight</td>
</tr>
<tr>
<td>25 - 29.9</td>
<td>Overweight</td>
</tr>
<tr>
<td>&gt;30</td>
<td>Obese</td>
</tr>
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</table>

From results regarding the decrease of ski jumpers BMI acquired from 1973 to 2000 and shown by Vaverka [V] and Müller [SM1] it has been noticed that the average BMI among ski jumpers dropped from a value above 23 in the past to a value under 20 in 2000 (see Fig. 1).

The last data about 106 ski jumpers who participated to the Olympic Games in Turin 2006 give an average BMI of 19.41 (ca. 0.5 less than what was measured in 2000).

This shows that the trend of losing weight for obtaining better performances has not been stopped with the introduction of the new FIS rules.

![Figure 1 - BMI trend in ski jumping competitions during the last 40 years.](image)

1.2 Forces acting on a ski jumper

Several forces act on a ski jumper during the three phases of the jump (in-run, take off, flight and landing). The combination of these forces will decide whether the ski jump is successful or not.
Roughly dividing the jump into 2 parts, the in-run and the flight, the main forces acting during these parts are drag, gravity, ski-snow friction during the in-run and drag, lift and gravity during the flight.

2- Experimental Setup

For the experiments, the wind tunnel of NTNU (Norwegian University of Science and Technology) in Trondheim has been used. The test section of the wind tunnel is 12.5 meters long, 1.8 m high, and 2.7 m wide. The wind tunnel is equipped with a 220KW fan that can produce a variation of speed between 0.5 - 30 m/s. The balance (Carl Schenck AG) used is a six component balance capable to measure the three forces and the three momentums around the three axes. Variations of forces and moments are measured using strain gauges glued to the balance body. The voltage outputs are measured by a LABVIEW based PC program.

3- Numerical simulation of the in-run

In order to evaluate the effect of BMI on the take off speed a numerical model has been built.

The mathematical model here presented includes friction forces between ski and snow, mass forces due to gravity and aerodynamic drag forces acting on the ski jumper.

The simulation has been divided in three parts, following the different shapes of the in run path.

The path (see Fig. 2) is divided in three parts one straight part with a constant heeling-angle $\theta_1$ (no curvature), one curved part with a constant radius of curvature $r$ and then another straight part with constant heeling angle $\theta_2$.

![Figure 2 - In-run path. The in-run path is divided into 3 different parts: 2 straight parts and a curved one between the 2 straight ones.](image)

The results obtained applying the model show that the BMI does not have a huge influence on the speed at take off. The difference between the take-off speed calculated for an athlete with a BMI around 30 (weight 85kg and height 170cm) and the speed calculated for an athlete with a BMI around 15 (weight 45kg and height 170cm) is about
1 m/s (see Fig. 3). Considering that most of the ski-jumpers have a BMI between 17 and 21, this difference is reduced and it has been calculated to be about 0.2 m/s.

Figure 3 - Effect of increase of BMI in the speed at take-off calculated for the Granåsen jumping hill in Trondheim (Norway). The curve which reaches the lower speed has been calculated for a speed skater with BMI 16 while the curve which shows the higher speed has been simulated for a ski jumper with BMI 25. \( L_1 = 50 \text{m}, \ L_2 = 6.8 \text{m}, \ r = 110 \text{m}, \ \theta_1 = 34.5^\circ, \ \theta_2 = 11^\circ, \ \text{TOTlength} = 101.9 \text{m}. \)

4- Experimental investigation on the aerodynamic forces

4.1 Skis and doll position in the wind tunnel

Figure 3 - Different angles between ski jumper and wind direction. \( \alpha \) is the angle between wind direction and skis, \( \beta \) is the angle between wind direction and ski jumper's body and \( \phi \) is the angle between wind direction and horizon line.
Skis and the doll have been tested separately since they can be considered as two separate systems. The ski’s wake does not in fact interact with the ski jumper’s body. This means that the 2 aerodynamic parameters (Lift and Drag) can be measured separately.

They were both connected to a shielded support connected to the 6 component balance.

The doll used for the test is 170cm tall and his position has been varied from 10degrees to 60degrees. The suit used is the same suit used by the Norwegian ski-jumpers during the Olympic Winter Games in 2006.

The correct angles were adjusted using the joints on the support. Trying to model a ski jump in the most realistic way possible, the angles were adjusted in relation to the flying path, wind direction and the tilt of a skier’s ankle. In the experiment, 3 different velocity levels have been used: 13 m/s, 20 m/s and 27 m/s, respectively. The ski-length is about 268cm and it has been tested at 6 angles relatives to 6 different flight positions. In order to evaluate the effect of the new FIS rules, the skis got cut in the back end for 5cm at a time and the same test has been done until a ski length of 248cm has been reached.

4.2 The flight path

In order to evaluate the effects of the new FIS rules on the aerodynamic forces, data regarding the positions assumed by a ski jumper during his flying path were needed. These data have been acquired by Schmölzer, & Müller [SM2]. The simplified flight path used for the model here presented has been divided in five different parts, assuming aero dynamical forces to be constant in each part. Forces during the flight path have been decomposed in vertical and horizontal forces [R].

- Take off 1 \((t<0.21s)\) \((\alpha=-5, \beta=58)\)
- Take off 2 \((0.21<t<0.63)\) \((\alpha=5, \beta=58)\)
- Flight 1 \((0.63<t<1.43)\) \((\alpha=25, \beta=45)\)
- Flight 2 \((1.43<t<2.71)\) \((\alpha=30, \beta=45)\)
- Landing \((t>2.71)\) \((\alpha=35, \beta=52)\)

5- Results

The main target of the aerodynamic test on skis is to evaluate the effects of the new rules on Lift and Drag. Lift and drag has been measured per each position a, with different ski length, from 248 to 268cm.

Table 2 – Experimental data for drag and lift.

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>(\alpha) [deg]</th>
<th>(\beta) [deg]</th>
<th>268cm [N]</th>
<th>248cm [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take Off 1</td>
<td>0.21</td>
<td>-6.78</td>
<td>61.86</td>
<td>184.7</td>
</tr>
<tr>
<td>Take Off 2</td>
<td>0.63</td>
<td>3.28</td>
<td>61.85</td>
<td>199.1</td>
</tr>
<tr>
<td>Flight 1</td>
<td>1.43</td>
<td>26.53</td>
<td>53.83</td>
<td>341.2</td>
</tr>
<tr>
<td>Flight 2</td>
<td>2.71</td>
<td>32.04</td>
<td>43.98</td>
<td>344.0</td>
</tr>
<tr>
<td>Landing</td>
<td>3.63</td>
<td>37.73</td>
<td>43.84</td>
<td>332.0</td>
</tr>
</tbody>
</table>
Table 3 – Experimental data and FIS table.

<table>
<thead>
<tr>
<th>FIS RULES</th>
<th>LIFT MEASURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>659,5289</td>
<td>268,2</td>
</tr>
<tr>
<td>635,688</td>
<td>262,8</td>
</tr>
<tr>
<td>615,82275</td>
<td>258,3</td>
</tr>
<tr>
<td>591,98445</td>
<td>252,9</td>
</tr>
<tr>
<td>572,1192</td>
<td>248,4</td>
</tr>
<tr>
<td>341,43</td>
<td>263</td>
</tr>
<tr>
<td>323,07</td>
<td>258</td>
</tr>
<tr>
<td>338,72</td>
<td>253</td>
</tr>
<tr>
<td>339,11</td>
<td>248</td>
</tr>
<tr>
<td>346,91</td>
<td>268</td>
</tr>
<tr>
<td>339,34</td>
<td>263</td>
</tr>
<tr>
<td>307,52</td>
<td>258</td>
</tr>
<tr>
<td>337,00</td>
<td>253</td>
</tr>
<tr>
<td>337,70</td>
<td>248</td>
</tr>
</tbody>
</table>

Figure 8 - Comparison between the FIS rules and the data obtained with the wind tunnel experiments.

The ski jumper system has been obtained by summing the aerodynamic forces calculated separately for skis and doll. Wakes and possible interferences between doll and skis have been neglected.

Comparing the curve obtained for the ski-jumper with the length-weight obtained from the new FIS rules (for a 180cm tall ski jumper) it has been obtained, for \(\alpha=30\), \(\beta=45\) (which is the position assumed for the longest period during the flight path). According to the flight path angles measured by Schmölzer and. Müller [SM2] two \(\phi\) angles have been chosen, \(\phi=40\) and \(\phi=30\) which represent the angles where the aerodynamic forces count more in the y direction and where f is the angle between the wind direction acting on the skier and the vertical axis parallel to the gravity force (fig. 8).

The flight path has been divided in 5 parts. Per each part, drag and lift of the ski jumper have been calculated using the experimental data. A vertical velocity at take off of 2.5m/s has been considered [VKK].

To evaluate the effect of the new FIS rules on a ski jumper’s flight path, two different ski lengths, (248cm and 268cm) have been considered. A ski length of 248 cm correspond to a ski jumper (180cm tall) who weighs 58kg while 268 correspond to a ski jumper (180 cm tall) who weighs 65kg.
Drag and Lift has been considered constant during each part of the flying path and the correction relative to the take off speed illustrated in par.1 has been taken into account.

The 2 curves presented in fig. 9 represent the flight path for 55kg ski jumper and a 67 kg ski jumper calculated using the new FIS rules. The solid curve is the path calculated for a 67kg ski jumper and the dotted curve is the curve obtained for a 55kg ski jumper.

The difference in jump length between the 2 jumpers has been estimated to be about 7 meters and the longest jump length has been obtained by the 55kg jumper.

The lighter jumper has then a big advantage due to his low body weight and this advantage is not enough compensated by the smaller aerodynamic forces acting on him during his flight.

It has been also estimated that, in order to compensate the disadvantage due to the higher weight, the ski jumper who weight 67kg has to increase his vertical take-off speed at up to 3m/s.

![Figure 9 - Simulated flight path for a 55kg ski jumper and a 67kg ski jumper in the Venlängerung jumping hill.](image)

6- Conclusions

The new rules imposed by FIS have not solved the problem of low BMI in ski jumping. Athletes are in fact keeping loosing weight in order to improve their performances.

It has been demonstrated that the negative effects due to higher weight can not be compensated with the adjustment imposed by the new rules. Furthermore, the increase of speed at take off is not enough to compensate the negative effect due to increase of BMI.

The possible solution proposed by some trainers, consisting on only increase the BMI by building up muscles in the thigh in order to obtain a higher vertical speed at take off could work but the vertical speed at take off sufficient to compensate the weight-effect should be around 3m/s, 20% higher than the normal vertical speed estimated by Virmavirta in 2.5m/s [VKK].
A better solution could be obtained by reducing the width of the skis instead of the length. This would not affect the stability of the jumper and at the same time will have a negative effect in terms of aerodynamic forces reducing the advantage of having a low BMI. New tests will then be carried out in order to evaluate this solution.

7- References

Abstract: Dynamic behaviour of golf balls during oblique impact is investigated using Abaqus (FEA software) to represent the ball structure and measured material properties. The properties of the mantle layer were measured from independent tests of material properties. Materials of golf balls were shown to possess viscoelastic and hyperelastic (or visco-hyperelastic) behaviours. The merit of this approach is that characterisation of new materials and modelling impact of a golf ball can be performed before construction of a prototype golf ball. This paper compares calculated and experimental coefficients of restitution (COR) of a hollow, multilayer golf ball.

Key words: Golf ball; Finite element analysis; Coefficient of restitution; Hyperelastic; Viscoelastic.

1- Introduction

Dynamic behaviour of both bodies is important in analysing impact responses between a golf ball and a club. In this paper we investigate modelling of the impact between a golf club head and a hollow golf ball - a ball designed to have a larger polar moment of inertia about the centre. This ball was struck at an angle of obliquity by a rigid body simulating the club head and dynamic behaviour during impact was analysed.

Experimental study on dynamic behaviour of golf balls can involve impacting a golf ball on a plate, either at normal or oblique angle. Results of such experiment were usually compared with an analytical solution from rigid body theory (Arakawa et al., 2006) or with the solution of a dissipative linear compliance impact model (Ujihashi 1994). FEA software such as Abaqus can be used as a tool in designing new golf equipments. Recent publications on golf balls tend to compare experimental results with the FEA results (for a few examples, see Tavares et al., 2006 and Tanaka et al., 2006).

This paper investigates dynamic behaviour of golf balls during oblique impact using Abaqus to represent the ball structure and measured material properties. Previous FEA
studies on the subject used either a) measured properties of the ball as a whole (not the
constituents) that were obtained from independent static and dynamic tests (Tavares et al., 2006) or b) predictions of properties obtained from rigorous parametric studies by
comparing FEA results with independent dynamic tests of the ball (Tanaka et al., 2006).
These investigations were phenomenological in that they selected properties which
matched a measured impact outcome. In contrast, the present paper obtains properties
for the mantle layer from independent tests of material properties. Materials of golf balls
were shown to possess viscoelastic and hyperelastic (or visco-hyperelastic) behaviour.
The merit of this approach is that characterisation of new materials and modelling
impact of a golf ball can be performed before construction of a prototype golf ball. This
paper compares calculated and experimental coefficients of restitution (COR) and initial
spin of a hollow, multilayer golf ball where the calculation uses measured material
properties.

2- Material properties of a hollow golf ball

The golf ball to be investigated consists of three layers; namely a hollow Ti alloy core, a
polymeric mantle and an ionomer resin cover. The study concentrates on the effect of
differences between phenomenologically determined coefficients and measured proper-
ties of the mantle materials.

2.1 Phenomenological coefficients

The core of the hollow ball is a thin-walled titanium alloy (Ti-6Al-4V) spherical shell.
Since this core is quite stiff and shell deformation is anticipated to be below a yielding
point, the core was modelled as an elastic material. The cover material for the golf ball
is made of ionomer resin. Here, the cover was defined as a hyperelastic material using
coefficients of Mooney-Rivlin strain energy function. The mantle material was defined
as hyperelastic and viscoelastic. The properties for mantle and cover layers were taken
from the phenomenologically determined coefficients given by Tanaka et al. (2006).
These properties were selected based on maximum load, contact time, deformation
history and rebound velocity by comparing dynamic test results with FEA simulations.
Table 1 gives the material properties and dimensions for each layer of the golf ball.

Table 1 - Dimensions and properties of layers of the hollow golf ball.

<table>
<thead>
<tr>
<th>material</th>
<th>core</th>
<th>mantle</th>
<th>cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>outer diameter (mm)</td>
<td>27.90</td>
<td>38.71</td>
<td>42.80</td>
</tr>
<tr>
<td>thickness (mm)</td>
<td>1.30</td>
<td>5.405</td>
<td>2.045</td>
</tr>
<tr>
<td>density (kg/m³)</td>
<td>4510</td>
<td>1155</td>
<td>950</td>
</tr>
<tr>
<td>elastic modulus (MPa)</td>
<td>116x10⁹</td>
<td>50</td>
<td>400</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.32</td>
<td>0.49</td>
<td>0.45</td>
</tr>
<tr>
<td>Prony parameters</td>
<td>g²</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>ν’</td>
<td>0.04</td>
<td>-</td>
</tr>
</tbody>
</table>
2.2 Measurements of visco-hyperelastic properties

Measurements were made on the mantle material only. The mantle layer consists of polybutadiene rubber material. A static compression test was conducted on a dog-bone sample of the mantle material. The deformation of this material is highly nonlinear (Fig. 1).

![Nominal stress-strain curve of mantle materials.](image)

The rate-dependent or viscoelastic behaviour of the mantle material was measured using the Dynamic Mechanical Analysis (DMA) technique which is a forced vibration test of a cantilever specimen with a maximum strain of 5%. It was conducted at a constant temperature on the sample of mantle material to obtain elastic storage and elastic loss moduli during a frequency sweep of 0-20 Hz. Tests were then repeated at different temperatures. The time-temperature shift function such as the William-Landel-Ferry is known to work well with most viscoelastic materials (Oyadiji 2004). Using this, the time-temperature superposition principle was applied to the DMA test results to extend the frequency range (Fig. 2).
3- Modelling impact using FEA

The Abaqus software was employed to model impact of a deformable hollow, multilayer golf ball with a rigid club face. Since the deformations will be asymmetric in an oblique impact, a 3D model was required. Construction of the FEA impact model can be categorised into the following key stages;

3.1 Geometrical construction

A deformable spherical body with hollow centre and thick outer layer was constructed. The thick layer was then sectioned into three different sub-layers with different material properties. This method of subsection removes the possibility of error in defining contact interaction of different layers of material. However, this method neglects the energy losses due to shear traction at the interface. A club face was modelled as a rectangular rigid plate using rigid shell elements.
3.2 Material definition

Material properties are specified in Abaqus for each layer - these properties were obtained either using test data or coefficients for a chosen constitutive equation of the material e.g. elastic, elastic-plastic, hyperelastic or viscoelastic.

The constitutive behaviour of hyperelastic material is defined in terms of ‘strain energy potential’, $U(\varepsilon)$ in Abaqus software. Abaqus computes the strain energy potential based on the user’s input of the nominal stress-strain test data. There are several forms of strain energy potential e.g. Mooney-Rivlin, Ogden and Marlow, where each form is suitable for different type of test data (uniaxial, biaxial, planar or volumetric test). The hyperelastic materials are normally nearly incompressible, hence modelling the dynamic behaviour using Abaqus requires accurate material definition especially if it is confined between stiffer components, as the case for this golf ball. During collision, the golf ball experienced compressive strain due to the contact force. Thus, Marlow form of the strain energy potential was chosen since only uniaxial compression test data (Fig. 1) was used for describing the hyperelastic behaviour. This form produces a reliable calibration for the case where only one type of test data is available (e.g. compression test data). Alternatively, a strain energy function can be selected with pre-defined coefficients.

The broad-band test data of viscoelastic behaviour were expressed in terms of storage and loss moduli. These data were calibrated by Abaqus in order to derive Prony series, which were used to define viscoelastic properties in time domain. Otherwise, the coefficients of Prony series were defined using the viscoelastic material definition.

3.3 Contact interaction

Interaction between the rigid plate and the golf ball was defined using a contact algorithm that allows slip motion once the shear stress on the interface reached a critical value, which is based on the Coulomb friction model. If the shear surface traction is below the friction limit, stick occurs where the elements vibrate in the direction parallel to the interface. The coefficient of friction between the ball and the plate was taken as 0.3 (Tanaka et al., 2006)\(^1\).

3.4 Meshing of elements

An eight node solid element was used to model the ball with three layers; core, mantle and cover. The colliding rigid plate was modelled as discrete rigid element. Meshing was made easier by partitioning the balls into 8 quadrants. The density of meshing can be controlled with fine mesh was concentrated on the area with significant deformations. An explicit formulation was used since this impact involves a transient dynamic event.

3.5 Initial and boundary conditions

An initial uniform velocity field was defined for the golf ball at the start of analysis ($t=0$). Reference node of the rigid plate which represents the motion of a golf club head was fixed for the entire analysis duration.

\(^1\) Alternative friction theories may be appropriate for the polymeric golf ball cover sliding on a metal club face.
3.6 Output

The measured material properties of the mantle layer were compared to the visco-hyperelastic coefficients of Tanaka et al. (2006). The core and cover material properties were kept similar in all simulations (as in Table 1). Hence, the simulations were divided according to the definitions of the mantle properties in Abaqus;

i) T - phenomenologically determined Mooney-Rivlin and three-element viscoelastic material properties for mantle - refer to Table 1.

ii) M - measured hyperelastic and viscoelastic material properties for mantle - refer to Fig. 1 and 2.

Simulations were conducted for an impact speed \( V_0 \) of 45 m/s and three different loft angles \( \theta \) of 10°, 20° and 30°; the purpose was to investigate the effect of mantle properties on calculated values of contact force, spin and COR.

The contact force between ball and plate was measured at the reference node. The velocity of the ball after impact was approximated as an average velocity of nodes in the region at two opposite diameter in the core layer. This layer has the highest stiffness; consequently, this measure minimises the effect of post-impact radial and tangential vibrations on the rebound velocity.

4- FEA results and discussion

![Figure 3 - Maximum normal contact force at different loft angle (\( V_0=45 \text{ m/s} \)). An inset shows the impact configuration of a golf ball and a rigid plate.](image-url)
The comparisons of calculated maximum normal force for simulations using Tanaka (T) and measured (M) material properties are shown in Fig. 3. The maximum normal force reduces with increasing angle. The differences are about 16-19% at these different angles. The measurement of spin shows differences up to 10% between simulations T and M (Fig. 4). Spin of the ball increases almost linearly with the loft angle.

![Figure 4 - Spin resulting from different loft angle (V0=45 m/s). An inset shows the cross-section mesh around the contact region of a hollow golf ball.](image)

Although significant, these disagreements in the results of simulations using material properties obtained from phenomenological tests and measurements are attributed to differences in the properties of polybutadiene rubber of the mantle layer; e.g. variation in the elastic modulus of the mantle layer will significantly affect the maximum normal contact force. A range of different polybutadiene rubbers are used in golf balls. The results of simulation T (Tanaka et al., 2006) do not necessarily represent experimental values since, with the exception of mantle density, the parameters in Table 1 were obtained to match performance of a solid rather than a hollow golf ball. The Tanaka mantle density has been adjusted to obtain the correct total mass of 45g for the hollow golf ball.

Comparisons of COR and spin for impact at 10 deg club face loft angle are shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>calculated phenomenological, T</th>
<th>calculated measured, M</th>
<th>experiment</th>
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<tbody>
<tr>
<td>contact time (ms)</td>
<td>0.345</td>
<td>0.384</td>
<td>-</td>
</tr>
<tr>
<td>spin (rpm)</td>
<td>2766</td>
<td>2498</td>
<td>4217</td>
</tr>
<tr>
<td>COR</td>
<td>0.855</td>
<td>0.878</td>
<td>0.814</td>
</tr>
</tbody>
</table>
The experimental results were conducted on a hollow ball that was struck by a golf club (Table 2). In our simulation, at an impact speed of 45 m/s the mantle of the hollow golf ball suffered a maximum strain of 0.2. As shown in Fig.1, the mantle material has an elastic modulus that decreases with increasing strain for strains in the range $0 < \varepsilon < 0.4$. Hence, the present simulation has used small strain, linear viscoelastic material properties somewhat outside their range of validity. An elastic modulus that decreases from the value in Table 1 with increasing strain would decrease the calculated COR. On the other hand, a flexible golf club face can increase the COR in comparison with that obtained from impact of a rigid golf club.

The simulation results show that a preliminary study of golf ball design and material selection can be conducted by FEA using properties of the constituents measured by independent tests of material properties. The scope of the FEA study can be extended to model dynamic behaviour of a flexible golf club striking a deformable golf ball using measured properties of both constituents.

- **Acknowledgement**

Hollow golf balls compliments of Nanodynamics, Buffalo, NY.

- **References**


