Cricket balls: construction, non-linear visco-elastic properties, quality control and implications for the game

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Compression and stress relaxation tests were applied to five different ball models (Kookaburra Special Test, Gray-Nicolls Super Cavalier, Regent Match red, Regent Match white, and Sanspareils-Greenlands Tournament). Of the five models tested, only the Kookaburra ball was manufactured consistently. All other balls proved to be produced inconsistently with a wide range of stiffness. Additionally, the other four balls revealed two different, yet externally indistinguishable constructions, which resulted in two clusters of different stiffness. The different constructions might be related to the tension of the woollen twine in Regent Match red and the lacquer surface finish and/or cork-rubber mixture in Regent Match white. Gray-Nicolls Super Cavalier was produced with two different core sizes (stiffer ball with smaller core), and Sanspareils-Greenlands Tournament exhibited two different core materials, namely cork or rubber core, with the latter being the softer one. The hard subtypes of Regent Match white, Regent Match red and Sanspareils-Greenlands Tournament turned out to be the hardest balls, the hard sub-type of Gray-Nicolls Super Cavalier and the soft sub-types of Regent Match red and Sanspareils-Greenlands Tournament showed intermediate stiffness, and the soft sub-types of Gray-Nicolls Super Cavalier and Regent Match red as well as the Kookaburra Special Test ball proved to be the softest. The viscosity coefficient of all balls increased with the deflection and the stress relaxation followed a power law. The peak impact forces calculated from the power law model correlated well with the experimentally measured peak forces. The two different constructions (sub-types) of Regent Match white, Gray-Nicolls Super Cavalier and Sanspareils-Greenlands Tournament behaved like two different balls of significantly different stiffness. The latter fact may have severe implications to the match, as softer balls are more forgiving by causing a smaller impact force, a longer contact with the bat, larger deflections, as well as larger contact areas during impact, and therefore allowing placing the ball preciser. A more stringent quality control and testing standard is required for cricket balls in order to avoid unequal chances for both teams. © 2008 John Wiley and Sons Asia Pte Ltd

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- cricket balls
- structure
- non-linear visco-elasticity
- stiffness
- impact modeling
- impact force
- soft and hard balls
1. INTRODUCTION

Cricket is the second most popular sport in the world behind soccer, and the most popular sport in India. Cricket equipment comprises the ball, the bat, the wicket and protective gear for the players. Traditionally, the bat is made from willow wood; the cricket rules do not allow any other material like aluminium and carbon composites. The ball consists of a cork nucleus (Table 1), encased by leather hemispheres, and joined by a circular seam of six rows of stitches around its equator. The mass of a cricket ball, Grade 1 County, must be between 155.9 and 163 g in men’s games [1,2]. Thus, the preferred mass is a minimum of 156 g to achieve maximal acceleration (Table 1).

The condition in which the cricket ball is used has decisive consequences for the game’s outcomes; be it its surface roughness and seam orientation for aerodynamics (especially for the swing of the ball) or its hardness, determining the ease or difficulty with which its bounce direction can be controlled. In contrast to other sport balls, specifically golf balls, most cricket balls are still hand-made, which may affect the consistency of manufacturing and thus the properties of a ball.

The magnitude of the impact force between the ball and the turf, bat, or protective apparel (e.g. face guards) depends on the stiffness of all materials and structures involved.

Furthermore, in contrast to golf balls, where the only important impact occurs between ball and club, cricket ball impacts extend to the turf, bat, and protective apparel like face guards.

The published literature does not provide much information on properties of cricket balls.

Carré et al. investigated the impact of a cricket ball (Readers ‘Grade 1 County’) and proposed that stiffness might increase with the deflection rate [3]. Impact tests were carried out at speeds of up to 6 m/s. The authors modelled the ball as a single spring-damper system and studied the impact of a cricket ball on a rigid surface. The authors developed an empirical model consisting of a Hertzian spring and a non-linear damper in parallel.

Subic et al. performed compression testing on the Kookaburra Tuf Pitch cricket ball at different deflection rates and found an exponential relationship between the loading velocity and ball stiffness [4]. These properties were required for developing a finite element model for impact between the ball and face guards, and for testing their designs.

Cheng et al. developed different theoretical (single non-linear Maxwell model and three Maxwell models in parallel) and numerical (finite element) models that can accurately analyse and describe the key characteristics of impact force on a cricket ball [5].

In light of the few studies conducted on cricket balls, the need for a thorough investigation of cricket ball properties is evident.

The aim of the present article is to:

- investigate internal constructions and structural properties of different brands of cricket balls;
- explore if (and how) construction affects properties;
- compare non-linear visco-elastic properties of different brands of cricket balls;
- develop a model for simulating impact;
- calculate peak forces at different impact speeds; and
- validate the model with measurements of impact forces.

The experimental data from mechanical testing and the observations made from internal constructions will be applied to propose a standard for quality control and to discuss the effect and implications of inconsistent manufacturing on the outcome of the game.

2. BALLS INVESTIGATED

The balls examined are listed in Table 1. All balls were new and were tested only once; either for stress relaxation or for compression.

3. COMPRESSION AND STRESS RELAXATION TESTS

3.1 Method

An Instron material testing machine (model no. 3366) was used to carry out both stress relaxation and compression tests.

For the stress relaxation tests, the balls were pre-loaded between 1.6 and 5.9 kN at a deflection rate of 500 mm/min, and the decreasing load $F$ was measured for $t = 3600$ s. The stress

![Table 1](https://www.sportstechjournal.com) Cricket balls investigated and their details ($M$ = machine made, $H$ = hand made; $T$ = cork layers wound under tension, $N$ = without tension wound cork layers; $2$, $4$ = no. of leather pieces; $C$ = cork core, $R$ = rubber core, $CR$ = core molded from granulated cork and rubber, $U$ = unknown core composition)

<table>
<thead>
<tr>
<th>Brand</th>
<th>Model</th>
<th>Colour</th>
<th>Country of origin</th>
<th>Construction</th>
<th>Mass*</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kookaburra</td>
<td>Special Test</td>
<td>red</td>
<td>Australia</td>
<td>$M$ $T$* (N***$) 2 CR [6]</td>
<td>156 g</td>
<td>Kr</td>
</tr>
<tr>
<td>Gray-Nicolls</td>
<td>Super Cavalier</td>
<td>white</td>
<td>Pakistan</td>
<td>$H$ $T$ 4 CR [7]</td>
<td>5.5 oz 156 g</td>
<td>Gw</td>
</tr>
<tr>
<td>Regent</td>
<td>Match</td>
<td>red</td>
<td>India</td>
<td>$H$ $T$ 4 U</td>
<td>156 g</td>
<td>Rr</td>
</tr>
<tr>
<td>Regent</td>
<td>Match</td>
<td>white</td>
<td>India</td>
<td>$H$ $N$ 2 CR</td>
<td>—</td>
<td>Rw</td>
</tr>
<tr>
<td>SG/Sanspareils-Greenlands</td>
<td>Tournament</td>
<td>red</td>
<td>India</td>
<td>$H$ $T$ 4 $C$* (C or R***$) [8]</td>
<td>—</td>
<td>Sr</td>
</tr>
</tbody>
</table>

* if indicated on the ball
** according to the manufacturer (if different from the actual construction)
*** actual construction (revealed through dissection)
relaxation showed a consistent linear behaviour when plotting $F$ against the relaxation time $t$ on a double-logarithmic coordinate system. Thus, the power law was applied to model the non-linear visco-elastic properties:

$$\log(F) = \log(A) - \log(t)$$

(1)

After antilogarithming Equation (1) we get:

$$F = At^{-B}$$

(2)

where the elasticity parameter $A$ depends on the initial load $F_0$ and thus on the constant deflection required for stress relaxation. $B$ is, in theory, the load-independent viscosity constant [9].

The planes of loading were perpendicular to the plane of the seam (plane 1), and parallel to the plane of the seam (plane 2). In each model (Table 1), 4-8 balls were tested in each plane.

For the compression tests, the balls were loaded up to 9 kN with crosshead speeds of 500, 160, 50, 16, and 5 mm/min. From the load–deflection curve, the stiffness, the deflection derivative of the load $F$, was calculated. In each model, three balls were tested at 500 mm/min, and at least one ball at the four other deflection rates.

All balls used for compression testing were also analysed by examining their mass and internal construction. After cutting the seams, the nature of their construction and the materials used were documented. Specifically noted were the nature, material and size of the core; the nature of the cork layers and woolen twine; and the consistency of the construction across different specimens of the same brand and model. Details of ball construction were correlated to the compression data and the mass of the balls.

### 3.2 Results

#### 3.2.1 Construction and stiffness

The individual results for all balls tested are as follows (preliminary results were reported by [10]).

$K_r$ showed higher stiffness at higher deflection rates, and thus revealed visco-elastic behaviour. In all other balls, however, the dependence on the deflection rate was less clear due to the poor consistency and non-uniform construction. The individual results for all balls tested are described subsequently:

![Figure 1](core_of_kr.png)

**Figure 1.** Core of $K_r$.

![Figure 2](stiffness_deflection_curves.png)

**Figure 2.** Stiffness-deflection curves of $K_r$ (a: plane 1; b: plane 2) at five different deflection rates (black: 500 mm/min; blue: 160 mm/min; purple: 50 mm/min; red: 16 mm/min; orange: 5 mm/min). The dashed green line represents the mean stiffness when compressing in the other plane at 500 mm/min. © 2008 Taylor and Francis. Reproduced by kind permission.
Kookaburra Special Test (Kr). All balls showed a uniform construction. Contrary to the claims of the manufacturer [6] the tension machine wound woolen twine surrounding the core was missing. The core consisted of a cork–rubber mixture (Figure 1). The stiffness was highly consistent, and showed a clear dependence on the deflection rate. When compressing in plane 1, the stiffness decreased after an initial peak, in contrast to compression in plane 2 (Figure 2). The mass of Kr was 159.85 g ± 2.94 (range: 155.38 g – 164.46 g; n = 22).

Regent white Match (Rw). All balls had a construction similar to that of Kr: a large core of molded rubber–cork without woolen twine windings (Figure 3). The stiffness behaviour was highly irregular and inconsistent (Figure 4). Two groups of balls can be distinguished from the stiffness results: a harder group with rapidly increasing stiffness, which dropped after the first millimeters of deflection (more rapid decrease when compressing in plane 1); and a softer group, which showed exactly the same stiffness behaviour as the Kr balls, compressed in planes 1 and 2. The stiffness of the softer group was slightly larger and more inconsistent than that of Kr. The reason for the clearly separated clusters of different stiffness is unclear, and may be due to the core (e.g. an inconsistent cork–rubber mixture), or due to the leather casing (e.g. a thicker layer of lacquer surface finish). The latter was very pronounced in contrast to other balls, and the lacquer layer usually cracked on compression. The different hardness of the balls was also verified by auditory tests as the pitch of the impact sound correlated with the hardness. The mass of the softer group was 149.54 g ± 3.12 (range: 143.05 g – 153.79 g; n = 17), and the one of the harder group was 161.23 g ± 2.85 (range: 157.81 g – 166.69 g; n = 14).

Gray-Nicolls Super Cavalier (Gw). All balls showed alternate layers of woolen twine and cork encasing an inner core of molded rubber–cork. Surprisingly, the cores were not uniform in size. Two distinct ranges of core sizes could be distinguished (Figure 5): a smaller core diameter (Ø4.4 ± 0.2 cm) and a larger one (Ø5.7 ± 0.3 cm). For those balls with smaller cores, the cork shavings were arranged in a more irregular and careless manner. There was no clear difference in stiffness between compression in planes 1 and 2. However, the balls with smaller cores were significantly stiffer than those with larger cores (Figure 6), forming two separated clusters of inconsistent stiffness curves. The pitch of the impact sound correlated with the hardness, comparable to Rw. The different construction did not influence the mass of Gw: 157.28 g ± 1.76 (range: 154.48 g – 160.87 g; n = 30).

Regent red Match (Rr). All balls exhibited the classical construction of a cricket ball, namely a core covered by layers of cork twined with wool. The cores were of varying hardness,
which was clearly felt when they were sawn in half. The indefinable hard material of the cores was mixed with a white or silvery substance (Figure 7). The stiffness behaviour was highly inconsistent (Figure 8) without any clear difference between planes 1 and 2. Again, two clusters of different stiffness were found, which did not correlate with the hardness of the cores. This could be related to the manufacturing process. The different stiffness did not influence the mass of $Rr: 154.64 \pm 3.94$ (range: 148.25 g – 162.77 g; n = 22).

**Sanspareils-Greenlands Tournament (Sr).** Although all balls were of the same model, two distinct types of constructions could be identified: one set of balls had neat layers of cork, shaped like the leather pieces of a baseball, with woolen twine covering a rubber sphere; the second set of balls had cork packed in a rough and irregular manner with woolen twine covering a core made of cork in varying degrees of woodiness, and ranging from spherical to completely irregular in shape (Figure 9). The balls with rubber cores were clearly less stiff than the ones with cork cores, forming two families of different stiffness curves, separated by a wide gap. (Figure 10). There was no clear difference between compression in planes 1 and 2. Again, the pitch of the impact sound correlated with the hardness. The mass of the softer group was significantly larger than the one of the harder group: 159.23 g ± 0.33 (range: 158.61 g – 159.58 g; n = 15) vs. 157.645 g ± 0.44 (range: 156.9 g – 158.35 g; n = 15).

In $Rw$, $Gw$, and $Sr$, the sub-type of the ball (hard or soft) could be predicted clearly from the pitch of the impact sound. Equally, the mass of $Rw$ and $Sr$ allowed the exact determination of the sub-type. However, the leather casing showed no hint suitable for distinguishing between the two sub-types of $Rw$, $Gw$, and $Sr$.

### 3.2.2 Stress relaxation

The viscosity coefficients $B$ of all sub-types (hard, soft) and of both compression planes (1 and 2) are shown in Figure 11 as functions of the deflection. In contrast to the theoretical power law equation of Findley et al. [9], $B$ was not constant, but increased linearly with deflection. In $Gw$ and $Rw$, the harder sub-type was more viscous, in contrast to $Sr$. The behaviour of the latter ball may be related to the two different core materials (cork and rubber). In $Rr$, there was no marked difference between the two sub-types. In general, $Rw$, $Kr$, and $Rr$ are more viscous than $Sr$ and $Gw$. The gradient of the stiffness can be classified as follows: $Kr < Sr$-hard $< Sr$-soft $< Gw$-soft $< Gw$-hard $< Rw$-hard $< Rw$-soft $< Rr$.

### 4. NON-LINEAR VISCO-ELASTICITY AND THE POWER LAW

#### 4.1 Method

Comparable to the procedure developed by Fuss [11] for the logarithmic law (modelling of golf balls), the constitutive equations of the power law will be developed accordingly. As
seen from the stress relaxation tests, a cricket ball obeys following power law:

\[ F = A t^{-B} \]

where \( t \) is the relaxation time, \( A \) is the multiplier, and \( B \) is the viscosity constant. \( A \) is a function of the initial load \( F_0 \), and the latter changes with the constant deflection \( x_0 \), \( F_0 = f(x_0) \). Thus, we obtain:

\[ F = x_0 A t^{-B} \]  

(3)

The parameter \( A \) is the velocity (deflection rate)-independent elasticity parameter, subsequently denoted ‘\( A \)’ in Equation (3). \( x_0 \) is the constant deflection of stress relaxation tests, applied by a Heaviside function \( H(t) \):

\[ x = x_0 H(t) \]  

(4)

Taking Laplace transform of Equations (3) and (4):

\[ \hat{F} = x_0 A \frac{\Gamma(-B + 1)}{s^{B+1}} \]  

(5)

\[ \hat{x} = \frac{x_0}{s} \]  

(6)

where the caret (\(^{\wedge}\)) denotes the transformed variable, and \( \Gamma \) symbolises the gamma function.

Substituting Equation (6) into Equation (5), we obtain the constitutive equation of the power law of visco-elasticity:

\[ \hat{F} = s^B \hat{x} A \Gamma(1 - B) \]  

(7)

Analysing Equation (7), we understand that:

- The product \( A \Gamma(1 - B) \) is constant (constant \( C \)).
- \( B \), the viscosity constant, ranges between 0 and 1: \( 0 \leq B < 1 \). If \( B = 0 \), then Equation (7) becomes \( F = xA \), a Hookean solid. If \( B \rightarrow 1 \), then the material or structure becomes maximally viscous, with \( \Gamma(1 - B) \) approaching \( +\infty \); thus, a solution of Equation (7) for \( B = 1 \) does not exist, as \( \Gamma(0) \) is not defined (transition from \( +\infty \) to \(-\infty \)).
- The load \( F \) is a fractional derivative, specifically the ‘\( B \)th time derivative’, of the deflection \( x \), multiplied by constant \( C \). Thus, inverse Laplace transform of Equation (7) yields:

\[ F = \frac{d^B x}{dt^B} A \Gamma(1 - B) \]  

(8)

From Equation (7), the relationship between stiffness and deflection rate can be derived by applying a ramp function to the deflection:

\[ x = \dot{x}_0 t \quad \text{or} \quad \hat{x} = \frac{x_0}{s^2} \]  

(9)

where \( \dot{x}_0 \) is the constant deflection rate.

Substituting Equation (9) into Equation (7)

\[ \hat{F} = \dot{x}_0 A \frac{\Gamma(-B + 1)}{s^{B+2}} \]  

(10)

Applying the recursion formula of the Gamma function, we obtain:

\[ \hat{F} = x_0 A \frac{\Gamma(-B + 1)}{\Gamma(B) s^{B+2}} \]  

(11)
Taking inverse Laplace transform,
\[ F_x = t^{1-B} \frac{A}{x_0(1-B)} \]  
Equation (12)

Replacing \( t \) by \( x = x_0 \):
\[ F_x = x^{1-B} \frac{A}{x_0(1-B)} \]  
Equation (13)

Finally, the stiffness \( k \) is the deflection derivative of the load \( F \):
\[ k_x = A x^{B} x_0^{B} \]  
Equation (14)

The relationship between stiffness and deflection rate results after exchanging the variable and the constant: the variable deflection becomes a specific deflection \( x_r \) and the constant deflection rate becomes the independent variable \( v \), the deflection velocity.
\[ k_v = A x_r^{B} v^{B} \]  
Equation (15)

Equation (15) has the same structure as Equation (2): the independent variable to the power of \( B \) multiplied by a constant. Thus, the relationship between stiffness and deflection rate also obeys the power law.

In a purely elastic material, where the viscosity parameter \( B \) is zero, Equation (15) becomes \( k = A \), which is the stiffness of a Hookean spring.

Equation (15) permits to calculate the velocity- or deflection rate-independent elasticity parameter \( A \) from different stiffnesses \( k \) at different deflection rates \( v \):
\[ A = k v x_r^{B} v^{-B} \]  
Equation (16)

In the following section, \( A \) is calculated from the stiffness \( k \) at the five different compression velocities (Figures 2, 4, 6, 8, 10) for all sub-types (hard and soft) and compression planes (1 and 2), according to Equation (16).

4.2 Results

Figure 12 shows the velocity-independent elasticity parameter \( A \) as a function of the deflection.

\( Kr \) turns out to be the softest ball, whereas \( Rw \)-hard and \( Sr \)-hard (cork core) are the stiffest balls. Although the stiffness increases more rapidly with deflection in the \( Rw \)-hard ball, it drops again after approximately 4 mm, in contrast to \( Sr \)-hard (more constant gradient). \( Rw \)-soft shows the same stiffness trend as the \( Kr \) ball in both compression planes, with the only difference is that \( Rw \)-soft is slightly stiffer than \( Kr \). In addition to these results, Figure 12 reveals the striking differences between hard and soft sub-types. The most pronounced difference appears in \( Rw \) with the largest difference between hard and soft sub-types, followed by \( Sr \), \( Gw \), and \( Rr \).

Parameter \( A \) is ideal to rank the balls (and their sub-types) in terms of velocity-independent stiffness. \( A \), however, does not immediately explain the behaviour of a ball on impact because neither \( A \) nor its gradient are constants. The three decisive parameters of a batsman’s feel and control of the ball are the peak force, contact time, and deflection of the ball; the
last of these is related to the contact area between ball and bat. Thus, these three parameters need to be calculated from impact modelling to quantify the relative differences between the balls and their sub-types, and to understand if these differences may have a significant impact on the game.

Figure 13 shows the consistency of manufacturing in terms of parameters $A$ of $Kr$ and $Rw$-soft, both compressed in plane 1 for deflections from 1 mm to 20 mm. Parameter $A$ of the two balls shows the same trend. The ranges of $A$ are wider in $Rw$-soft than in $Kr$, which shows clearly, that $Kr$ is more consistently manufactured.

The stiffness of $Kr$ is $0.738 \pm 0.022$ of $Rw$-soft on average. The standard deviations of $Kr$ and $Rw$-soft are $12940 \pm 3841$ and $34862 \pm 9198$, respectively. The mean of the standard deviation of $Rw$-soft is 2.7 times the mean of the standard deviation of $Kr$ on average.

5. IMPACT MODELLING

5.1 Method

For impact modelling, it is important to consider that:

a) an impact is an unsymmetrical (single-sided) compression whereas compression testing is double-sided; and

b) the reaction force at the contact area and the inertial force of the decelerated or accelerated object, which is its mass
times the acceleration of its centre of mass (COM), are in equilibrium at all times.

One of the main problems of impact modelling is the conversion of the stiffness derived from compression tests into the stiffness of an impacting object. In contrast to compression tests, where the deflection corresponds to the amount by which the object is compressed, the deflection of an impacting object is measured from the displacement of its COM, which can be calculated from dividing the impact force by the mass of the object and subsequently integrating with time twice. The displacement of the COM under compression is half the overall deflection. Thus, it seems all too logical to accept, that the compression stiffness has to be doubled to obtain the impact stiffness. This corresponds to Cross's hypothesis [12] assuming that only the bottom half or contact side of the object is compressed on impact. This hypothesis was examined by Carré- et al. [3] by comparing the force-deflection curve of a whole ball to the one of a ball sawn in half [3].

Specifically, the force was plotted against half the deflection for the whole ball and the total deflection for the half ball. The reason for this was simply that the whole ball is expected to produce half the stiffness of the half ball, and thus, the two force-deflection curves should be identical when plotting the force against half the deflection of the whole ball, assuming that the hypothesis is correct. In theory, considering that both halves are replaced by springs, and thus the whole ball consists of two identical springs in parallel, it is evident that the equivalent stiffness of two identical springs in parallel is half the stiffness of the single spring.

Nevertheless, the two force-deflection curves were not identical, and the authors' results (Figure 6 in Carré et al. [3]) proved that the stiffness of the half ball is smaller than twice the stiffness of the whole ball. Specifically, the multiplier of the stiffness calculated from Figure 6 in Carré et al. [3] between 0.5 and 1.75 kN (the ball was loaded up to 2 kN) in 0.25 kN increments is between 1.44 and 1.64, with a mean of 1.56 ± 0.082, which stands in sharp contrast to the expected multiplier of 2.

Carré et al. [3] explain that their data suggests 'that sawing the ball in half reduces the stiffness of the system, possibly because the flat, sawn top of the ball is free to deform outwards, compared to the constraint applied by the other half of the ball, for a whole ball'.

However, the equatorial plane of a whole ball is free to expand on compression, whereas in the half ball, it is in contact with one of the compression plates and its expansion is constrained due to friction between the sawn top of the ball and one compression anvil. Thus, experimental conditions may lead to an overestimation of the mean stiffness multiplier of 1.56. Furthermore, Carré et al. [3] tested the same ball twice; first as a whole ball, and subsequently one half thereof. It became apparent from the present study, that cricket balls are permanently deformed after the first compression, which results into an increase in stiffness on repeated loading. This effect also becomes evident when subduing a linear visco-elastic model to cyclic loading. In the light of this, the mean stiffness multiplier may have been overestimated by Carré et al. [3].

The assumption, that only the bottom half of the ball is being compressed in an impact and the top half of the ball

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**Figure 13.** Box-Whisker plot of parameter A against deflection, showing the range of parameter A of Kr and Rw-soft.
In double-sided compression, the displacement of the COM is not linear, as the displacement of the COM is decisive for the impact. The deflection would be zero. However, the multiplier of the stiffness is 0.5. If the force was constant throughout the length of the object from 0 to 1, the overall deflection of the impacting object is 1.333. Due to the initial conditions, we can consider the initial deflection of the object to be zero.

Due to the initial conditions, $x = 0$ when $F = 0$, $C$ is zero as well. Considering unit-force, -modulus and -area, and solving for $L$ from 0 to 1, the overall deflection of the impacting object is 0.5. If the force was constant throughout the length of the object, which is the case in compression experiments, the overall deflection would be 1. However, the multiplier of the stiffness is not zero, as the displacement of the COM is decisive for the impact. In double-sided compression, the displacement of the COM would be 0.5. Solving Equation (19) for the bottom half, that is, for $L$ from the COM ($L = 0.5$) to the contact ($L = 1$), we get a displacement of the COM of 0.375. The increase in stiffness from a displacement of 0.5 to 0.375 is 1.333 [11].

As mentioned before, Equations (18) and (19) are based on an object with constant and uniform cross-section. This is, of course, not the case in a spherical object, such as a sports ball. In addition to Equation (17), where $F_L$ is a function of $L$, we can consider $A_e$ a function of $L$ as well and derive the displacement equation from there. This, however, requires that each $F_L$ results into a uniformly distributed stress across the specific $A_e$ of each layer $dL$. From FEA we know that this is not the case (e.g. golf balls; see Figure 7 in Kai [13]), the more so if the ball is non-homogenous and anisotropic like a cricket ball.

The multiplier of 1.333 calculated above, required to convert the stiffness obtained from compression tests into the stiffness at impact, will be used as a theoretical value subsequently, and the results of impact modelling will be validated against data from impact experiments. This will verify whether the multiplier has been over- or underestimated.

One further point has to be addressed in this connection, as the stiffness obtained from compression tests is a function of the constant deflection rate, whereas the velocity of the COM changes during the impact. Therefore, it is important to make the compression stiffness independent of the velocity or deflection rate, by applying Equation (16) and converting the stiffness $k$ into the velocity independent elasticity parameter $A$.

Comparable to the procedure developed by Fuss [11] for the logarithmic law (impact modelling of golf balls), the constitutive impact equations of the power law will be developed accordingly. The impact is modelled form the equilibrium of three forces: the aforementioned reaction force $F_R$ at the area of contact; its inertial force $F_I$ and an applied force $F_A$. The latter accelerates the object of mass $m$ to the velocity $v_0$ at the initial instant of impact. $F_A$ is applied immediately before impact by a unit impulse acceleration (Dirac delta function $\delta(t)$).

$$F_A = a m = v_0 \delta(t) m$$

Through integration, the unit impulse acceleration results in unit step velocity (Heaviside function) if the object would continue to move freely. The unit step is brought to the specific initial velocity by multiplying by $v_0$.

At $t = 0$, $F_A > 0$, and at $t > 0$, $F_A = 0$. This results into the initial conditions of $x_0 = 0$ and $x_0 = 0$ at $t = 0$, and $x_0 = v_0$ at $t > 0$.

The force equilibrium of horizontal impact is thus given by:

$$F_I + F_R = F_A$$

$F_I$ is the deceleration or acceleration of the COM after impact:

$$F_I = a m = \ddot{x} m$$

$F_R$ is the reaction force at the contact between object and frame, the transformed Equations (7).

$$\ddot{F} = s^B \dot{x} A \Gamma(1 - B)$$

Parameter $A$ in this case is the velocity independent elasticity parameter, derived from compression tests, times 1.333.

Taking Laplace transform of Equations (20) and (22) and substituting them, including Equation (7), into Equation (21):

$$s^2 \ddot{x} m + s^B \dot{x} A \Gamma(-B + 1) = m v_0$$

Dividing by $m$ and solving for $\dot{x}$, the transformed displacement of the COM:

$$\dot{x} = v_0 \frac{1}{s^2 + s^B A \Gamma(1 - B) / m}$$

Alternatively, we can omit $F_A$ in Equation (21) and consider the initial conditions, $x_0 = v_0$ and $x_0 = 0$, to obtain the same result.

In a purely elastic body, the viscosity parameter $B$ is zero and the inverse Laplace transform of Equation (24) yields:

$$x = v_0 \sqrt{\frac{m}{A}} \sin \left( \sqrt{\frac{A}{m}} \right)$$

which is the constitutive equation of undamped oscillation.
After substituting Equation (24) into Equation (7), we obtain the transformed equation of the reaction force \( F_R \):

\[
\dot{F}_R = v_0 A \Gamma (1 - B) \frac{s^B}{s^2 + s^B A \Gamma (1 - B) / m} \tag{26}
\]

Again, as mentioned above, it becomes evident, that \( F \) is the \( B^{th} \) time derivative of \( x \), multiplied by \( A \Gamma (1 - B) \).

Velocity and acceleration of the COM result from differentiating Equation (24):

\[
s \ddot{x} = v_0 \frac{s}{s^2 + s^B A \Gamma (1 - B) / m} \tag{27}
\]

\[
s^2 \ddot{x} = v_0 \frac{s^2}{s^2 + s^B A \Gamma (1 - B) / m} \tag{28}
\]

The inertial force \( F_I \) results from multiplying the acceleration of the COM, Equation (28), by the mass \( m \):

\[
F_I = v_0 \frac{ms^2}{s^2 + s^B A \Gamma (1 - B) / m} \tag{29}
\]

Due to the equilibrium of \( F_R + F_I = 0 \) we understand that the \( B^{th} \) time derivative of the COM's displacement times \( A \Gamma (1 - B) \) equals the displacement's \( 2^{nd} \) time derivative times \( m \). In fractional calculus terms, considering that \( B \) is a non-integer \((0 \leq B < 1)\) and omitting \( F_I \), we can thus rewrite Equation (21) as a linear extraordinary differential equation (EODE):

\[
A \Gamma (1 - B) \frac{d^B x}{dt^B} + m \frac{d^2 x}{dt^2} = 0 \tag{30}
\]

Based on the parameters \( A \) (multiplied by 1.333) and \( B \) as functions of the displacement \( x \) (Figures 11 and 12), the peak impact force at different initial velocities is calculated from Equation (26) by applying Piessen and Huysmans' [14] routine for inverse Laplace transform, programmed in Matlab. In addition to the peak force, the displacement of the COM at the peak force (which is slightly smaller than the maximal displacement) was determined from Equation (24) as well as the time between initial contact and the peak force.

### 5.2 Results

The three key parameters for assessing the mechanical indicators of the impact,

- the peak force,
- the displacement of the COM at the peak force (which is related to the size of the contact area); and
- the contact time before peak force

are plotted in Figures 14,15,16 for velocities from 0 to 30 m/s.

The difference in stiffness between hard and soft sub-types (\( R_w > S_r > G_w > R_r \)), as seen in Figure 12, is mirrored in the differences of peak force, displacement and contact time at an initial velocity of 30 m/s. Only at 15 m/s, the peak force difference between \( R_r \)-hard and \( R_r \)-soft is slightly larger than the difference between \( G_w \)-hard and \( G_w \)-soft. For comparison, at 30 m/s, the force difference between \( K_r \)-plane1 and -plane2 is larger than the difference of \( G_w \) and \( R_r \) sub-types (not, however, at 15 m/s).

In general, \( R_w \)-hard, \( S_r \)-hard and \( R_r \)-hard exhibit the highest impact forces, largest COM displacements and shortest contact times, whereas \( K_r \), \( G_w \)-soft, \( S_r \)-soft and \( R_w \)-soft are at the lower end (softest balls).

It has to be mentioned again, that it is more important to compare the key mechanical parameters across the balls instead of concentrating on isolated absolute values. The latter might not be sufficiently accurate as the multiplier of 1.333 required to convert \( A_{\text{compression}} \) into \( A_{\text{impact}} \) can be over- or underestimated and is thus the critical factor for impact modelling. Nevertheless, measurement of impact forces allows assessment of the multiplier.

### 6. MEASUREMENT OF THE PEAK IMPACT FORCE

#### 6.1 Method

Three harder balls (sub-type \( S_r \)-hard, cork core) and three softer balls (\( K_r \)) were selected for measuring the impact force. The \( S_r \)-hard balls were distinguished from the pitch of the impact sound before the experiment and confirmed by dissection afterwards. Each ball was dropped four times from a height of 5.3 m on a portable force plate (Kistler, model 9286A). This drop height results into a velocity of approximately 10.2 m/s before impact. The weight, or gravitational force, of the ball is negligible compared to the peak impact forces and thus does not have to be included in Equation (21). The reaction forces were recorded at 10 kHz and the peak forces were determined by fitting a polynomial regression into the force data.

#### 6.2 Results

The results of the 12 impacts per ball type are represented in Figure 17, together with the specific force-velocity graphs (\( K_r \), \( S_r \)-hard) of Figure 14 for comparison.
The range and standard deviation are, as expected from the compression tests, smaller in Kr than in Sr-hard. Mean ± standard deviation of Kr and Sr-hard are 3095 ± 274 N and 5229 ± 794 N respectively. The measured mean peak force, however, is slightly higher than the one calculated, which means that the multiplier of 1.333 has been underestimated minimally. Nevertheless, the calculated peak force is well within one standard deviation of the measured peak force. When raising the multiplier from 1.333 to 1.5, the calculated peak force would increase by approximately 1.06, which is still within one standard deviation of the experimental data.

7. DISCUSSION

In this study, all analyses involved new balls only. This is because new balls are permanently deformed after the first compression. During the game, however, a cricket ball becomes softer with time. This is why the ‘openers’ are usually the most experienced batsmen of the team, as they have to face a new, and thus hard ball as well as the most aggressive fast bowlers (high ball speed). Yet, ball degradation and softening is a feature of every cricket ball and thus affects both teams.

There are, however, two specific features, identified in this study, which can cause an advantage or disadvantage to a team:

1) inconsistent manufacturing of balls of identical construction, causing a wide range of ball stiffness; and
2) manufacturing of one specific ball at two different, yet externally indistinguishable constructions, and thereby even more widening the range of the originally inconsistently produced ball.

The former applies to Rr, possibly related to the tension of the woolen twine, whereas the latter appears in:

- Rw: possibly lacquer surface finish and/or cork-rubber mixture;
- Gw: two different sizes of core; and
- Sr: two different core materials (cork or rubber).

According to Bhatia [15], Sanspareils-Greenlands ‘balls are checked exhaustively at every stage within the factory ... A minor element out of place could change the way a ball behaves’. Accordingly, Sanspareils-Greenlands claim that ‘all of their cricket equipment is manufactured to strict quality controls’ [8]. The present study, however, proves those claims untrue, as the cores of two Sr sub-types were produced either from rubber or cork, resulting in different stiffness. This clearly indicates a failure of both quality control and consistent manufacturing techniques.

According to the rules of cricket a team captain may demand a new ball at the start of each innings [2]. This rule, however, leads to unequal chances for both teams, as a softer ball provides one team with an advantage over the other team.

The skill of playing a shot is related to the swing style, the timing and the placement of the ball or direction aimed to avoid fielders. As mentioned above, more experienced batsmen deal more easily with faster bowling velocities and initially harder balls.

Softer balls are more forgiving: they cause a smaller impact force (Figure 14), are longer in contact with the bat (Figure 16), and show larger deflections (Figure 15) and thus larger contact areas during impact. This allows placing the ball preciser.

If a ball has two sub-types: a harder and a softer one, then the ratio of ‘same conditions: advantage:disadvantage’ when using one ball per innings is 2:1:1, and when using two balls 4:1:1.
Interestingly, the former head coach of the Pakistan cricket team, Bob Woolmer (1948–2007) used three different brands of cricket balls in practice matches [16]; specifically, Kookaburra, Grays, and a South African ball as first, second, and third new balls. Playing with different ball models within one innings is supposed to keep the batsman concentrated and to avoid getting him used to one ball. Thus, playing with more balls per innings reduces the advantage or disadvantage which results from inconsistent manufacturing and different ball constructions, and possibly makes the match more interesting.

As advice, a coach can attempt to distinguish harder and softer balls (within one specific model) by dropping the balls from a height of approximately 1 m on a smooth and hard surface and judge the balls from the pitch of the impact sound: the higher the pitch, the harder the ball. This procedure, however, is rather a rough guideline than an accurate test. A more precise method is to weigh the balls, which allows distinguishing between soft and hard types of Rw and Sr (Figure 18). In Rw balls, a mass of 154 g and 157.5 g defines the softer and harder sub-types respectively (Figure 18). Equally, in Sr balls, a mass of 158.5 g clearly separates the sub-types (Figure 18). Furthermore, the mass of a ball indicates the conformity with the Laws of Cricket (2003) [2], as the mass is not always exactly 156 g, even when indicated on the ball (Table 1).

The hardest balls investigated reach a peak force of about 18 kN at a speed of 30 m/s upon impact with a rigid surface (Figure 14).

Considering these high impact forces, it is not further astonishing that such impacts can even be lethal, as seen in the accident of Raman Lamba [17,18]. Raman Lamba was hit on the head when fielding, and subsequently suffered from a brain hemorrhage which eventually turned out to be fatal. Subic et al. [4] demonstrated that the knowledge and FEA simulation of peak forces during impact are decisive for designing protective equipment.

In contrast to Subic et al. [4], who found an exponential relationship between the loading velocity and the ball stiffness (Kookaburra Tuf Pitch), the model used in the present study is based on a power law, verified by stress relaxation. Thus, the relationship between the loading velocity and the ball stiffness follows a power law as well (Equation 15). An exponential relationship generally results from linear visco-elastic spring-damper systems like Prony series of Maxwell elements in parallel, implemented in some FEA software for modelling of quasi-linear visco-elasticity and thus more suited for FEA than real non-linear visco-elastic models (e.g. power law). The ball model investigated by Subic et al. [4], Kookaburra Tuf Pitch, and the Kookaburra Special Test, analysed in this study are identical according to the manufacturer [6], only the Tuf Pitch’s leather cover is selected and finished for greater resistance to abrasion.

Carré et al. [3] modelled the impact of a cricket ball (Readers ‘Grade 1 County’) based on a non-linear Kelvin-Voight model consisting of a Hertzian spring and a non-linear damper in parallel at impact speeds of up to 6 m/s:

$$F_x = x^a k + x q (d - x)$$  \hspace{1cm} (31)

where $a$ is the constant exponent of the Hertzian spring, $d$ is the ball’s diameter, and $k$ and $q$, the elasticity and viscosity model coefficients, are exponential functions of the velocity before impact.

The authors did not observe a reduction of the coefficient of restitution (COR) when increasing the impact speed to 6 m/s, as the COR remained constant at approximately 0.5. In addition, they suggest that the stiffness may increase with the deflection rate, a fact that has been proved by Subic et al. [4]. Exceptioning the Kr balls (‘the most widely used two piece ball in the world’ [6]), none of the other brands showed an
acceptable degree of consistency in stiffness. Even the $Kr$ balls did not have the construction that was indicated and claimed by the manufacturers [6] (Table 1). A certain degree of variation in properties is only natural considering the biological origin of the materials used and the manual production process. Nevertheless, the fact that the machine-made $Kr$ balls were quite consistent shows that an automated manufacturing process improves the consistency. If properties (cork or rubber cores) and quality of the materials or the manufacturing process are not standardized, a high degree of inconsistency is expected. Therefore, it is recommended that standardized testing of the different balls is encouraged and enforced by the governing bodies of the sport. The stress-relaxation and compression tests performed in this study can be used for this purpose. Randomly picked specimens from a batch of newly manufactured balls can be tested to verify that they provide a consistent stiffness profile with respect to deflection. Balls that do not match those standards can be dissected to analyse the reason of inconsistency which must be avoided in future manufacturing. The inconsistency in the results of all models but $Kr$ was directly traced back to their constructions.

7.1 Current standard of testing

The British Standard for specification of cricket balls [1] lists three mechanical tests as performance requirements:

a) height of bounce;

b) hardness; and

c) impact resistance.

In the first bounce height test, the ball has to fall freely through a distance of 2 m onto a smooth, flat horizontal concrete base. The height of the first bounce is measured to an accuracy of ±5 mm, from the bottom of the ball and bounces on the seam of the ball are ignored. From the bounce height, the COR is calculated from the square root of the ratio of bounce height to drop height. Yet, it is generally known from golf balls that the COR drops with the impact velocity [19]. A drop from 2 m results in an impact velocity of 6.26 m/s. Impacts of cricket balls occur at far higher velocities than 6 m/s. Furthermore, as the viscosity of cricket balls increases with deflection (Figure 11), it is expected that the COR drops with deflection and thus with impact velocity. A single test, especially at slow speed may not give much information.

In the hardness test, the ball is placed with its seam parallel to the base plate. A steel guided striker (of mass 5 kg ± 0.1 kg with a flat, circular striking surface of diameter 125 mm) hits the ball with an impact velocity of 4.66 m/s (drop height 1.1 m), whereby the peak deceleration (in g) is measured during impact. The peak deceleration represents the hardness of the specimen. The disadvantage of the test is that the hardness is measured at one specific velocity and one deflection only. The hardness, or stiffness, changes with deflection and velocity.

The impact resistance test applies the same procedure as the hardness test, only the impact velocity is higher: 6.26 m/s (drop height 2 m). This procedure has to be carried out in the six main directions of the ball. Supposedly, the ball should not be damaged during this procedure.

7.2 Recommendation and proposal for standardisation

 Cricket ball testing standards should comprise compression testing, determination of the stiffness (mean ± standard deviation) at various standardized deflection rates, stress relaxation for determination of the viscosity, bounce test for determination of the COR, analysis of consistent mass and construction, as well as comparison between used and new balls. Furthermore, this data and the construction of the ball including a figure of the cross section should be made available on the ball carton, comparable to golf ball package design.

8. CONCLUSION

1) Of the five cricket ball models tested (Kookaburra Special Test, Gray-Nicolls Super Cavalier, Regent Match red, Regent Match white, Sanspareils-Greenlands Tournament) only the Kookaburra ball was manufactured consistently (Figure 18). All other balls proved to be produced inconsistently with a wide range of stiffness. Additionally, the other four balls revealed two different, yet externally indistinguishable constructions, which resulted in two clusters of different stiffness. The different constructions might be related to the tension of the woolen twine in Regent Match red and lacquer surface finish and/or cork-rubber mixture in Regent Match white. Gray-Nicolls Super Cavalier was produced with two different core sizes (stiffer ball with smaller core), and Sanspareils-Greenlands Tournament exhibited two different core materials, namely cork or rubber core, with the latter being the softer one.

2) The viscosity coefficient of all balls increased with the deflection and the stress relaxation followed a power law

3) The peak impact forces calculated from the power law model correlated well with the experimentally measured peak forces

4) The two different constructions (sub-types) of Regent Match white, Gray-Nicolls Super Cavalier and Sanspareils-Greenlands Tournament behaved like two different balls of significantly different stiffness.

5) The latter fact may have severe implications to the match, as softer balls are more forgiving by causing a smaller impact force, a longer contact with the bat, larger deflections as well as larger contact areas during impact, and thus allow placing the ball preciser.

6) A more stringent quality control and testing standard is required for cricket balls in order to avoid unequal chances for both teams.

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