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# Use of image based sports case studies for teaching mechanics

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**Abstract**

Mechanics is a fundamental topic required for both undergraduate and postgraduate students on engineering and technology courses. It can be difficult to motivate and engage students in the theoretical aspects of the topic, especially if they are without a strong mathematical background. There are many sporting examples that can be used to explain some of the basic concepts in mechanics. As many sport interactions are high-speed, visualizing the relation to mechanics can be challenging. From our own research, and that published in the field, we now have access to a range of high quality images that have been generated from high-speed video and photogrammetry work, computational simulations or flow visualizations. Two case studies in which images from ball sport research have been used to explain two key engineering subjects: solid and fluid mechanics. A strategy for future collaboration of academics to share and have access to a range of high quality experimental images was also proposed.



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*Keywords:* Education, Images, Mechanics; Ball sports

## 1. Introduction

The idea of using sporting examples to teach mechanics is not novel and has been used to inspire students long before sports engineering was recognized as an academic discipline. Classic examples include the flight of a projectile for teaching kinematic equations and simple aerodynamics, the flex of a pole vault to investigate bending equations and material properties, or the bounce of ball to calculate coefficient of restitution. These examples and many more, use sport to provide context to the problem and allow students to relate more easily with the more complex theoretical aspects.

It is beneficial for universities to deliver informative lectures that relate to recent research activities and provide an enjoyable learning experience for the students. We believe sporting examples supported by experimental images or videos have the potential to engage the students as well as providing an insight into the research and commercial aspects of academia. As many sports events are high-speed by nature, visualizing the relation to mechanics without the aid of imaging techniques can be challenging. For example, it is often difficult to convince a student how much a tennis ball deforms on impact with only the aid of television footage. Recent advances in imaging technology and the availability of equipment such as high-speed video cameras means that there is more opportunity to generate high quality images that capture the sporting event in action and reveal the fascinating mechanical responses.

This paper focuses on how images from ball sports can be used as case studies to introduce a number of mechanics topics. We have specifically chosen examples that utilize appropriate images, and where available, we have cited references that can be used to explain the theory or as a source for additional lecture content. As a sports engineering community we are able to create models of complex interactions that assist in describing the theoretical content. Often, these models are validated using an imaging method. It is rare however for validation footage, or images from, to be available in the publication. We believe additional images are necessary to help contextualize the problem and provide a reference point for the students to relate. We have provided a suggestion for improving the availability of such images for use in teaching or public engagement events.

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## 2. Case study 1) Solid mechanics – 'the bounce of a ball'

An early topic introduced in solid mechanics courses is impulse and momentum. Even at school level (UK higher education ages 15 - 17), impacts of sports balls are used to explain the theory of conversation of momentum [1]. Coefficient of restitution (COR) - ratio of inbound and outbound velocities - is typically introduced during the first year of a university engineering degree course. As COR can also be derived from the square root of the ratio of rebound height to release height of a ball, it lends itself nicely to a practical demonstration in which the bounce of a ball is filmed or photographed. This measurement technique is used by FIFA as a measure of pitch hardness [2] and the ITF in their ball approval process [3]; these associations can often help to bring relevance to the topic. Early sports engineering research often used strobe photography to capture the path of a bouncing ball [4], although this technique is rarely used now with the availability of high-speed cameras, the original images are still some of the best for illustrating the topic of impulse and momentum (Fig. 1). For example, Fig. 1 can be given to a class with the task to calculate COR from the relative bounce heights. This is a simple and straightforward way to incorporate a sporting example in the lecture without the need to collect additional experimental data or perform calibration. A collection of images similar to Fig. 1 showcasing different COR values (for example, due to changes in ball material or environmental conditions) would be particularly beneficial.

Fig. 1. Stroboscopic image of a ball bounce (image courtesy of Professor Andrew Davidhazy, Rochester Institute of Technology)

The theme of ball impacts can be extended to facilitate teaching of other topics, such as stiffness and damping which dictate the bounce behavior. A detailed description of the theory of ball impacts is provided by Cross (1999); although this publication lacks the experimental images which could help communicate this topic [5]. High-speed cameras can be used to capture a more detailed view of the ball impact, revealing high magnitude temporal deformations. The amount of deformation can be used to explain the complex topic of contact pressure. Images generated from computer simulations, such as finite element models (Fig. 2), can be given to a class with the task of calculating maximum deformation. They also provide additional insight into temporal stresses and section views. Having these images for a range of balls (perhaps matching those in Fig. 1) could make for an insightful lecture. Table 1 provides some further examples of work published in the ISEA journal, *Sports Engineering*, that could be used for teaching solid mechanics. In the references provided, experimental imaging techniques played an important role in the research into the impact mechanics of the various ball sports.

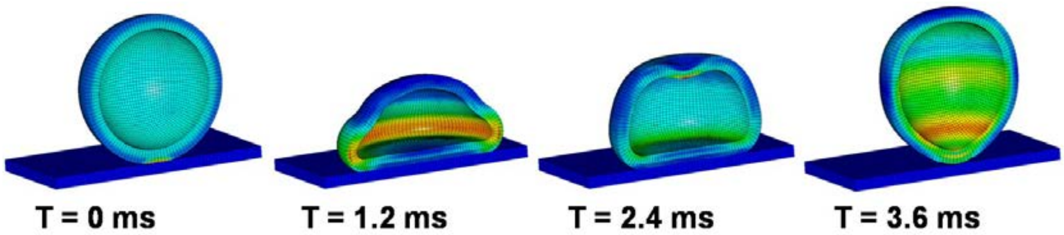


Fig. 2. Finite element model of a tennis ball during impact with a rigid surface (authors' own image).

Table 1. A selection of ball sport papers published in *Sports Engineering* containing images suitable for inclusion in a solid mechanics lecture.

| Imaging technique | Sport | Summary | Suitability of images | Authors |
|---|---|---|---|---|
| High-speed video | Table tennis | Calculation of deformation and contact forces of hollow elastic spheres (table tennis balls) impacting with a hard, flat surface. | Reference figure 2 is from high-speed video footage captured at 9000 fps The images are well sized for use in lecture slides. | Hubbard and Stronge (2001) [6] |
| Simulation (finite element analysis) | Football | Computer simulation to investigate the fundamental characteristics causing a football to spin after contact with the foot. | Figure 5 in the reference illustrates the pressure contours of the deformed foot and ball during impact. Although a clear illustration of ball deformation, the images are of poor resolution and the legends are illegible. | Asai *et al.* (2002) [7] |
| High-speed video | Cricket | The impact behavior of a cricket ball projected onto a playing pitch was used as a measure of pitch performance. | Figure 1c in the reference shows superposition of a high-speed video frames and consequently illustrates the flight path of the ball. This is a good example of relating the experimental technique back to a sporting event. However, the image is very small and unlikely to scale well on a lecture slide. It is also in greyscale. | James *et al.* (2004) [8] |
| Simulation (finite element analysis) | Tennis | Development of a finite element model of a tennis ball impacting an oblique surface. The model was used to predict COR and spin rates after impact. | Simulated images generated from the finite element model are presented. In particular, reference figure 8 shows the difference between the deformation shape of the ball from normal and oblique impacts. The image is annotated and relates to graphical outputs in the paper. | Goodwill *et al.* (2005) [9] |
| Scanning laser doppler vibrometer | Football | Investigation of the mechanical and dynamic response of footballs using the vibrometry technique. The balls were excited using an acoustic source rather than impacting an object. | Contour maps of the surface velocity of two balls of differing constructions are shown in figures 5, 6 and 7 of the reference. These images are quite novel and demonstrate a different approach to investigating the mechanical response of a ball. | Ronkainen and Harland (2007) [10] |
| High-speed video | Softballs | The dynamic response of a softball was investigated by firing it at a rigid cylinder. The measurement technique in this case was not optical, and used load cells to record the impact force. | Despite not using an imaging technique to collect data, the authors have included a high-speed video image of the deformation of a softball (reference figure 8). There are a number of graphical outputs included in the paper that could also be used in a lecture slide. The inclusion of this image demonstrates that although not necessary for the data collection, visual observation of the interaction can be helpful in explaining the experimental results. | Smith *et al.* (2010) [11] |
| High-speed video | Hurling | Viscoelastic impact characterization of polymer ball (sliotar). | Reference figure 3 shows maximum deformation of four different ball types when filmed at 4000 fps. The image has been annotated with a dashed line to indicate the original ball size. This is a simple technique, yet helps to convey the amount of deformation of each ball. The images are a suitable quality for use in a lecture, particularly when combined with the cross-section photographs of each ball type (reference figure 1). | Collins *et al.* (2011) [12] |
| Photography | Tennis | The footprint of a tennis ball during impact was measured using two novel techniques; 1) a ball covered in paint was projected onto a surface and the corresponding print measured, 2) a ball was fired onto a blackboard covered with a fine layer of chalk dust, the removal of dust under impact from the ball revealed the contact patch. | Paint and chalk footprint images are in colour and of good size for use in a lecture slide (reference figures 5, 6 and 8). A high-speed camera was also used to capture the interaction at 300 – 600 fps, although footage was not published. An excellent lecture slide would be to combine the footprint photograph with corresponding video footage and graphical output. The paper also refers to the commercial system 'Hawkeye'; this association helps provide further context to the mechanical topic. | Cross (2014) [13] |

## 3. Case study 2) Fluid mechanics – ‘the flight of a ball’

The application of ball sports to fluid mechanics begins at foundation level where Newton’s equations of motion are used to derive the trajectory of a projectile. Goff’s 2013 review paper on the aerodynamics of sports projectiles contains much of the necessary theory [14]. A straight-forward lecture task could be to calculate the flight time of a tennis ball between one player and their opponent. This could be married with corresponding video footage (provided appropriate information is available on the initial ball velocity and angle) to help illustrate the flight path shape. With the basics mastered, aerodynamic drag force can then be included in the equations of motion and more accurate flight paths calculated. There are a number of publications in which the trajectory of a ball has been modelled and can be used as additional resources to explain the theory [15, 16]; in some cases the model has been validated against experimental data and images are also available [17].

The curved flight path of a ball in the vertical plane can easily be described by the kinematic equation approach. However, the curved path of a ball in the horizontal plane (swing) is a more interesting phenomenon and allows the introduction of more advanced fluid mechanics topics such as boundary layers and the Bernoulli equation. To begin, one of the better-understood causes of the swing of a ball is the Magnus effect, this can be more easily explained with the use of images such as Fig. 3. This type of swing is very common when the balls are isotropic (e.g. golf, tennis and baseball) [18]. Goff, in his book, ‘Gold Medal Physics’ provides a detailed explanation of the influence of the Magnus effect to describe the famous ‘banana’ free-kicks by David Beckham [19]. This in itself is an excellent case study to use in a lecture, but can be further enhanced by the inclusion of television footage and experimental images showing the ball curving in flight. Flow visualization techniques are often employed to capture the wake pattern of fluid flowing over the surface of a ball. They can be taken in a wind tunnel [20], water channel [21] (Fig. 3) or filmed from the projection of the ball [22, 23].

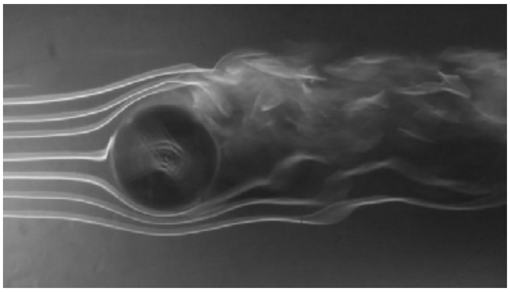

Fig. 3. Illustration of the Magnus effect using dye flow visualization of a spinning cricket ball in a water channel (image courtesy of Dr Rabi Mehta, Sports Aerodynamic Consultant)

The swing of a cricket ball introduces another area for discussion as the seam of a ball can induce swing without any significant degree of spin. The seam trips the boundary layer on the ‘seam side’ into turbulent flow, whilst the ‘non-seam side’ remains laminar. The turbulent layer separates from the surface of the ball later than the laminar layer. This subsequent asymmetric wake causes a pressure differential giving rise to the lateral side force causing the ball to curve in flight. Since the theory behind the swing of the cricket ball was proposed by Cooke and Lyttleton in 1955 and 1957 [18], experimental results to better understand this effect have been well documented, perhaps most notably by Mehta *et al*. in their seminal article for Nature [24]. Visualization of the wake structure from a cricket ball (Fig. 4) provides a clear illustration of the effect and allows students to relate to this complex topic. Images similar to those shown in Fig. 3 and 4 illustrating the wake structure for different balls or scenarios would be particularly beneficial. Table 2 contains examples of fluid mechanics papers published in *Sports Engineering* that contain data or images suitable for inclusion in lecture material.

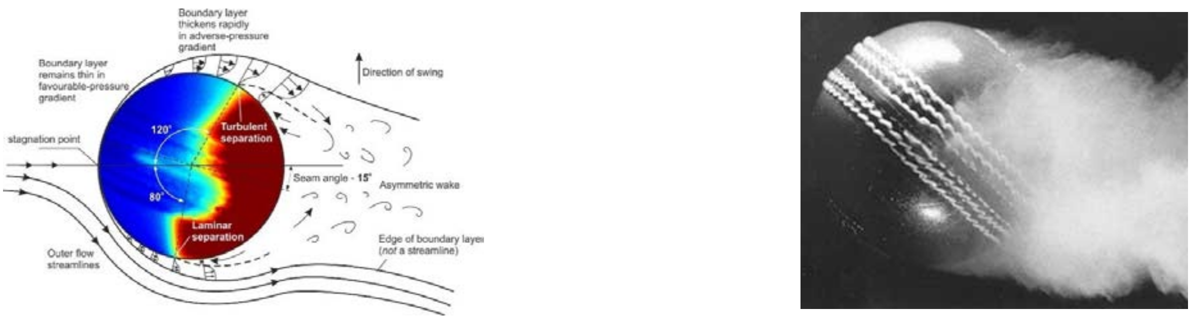


Fig. 4. Left: Infrared visualization technique to show separation points on a cricket ball (image courtesy of Dr James Scobie and Dr Gary Lock, University of Bath). Right: Smoke flow visualization over a cricket ball with the seam tripping the flow causing an asymmetric wake (image courtesy of Dr Rabi Mehta, Sports Aerodynamic Consultant).

Table 2. A selection of ball sport papers published in *Sports Engineering* containing images suitable for inclusion in a fluid mechanics lecture.

| Imaging technique | Sport | Description | Suitability of images | Authors |
|---|---|---|---|---|
| Flow visualization (smoke) | Cricket | General description of cricket ball swing including a discussion of the controversial 'white ball' used in the 1999 and 2003 World Cup tournaments. | The iconic smoke flow visualization image shown above (Fig. 4 (right)) is used in this paper (reference figure 2) to illustrate the wake and separation points. The image together with the description and included schematics (reference figure 1) provides a comprehensive overview of the causes of cricket ball swing. As a lecture, this could further be enhanced by inclusion of video footage of a swing ball. | Mehta (2005) [25] |
| Flow visualization (titanium tetrachloride) | Football | An overview of the aerodynamics of a football. The paper makes use of images collected for an earlier conference paper [26] in which a football was coated in titanium tetrachloride and the kick trajectory captured with a high-speed camera. | This paper combines traditional fluid mechanics techniques such as wind tunnel test with a novel approach using a coated ball. The flow visualization images (Figures 5, 6, 7, 10 and 11 in the reference paper) are useful for showing the wake of the ball but are small due to the high frame rate of 4500 fps. A video using this technique was submitted to the ISEA image competition in 2014 and would make an excellent addition to a lecture case study. | Asai *et al.* (2007) [22] |
| Computational fluid dynamics | Golf | The aerodynamic characteristics of a golf ball were obtained computationally using Large eddy simulations. The flow patterns were visualized using the spark tracing method and with velocity vectors. | The paper presents a number of colour, high quality images (reference Figures 6 and 7) showing the flow pattern around a golf ball. The images are from simulations so different test configurations can be easily generated. The paper also includes a flight simulation of the model golf ball. This is a nice addition as it ties together the two topics: kinematic equations and boundary layers. | Aoki *et al.* (2010) [27] |
| High-speed video | Football | The trajectory of a football was used to calculate drag and lift coefficients for balls with different panel configurations. | High-speed video was the main data collection method used in this publication. Although the paper presents a very clear description of the trajectory calculations, only simulated images are provided. These images are useful in a lecture application, but would be further enhanced if captured video data was also available. | Barber and Carré (2010) [28] |
| Flow visualization (dust separation) | Football | A non-spinning ball is projected through a dust cloud to observe boundary layer separation. | Figure 4, 6 and 7 of the reference paper shows a football passing through a dust cloud. The boundary layer separation can be clearly seen in the images and it is an interesting approach to use without requiring the use of a wind tunnel. The images are of a suitable size for use in a lecture. | Goff *et al.* (2011) [23] |
| Flow visualization (infrared) | Cricket and golf | The fluid dynamic effects of a number of sports balls were demonstrated using a novel infrared flow visualization technique. | A number of images (including Fig. 4 (left) above) are included in this paper and clearly show the separation points of the boundary layer. The concept is perhaps more challenging for students to understand with the introduction of the infrared technique, but the images are well annotated, of high quality and in colour. | Scobie *et al.* (2014) [29] |

## 4. Discussion

Within the literature there exists a wealth of examples in which sports engineering can be used to explain mechanics topics. These examples are often aided by the inclusion of images in which the theory can be visualized to help students relate to and engage with the topic. Since many of these studies were published, there have been advances in imaging technology and experimental techniques providing the potential to generate higher quality and more detailed photos or videos. Whilst more recent academic publications often include highly informative images, they are not always suitable for use in lecture slides. There is a low uptake of researchers who make use of the option to include supplementary material with their publication. However, there have also been significant developments in data storage and sharing capabilities. We suggest that an online repository is created on the ISEA website to facilitate the sharing of images for use in lectures or public engagement events, with full accreditation given to the owners. We propose that the images are required to have a minimum resolution and recommended aspect ratio to ensure consistency.

An ideal lecture slide could first introduce the theoretical content, include a visual demonstration of the mechanics, and finally, provide a sporting example of the theory in action. For example, Fig. 4 (left) shows an annotated image of the boundary layer separation points describing the theory of cricket ball swing, and Fig. 4 (right) shows an image from an experiment illustrating the wake pattern using smoke visualization. If these two images are combined with a video, photo or practical demonstration of swing in a sporting environment, it will produce a comprehensive overview of the topic that should capture the attention of the audience.

The relation back to the sporting event is important and often missing from publications, as although the experimental research and theory may be obvious to the academic, this is not always the case for the students.

## 5. Conclusion

The application of sporting examples to mechanics can provide context to the theory and could result in a more engaged cohort of students. Images are vital to capture the attention of the audience and can often bring light to a difficult or complex topic. Within our field there are many published resources that we can draw upon in our lectures but with advances in imaging technology we believe some of our lecture notes need updating. We would like to call upon our colleagues to continue to collect high quality images during their research and share these with the community; not only will they lead to better research publications, but they will also help inspire and encourage the next generation of engineering students.

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