RESOURCE LETTER

Resource Letter PS-2: Physics of Sports

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This Resource Letter provides a guide to the literature on the physics of sports, updating Resource Letter PS-1, published 25 years ago (Ref. 17). The intent is to suggest literature for anyone curious about the basic physics of particular sports, for physics teachers searching for sports examples to augment their teaching, and for physicists contemplating research on unsolved sports-related questions.
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I. INTRODUCTION

An astonishing fraction of the world's population exhibits interest in sporting events. Somewhere between 500 million to 1 billion people watched the live television coverage of the 2008 Olympic Games opening ceremonies and the 2006 and 2010 World Cup soccer finals. In most cultures, participation in organized sporting activities is widespread, e.g., the U.S. Census Bureau's *2010 Statistical Abstract* indicates that more than 40 million Americans bowl, more than 20 million play basketball and golf, and more than 10 million participate in soccer, tennis, baseball, softball, and volleyball. There is increasing awareness that regular strenuous exercise, often in the form of social activities such as games or team sports, is an important component for maintaining health in individuals of all ages.

Yet, while media coverage of sports is pervasive and literature describing sporting activities is vast, even for popular sports it is sometimes difficult to find comprehensive descriptions of the underlying physics. Several different varieties of scientists regularly analyze physics-related aspects of sports and each has different strengths and limitations.

(1) Researchers in *physical education* or *kinesiology* often concentrate on the practical aspects of training and performance. Physics is often not the central focus of these analyses; however, these researchers are often athletes or interact regularly with athletes and thus have a relatively sophisticated understanding of the activity.

(2) *Biomechanics* researchers often investigate subjects such as the mechanics of joints, bone fractures, or motion in general. One common experimental approach is to attach reflecting markers to an athlete's joints and then film an activity using a strategically placed array of synchronized digital cameras. Specialized software then provides a digital record of the position of the athlete's body segments, frame by frame. These studies provide information about what actually happens in an athletic activity and make it possible to accurately calculate forces and torques on athletes and their individual body segments.

(3) *Mechanical engineers* occasionally undertake analyses of sports or sports equipment. Sometimes the objective is to enhance performance, as in the design of tennis rackets; sometimes the objective is to improve safety, as in the design of helmets for cycling or for American football.

(4) Finally, *physicists* sometimes publish papers about sports. Often, sports phenomena are used as examples for teaching physics or for motivating student interest in physics. Some of these articles are authored by scientists who have never been serious participants in the sport being analyzed; this can create a situation where coaches or athletes find that the underlying assumptions about a sporting activity are inaccurate or highly simplified. Moreover, some articles authored by physicists make no effort to use technical language familiar to participants of the sport, making these articles difficult for enthusiasts to comprehend.

The literature on the physics of ten-pin bowling, a sport I took up in midlife, offers examples of these problems. Prior to my article in this journal (Ref. 79), most then-available bowling physics articles assumed that friction is constant over a bowling lane and that a bowling ball is a uniform sphere with a center of mass coinciding with the center of the sphere; any serious bowler knows these assumptions matter and are simply untrue. Publications by mechanical engineers did make realistic assumptions but failed to address directly a fundamental question: What is the primary reason bowling balls curve on their path to the pins? Also, finally, the literature written by bowlers and ball drillers does not use physics-familiar terms such as "torque," "angular momentum," or "moments of inertia," but instead uses a specialized technical language unique to bowling to describe how mass offsets affect ball trajectory. To address this, my article included a table defining key physics and bowling terms in both languages—a Rosetta stone of physics patois and bowling-speak.

There are lessons here: If you aspire to perform research on sports and be taken seriously by both physicists and enthusiasts, pick a sport you know very well, either as a serious participant or life-long aficionado, or else acquire such a person as a coauthor. Otherwise, you will miss a lot and may blunder. Also, be careful not to underestimate coaches. The best coaches are wonderful observers of the subtle features of athletic activity. They may not always understand physics but they know exactly what happens. Woe to the physicist who ignores what they say they see.

As asserted in Resource Letter PS-1 (Ref. 17), the physical factors that underlie many well-known sporting activities are subject to ongoing debate in the literature and deserve research attention. Most of the reasons why this persists today—even though the relevant physics is classical—also haven't changed since 1986.

- Many familiar sports (baseball, soccer, American football, and basketball) are relatively young, having developed into a form recognizable to a modern enthusiast only in the late 1800s or early 1900s;
- The widespread association of sports with schools and universities, the present-day concepts of eligibility, and the distinction between amateur and professional activities developed mostly after World War I; the intense and highly technical approach to training athletes developed only after World War II;
- For individual sporting events, the depth of research analysis varies widely depending on social and economic factors and, in some sports, on rules which arbitrarily specify properties of the equipment. Thus, there has been more research on tennis and golf, both sports historically having educated and affluent enthusiasts and requiring rackets or clubs where the rules permit considerable variation, and less research on soccer and basketball, sports traditionally popular with the working classes and requiring equipment with narrowly defined properties.

However, since 1986, several things have changed. First, inexpensive digital video cameras are now easily obtainable and nearly every household contains a laptop or desktop computer nearly as powerful as the university mainframe computers of yesteryear. Second, the internet, search engines, and the ongoing transformation of library collections to electronic form have made it far easier to discover what is known about a vast range of topics, including sport science. These revolutions allow individuals the opportunity to disseminate information about popular subjects, with the result that numerous websites, blogs, and self-published books are now available, most which haven't undergone peer review.

Third, today there are vastly more sports science books intended for elementary, high-school, and introductory college-level students. Many of these are obviously aimed at a popular audience, as they have titles like *The Physics of Football: Discover the Science of Bone-Crunching Hits, Soaring Field Goals, and Awe-Inspiring Passes* (Ref. 102). Much of this literature has a short life and fails to find its way into college libraries. Some of these books are frustrating if you are seriously interested in sports, as often their focus isn't really analysis of sports but rather teaching or raising enthusiasm for basic science. Others are marketed specifically for enthusiasts of particular sports and contain little or no in-depth scientific analysis; *The Physics of NASCAR* (Ref. 226), for example, contains (count 'em) no equations and, frankly, very little physics. However, a few elementary books are simply wonderful, e.g., check out *The Physics of Hockey* (Ref. 209), *The Physics of Rugby* (Ref. 100), or *Physics of Sailing* (Ref. 198).

Fourth, since 1986, there have been some subtle changes in the focus of serious sports physics literature. For example, the literature now includes numerous articles about how the details of ball-bat or ball-racquet and ball-ground interactions affect play in sports such as baseball, tennis, and golf. These articles demonstrate that the interactions are highly nonlinear and one shouldn't ignore ball spin, variations in surface friction, or the vibrational properties of the striking implements. Also, whereas the literature prior to 1986 focused almost exclusively on Olympic and major sports, subsequent articles have appeared on numerous more exotic activities such as bungee jumping (Refs. 242, 243, and 245), atlatl (spear) throwing (Ref. 236), and sepaktakraw (Ref. 230).

Fifth, since 1986, several academic disciplines besides physics have focused increased attention on sports-related problems, with the result that the boundaries between sport-research disciplines are increasingly blurred. For physicists, one area where this blurring provides an opportunity involves questions that traditionally belong to the social sciences, especially economics and sociology. Semipopular books such as *Soccernomics* (Ref. 101) and *Baseball Between the Numbers: Why Everything You Know About the Game is Wrong* (Ref. 29) ask questions such as: Are the more successful World Cup soccer teams from rich countries or poor countries, after correcting for other variables? In baseball, does team success depend more strongly on batting average, on-base percentage, or home runs? These aren't physics questions, but answering them involves modeling and the statistical analysis of messy data sets, both familiar activities for physicists. Both researchers and physics teachers should consider visiting or crossing this physics-social science boundary. Researchers will find that a physicist's intellectual tools are perfect for numerous sports-related questions. Also, teachers should agree that the practice of questioning common knowledge—and then designing tests to address these questions—is an essential element of what we teach science students at all levels. You might ask yourself if you are interested in sports primarily to find interesting physics or to answer interesting questions. If the latter is true, you might consider tackling some nonphysics questions. Because some physicists might find these nonphysics questions interesting, I have included a few such publications in the lists that follow.

Finally, one of my sons is presently a history-of-science graduate student. As I observe how that field progresses, I suggest that some analyses of the history of sports physics might be fruitful. To that end I have included a few references to publications of purely historical interest, such as Newton's 1671 paper on light and tennis balls (Ref. 167), and Coriolis's 1835 monograph on billiards (Ref. 75).

The list of books and articles below is in no way complete; rather, my intent was to include representative examples of the variety and level of materials that are available for different sporting activities. Within each sport category, I list books before journal articles, with entries in reverse chronological order.

I have not attempted to compile a comprehensive list of online websites, as these are of varying quality and often disappear or acquire new web addresses over time periods like one or two years. Nevertheless, web searches are worth the trouble as they often turn up videos that are highly enlightening and not readily available elsewhere. As this is written, Rod Cross maintains a website with material on a variety of sports (http://www.physics.usyd.edu.au/~cross/). Baseball enthusiasts will enjoy the sites of Alan Nathan (http://webusers.npl.illinois.edu/~a-nathan/pob) and Dan Russell (http://paws.kettering.edu/~drussell/bats.html). Readers with interest in billiards should visit the site of David Alciatore (http://billiards.colostate.edu).

II. PERIODICALS

American Journal of Physics
European Journal of Physics

Both these journals publish articles aimed at physics teachers and individuals interested in the "cultural aspects of physics" and occasionally include sports articles.

Engineering of Sport
International Journal of Sports Science and Engineering
Sports Engineering

These periodicals all focus on sports from an engineering perspective. *Engineering of Sport* is not a journal, but a series of volumes presenting papers from biennial conferences of the International Sports Engineering Association (ISEA); *Sports Engineering* is a journal published by the ISEA. Some articles in these periodicals are well worth the attention of physicists interested in current research on a broad variety of sports, including baseball, climbing, cycling, football, golf, gymnastics, lawn sports, snow sports, tennis, and water sports. See especially **Engineering of Sport 7**, edited by M. Estivalet and P. Brisson (Springer, Paris, 2008); **Engineering of Sport 6**, edited by E. F. Moritz and S. Haake (Springer, New York, 2006); **Engineering of Sport 5**, edited by M. Hubbard, R. D. Mehta, and J. M. Pallis (International Sports Engineering Association, Sheffield, 2004); and **Engineering of Sport 4**, edited by S. Ujihashi and S. Haake (Blackwell, Malden, 2004).

Sports Technology

This journal was new in 2008 and has attracted some excellent articles concerning both equipment and performance in many different sports.

International Journal of Computer Science in Sport
Journal of Applied Biomechanics (formerly International Journal of Sport Biomechanics)
Journal of Biomechanics
Journal of Science and Medicine in Sport
Medicine & Science in Sports & Exercise

There are occasional sports physics articles in these journals, but more often they focus on other issues such as the performance aspects of sports, sports injuries, or kinesiology.

Physics Teacher
Physics World

Both of these journals occasionally publish elementary and popular articles about sports—*Physics Teacher* from an American perspective and *Physics World* from a European perspective.

III. TEXTBOOKS AND MULTISPORT COMPILATIONS

1. **Gold Medal Physics: The Science of Sports**, J. E. Goff (Johns Hopkins U. P., Baltimore, 2010). This book discusses a wide variety of sports, using only elementary equations. (E)
2. **Projectile Dynamics in Sports: Principles and Applications**, C. White (Routledge, London, 2010). This book includes some problem sets and many worked examples, covering field events as well as baseball, cricket, football, golf, rugby, soccer, and tennis. Although it might serve as an intermediate-level mechanics textbook, it assumes a technical knowledge of sports that is unusual for a mechanics text. An appealing feature is that it reviews strategy and historical aspects of many sporting activities. (I)
3. **An Introduction to Biomechanics of Sport and Exercise**, J. Watkins (Elsevier, Edinburgh, 2007). This is an introductory biomechanics textbook, with mostly sports examples, intended for physical education majors. (E)
4. **Spinning Flight: Dynamics of Frisbees, Boomerangs, Samaras, and Skipping Stones**, R. D. Lorenz (Springer, New York, 2006). The author is an aerospace engineer and this book treats a host of flying objects that haven't gotten much attention elsewhere. (I)
5. **Anthology of Statistics in Sports**, edited by J. Albert, J. Bennett, and J. J. Cochran (Society of Industrial and Applied Mathematics, Philadelphia, 2005). This is not a physics book, but a compilation of papers by statisticians about many different sports. (I)
6. **Notational Analysis of Sport (Second edition)**, M. Hughes and I. M. Franks (Routledge, London, 2004). Coaches, researchers, or fans interested in analysis of strategy in team and some individual sports all can benefit from concise play-by-play summaries of game events. This book reviews how to construct notations to accomplish this, with illustrations from sports familiar to any British fan. This book isn't about physics *per se*, but is a useful starting place for any scientist interested in quantitative analysis of sporting strategy. (I)

7. **Materials in Sports Equipment**, edited by M. Jenkins (Woodhead, Cambridge, U.K., 2003). Each chapter discusses material science issues affecting different sporting equipment, including balls and field implements, bicycles, golf clubs, mountaineering equipment, protective gear, shoes, ski equipment, and tennis rackets. (I)
8. **The Dynamics of Sports: Why That's the Way the Ball Bounces (Fourth edition)**, D. F. Griffing (Dalog, Oxford, OH, 1999). This is a textbook for an introductory precalculus physics course with a sports theme. (E)
9. **Sports Science Projects: The Physics of Balls in Motion**, M. P. Goodstein (Enslow, Berkeley Heights, 1999). This is one of a series of books by the same author suggesting science-fair projects for elementary and secondary school students. This book focuses on projects involving baseballs, basketballs, footballs, golf balls, and tennis balls. (E)
10. **Computer Modeling: From Sports to Spacecraft… From Order to Chaos**, J. M. A. Danby (Willman-Bell, Richmond, 1997). This book is a textbook introducing numerical computational methods for solving differential equations, with chapters focusing on examples from sports as well as biology, economics, and various familiar physical systems. (I)
11. **Biomechanics of Sports Techniques (Fourth edition)**, J. G. Hay (Prentice Hall, Englewood Cliffs, 1993). This is the last-published edition of a classic introductory college textbook on sport biomechanics; it presents analysis and references on many topics. (E)
12. **The Physics of Sports**, edited by A. Armenti (American Institute of Physics, New York, 1992). This is a compilation of 57 classic sports physics articles, with the editor's insightful commentary on the articles in each sports group. Any physicist contemplating research on sports should own this book. (I)
13. **The Mathematics of Projectiles in Sport**, N. DeMestre (Cambridge U. P., Cambridge, U.K., 1991). This material was prepared for undergraduate mathematics students. The book develops a sports-appropriate mathematical framework and set of differential equations and then applies them to various sports. (I)
14. **Modeling with Projectiles**, D. Hart and T. Croft (Ellis Horwood, Chichester, 1988). This book is aimed at introductory college physics students and uses sports-related projectile motion questions as a framework for developing problem-solving skills. There are numerous worked and unworked problems as well as colorful historical examples. (E/I)
15. **Biomechanics of Sport**, C. L. Vaughan (CRC, Boca Raton, 1988). This is a collection of review articles with extensive reference lists on the biomechanics of running, swimming, rowing, skating, weight lifting, track and field, skiing, tennis, and cycling. (I)
16. **A Bibliography of Biomechanics Literature (Fifth edition)**, J. G. Hay (Iowa City, 1987). This is a collection of several thousand references to journal articles and dissertations on biomechanics, organized by sport and by subject. James Hay was a pioneering teacher-researcher in the field of biomechanics, and before search engines and the internet this bibliography was an essential resource for any serious sports researcher. Today it is still valuable as it includes references to many classic publications. (I)
17. **Resource letter PS-1: Physics of sports**, C. Frohlich, Am. J. Phys. **54**, 590–593 (1986). This is the first edition of the present Resource Letter. (E)
18. **Mathematics in Sport**, M. S. Townend (Halsted, New York, 1984). This is an elementary physics analysis of many activities and sports, originally written as a text for a mathematics course for undergraduate physical-education majors. (E)
19. **SportScience: Physical Laws and Optimum Performance**, P. J. Brancazio (Simon and Schuster, New York, 1984). This is a wonderful book aimed at the student who has had an introductory physics course, but with a reference list if he or she gets more serious. (E)
20. **The Physics of Ball Games**, C. B. Daish (English U. P., London, 1972). This is a classic, one of the earliest book-length monographs on sports physics, focusing especially on golf, cricket, and billiards. In most printings, this book was published in two separate volumes. It is hard to find, even in good libraries, and ought to be reprinted. (I)
21. **Young Scientist and Sports**, G. Barr (Whittlesey House, McGraw-Hill, New York, 1962); republished with the title **Sports Science for Young People** (Dover, New York, 1990). Written for children, this is a very elementary discussion of how physics affects various aspects of baseball, football, and basketball. (E)

IV. ARTICLES ABOUT PARTICULAR SPORTS

A. Archery

22. "Bow and catapult internal dynamics," M. Denny, Eur. J. Phys. **24**, 367–378 (2003). (I)
23. "Bow and arrow dynamics," W. C. Marlow, Am. J. Phys. **49**, 320–333 (1981). (I)
24. "An optimally designed archery," T.-C. Soong, in **Mechanics and Sport, AMD Vol. 4**, edited by J. L. Bleustein (American Society of Mechanical Engineers, New York, 1973), pp. 85–100. (A)
25. "Ballistics of the modern-working recurve bow and arrow," B. G. Schuster, Am. J. Phys. **37**, 364–373 (1969). (I)
26. "Physics of bow and arrows," P. E. Klopsteg, Am. J. Phys. **11**, 175–192 (1943). (E)
27. "The dynamics of a bow and arrow," C. N. Hickman, J. Appl. Phys. **8**, 404–409 (1937). (I)

B. Baseball and Cricket

28. **Physics of Baseball and Softball**, R. Cross (Springer, New York, 2011). This book is destined to be the ultimate reference, supplanting all others, concerning bats, balls, and bat-ball interaction. Americans will be appalled to learn that the author, Rod Cross, is Australian. (I)
29. **Baseball Between the Numbers: Why Everything You Know About the Game is Wrong**, edited by J. Keri (Basic Books, New York, 2006). This is not a physics book, but there is plenty of straightforward data analysis to debunk many commonly held beliefs about the game. (E)
30. **The Physics of Baseball (Third Edition)**, R. K. Adair (Perennial, New York, 2002). This book came about when Bart Giamatti, then Commissioner of Baseball and formally a Yale faculty member, asked Adair, a Yale

physicist, to weigh in on various science issues that affected baseball. Unfortunately, this book is too technical for most of the public and frustrating for the scientist because Adair doesn't include an adequate reference list and incorporates almost no research published after about 1990. (E)

31. **Keep Your Eye on the Ball: Curveballs, Knuckleballs and Fallacies of Baseball (Second edition)**, R. G. Watts and A. T. Bahill (Freeman, New York, 2000). Although the authors state this book is "written for the inquiring lay person or fan," it makes a more comprehensive effort to use introductory physics than many books about popular sports. An unusual feature is a chapter describing Bahill's research concerning human physical limitations on the visual tracking of pitched baseballs, which has huge implications for some common myths about hitting. (E)

32. "Effects of altitude and atmospheric conditions on the flight of a baseball," A. T. Bahill, D. G. Baldwin, and J. S. Ramberg, Int. J. Sports Sci. Eng. **3**, 109–128 (2009). (I)

33. "Cricket balls: Construction, non-linear visco-elastic properties, quality control and implications for the game," F. K. Fuss, Sports Tech. **1**, 41–55 (2008). (I)

34. "Development of a fast-solving numerical model for the structural analysis of cricket balls," N. Cheng, A. Subic, and M. Takla, Sports Tech. **1**, 132–144 (2008). (I)

35. "The effect of spin on the flight of a baseball," A. M. Nathan, Am. J. Phys. **76**, 119–124 (2008). (I)

36. "Influence of a humidor on the aerodynamics of baseballs," E. R. Meyer and J. L. Bohn, Am. J. Phys. **76**, 1015–1021 (2008). (I)

37. "Paradoxical pop-ups: Why are they difficult to catch?," M. K. McBeath, A. M. Nathan, A. T. Bahill, and D. G. Baldwin, Am. J. Phys. **76**, 723–729 (2008). (I)

38. "Progress in measuring the performance of baseball and softball bats," L. Smith, Sports Tech. **1**, 291–299 (2008). (I)

39. "Scattering of a baseball by a bat," R. Cross and A. M. Nathan, Am. J. Phys. **74**, 896–904 (2006). (I)

40. "Characterizing the performance of baseball bats," A. M. Nathan, Am. J. Phys. **71**, 134–143 (2003). (I)

41. "How to hit home runs: Optimum baseball bat swing parameters for maximum range trajectories," G. S. Sawicki, M. Hubbard, and W. J. Stronge, Am. J. Phys. **71**, 1152–1162 (2003); see also the discussion in Am. J. Phys. **73**, 184–189 (2005). (I)

42. "Evaluating baseball bat performance," L. V. Smith, Sports Eng. **4**, 205–214 (2001). (I)

43. "The sweet spot of a baseball bat," R. Cross, Am. J. Phys. **66**, 772–779 (1998); see also the discussion in Am. J. Phys. **69**, 229–232 (2001). (I)

44. "Cricket ball aerodynamics: Myth vs science," R. D. Mehta, in **The Engineering of Sport: Research Development and Innovation**, edited by A. J. Subic and S. J. Haake (Blackwell Science, London, 2000), pp. 153–167. (I)

45. "Dynamics of the baseball–bat collision," A. M. Nathan, Am. J. Phys. **68**, 979–990 (2000). (I)

46. "The dynamic behaviour of cricket balls during impact and variations due to grass and soil type," M. J. Carré, S. W. Baker, A. J. Newell, and S. J. Haake, Sports Eng. **2**, 145–160 (1999). (I)

47. "Baseball: Pitching no-hitters," C. Frohlich, Chance **7** (3), 24–30 (1994). This isn't about physics, but uses methods familiar to physicists and applies them to a question about sports. (I)

48. "The dynamical theory of the baseball bat," L. Van Zandt, Am. J. Phys. **60**, 172–181 (1992). (A)

49. "Visual judgments and misjudgments in cricket, and the art of flight," D. Regan, Perception **21**, 91–115 (1992). (I)

50. "The effects of coefficient of restitution variations on long fly balls," D. T. Kagan, Am. J. Phys. **58**, 151–154 (1990). (I)

51. "Models of baseball bats," H. Brody, Am. J. Phys. **58**, 756–758 (1990). (I)

52. "Baseball-bat collisions and the resulting trajectories of spinning balls," R. G. Watts and S. Baroni, Am. J. Phys. **57**, 40–45 (1989). (I)

53. "The lateral force on a spinning sphere: Aerodynamics of a curveball," R. G. Watts and R. Ferrer, Am. J. Phys. **55**, 40–44 (1987). (I)

54. "Aerodynamics of a knuckleball," R. G. Watts and E. Sawyer, Am. J. Phys. **43**, 960–963 (1986). (I)

55. "The sweet spot of a baseball bat," H. Brody, Am. J. Phys. **54**, 640–643 (1986). (I)

56. "Looking into Chapman's homer: The physics of judging a fly ball," P. J. Brancazio, Am. J. Phys. **53**, 849–855 (1985). (I)

57. "Trajectory of a fly ball," P. J. Brancazio, Phys. Teach. **23**, 20–23 (1985). (I)

58. "Aerodynamic drag crisis and its possible effect on the flight of baseballs," C. Frohlich, Am. J. Phys. **52**, 325–334 (1984). (I)

59. "Why can't batters keep their eyes on the ball?," A. T. Bahill, Am. Sci. **72**, 249–253 (1984). (E)

60. "Aerodynamics of the cricket ball," R D Mehta and D. H. Wood, New Sci. **87**, 442–447 (1983).

61. "Aerodynamics of a knuckleball," R. G. Watts and E. Sawyer, Am. J. Phys. **43**, 960–963 (1975). (I)

62. "Catching a baseball," S. Chapman, Am. J. Phys. **36**, 868–870 (1968). (I)

63. "Batting the ball," P. Kirkpatrick, Am. J. Phys. **31**, 606–613 (1963). (E)

64. "An analysis of the aerodynamics of pitched baseballs," C. Selin, Res. Q. **30**, 232–240 (1959). (E)

65. "Effect of spin and speed on the lateral deflection (curve) of a baseball; and the Magnus effect for smooth spheres," L. J. Briggs, Am. J. Phys. **27**, 589–596 (1959). (I)

C. Basketball

66. **The Physics of Basketball**, J. J. Fontanella (Johns Hopkins U. P., Baltimore, 2006). This is an elementary treatment of basketball physics written from the perspective of a former small-college basketball player who now teaches college physics. (E)

67. **Physics of Sports (Basketball)**, P. C. Reddy (Ashish, Delhi, 1992). This book is somewhat disappointing, as there is little physics in it other than an extensive description of the author's investigations of shooting trajectories for college players in India. (E)

68. "Thump, ring: The sound of a bouncing ball," J. I. Katz, Eur. J. Phys. **31**, 849–856 (2010). (I)

69. "Dynamics of basketball-rim interactions," H. Okubo and M. Hubbard, Sports Eng. **7**, 15–29 (2004). (I)

70. "Numerical analysis of the basketball shot," L. Silverberg, C. Tran, and K. Adcock, J. Dyn. Syst., Meas., Control **125**, 531–540 (2003). (A)

71. "Kinematics of the free throw in basketball," A. Tan and G. Miller, Am. J. Phys. **49**, 542–544 (1981). (I)

72. "Physics of basketball," P. J. Brancazio, Am. J. Phys. **49**, 356–365 (1981). (I)

D. Billiards and Pool

73. **Amateur Physics for the Amateur Pool Player (Third edition)**, R. Shepard (Argonne National Laboratory, Argonne, IL,1997). This book is not directed "toward either the pool student or the physics student, but rather toward the amateur who enjoys both." (I)

74. **The Physics of Pocket Billiards**, W. C. Marlow (Marlow Advanced Systems Technologies, Palm Beach Gardens, 1994). The level of detail in this book about many aspects of the game of pool will be of interest only to a serious pool enthusiast and not to the casual physicist. (I)

75. **Mathematical Theory of Spin, Friction, and Collision in the Game of Billiards**, G.-G. Coriolis (original French edition: Carillan-Goeury, Paris, France, 1835; English translation by D. Nadler, San Francisco, 2005). This is very technical, very mathematical, and of more historical than practical interest. This may be the earliest book-length monograph on sports physics. (A)

76. "Cue and ball deflection (or 'squirt') in billiards," R. Cross, Am. J. Phys. **76**, 205–212 (2008). (I)

77. "Analysis of billiard ball collisions in two dimensions," R. E. Wallace and M. C. Schroeder, Am. J. Phys. **56**, 815–819 (1988). (I)

E. Bowling

78. "Design of an instrumented bowling ball and its application to performance analysis in tenpin bowling," F. K. Fuss, Sports Tech. **2**, 97–110 (2009). (I)

79. "What makes bowling balls hook?," C. Frohlich, Am. J. Phys. **72**, 1170–1177 (2004). (I)

80. "The trajectory of a ball in lawn bowls," R. Cross, Am. J. Phys. **66**, 735–738 (1998). (I)

81. "On the dynamics of a weighted bowling ball," R. L. Huston, C. Passerello, J. M. Winget, and J. Sears, J. Appl. Mech. **46**, 937–943 (1979). (A)

82. "Bowling frames: Paths of a bowling ball," D. C. Hopkins and J. D. Patterson, Amer. J. Phys. **45**, 263–266 (1977). (I)

F. Cycling and Bicycles

83. **Bicycling Science (Third edition)**, D. G. Wilson (MIT U. P., Cambridge, MA, 2004). This is a very readable review of the past, present, and future of many aspects of human-powered transportation from an engineering perspective. (I)

84. **Bicycles and Tricycles: An Elementary Treatise on their Design and Construction**, A. Sharp (MIT U. P., Cambridge, MA, 1979; reprint of 1896 edition). Many consider this to be the first serious engineering-based analysis of bicycle design, tremendously influential in its own time and still of historical interest. (A)

85. "Linearized dynamic equations for the balance and steer of a bicycle: A benchmark and review," J. P. Meijaard, J. M. Papadopoulos, A. Ruina, and A. L. Schwab, Proc. R. Soc. London, Ser. A **463**, 1955–1982 (2007). (A)

86. "Aerodynamics of a cycling team in a time trial: Does the cyclist at the front benefit?," A. Íñiguez-de-la Torre and J. Íñiguez, Eur. J. Phys. **30**, 1365–1369 (2009). (E).

87. "Cycling and the wind: Does sidewind brake?" A. Íñiguez-de-la Torre and J. Íñiguez, Eur. J. Phys. **27**, 71–74 (2006). (I)

88. "Inclined-plane model of the 2004 Tour de France," B. L. Hannas and J. E. Goff, Eur. J. Phys. **26**, 251–259 (2005). (I)

89. "Improving cycling performance with large sprockets," S. C. Burgess, Sports Eng. **1**, 107–113 (1999). (I)

90. "Determination of F_r and K_d from the solution of the equation of motion of a cyclist," W. Hennekam and J. Bontsema, Eur. J. Phys. **12**, 59–63 (1991).

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