

BODY MECHANICS OF SPORT

First edition

6 units

30 lessons + exams

A video for every lesson

FIRST EDITION

COURSE GUIDE

Body Mechanics of Sport is a one-semester elective for students in grades 8–12. It teaches the physics of human movement through sport: Newton’s laws and the ground that pushes back, the levers of the body, the center of mass and balance, the kinetic chain, momentum and impulse, the coefficient of restitution, projectile motion, the Magnus effect, friction, pendulums, energy and power. Every physical idea is stated with real numbers and units and worked through in examples and practice problems.

The physics is taught through the true stories of the people who found it and used it. Giovanni Borelli draws the arm as a lever in 1680; Dick Fosbury arches over the bar in Mexico City; Lyman Briggs counts the turns of a curveball with a paper tape; physicists explain Roberto Carlos’s famous free kick; William G. Morgan invents volleyball at the Holyoke YMCA; Edward Stimpson builds a ramp to measure green speed; Eadweard Muybridge photographs a galloping horse. Each lesson moves from **the story** to **how they figured it out**, then to **the physics** with worked examples, and finally **on the field**, where students see how athletes use the idea, and what can go wrong.

Students measure their own bodies. They find their center of mass on a reaction board, compute the force of the floor in a jump, time their throws and serves with slow-motion video, map their own hitting zone, build a Stimpmeter, test the split step, learn heading safely with a balloon, and finish with a three-week motion study of a skill of their choosing. Safety is taught as physics and as stewardship: pitch counts, heading guidelines, soft landings, warm-ups and rest. Scripture is woven in lightly, from “fearfully and wonderfully made” to Paul’s reminder that the body is a temple.

Videos were chosen lesson by lesson from science and university channels (Veritasium, the National Science Foundation’s Science of NFL Football, Yale, TED-Ed, the USGA, the National Baseball Hall of Fame, SABR and others) and from established coaching channels in

each sport. Every video was previewed frame by frame and its description read. Videos showing brief uniforms or swimwear were rejected, which is why most tennis and volleyball videos feature coaches in practice clothing rather than match footage. Sponsor segments and descriptions were checked as well. Some coaching channels mention their own paid programs; the parent note says so, and nothing in the course requires them. The “when” note tells the student when to watch.

Start with Lesson 1.1 →

WHO IT IS FOR

Grades 8–12. The prerequisite is Algebra I (solving equations, square roots); basic right-triangle trigonometry is introduced where needed and used in the hard problems, so an 8th grader can follow every lesson while an 11th grader is still stretched. Students work largely on their own; a parent supervises the physical projects and checks practice sets against the answers. Nothing needs to be bought beyond household items, soft balls and a phone camera; trips to a court, course, field or bowling center are optional.

HOW TO USE THIS COURSE

1. **The weekly rhythm.** Each lesson takes three sessions of about 50 minutes. Session 1: the warm-up, the video, the core ideas and the worked examples. Session 2: the project and the scorebook. Session 3: the practice set, checked against the answers, with every missed problem reworked. Each unit ends with a test day, and the midterm and final each have a review day. At five sessions a week the course fills a semester of 20 weeks.
2. **Story, then physics, then the field.** Read the core ideas in order. *The story* gives a real moment with names, dates and places; *how they figured it out* shows what people measured and what was wrong before; *the physics* states the principle with formulas; *on the field* shows how athletes use it, including the risk side. Cover the solution to each worked example, try it yourself, and compare line by line.
3. **Picture study.** Each lesson has one public-domain painting, engraving, diagram or historic photograph. Look at it quietly for two minutes, put it away and describe what you saw, then work through the “look for” items and the questions, which point back to the lesson’s physics.

4. **The scorebook habit.** Keep one bound graph-paper notebook for the semester: your scorebook. Every project follows the same steps: *predict*, *measure* (repeated trials, with units), *compute* (the physics), and *decide* (what you would change, and why). Record what actually happened, not what should have happened.
5. **Practice sets and corrections.** Problems are marked easy, medium, hard and challenge. Do all of the easy and medium problems and most of the hard ones; the challenge problem is for students who want more. Show the formula, the substitution with units and the answer. Check against the answers the same day and rework every miss.
6. **Unit tests, midterm and final.** Each unit test is worth 100 points and mixes calculations, concept questions and one short essay. The midterm (after Unit 3) and the final (after Unit 6) are each worth 100 points. Calculators are allowed, and all work must be shown.
7. **Video and measurement.** A phone with slow-motion video is the most useful tool in the course. Film square to the motion, with a meter stick in the plane of movement, and use the recording frame rate (often 240 frames per second) to turn frames into seconds. Lesson 6.1 teaches the method in full; earlier projects give simple instructions.
8. **Optional books and games.** Some units list free resources: online textbooks, governing-body guidelines, classic books on Project Gutenberg and free analysis software. They are never required; every project works without them.
9. **Safety first, every lesson.** Every physical lesson has a safety note. Warm up; use soft balls indoors and keep clear of windows and people; swing bats, clubs and rackets only outdoors in a clear circle with an adult watching; follow the Pitch Smart pitch counts and U.S. Soccer's heading guidance (heading is taught only with a balloon); lift bowling balls with bent knees; drink water and rest in the heat. Stop if anything hurts and tell a parent. The course does not give medical advice.

SCOPE AND SEQUENCE

UNIT 1 • WEEKS UNDEFINED

undefined

The body as a machine: Newton's laws and the ground reaction force, levers in the body from Borelli to the biceps, the center of mass and the Fosbury flop, the kinetic chain, and work, power and deliberate practice.

UNIT 3 • WEEKS UNDEFINED

undefined

Soccer: impulse in the instep drive, spin and Roberto Carlos's free kick, the cushioned first touch, cutting and the FIFA 11+, and the physics behind the youth heading guidelines, practiced only with a balloon.

UNIT 5 • WEEKS UNDEFINED

undefined

Golf and bowling: the swing as a double pendulum, loft, spin and launch, putting and the Stimpmeter, the timing of the bowling approach, and the friction and oil behind the hook ball.

UNIT 2 • WEEKS UNDEFINED

undefined

Baseball and softball: the bat-ball collision and the sweet spot, the Magnus effect and Lyman Briggs's curveball study, throwing mechanics and Pitch Smart arm care, the outfielder's gaze heuristic, and Ted Williams's science of hitting.

UNIT 4 • WEEKS UNDEFINED

undefined

Tennis and volleyball: the serve as a kinetic chain and the window over the net, topspin and the forehand, the split step and reaction time, the forearm pass as a reflection, and the spike, with the history of William G. Morgan's game.

UNIT 6 • WEEKS UNDEFINED

undefined

Training and the whole athlete: video analysis from Muybridge to the phone, strength, flexibility, rest and sleep, injury prevention, energy, heat and sportsmanship, and a capstone motion study of the student's own skill.

WEEKLY PACING CALENDAR

WEEK	PLAN
1	- Day 1: Lesson 1.1 Newton's Laws in Sport: video, teaching and worked examples - Day 2: Lesson 1.1: project and notebook - Day 3: Lesson 1.1: practice set and corrections

WEEK	PLAN
	- Day 4: Lesson 1.2 Levers in the Body: video, teaching and worked examples - Day 5: Lesson 1.2: project and notebook <i>Five sessions a week of about 50 minutes. Families on a four-day week can combine the practice day of one lesson with the teaching day of the next.</i>
2	- Day 1: Lesson 1.2: practice set and corrections - Day 2: Lesson 1.3 Center of Mass, Balance and the Base of Support: video, teaching and worked examples - Day 3: Lesson 1.3: project and notebook - Day 4: Lesson 1.3: practice set and corrections - Day 5: Lesson 1.4 The Kinetic Chain: video, teaching and worked examples
3	- Day 1: Lesson 1.4: project and notebook - Day 2: Lesson 1.4: practice set and corrections - Day 3: Lesson 1.5 Muscles, Practice and Deliberate Practice: video, teaching and worked examples - Day 4: Lesson 1.5: project and notebook - Day 5: Lesson 1.5: practice set and corrections
4	- Day 1: Unit 1 test - Day 2: Lesson 2.1 The Batting Swing: video, teaching and worked examples - Day 3: Lesson 2.1: project and notebook - Day 4: Lesson 2.1: practice set and corrections - Day 5: Lesson 2.2 The Pitch and the Magnus Effect: video, teaching and worked examples
5	- Day 1: Lesson 2.2: project and notebook - Day 2: Lesson 2.2: practice set and corrections - Day 3: Lesson 2.3 Throwing Mechanics and Arm Care: video, teaching and worked examples - Day 4: Lesson 2.3: project and notebook - Day 5: Lesson 2.3: practice set and corrections
6	- Day 1: Lesson 2.4 Fielding and the Outfielder's Path: video, teaching and worked examples - Day 2: Lesson 2.4: project and notebook - Day 3: Lesson 2.4: practice set and corrections

WEEK	PLAN
	- Day 4: Lesson 2.5 Ted Williams and the Science of Hitting: video, teaching and worked examples - Day 5: Lesson 2.5: project and notebook
7	- Day 1: Lesson 2.5: practice set and corrections - Day 2: Unit 2 test - Day 3: Review day for the midterm - Day 4: Midterm exam - Day 5: Lesson 3.1 The Instep Drive: The Physics of the Kick: video, teaching and worked examples
8	- Day 1: Lesson 3.1: project and notebook - Day 2: Lesson 3.1: practice set and corrections - Day 3: Lesson 3.2 Bending It: Spin and the Famous Free Kick: video, teaching and worked examples - Day 4: Lesson 3.2: project and notebook - Day 5: Lesson 3.2: practice set and corrections
9	- Day 1: Lesson 3.3 First Touch: Absorbing Momentum: video, teaching and worked examples - Day 2: Lesson 3.3: project and notebook - Day 3: Lesson 3.3: practice set and corrections - Day 4: Lesson 3.4 Balance, Cutting and Protecting the Knee: video, teaching and worked examples - Day 5: Lesson 3.4: project and notebook
10	- Day 1: Lesson 3.4: practice set and corrections - Day 2: Lesson 3.5 Heading: Physics and Safety Rules: video, teaching and worked examples - Day 3: Lesson 3.5: project and notebook - Day 4: Lesson 3.5: practice set and corrections - Day 5: Unit 3 test
11	- Day 1: Lesson 4.1 The Tennis Serve as a Kinetic Chain: video, teaching and worked examples - Day 2: Lesson 4.1: project and notebook - Day 3: Lesson 4.1: practice set and corrections - Day 4: Lesson 4.2 Topspin and the Forehand: video, teaching and worked examples

WEEK	PLAN
	Day 5: Lesson 4.2: project and notebook
12	- Day 1: Lesson 4.2: practice set and corrections - Day 2: Lesson 4.3 Footwork, the Split Step and Reaction Time: video, teaching and worked examples - Day 3: Lesson 4.3: project and notebook - Day 4: Lesson 4.3: practice set and corrections - Day 5: Lesson 4.4 The Volleyball Pass: Platform Angle and Reflection: video, teaching and worked examples
13	- Day 1: Lesson 4.4: project and notebook - Day 2: Lesson 4.4: practice set and corrections - Day 3: Lesson 4.5 The Spike and the Jump Serve: video, teaching and worked examples - Day 4: Lesson 4.5: project and notebook - Day 5: Lesson 4.5: practice set and corrections
14	- Day 1: Unit 4 test - Day 2: Review day for the final - Day 3: Final exam

MATERIALS

A phone or tablet with slow-motion video, and a small stand or a stack of books to hold it

The main measuring instrument of the course. 240 frames per second is ideal; 120 works.

A tape measure, a meter stick, a stopwatch (or phone), a protractor and a 30 cm ruler

For distances, scales in videos, times, angles and reaction-time tests.

A bathroom scale and a kitchen scale

For the reaction board (Lesson 1.3), body mass in force calculations, and weighing balloons and balls.

Soft balls: a foam ball, a tennis ball, a soccer ball and several balloons

For throwing, kicking, passing and heading experiments. Heading is practiced only with a balloon or very soft foam ball.

A sturdy plank about 2 m long, string, small weights, chalk and masking tape, cones or markers

For the reaction board, pendulums, wall-reach jumps and marking targets.

Optional sport equipment

A plastic bat and tee, a racket, a plastic or junior golf club and practice balls, plastic bottles for a home bowling lane. Real bats, clubs and rackets are used only outdoors with an adult; trips to a court, course or bowling center are optional and supervised.

A scientific calculator, graph paper and free spreadsheet software

For square roots, trigonometry, means and standard deviations, and graphs.

A bound graph-paper notebook (the scorebook) and pencil

For predictions, data tables, diagrams, graphs and corrected practice problems.

GRADING

Grades come from the practice sets, the projects, the scorebook, the six unit tests, the midterm and the final. A calculation earns full credit when the formula, the substitution with units and the answer are all shown. A project earns full credit for honest, repeated measurements carefully recorded, computed with the right physics and followed by a reasoned decision, even when the data disagree with the prediction.

PART	%
Practice sets (completed and corrected)	15
Projects (measurements, physics, decision)	25
Scorebook (organization, honesty, completeness)	10
Unit tests	30
Midterm exam	10
Final exam	10

Scale: A 90–100, B 80–89, C 70–79, D 60–69, F below 60.

- Practice sets are graded for completion and correction, not first-try accuracy: a problem done, checked and correctly reworked earns full credit.

- On tests, give partial credit for a correct setup (the right formula with the right quantities) even if the arithmetic slips. An answer with no work earns at most half credit; an answer with wrong or missing units loses a point.
- A project earns full marks when it has a prediction, the required number of measured trials, correct calculations, a comparison with the physics, and a written decision with a reason. Safety rules must be followed for any credit.
- For a high-school transcript this course is one half credit of science elective (physics of sport). Keep the scorebook, the unit tests and the capstone report as the record of work.

A NOTE TO PARENTS

You do not need to be a physicist to supervise this course well. Your jobs are to keep the rhythm (three sessions per lesson), check the practice sets against the answers, ask the student to explain one worked example aloud each week, look at the scorebook, and be present for the physical projects, especially anything involving bats, clubs, rackets, jumps or throwing. The best question you can ask is “How do you know?” A student who can answer from his own measurements is learning physics.

Safety is taught as part of the physics. The course follows Major League Baseball and USA Baseball’s Pitch Smart guidelines for young pitchers and U.S. Soccer’s heading guidance (no heading for players 10 and under; limited heading in practice for ages 11–13); heading is practiced only with a balloon. Bats, clubs and rackets are swung only outdoors with an adult watching. The lessons on injury prevention teach principles, not medical advice; any pain or injury should be seen by a doctor.

The course is also about stewardship. Scripture teaches that we are “fearfully and wonderfully made” (Psalm 139:14) and that the body is a temple belonging to God (1 Corinthians 6:19-20). Physical training has real value, and godliness more (1 Timothy 4:8). Praise careful measurement, honest records, safe habits and good sportsmanship more than raw results, and expect the student to discover how much physics is at work in every game the family plays.

UNIT 1

THE BODY AS A MACHINE

Before we study any one sport, we study the machine every sport uses. This unit starts with Newton's three laws and the ground that pushes back, then follows Giovanni Borelli in treating bones as levers, finds the center of mass that decides balance and made the Fosbury flop possible, traces the kinetic chain that whips speed from the legs to the hand, and ends with how muscles do work and how practice changes skill.

The projects measure your own body: the force of the floor in a jump, your arm's lever arms, your center of mass on a reaction board, the speed each link of the chain adds to a throw, and your own learning curve. The physics uses algebra, square roots and a little trigonometry.

PREREQUISITES

- Algebra I: solving linear equations, square roots and substituting into formulas
- Metric units: meters, kilograms, seconds
- Helpful: basic trigonometry (sine, cosine and tangent) for tilted levers and tipping angles

MASTERY CHECKLIST

- ☐ I can apply Newton's three laws to sport movements and compute forces with

$$F = ma.$$

- ☐ I can classify the levers of the body and compute a muscle force from the balance of torques.
- ☐ I can compute a center of mass, find my own with a reaction board, and explain stability.
- ☐ I can describe the kinetic chain and use

$$v = \text{with radians per second.}$$

$$\omega r$$

- ☐ I can compute work and power and explain what makes practice deliberate.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **OpenStax College Physics 2e: Forces and Torques in Muscles and Joints**: Free online textbook section with worked examples of muscle and joint forces. Extends Lessons 1.2 and 1.3. Ages 14+.
- **Khan Academy: Forces and Newton's laws of motion**: Free videos and practice problems on Newton's laws for Lesson 1.1.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

1.1	Newton's Laws in Sport	3 sessions of 50 minutes
1.2	Levers in the Body	3 sessions of 50 minutes
1.3	Center of Mass, Balance and the Base of Support	3 sessions of 50 minutes
1.4	The Kinetic Chain	3 sessions of 50 minutes
1.5	Muscles, Practice and Deliberate Practice	3 sessions of 50 minutes

UNIT 1 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$. Show your work for every calculation: write the formula, substitute with units, and give the answer with its unit. Answer the concept questions in complete sentences. The test is worth 100 points.

1. **5 pts**

State Newton's three laws of motion in your own words.

2. **6 pts**

A 75 kg sprinter accelerates from rest to 7.5 m/s in 2.5 s. Find the average acceleration and net force.

3. **7 pts**

A student jumps 0.45 m high (center of mass rise). Find her takeoff speed. If her push-off lasted 0.28 s and her mass is 52 kg, find the average floor force.

4. (6 pts)

Explain why a runner cannot start on slippery ice, using the third law.

5. (5 pts)

Classify each lever: (a) the triceps straightening the elbow, (b) rising onto your toes, (c) the quadriceps straightening the knee.

6. (8 pts)

A 4.0 kg weight is held 0.33 m from the elbow, forearm horizontal; the biceps attaches 0.044 m from the elbow. Find the biceps force, ignoring the forearm's weight, and the mechanical advantage.

7. (6 pts)

Why are most levers in the body third-class levers? What do they trade, and what do they gain?

8. (7 pts)

Masses of 30 kg, 20 kg and 10 kg sit at 0, 1.0 m and 2.0 m. Find the center of mass.

9. (7 pts)

A reaction board is 2.1 m long. A 56 kg student lies on it with her feet at the block, and the zeroed scale reads 26 kg. Find her center of mass from her feet and as a percentage of her 1.65 m height.

10. (6 pts)

Find the sideways tipping angle for a stance with feet 0.50 m apart and the center of mass 0.90 m high.

11. (6 pts)

Explain how the Fosbury flop allows a jumper to clear a bar higher than his center of mass rises.

12. (7 pts)

Convert a trunk rotation of $1,200^\circ$ per second to rad/s. If the shoulder is 0.20 m from the trunk's axis, how fast is it moving?

13. (6 pts)

Describe the proximal-to-distal sequence in a throw and explain why timing matters.

14. (6 pts)

A 55 kg student climbs a 4.0 m rope in 12 s. Find the work done against gravity and the average power.

15. (12 pts)

Short essay. In about 150 words, explain what Ericsson meant by deliberate practice and how you would use it to improve one skill in a sport you play. Include how you would measure progress.

ANSWER KEY

1. First: an object keeps its velocity unless a net force acts. Second: net force equals mass times acceleration. Third: forces come in equal and opposite pairs acting on different objects.
2. $a = 3.0 \text{ m/s}^2$; $F = 225 \text{ N}$.
3. $v = \sqrt{2(9.8)(0.45)} \approx 2.97 \text{ m/s}$; $a \approx 10.6 \text{ m/s}^2$; $F = 52(9.8 + 10.6) \approx 1,060 \text{ N}$.
4. To move forward, the runner must push backward on the ground and receive an equal forward push. On ice there is too little friction for the ground to supply a horizontal push, so no forward force acts.
5. (a) first class, (b) second class, (c) third class.
6. $F = \frac{39.2 \times 0.33}{0.044} \approx 294 \text{ N}$; $MA = 0.044/0.33 \approx 0.13$.
7. They trade force for speed and range: the muscle must pull much harder than the load, but the hand or foot moves much faster and farther than the muscle shortens.
8. $x = \frac{0 + 20 + 20}{60} \approx 0.67 \text{ m}$.
9. $x = \frac{26 \times 2.1}{56} = 0.975 \text{ m}$; about 59% of her height.
10. $\tan \theta = 0.25/0.90$, $\theta \approx 15.5^\circ$.
11. He arches over the bar so that different parts of his body cross it at different times; the arched body's center of mass lies below the body, so it can pass at or slightly beneath the bar while every part of the body passes over.
12. $\omega \approx 20.9 \text{ rad/s}$; $v \approx 4.2 \text{ m/s}$.
13. Segments reach peak speed from the center outward: hips, trunk, upper arm, forearm, hand. Each segment slows as the next speeds up, passing on its motion; if two turn together or out of order, the speed does not build up and the arm must work harder.
14. $W = 55 \times 9.8 \times 4.0 = 2,156 \text{ J}$; $P \approx 180 \text{ W}$.
15. Answers vary. A strong essay defines deliberate practice (targeted at a specific weakness, at the edge of ability, with immediate feedback, often designed by a coach), distinguishes it from repetition, describes a concrete plan, and names a measurable test (for example, makes out of 20) recorded over time.

PORTFOLIO PIECE: MY BODY MACHINE REPORT

Write a three-page illustrated report on your own body as a machine, using the measurements from this unit's projects. Include: your jump test with takeoff speed and floor force; a labelled diagram of your forearm as a lever with the biceps force for a 1 kg load; your center of mass in three positions from the reaction board; your throwing-distance results by style with estimated speeds; and your learning curve. For each, give the physics formula you used, one sentence on what surprised you, and one way the result could help you play a sport better or more safely.

LOOK FOR	WHAT IT MEANS
Measurements	All five measurements are present, with real data, repeated trials and units.
Physics	Each result is computed correctly from a stated formula, with work shown.
Diagrams	Clear, labelled diagrams of the lever, the center of mass and the kinetic chain.
Interpretation	Each result is connected to a specific improvement in technique or safety.

1.1 NEWTON'S LAWS IN SPORT

OBJECTIVES

- State Newton's three laws of motion and recognize each one in a sport movement.
- Use $F = ma$ and weight $W = mg$ to compute forces on athletes and balls, with units.
- Explain how an athlete moves by pushing on the ground, and compute a takeoff speed and ground force from a jump.

Warm-up. Stand on a smooth floor in socks and try to start a sprint. Then try in athletic shoes on the same floor. In one sentence, explain why the first start failed: what must the floor do for you to move forward?

WATCH

Newton's Second Law of Motion [Science of NFL Football]

National Science Foundation News · 3:51

https://www.youtube.com/watch?v=qu_P4lbmV_I

WHEN TO WATCH

After “the physics” paragraph. Watch for the equation on the screen and say aloud which quantity is the force, the mass and the acceleration.

BACKUP VIDEO

Newton's Third Law of Motion [Science of NFL Football]

National Science Foundation News · 4:12

<https://www.youtube.com/watch?v=e1lzB36aHD4>

Optional, after the worked examples. It shows action and reaction and the momentum of colliding players.

KEY TERMS

force

A push or pull, measured in newtons (N). One newton accelerates 1 kg by 1 m/s².

inertia

The tendency of an object to keep its state of motion; measured by its mass.

net force

The sum of all forces on an object, taking direction into account.

weight

The pull of gravity on a mass: $W = mg$, with $g = 9.8 \text{ m/s}^2$.

ground reaction force

The push of the ground back on an athlete, equal and opposite to the athlete's push on the ground.

CORE IDEAS

The story. In July 1687 the Royal Society in London published Isaac Newton's *Philosophiæ Naturalis Principia Mathematica*, paid for by his friend Edmond Halley. Its opening pages state three laws of motion. Newton was thinking about planets and cannonballs, not sprinters, but every movement in every sport obeys his three laws. A sprinter exploding from the blocks, a goalkeeper diving, a skater gliding across the ice and a basketball leaving a shooter's fingertips are all Newton's laws at work.

How they figured it out. For nearly two thousand years many scholars followed Aristotle, who taught that a moving thing needs a constant push to keep moving. Galileo rolled balls down ramps and saw that, with less friction, they rolled farther; he concluded that motion continues unless something stops it. Newton turned this into a law and added two more: force produces acceleration in proportion to mass, and forces always come in pairs. Modern sport scientists test these laws with *force plates*, metal platforms with sensors that record how hard and in what direction an athlete pushes on the ground, thousands of times a second.

The physics. *First law:* an object keeps moving at constant velocity (or stays at rest) unless a net force acts on it. *Second law:* $F_{\text{net}} = ma$, so a 60 kg sprinter who speeds up by 4 m/s every second needs a net forward force of $60 \times 4 = 240 \text{ N}$. *Third law:* when you push on something, it pushes back on you with an equal and opposite force. You cannot push yourself forward; you push *backward* on the ground, and the ground pushes you forward. In a jump, the ground pushes up harder than your weight $W = mg$, so the net upward force is $F - mg$ and you accelerate upward. Once you leave the ground, only gravity acts, and the takeoff speed v decides the height: $h = \frac{v^2}{2g}$.

On the field. Spikes and cleats exist because of the third law: they let you push backward on the ground without slipping. A sprinter leans forward so that the push from the blocks drives him forward rather than only upward. Linemen stay low so that their push is horizontal. A good jumper does not “float”; he pushes hard and fast against the floor, because the height is set the instant his feet leave it. Knowing the laws helps you coach yourself: if you want more speed, ask where the force comes from and in what direction it points.

Think it through. A basketball thrown in a chest pass pushes back on the passer’s hands just as hard as the hands push the ball. On a court, friction from the floor keeps the passer still. On ice, the same pass would slide the passer slowly backward. Every sport is a conversation between the athlete and the ground.

PICTURE STUDY



Portrait of Sir Isaac Newton, Godfrey Kneller, 1689 · Oil on canvas · Private collection, England

Image: [Wikimedia Commons](#), public domain

Godfrey Kneller, the leading portrait painter in England, painted Newton in 1689, two years after the *Principia* appeared. Newton was then a professor at Cambridge. It is the earliest known portrait of him, and it shows him without a wig, as a working scholar rather than a courtier.

Look closely

- Look at Newton's face and eyes. What does the painter suggest about the kind of thinking that produced three short laws that explain all motion?
- Notice the plain dark gown and the simple background. What has Kneller left out, and why might that suit Newton?
- Find where the light falls. How does it lead your eye to the face?

Talk about it

1. Newton stated his laws for planets and cannonballs. Name one movement in your own favorite sport that shows each of the three laws.
2. Newton said that if he had seen further, it was “by standing on the shoulders of giants.” Whose work did he build on in the first law?

Safety first. Warm up with easy jogging and a few practice jumps before the jump test. Jump on a dry, non-slip floor in athletic shoes, away from furniture, and land softly with bent knees. Stop if anything hurts, and tell a parent.

PROJECT

The Jump Test: Measuring the Force of the Ground

You cannot see a force, but you can measure what it does. In this project you will measure your own vertical jump, compute your takeoff speed, time your push-off with a phone's slow-motion video, and work out how hard the floor pushed on you.

You will need

- A wall with a smooth, washable surface (or a sheet of paper taped high on a wall)
- Chalk or a small piece of masking tape
- A tape measure
- A phone with slow-motion video (optional but very helpful)
- A bathroom scale
- The scorebook and a calculator

Steps

1. Weigh yourself on the bathroom scale and record your mass in kilograms.
2. **Predict.** Write how many centimeters higher you think you can reach by jumping, and how many times your body weight the floor will push on you.
3. Warm up for five minutes: jog in place, skip, and do a few easy practice jumps.
4. Stand sideways to the wall with chalk on your fingertips. Reach as high as you can with feet flat, and mark the wall. This is your standing reach.
5. From a standing start (no run-up), bend and jump, touching the wall at the top. Do five jumps with a short rest between them. Measure each jump height: the jump mark minus the standing mark.
6. Record all five heights. Find the mean and the best.
7. If you have a phone, film one jump in slow motion from the side. Count the frames from the moment you start pushing up (lowest point) to the moment your toes leave the floor, and convert to seconds (at 240 frames per second, each frame is $1/240$ s).

8. Compute your takeoff speed $v = \sqrt{2gh}$ from your mean height.
9. Compute your average acceleration during the push-off, $a = v/t$, and the average floor force $F = m(g + a)$.
10. Divide the floor force by your weight mg to find how many “body weights” the floor pushed with.
11. Try five more jumps using a quick arm swing upward. Did the height change? Explain with the third law: what did your arms push on, and what pushed back?
12. **Decide.** Write two changes to your jumping technique that your data suggest, and explain them with Newton’s laws.

Tips

- If you have no slow-motion video, use 0.30 s as a typical push-off time and say so in your scorebook.
- Measure the heights in meters before putting them in the formulas.

Check your work

- ☐ I recorded five measured jumps with and without an arm swing.
- ☐ I computed takeoff speed, average force and force in body weights, with units.
- ☐ I explained the arm-swing result with the third law.

SCOREBOOK

1. Jump table: trial, jump height (m), takeoff speed (m/s). Add a row for the mean.
2. Draw a free-body diagram of yourself during the push-off: an arrow for your weight down and a longer arrow for the floor’s push up. Label each with its value in newtons.
3. Draw three small sketches from one sport, each labelled with the law of motion it shows best.

KEY FORMULAS

$$F_{\text{net}} = ma$$

$$W = mg, \quad g = 9.8 \text{ m/s}^2$$

$$a = \frac{\Delta v}{\Delta t}$$

$$h = \frac{v^2}{2g} \quad v = \sqrt{2gh}$$

From history. Newton was elected to the Royal Society in 1672 and became its president in 1703. Galileo's ramp experiments, which led to the idea of inertia, were published in his *Two New Sciences* in 1638. The first commercial force plates for sport and medicine appeared in the 1970s.

WORKED EXAMPLES

Example 1. A 60 kg sprinter goes from rest to 6.0 m/s in the first 1.5 s of a sprint. Find her average acceleration and the average net horizontal force on her.

Show solution

1. Acceleration: $a = \frac{\Delta v}{\Delta t} = \frac{6.0 - 0}{1.5} = 4.0 \text{ m/s}^2$.

2. Net force: $F = ma = 60 \times 4.0 = 240 \text{ N}$.

3. This force comes from the ground pushing forward on her shoes, in reaction to her shoes pushing backward on the ground.

Answer: About 4.0 m/s^2 and 240 N, provided by the ground's reaction to her push.

Example 2. A 50 kg student reaches 0.40 m higher on a wall when he jumps than when he stands. Slow-motion video shows his push-off lasted 0.30 s. Find his takeoff speed and the average force of the floor on him.

Show solution

1. Takeoff speed: $v = \sqrt{2gh} = \sqrt{2(9.8)(0.40)} = \sqrt{7.84} = 2.8 \text{ m/s}$.
2. Average upward acceleration during the push: $a = \frac{2.8}{0.30} \approx 9.3 \text{ m/s}^2$.
3. Net force: $F - mg = ma$, so $F = m(g + a) = 50(9.8 + 9.3) \approx 960 \text{ N}$.
4. Compare with his weight, $50 \times 9.8 = 490 \text{ N}$: the floor pushed with about twice his weight.

Answer: Takeoff speed 2.8 m/s; the floor pushed up with about 960 N, nearly twice his body weight.

Example 3. A player gives a 0.62 kg basketball a chest pass, taking it from rest to 8.0 m/s in 0.15 s. Find the force on the ball. If the passer, 50 kg, stood on frictionless ice, how fast would she slide backward?

Show solution

1. Acceleration of the ball: $a = 8.0/0.15 \approx 53 \text{ m/s}^2$; force $F = 0.62 \times 53 \approx 33 \text{ N}$.
2. Third law: the ball pushes back on her hands with 33 N for the same 0.15 s.
3. Her backward speed: $a = 33/50 = 0.66 \text{ m/s}^2$, for 0.15 s, so
 $v \approx 0.66 \times 0.15 \approx 0.10 \text{ m/s}$.

Answer: About 33 N on the ball; on ice she would slide backward at about 0.10 m/s.

PRACTICE

1. Easy A 70 kg runner accelerates at 3.0 m/s^2 . What net force acts on him?

Show answer

$$F = 70 \times 3.0 = 210 \text{ N}.$$

2. Easy Find the weight of a 55 kg student in newtons.

Show answer

$$W = 55 \times 9.8 = 539 \text{ N}.$$

3. **Easy** A hockey puck slides across the ice and slows down only very slightly. Which of Newton's laws does this show best, and why does it slow at all?

Show answer

The first law: it keeps moving because almost no force acts on it. It slows a little because of small friction from the ice and air resistance.

4. **Medium** A pitcher takes a 0.145 kg baseball from rest to 35 m/s in 0.10 s. Find the average force on the ball.

Show answer

$$a = 350 \text{ m/s}^2; F = 0.145 \times 350 \approx 51 \text{ N}.$$

5. **Medium** A student's jumping reach is 0.50 m above her standing reach. Find her takeoff speed.

Show answer

$$v = \sqrt{2(9.8)(0.50)} = \sqrt{9.8} \approx 3.1 \text{ m/s}.$$

6. **Medium** A 65 kg athlete pushes on a force plate during a jump, and the plate reads 1,300 N. Find the net force and his upward acceleration.

Show answer

$$\text{Weight } 637 \text{ N; net } 1300 - 637 = 663 \text{ N; } a = 663/65 \approx 10.2 \text{ m/s}^2.$$

7. **Medium** Explain, using the third law, why a sprinter pushes *backward* on the starting blocks.

Show answer

The blocks push on the sprinter with a force equal and opposite to his push. To be driven forward, he must push backward (and down) on the blocks.

8. **Medium** In what year was Newton's *Principia* published, and who paid for its printing?

Show answer

1687; Edmond Halley paid for it.

9. **Hard** A 50 kg student on a skateboard throws a 4.0 kg medicine ball forward at 3.0 m/s. Using the fact that the push on the ball equals the push on the student, find the student's backward speed (ignore friction).

Show answer

Both receive the same impulse: $4.0 \times 3.0 = 12 \text{ kg}\cdot\text{m/s}$, so
 $v = 12/50 = 0.24 \text{ m/s}$.

10. **Hard** A 60 kg player leaves the ground at 2.4 m/s after a push-off lasting 0.25 s. Find the average ground force and compare it with her weight.

Show answer

$a = 9.6 \text{ m/s}^2$; $F = 60(9.8 + 9.6) \approx 1,160 \text{ N}$, about 2.0 times her weight of 588 N.

11. **Hard** A 0.43 kg soccer ball rolling at 5.0 m/s stops after 10 m on grass. Find its deceleration and the average resisting force.

Show answer

$$a = \frac{v^2}{2d} = \frac{25}{20} = 1.25 \text{ m/s}^2; F = 0.43 \times 1.25 \approx 0.54 \text{ N}.$$

12. **Challenge** *Illustrative.* A 70 kg sprinter receives an average net forward force of 350 N. How long does he take to reach 10 m/s, and how far does he travel meanwhile? Why do real sprinters take longer?

Show answer

$a = 5.0 \text{ m/s}^2$; $t = 2.0 \text{ s}$; $d = \frac{1}{2}(5.0)(2.0)^2 = 10 \text{ m}$. Real sprinters cannot keep up so large a forward force: as they speed up, each foot is on the ground for less time and air resistance grows, so the net force falls.

COMMON MISTAKES

- Forgetting that a jumper must overcome his own weight: the floor force is $m(g + a)$, not ma .
- Using centimeters in $v = \sqrt{2gh}$ instead of meters.
- Thinking the third-law pair forces cancel. They act on *different* objects (the ground and you), so they do not cancel.

Make it a game • Name That Law. Your parent calls out sport moments: a sprinter pushing off the blocks, a goalie diving, a bowling ball rolling to a stop. You have five seconds to name the law and say who pushes on whom. Then swap roles, and your parent sneaks in one wrong answer for you to catch. First to ten points wins. Finish by computing the weight of a 60 kg athlete.

1.2 LEVERS IN THE BODY

OBJECTIVES

- Identify the fulcrum, effort and load in a lever and classify the three classes of lever in the body.
- Compute torque $\tau = rF$ and use the balance of torques to find a muscle force.
- Explain why most body levers trade force for speed, and why that suits sport.

Warm-up. Hold a full water bottle in your hand with your elbow bent at a right angle and your upper arm at your side. Now hold it with your arm straight out in front of you. Which is harder? Where on your arm do you feel the effort? Write a one-sentence guess about why.

WATCH

The 3 Classes of Levers || How we use levers in the world and our bodies || By: Kinesiology Kris

KinesiologyKris · 6:17

https://www.youtube.com/watch?v=A0y_2b8SSbs

WHEN TO WATCH

After “the story” paragraph. Pause at each class of lever and sketch it in your scorebook with F, E and L labelled.

KEY TERMS

lever

A rigid bar that turns about a fixed point. In the body, bones are the bars and joints are the fixed points.

fulcrum

The pivot point about which a lever turns: in the body, a joint.

torque

The turning effect of a force: force times its perpendicular distance from the fulcrum, $\tau = rF$, in newton-meters (N·m).

moment arm

The perpendicular distance from the fulcrum to the line of a force.

mechanical advantage

Effort arm divided by load arm.

Greater than 1 multiplies force; less than 1 multiplies speed and distance.

CORE IDEAS

The story. Giovanni Alfonso Borelli (1608–1679) was an Italian mathematician who taught at Messina and Pisa and spent his last years in Rome, living with a community of teaching priests. There he finished *De Motu Animalium* (“On the Movement of Animals”), published in Rome in 1680 and 1681, after his death. Its copper plates show bones as bars, joints as pivots and muscles as ropes, with weights hanging from them. Borelli is often called the father of biomechanics: he was the first to treat the body as a machine made of levers and to calculate the forces in its muscles.

How they figured it out. Archimedes had stated the law of the lever in the third century BC: weights balance when they are inversely proportional to their distances from the fulcrum. Borelli applied that law to the arm. He noticed that the muscles attach very close to the joints, while the hand holds a load far away. His calculations showed something surprising: to hold even a modest weight, a muscle must pull many times harder than the weight itself. People had assumed muscles were built for force; Borelli showed they are built, in most places, for *speed and range*.

The physics. A force F acting at a perpendicular distance r from the fulcrum produces a torque $\tau = rF$. A lever is balanced when the torques on each side are equal: $F_E r_E = F_L r_L$. The *first class* has the fulcrum between effort and load (your head nodding on the top of the spine; the triceps straightening the elbow). The *second class* has the load between fulcrum and effort (rising onto the balls of your feet). The *third class* has the effort between fulcrum and load: the biceps bending the elbow, the quadriceps straightening the knee. In the elbow the biceps attaches about 4 cm from the joint while the hand is about 35 cm away, so the mechanical advantage is about $4/35 \approx 0.11$. The muscle must pull about 9 times the load, but the hand moves about 9 times as far and as fast as the muscle shortens.

On the field. Sport is mostly about speed, and third-class levers are speed multipliers. A small, quick shortening of a muscle near the shoulder becomes a fast movement of the hand, and a bat, racket or club lengthens the lever further, so the tip moves faster still. The price is force: the muscles and tendons near the joints

carry large loads, which is one reason tendons are so strong and why good technique, which keeps loads close to the body when lifting, matters. When you carry a heavy bag, hold it close; when you want speed, extend the lever.

Think it through. The same arm is a different machine depending on its angle. Torque depends on the *perpendicular* distance, so a load held with the forearm horizontal has its largest moment arm, and the effort is hardest there, exactly as you felt in the warm-up.

PICTURE STUDY

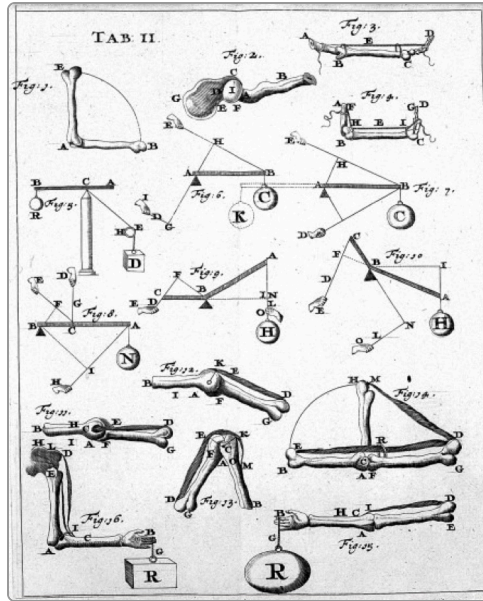


Table II from *De Motu Animalium*, Giovanni Alfonso Borelli, 1680 · Copper engraving in a printed book · Published in Rome

Image: [Wikimedia Commons](#), public domain

This plate from Borelli's book shows the arm and leg as machines. Each little figure is a problem in physics: a bone as a bar, a joint as a pivot, a muscle as a cord, and a weight hanging at the hand. Borelli placed ordinary balances beside the limbs so his readers could see that the same law of the lever governs both.

Look closely

- Find a figure where a forearm holds a weight. Point to the fulcrum, the place the muscle pulls, and the load.
- Find the plain balance beams with weights. Why do you think Borelli drew them beside the bones?
- Compare the distance from the joint to the muscle's attachment with the distance from the joint to the weight. Which is longer, and what does that tell you about the muscle's force?
- Find the bent knee. Which muscle would straighten it, and where would it pull?

Talk about it

1. Borelli drew muscles as straight ropes. What does this simplification make easy to calculate, and what does it leave out?

2. Choose one figure and write a torque equation for it, using letters for the distances.

Safety first. Use light loads only (a water bottle or a 1–2 kg jug). Never test your strength with heavy weights for this lesson. Keep your wrist straight when holding a load, and stop if anything hurts.

PROJECT

Measure Your Own Levers

First you will test the law of the lever with a ruler and coins. Then you will measure your own forearm and calculate the force in your biceps when you hold a jug of water, and compare it with what you feel.

You will need

- A 30 cm ruler and a round pencil (as the fulcrum)
- Twelve identical coins
- A tape measure
- A jug or bottle of water of known mass (1 L of water has a mass of 1 kg)
- The scorebook and a calculator
- A partner

Steps

1. Balance the ruler on the pencil at its 15 cm mark.
2. Stack 2 coins at the 5 cm mark (10 cm left of the fulcrum). Predict where a stack of 4 coins must go on the right to balance, then test. Record the result.
3. Repeat with three other arrangements of your choosing. For each, compute (coins $\times$ distance) on both sides.
4. Now measure your arm. Bend your elbow to a right angle. With a partner, find the biceps tendon in the crook of your elbow and measure from the elbow crease to the tendon's lower end; a typical value is 4–5 cm. Record it as r_E .
5. Measure from the elbow to the center of your palm. Record it as r_L .
6. Compute your mechanical advantage r_E/r_L and your speed ratio r_L/r_E .
7. Hold a 1 kg (1 L) bottle of water in your palm with your forearm horizontal for 10 seconds. Compute the biceps force needed, ignoring the forearm's weight.
8. Estimate your forearm's weight as about 2% of your body weight, acting at the middle of the forearm. Add its torque and recompute.

9. Hold the bottle at three angles (forearm horizontal, 45° up, 45° down) and rate the effort from 1 to 5. Compute the moment arm at each angle and see whether your ratings follow it.
10. **Decide.** Write two rules for carrying heavy things safely and one rule for swinging a racket or bat fast, each explained with torques.

Tips

- Use meters in every torque calculation.
- Keep the 1 kg load light; the point is to measure, not to strain.

Check your work

- ☐ I verified the law of the lever with at least four coin arrangements.
- ☐ I measured my own lever arms and computed the biceps force with and without the forearm's weight.
- ☐ I compared the computed moment arm at three angles with how hard each felt.

SCOREBOOK

1. Coin table: left coins, left distance, left product, right coins, right distance, right product, balanced?
2. Draw your forearm as a lever with F, E and L labelled and the measured distances marked.
3. Sketch one first-, one second- and one third-class lever from a sport, labelled.

KEY FORMULAS

$$\tau = rF \quad (\tau = rF \sin \theta \text{ in general})$$

$$F_E r_E = F_L r_L$$

$$\text{MA} = \frac{r_E}{r_L} \quad \frac{v_{\text{load}}}{v_{\text{effort}}} = \frac{r_L}{r_E}$$

From history. Archimedes, who stated the law of the lever, is credited with the saying “Give me a place to stand, and I will move the earth.” Borelli dedicated *De Motu Animalium* to Queen Christina of Sweden, who lived in Rome and supported his work. Modern biomechanics still uses his method: draw the bones as bars, the joints as pivots and the muscles as forces, then balance the torques.

WORKED EXAMPLES

Example 1. You hold a 5.0 kg dumbbell in your hand with your forearm horizontal. The dumbbell is 35 cm from the elbow and the biceps tendon attaches 4.0 cm from the elbow. Ignoring the forearm's own weight, find the biceps force.

Show solution

1. Load: $F_L = 5.0 \times 9.8 = 49 \text{ N}$.

2. Balance of torques about the elbow: $F_E(0.040) = 49(0.35)$.

3. $F_E = \frac{49 \times 0.35}{0.040} \approx 429 \text{ N}$.

Answer: About 430 N, nearly 9 times the weight of the dumbbell.

Example 2. Your head weighs about 50 N, and its center of mass is 2.0 cm in front of the joint where the head rests on the top of the spine. The neck muscles at the back attach 5.0 cm behind that joint. What force must they pull with to hold your head level? Which class of lever is this?

Show solution

1. The joint is the fulcrum, with the load in front and the effort behind: a first-class lever.

2. Balance: $F_E(5.0) = 50(2.0)$.

3. $F_E = 100/5.0 = 20 \text{ N}$.

Answer: About 20 N, from a first-class lever. (Bending your head far forward to look at a phone moves the load farther in front and raises this force several times.)

Example 3. A tennis player's hand is 0.60 m from the shoulder and the center of the racket strings is 1.25 m from the shoulder. If the arm and racket swing together at an angular velocity of 20 rad/s, how fast are the hand and the strings moving?

Show solution

1. For rotation, speed $v = \omega r$.

2. Hand: $20 \times 0.60 = 12 \text{ m/s}$.

3. Strings: $20 \times 1.25 = 25 \text{ m/s}$.

Answer: Hand 12 m/s, strings 25 m/s. Lengthening the lever doubled the speed at the point of contact.

PRACTICE

1. **Easy** A force of 40 N acts at right angles 0.50 m from a fulcrum. Find the torque.

Show answer

$$\tau = 0.50 \times 40 = 20 \text{ N}\cdot\text{m}.$$

2. **Easy** Classify each as a first-, second- or third-class lever: (a) rising onto the balls of your feet, (b) bending the elbow with the biceps, (c) nodding your head.

Show answer

(a) second class, (b) third class, (c) first class.

3. **Easy** A lever has an effort arm of 4 cm and a load arm of 32 cm. Find its mechanical advantage and say whether it favors force or speed.

Show answer

$$4/32 = 0.125; \text{ it favors speed.}$$

4. **Medium** Hold a 3.0 kg jug 32 cm from the elbow, with the biceps attached 4.0 cm from the elbow and the forearm horizontal. Find the biceps force, ignoring the forearm's weight.

Show answer

$$F = \frac{29.4 \times 0.32}{0.040} \approx 235 \text{ N}.$$

5. **Medium** On a seesaw, a 300 N child sits 2.0 m from the pivot. Where must a 400 N child sit to balance?

Show answer

$$300 \times 2.0 = 400 \times r, \text{ so } r = 1.5 \text{ m.}$$

6. **Medium** The biceps shortens at 0.10 m/s. Its tendon attaches 4.0 cm from the elbow and the hand is 32 cm away. How fast does the hand move?

Show answer

$$\text{Ratio } 32/4 = 8; 8 \times 0.10 = 0.80 \text{ m/s.}$$

7. **Medium** Why does the body use third-class levers at most joints even though they need large muscle forces?

Show answer

They multiply speed and range of motion, which most movements (running, throwing, swinging) need, and they keep muscles compact near the joints.

8. **Medium** What did Borelli conclude about muscle forces, and in what book?

Show answer

In *De Motu Animalium* (1680–81) he showed that muscles, attached close to the joints, must pull many times harder than the loads they hold.

9. **Hard** The forearm and hand weigh 20 N with their center of mass 15 cm from the elbow. A 50 N load is held 35 cm from the elbow; the biceps attaches 5.0 cm from the elbow. Find the biceps force with the forearm horizontal.

Show answer

$$F = \frac{20(15) + 50(35)}{5.0} = \frac{300 + 1750}{5.0} = 410 \text{ N.}$$

10. **Hard** Seated with the lower leg horizontal, a student wears a 20 N ankle weight 40 cm from the knee. The lower leg weighs 40 N with its center 20 cm from the knee. The quadriceps acts through the kneecap tendon 4.0 cm from the knee. Find the muscle force.

Show answer

$$F = \frac{20(40) + 40(20)}{4.0} = 400 \text{ N.}$$

11. **Hard** A 49 N load is held 0.35 m from the elbow. Find its torque when the forearm is horizontal and when the forearm points 30° below the horizontal.

Show answer

Horizontal: $0.35 \times 49 \approx 17.2 \text{ N}\cdot\text{m}$. At 30° below: moment arm $0.35 \cos 30^\circ \approx 0.303 \text{ m}$, torque $\approx 14.9 \text{ N}\cdot\text{m}$.

12. **Challenge** A bat is swung with the hands 0.15 m from the turning axis through the body, and the ball strikes the bat 0.85 m from the axis. If the hands move at 6.0 m/s, how fast is the contact point moving? What does this mean for a hitter who chokes up 0.10 m on the bat?

Show answer

$\omega = 6.0/0.15 = 40 \text{ rad/s}$; contact point $40 \times 0.85 = 34 \text{ m/s}$. Choking up moves the contact point to 0.75 m: 30 m/s, a little slower but easier to control, a trade of speed for accuracy.

COMMON MISTAKES

- Measuring the moment arm along the bone instead of perpendicular to the force when the limb is tilted.
- Mixing centimeters and meters in the same torque equation (the ratio is fine if both sides use the same unit).
- Thinking a mechanical advantage less than 1 is a design fault; it is the body's way of gaining speed.

Make it a game • Three-Class Lever Hunt. Set a three-minute timer and hunt the house for levers: a broom, nutcracker, scissors, wheelbarrow, bottle opener. For each find, write F, E and L on slips of paper and place them at the fulcrum, effort and load. Your parent names the class; you defend it. One point per correct class, two if you can say which way the mechanical advantage points.

1.3 CENTER OF MASS, BALANCE AND THE BASE OF SUPPORT

OBJECTIVES

- Compute a center of mass from masses and positions, and find your own with a reaction board.
- Explain stability using the center of mass and the base of support, and compute a tipping angle.
- Explain how the Fosbury flop lets a high jumper clear a bar while raising the center of mass less.

Warm-up. Stand with your heels against a wall and try to touch your toes without moving your feet or bending your knees. What happens? Now step 30 cm away from the wall and try again. Write one sentence about where your weight had to go.

WATCH

In high jump, your centre of mass goes under the bar

Veritasium · 4:42

<https://www.youtube.com/watch?v=XBtBdNHBNSI>

WHEN TO WATCH

After “the story” paragraph. Watch where the jumper’s hips are compared with the bar at the top of each jump.

BACKUP VIDEO

How One Man Changed the High Jump Forever | The Olympics on the Record

Olympic Games · 4:24

<https://www.youtube.com/watch?v=CZsH46Ek2ao>

Before “the story,” to see Fosbury’s jumps at Mexico City in 1968.

KEY TERMS

center of mass

The point where the whole mass of an object can be treated as concentrated; the balance point.

base of support

The area on the ground enclosed by the points of contact, such as the outline of both feet.

stability

Resistance to being tipped over;
greater with a lower center of mass
and a wider base.

reaction board

A board supported at two ends, with a
scale under one end, used to find a
person's center of mass.

CORE IDEAS

The story. On October 20, 1968, at the Olympic Games in Mexico City, a tall American engineering student named Dick Fosbury ran a curved approach to the high-jump bar, turned his back to it, and arched over head first. The crowd had never seen anything like it. He won the gold medal with an Olympic record of 2.24 m. Within ten years most of the world's best high jumpers used his "Fosbury flop." Its secret is the center of mass. More than a century earlier, on June 30, 1859, the French acrobat Charles Blondin had walked a rope across the Niagara gorge, with crowds watching from both banks, carrying a long balancing pole. Both men were masters of the same idea: where your mass is, compared with what holds you up.

How they figured it out. Archimedes found the centers of mass of flat shapes in the third century BC. For the human body, nineteenth-century German scientists Wilhelm Braune and Otto Fischer found the mass and balance point of each limb, and later researchers built tables still used today: in a standing adult, the center of mass lies a little below the navel, about 55–57% of the height above the floor. High jumpers had used the scissors and then the straddle, rolling face-down over the bar. Fosbury's arch let different parts of his body cross the bar at different times, so his center of mass never had to rise as high as the bar itself, and it may even pass a little *beneath* it. Soft foam landing pits, new in the 1960s, made the backward landing safe.

The physics. For masses $m_1, m_2, \dots$ at positions $x_1, x_2, \dots$, the center of mass is $x_{\text{cm}} = \frac{\sum m_i x_i}{\sum m_i}$. A body standing still is stable when its center of mass lies over its base of support. Tilt it, and it tips over once the center of mass passes the edge of the base. For a center of mass at height h above the middle of a base of width b , the tipping angle is $\tan \theta = \frac{b/2}{h}$. Lowering the center of mass or widening the base raises that angle. In a jump, the height the center of mass rises depends only on its takeoff speed, $h = v^2/2g$; arching the body lets the bar be higher than the center of mass ever goes.

On the field. A wrestler, a lineman and a defender all lower their hips and widen their feet before contact: a lower center of mass and a wider base make them harder to tip. A sprinter at the start does the opposite: he leans his center of mass far ahead of his feet so that he begins to fall forward and must run to catch himself. A batter, a golfer and a tennis player keep their center of mass between their feet while swinging. Blondin's pole, heavy and long, made his whole system turn more slowly when he wobbled, giving him time to correct.

Think it through. Stability is not always good. A goalkeeper who is too stable cannot dive quickly. Good athletes choose how stable to be: stable when they must resist a push, unstable on purpose when they want to move fast.

PICTURE STUDY



Blondin Crossing the Niagara River, William England, 1859 · Stereoscopic photograph · Niagara Falls, between the United States and Canada

Image: [Wikimedia Commons](#), public domain

William England, a photographer for the London Stereoscopic Company, toured North America in 1859 and photographed Charles Blondin on his rope across the gorge below Niagara Falls. Blondin crossed many times that summer, sometimes blindfolded or pushing a wheelbarrow. Every crossing was a problem of keeping his center of mass above a base of support only a few centimeters wide.

Look closely

- Look at Blondin and his pole. How long is the pole compared with his body, and how does it droop at the ends?
- Look at the rope. Where does it sag, and where would Blondin need to work hardest?
- Find the thin guy lines below the main rope. What do they do for the rope's steadiness, and for his?

Talk about it

1. Blondin's base of support was a rope. Explain, using the center of mass, why he could stand on it at all.

2. Blondin had practiced for years. Was his crossing courage, skill, or recklessness? What would make it each one?

Safety first. Do the balance tests on a carpet or grass with clear space around you and a partner close by. Never practice a high jump or any backward landing without a proper landing pit and a coach. For the reaction board, use a sturdy plank lying on the floor, and move onto it slowly.

PROJECT

Find Your Center of Mass and Test Your Balance

You will build a reaction board from a plank and a bathroom scale, find your own center of mass lying down and in two other positions, and then test how stance changes your stability.

You will need

- A sturdy board or plank, about 2 m long and strong enough to lie on
- A bathroom scale
- A block or thick book the same height as the scale
- A tape measure
- A partner
- The scorebook and a calculator

Steps

1. Weigh yourself and record your mass.
2. Set the plank with one end on the block and the other end resting on the scale, so it is level. Measure the length L between the two support points.
3. Read the scale with the plank alone. Record it as S_0 .
4. **Predict.** Write where you expect your center of mass to be, as a percentage of your height.
5. Lie on your back on the plank with your soles exactly over the block support. Read the scale S three times, getting off and on each time.
6. Compute $x = (S - S_0)L/W$ (using kilograms for both S and W) and the percentage of your height.
7. Repeat with your arms stretched above your head, and again with your knees pulled up to your chest. How far did your center of mass move each time?
8. Balance test: stand on one foot with eyes open and time how long you can hold still (stop at 60 s). Repeat with eyes closed. Have your partner stand close.

9. Push test: stand with feet together while your partner gives a gentle, steady sideways push on your shoulder and notes when you have to step. Repeat with feet wide and knees bent. Compare.
10. **Decide.** Write the stance you would use to receive a push in a sport, and the stance you would use to start running fast, and explain both with the center of mass and base of support.

Tips

- Lie very still while the scale is read; any movement changes the reading.
- Keep the partner's pushes gentle and steady, never sudden.

Check your work

- ☐ I found my center of mass three times in three positions, with the calculation shown.
- ☐ I timed one-foot balance with eyes open and closed.
- ☐ I explained my two stances with the center of mass and the base of support.

SCOREBOOK

1. Reaction-board table: position, scale readings (three), mean, x in meters, x as a percentage of height.
2. Draw yourself standing in two stances, from the front. Mark the center of mass with a dot, draw the base of support, and draw the tipping angle for each.
3. Draw the Fosbury flop at the top of the jump and mark where the center of mass would be.

KEY FORMULAS

$$x_{\text{cm}} = \frac{\sum m_i x_i}{\sum m_i}$$

$$\tan \theta_{\text{tip}} = \frac{b/2}{h}$$

$$\text{reaction board: } x_{\text{cm}} = \frac{S L}{W}$$

From history. Fosbury first used his flop as a high-school jumper in Medford, Oregon, in the early 1960s, when it was called a curious style; he kept refining it at Oregon State University. Blondin, whose real name was Jean-François Gravellet, lived until 1897 and performed on the high wire into his seventies.

WORKED EXAMPLES

Example 1. Model a 60 kg person lying on her back, feet at $x = 0$: legs 20 kg centered at 0.45 m, trunk and arms 34 kg centered at 1.15 m, head 6 kg centered at 1.60 m. Find the center of mass and express it as a percentage of her 1.70 m height.

Show solution

1. $\sum m_i x_i = 20(0.45) + 34(1.15) + 6(1.60) = 9.0 + 39.1 + 9.6 = 57.7 \text{ kg}\cdot\text{m}.$
2. $x_{\text{cm}} = 57.7/60 \approx 0.96 \text{ m}.$
3. $0.96/1.70 \approx 0.57.$

Answer: About 0.96 m from the feet, 57% of her height.

Example 2. A reaction board 2.0 m long rests on a block at one end and on a bathroom scale at the other. With the board alone the scale is zeroed. A 60 kg student lies on it with his feet over the block, and the scale reads 28.5 kg. Where is his center of mass?

Show solution

1. Torques about the block: the scale's push times the board length equals his weight times the distance to his center of mass.
2. Using kilograms on both sides (the 9.8 cancels): $28.5 \times 2.0 = 60 \times x.$
3. $x = 57/60 = 0.95 \text{ m}.$

Answer: 0.95 m from the soles of his feet.

Example 3. A player stands with feet 0.30 m apart and her center of mass 1.00 m high. In a defensive stance her feet are 0.60 m apart and her center of mass 0.85 m high. Find the sideways tipping angle in each stance.

Show solution

1. Upright: $\tan \theta = 0.15/1.00$, $\theta \approx 8.5^\circ$.
2. Defensive: $\tan \theta = 0.30/0.85 \approx 0.353$, $\theta \approx 19.4^\circ$.

Answer: About 8.5° upright and 19.4° in the defensive stance: more than twice as hard to tip.

Example 4. Illustrative. A jumper's center of mass is 1.25 m high at takeoff. How fast must it be moving upward to rise to a 2.24 m bar? How much less speed is needed if an arched body lets the center of mass pass 0.10 m below the bar?

Show solution

1. Rise to the bar: $2.24 - 1.25 = 0.99$ m; $v = \sqrt{2(9.8)(0.99)} \approx 4.40$ m/s.
2. Rise 0.89 m: $v = \sqrt{2(9.8)(0.89)} \approx 4.18$ m/s.

Answer: About 4.40 m/s against 4.18 m/s: the flop saves about 0.2 m/s of vertical takeoff speed, a large saving at this level.

PRACTICE

1. Easy A 2 kg mass sits at $x = 0$ and a 3 kg mass at $x = 1.0$ m. Find the center of mass.

Show answer

$$x = \frac{0 + 3}{5} = 0.6 \text{ m.}$$

2. Easy Name two ways an athlete can make himself harder to push over.

Show answer

Lower the center of mass (bend the knees) and widen the base of support (spread the feet), ideally in the direction of the push.

3. **Easy** In what year and city did Dick Fosbury win the Olympic high jump, and at what height?

Show answer

Mexico City, 1968, with 2.24 m (an Olympic record).

4. **Medium** A 70 kg man and a 30 kg child sit on opposite ends of a 3.0 m seesaw plank. Where is their combined center of mass, measured from the man?

Show answer

$$x = \frac{30 \times 3.0}{100} = 0.9 \text{ m.}$$

5. **Medium** A reaction board 2.0 m long; a 50 kg student lies on it and the zeroed scale reads 23 kg. Find her center of mass from her feet.

Show answer

$$x = \frac{23 \times 2.0}{50} = 0.92 \text{ m.}$$

6. **Medium** Find the sideways tipping angle for feet 0.40 m apart with the center of mass 0.95 m high.

Show answer

$$\tan \theta = 0.20/0.95, \theta \approx 11.9^\circ.$$

7. **Medium** Why does a sprinter lean his center of mass forward of his feet at the start?

Show answer

So that gravity tips him forward and his push from the ground drives him forward, not just up; he “falls” into his first strides.

8. **Hard** A jumper’s center of mass rises 1.00 m. Find the vertical takeoff speed. If he could raise it only 0.90 m, by what percent would the speed fall?

Show answer

$$v = \sqrt{19.6} \approx 4.43 \text{ m/s; } \sqrt{17.64} = 4.20 \text{ m/s, about 5\% less.}$$

9. **Hard** A gymnast holds a 3 kg hand weight out at 0.70 m from the center line of her 45 kg body. How far does her combined center of mass shift sideways?

Show answer

$$x = \frac{3 \times 0.70}{48} \approx 0.044 \text{ m, about 4.4 cm.}$$

10. **Hard** Explain why Blondin's long, heavy pole helped him balance even though it added weight.

Show answer

Its mass, spread far from his body, made the whole system much harder to set turning (a larger moment of inertia), so he tipped more slowly and had time to shift his weight back over the rope. Its drooping ends also lowered the combined center of mass a little.

11. **Challenge** A uniform 2.0 m board weighing 80 N rests on a block at one end and a scale at the other. The scale is *not* zeroed. A 600 N person lies on it, and the scale reads 325 N. Find the person's center of mass from the block.

Show answer

The board alone puts 40 N on the scale. The person adds 285 N:

$$x = \frac{285 \times 2.0}{600} = 0.95 \text{ m.}$$

COMMON MISTAKES

- Forgetting to subtract the plank's own reading from the scale reading.
- Thinking the center of mass must be inside the body; in an arch or a pike it can lie outside it.
- Using the height of the person instead of the distance between supports for L .

Make it a game • Tipping Point Duel. Tilt a thick book over the edge of a table until it just tips. Before you do, each of you writes a guess for the tipping angle, using the center of mass and the width of the base. Measure with a protractor. Closest guess wins a point. Then each player stands on one foot, eyes open, and times how long the center of mass stays over the base.

1.4 THE KINETIC CHAIN

OBJECTIVES

- Describe the kinetic chain and the proximal-to-distal sequence in throwing, kicking and striking.
- Convert angular velocities between degrees per second and radians per second and use $v = \omega r$.
- Measure how adding each link of the chain increases the speed of a throw.

Warm-up. Sit on a chair and throw a rolled-up pair of socks at a target using only your forearm and wrist. Then stand and throw it with a step and a full turn of your body. Describe the difference in two sentences. Where did the extra speed come from?

WATCH

Pitching Mechanics - Sequencing the Kinetic Chain

YouGoProBaseball · 13:41

<https://www.youtube.com/watch?v=ZuErBJ025xs>

WHEN TO WATCH

After “the physics” paragraph. As the coach shows each phase, name the body segment that is speeding up and the one that is slowing down.

Note: The video’s description links to the coach’s paid training program; the lesson does not depend on it.

KEY TERMS

kinetic chain

The linked segments of the body (legs, hips, trunk, arm, hand) working in sequence to produce motion.

angular velocity

How fast something turns, in degrees per second or radians per second (rad/s).

proximal-to-distal sequence

The order in which segments reach peak speed, from those near the body’s center to those farther out.

radian

The angle at which the arc length equals the radius; $180^\circ = \pi$ rad.

CORE IDEAS

The story. In 1872 Winslow Homer painted a line of schoolboys playing “snap the whip” in a field. The boys near the anchor barely move, while the boys at the end are flung so fast that they lose their grip and tumble into the grass. Every throw, kick and serve in sport works the same way. In 1875 the German engineer Franz Reuleaux described linked machine parts as a “kinematic chain,” and in 1955 the American orthopedic surgeon Arthur Steindler applied the idea to the human body, calling it the kinetic chain.

How they figured it out. Coaches long told pitchers to “throw with your legs,” but it took high-speed cameras and motion-capture markers to show what that meant. At the American Sports Medicine Institute in Birmingham, Alabama, biomechanist Glenn Fleisig and his colleagues filmed hundreds of pitchers from youth to professional. They found a clear order: the stride foot lands, the pelvis rotates and reaches a peak of roughly 600° per second, then the upper trunk peaks at roughly $1,100\text{--}1,200^\circ$ per second, then the elbow straightens at over $2,000^\circ$ per second, and the shoulder rotates inward at about $7,000^\circ$ per second, among the fastest motions in any sport. Each segment speeds up and then slows down, passing its motion outward to the next.

The physics. A point on a turning segment moves at $v = \omega r$, where ω is the angular velocity in radians per second and r is the distance from the turning axis. To convert, $\omega_{\text{rad/s}} = \omega_{\text{deg/s}} \times \frac{\pi}{180}$. A big, heavy segment like the hips can store a great deal of motion but turns slowly; a light, short segment like the hand can turn very fast. When the trunk slows down, the arm attached to it is whipped forward, just as the end boy is flung when the boys near the anchor stop. Timing is everything: if the arm starts too early, the speed of the trunk is wasted; if a link is skipped, the chain is broken and the end segment must work alone.

On the field. The same sequence drives a soccer kick (hip, thigh, shank, foot), a tennis serve (legs, hips, trunk, upper arm, forearm, racket), a golf swing and a volleyball spike. Coaches call a break in the chain an “energy leak”: a pitcher who does not stride, or a hitter whose hips and shoulders turn together, loses speed and often makes the small links work too hard. That is why good mechanics are both faster and safer for the shoulder and elbow.

Think it through. The end of the chain is fastest, but it is not where the power is made. Most of the energy comes from the big muscles of the legs and trunk. The arm is more like the tip of a whip than its handle.

PICTURE STUDY



Snap the Whip, Winslow Homer, 1872 · Oil on canvas · Butler Institute of American Art, Youngstown, Ohio

Image: [Wikimedia Commons](#), public domain

Winslow Homer painted *Snap the Whip* in 1872, in the years after the American Civil War, and it became one of his best-loved pictures. Boys from a one-room schoolhouse run in a chain across a field. The anchor at one end plants his feet, and the line swings around him faster and faster until the boys at the end cannot hold on.

Look closely

- Find the anchor boy. How are his feet and body placed compared with the boys in the middle?
- Look at the boys at the far end. What has happened to them, and why?
- Follow the line of joined hands. Where is the grip strained most?
- Find the schoolhouse and the hills behind. How does Homer show that the line is moving?

Talk about it

1. Using $v = \omega r$, explain why the boys farthest from the anchor move fastest even though the whole line turns together.
2. In a throw, which part of your body plays the anchor, and which plays the boy at the end?

Safety first. Throw only a soft ball or rolled socks indoors, and a tennis ball outdoors in an open space with no one in front of you. Warm up the shoulder with arm circles and easy throws first. Throw at most 30 hard throws in a session and stop if your arm hurts.

PROJECT

Building the Chain One Link at a Time

You will measure how far you can throw a ball using more and more links of the kinetic chain, and calculate how much each link adds to the speed.

You will need

- A tennis ball or other soft ball (several if possible)
- A long tape measure or a measuring wheel (or count paces of known length)
- Cones or markers
- A chair
- An open field or yard with a parent present
- The scorebook and a calculator

Steps

1. Mark a throwing line in an open field with no people, windows or cars in the throwing direction.
2. Warm up: arm circles, then ten easy throws at short range.
3. **Predict.** For each of the four styles below, predict your throwing distance.
4. Style A, seated: sit on a chair at the line and throw with the arm only, trunk still. Throw 5 times; mark and measure each landing point.
5. Style B, standing still: feet side by side, no step, but you may turn your shoulders. 5 throws.
6. Style C, step: step forward with the opposite foot and turn hips and shoulders together. 5 throws.
7. Style D, full chain: a crow-hop or long stride, hips turning first, then the shoulders, then the arm. 5 throws.
8. Find the mean distance for each style. Estimate each release speed with $v \approx \sqrt{gR}$.
9. Compute the percent increase in speed from A to B, B to C and C to D. Which link added the most?

10. If you can, film style D in slow motion from the side. Watch when the hips, shoulders and hand each reach top speed. Are they in order?
11. **Decide.** Write the one change to your throwing that your data say would help most, and why.

Tips

- Throw at a similar launch angle each time; aim for a point high in the sky about 45° up.
- Wind changes distance; throw all styles in the same direction within a few minutes.

Check your work

- ☐ I made 5 throws in each of the four styles and measured every one.
- ☐ I computed mean distance, estimated speed and the percent gain for each added link.
- ☐ I wrote a decision based on my own data.

SCOREBOOK

1. Throw table: style, five distances, mean distance, estimated speed, percent gain over the previous style.
2. Draw a bar graph of estimated speed for styles A–D.
3. Draw a stick-figure sequence of a throw in four frames and mark which segment is moving fastest in each frame.

KEY FORMULAS

$$v = \omega r$$

$$\omega_{\text{rad/s}} = \omega_{\text{deg/s}} \times \frac{\pi}{180}$$

$$a_c = \frac{v^2}{r} = \omega^2 r$$

$$R \approx \frac{v^2}{g} \quad (\text{launch at } 45^\circ, \text{ no air resistance})$$

From history. Homer worked as an illustrator for *Harper's Weekly*, which printed a wood-engraving of *Snap the Whip* in 1873, and painted a second, smaller version now at the Metropolitan Museum of Art. Glenn Fleisig's studies of pitchers helped shape the youth pitch-count guidelines you will meet in Unit 2.

WORKED EXAMPLES

Example 1. A pitcher's shoulder rotates inward at about $7,000^\circ$ per second. With the elbow bent, the ball is about 0.30 m from the axis of that rotation. Find the angular velocity in rad/s and the ball speed it alone would produce.

Show solution

1. $\omega = 7000 \times \frac{\pi}{180} \approx 122 \text{ rad/s}.$
2. $v = \omega r = 122 \times 0.30 \approx 37 \text{ m/s}.$
3. Convert: $37 \times 3.6 \approx 132 \text{ km/h} \approx 82 \text{ mph}.$

Answer: About 122 rad/s and 37 m/s (about 82 mph). This motion contributes much of the final speed, but it is possible only because the legs and trunk have already sped up the whole arm.

Example 2. In Homer's painting, suppose the boys hold hands 1.0 m apart and the line turns about the anchor boy at 1.0 rad/s. How fast is the 8th boy from the anchor moving? What inward force must his grip supply if his mass is 40 kg?

Show solution

1. Speed: $v = \omega r = 1.0 \times 8.0 = 8.0 \text{ m/s}$, a fast sprint.
2. Centripetal acceleration: $a = v^2/r = 64/8.0 = 8.0 \text{ m/s}^2.$
3. Force: $F = ma = 40 \times 8.0 = 320 \text{ N}.$

Answer: 8.0 m/s and 320 N, about 80% of his own weight, which is why the boy at the end lets go.

Example 3. A student throws a ball 12 m with her arm only and 27 m with a full stride and body turn. Assuming a 45° launch and no air resistance, estimate each release speed.

Show solution

1. Arm only: $v = \sqrt{gR} = \sqrt{9.8 \times 12} \approx 10.8 \text{ m/s}$.
2. Full chain: $v = \sqrt{9.8 \times 27} \approx 16.3 \text{ m/s}$.
3. Ratio: $16.3/10.8 \approx 1.5$.

Answer: About 10.8 m/s and 16.3 m/s; the full kinetic chain added about 50% to the speed.

PRACTICE

1. **Easy** Convert 180° per second to radians per second.

Show answer

$$\pi \approx 3.14 \text{ rad/s}.$$

2. **Easy** List the segments of the kinetic chain in a baseball throw, in order.

Show answer

Legs (stride), pelvis (hips), trunk, upper arm (shoulder), forearm (elbow), hand and wrist, ball.

3. **Easy** A point 0.50 m from an axis turns at 10 rad/s. How fast is it moving?

Show answer

$$v = 10 \times 0.50 = 5.0 \text{ m/s}.$$

4. **Medium** Convert the peak pelvis rotation, 600° per second, and the peak trunk rotation, 1,150° per second, to rad/s.

Show answer

$$10.5 \text{ rad/s and } 20.1 \text{ rad/s}.$$

5. **Medium** A soccer player's foot is 0.90 m from the hip and the whole leg swings at 20 rad/s. How fast is the foot moving?

Show answer

$$v = 20 \times 0.90 = 18 \text{ m/s}.$$

6. **Medium** A ball thrown at 45° lands 20 m away. Estimate its release speed, ignoring air resistance.

Show answer

$$v = \sqrt{9.8 \times 20} \approx 14 \text{ m/s.}$$

7. **Medium** What happens to a throw if the hips and shoulders turn at the same time instead of one after the other?

Show answer

The trunk cannot be whipped by the hips, so the speed does not build up link by link; the throw is slower and the arm must work harder.

8. **Medium** Who applied the term “kinetic chain” to the human body, and when?

Show answer

Arthur Steindler, in 1955, borrowing Franz Reuleaux’s 1875 engineering idea of a kinematic chain.

9. **Hard** A tennis player’s racket center is 1.4 m from the shoulder axis at contact and the strings move at 45 m/s. Find the angular velocity of arm and racket in rad/s and degrees per second.

Show answer

$$\omega = 45/1.4 \approx 32 \text{ rad/s, about } 1,840^\circ/\text{s.}$$

10. **Hard** In a line of skaters turning at 1.2 rad/s, how far from the pivot must a skater be for his speed to reach 9.0 m/s, and what is his centripetal acceleration there?

Show answer

$$r = 9.0/1.2 = 7.5 \text{ m; } a = 81/7.5 = 10.8 \text{ m/s}^2.$$

11. **Hard** Explain why a pitcher who skips the stride and throws “all arm” is at greater risk of a sore elbow.

Show answer

Without the legs and trunk, the small muscles and ligaments of the shoulder and elbow must produce nearly all the speed, carrying larger loads in fewer, weaker links.

12. **Challenge** A whip handle is moved at 3 m/s. If each section of a whip, moving outward, carries the same energy into a mass one-fourth as large, by what factor does the speed rise at each section, and how many sections are needed to exceed the speed of sound, 343 m/s?

Show answer

Equal energy $\frac{1}{2}mv^2$ with a quarter of the mass means v^2 quadruples, so speed doubles at each section. $3 \times 2^n > 343$ requires $2^n > 114$, so $n = 7$ sections ($3 \times 128 = 384$ m/s). The crack of a whip is a small sonic boom from its tip.

COMMON MISTAKES

- Using degrees per second in $v = \omega r$ instead of radians per second.
- Thinking the arm makes most of the power; it delivers speed that the legs and trunk produced.
- Turning the hips and shoulders together, which breaks the chain.

Make it a game • Slow-Motion Chain. Perform a throw or a kick in slow motion, one link at a time, while your parent calls out which body link just moved: hips, trunk, shoulder, elbow, wrist. Then your parent performs and you call the order. Finish with a lightning round: your parent shouts degrees per second, and you answer in radians per second. Five correct in a row wins.

1.5 MUSCLES, PRACTICE AND DELIBERATE PRACTICE

OBJECTIVES

- Compute work and power for simple sport movements, with units.
- Describe how skills are learned in stages and what makes practice “deliberate.”
- Measure and graph your own learning curve for a new motor skill.

Warm-up. Write your name five times with your usual hand and five times with your other hand. Time both. Then write it five more times with your other hand while watching one letter you want to improve. What changed?

WATCH

The New Science of Expertise: Anders Ericsson

Rotman School of Management • 3:33

<https://www.youtube.com/watch?v=1feChwxfzoY>

WHEN TO WATCH

After “the story” paragraph. Write down the three features of deliberate practice that Ericsson names.

BACKUP VIDEO

What People Get Wrong About Deliberate Practice

Benjamin Keep, PhD, JD • 9:21

<https://www.youtube.com/watch?v=WbUOY9iolqw>

Optional, after “how they figured it out.” A clear account of what the 10,000-hour idea gets wrong.

KEY TERMS

work

Force times the distance moved in the direction of the force, $W = Fd$, in joules (J).

power

The rate of doing work, $P = W/t$, in watts (W).

deliberate practice

Practice designed to improve a specific weakness, at the edge of one's ability, with immediate feedback, usually guided by a teacher.

learning curve

A graph of performance against practice; it usually rises steeply at first and then levels off.

motor learning

The lasting change in skill that comes from practice, as the brain and nerves refine a movement.

CORE IDEAS

The story. In 1993 the Swedish psychologist K. Anders Ericsson and two German colleagues, Ralf Krampe and Clemens Tesch-Römer, published a study of violin students at a music academy in Berlin. They divided them into three groups: the “best,” whom the teachers expected to become international soloists; the “good”; and those training to be music teachers. All had played for more than ten years. The students estimated how much they had practiced alone in every year since they began. By age 18, the best had practiced about 7,400 hours in total, the good about 5,300 and the future teachers about 3,400. Ericsson spent the rest of his career showing that the same pattern holds in chess, medicine and sport.

How they figured it out. Ericsson's key finding was not simply “practice more.” The best students spent their hours on *deliberate practice*: practice designed by a teacher to work on a specific weakness, done alone with full concentration, with feedback, at the edge of what they could do. Just playing pieces they already knew did not count. Popular writers later turned his work into a “10,000-hour rule,” which Ericsson said was a misreading: there is nothing special about the number, and the kind of practice matters more than the total. Earlier, in 1967, Paul Fitts and Michael Posner had described three stages of learning a movement: the *cognitive* stage (thinking about each step), the *associative* stage (refining, with fewer errors) and the *autonomous* stage (the movement runs without conscious thought).

The physics. Muscles do work by pulling through a distance: $W = Fd$, in joules. Lifting your own body up a height h takes $W = mgh$. Power is how fast the work is done, $P = W/t$, in watts. A 60 kg student who runs up 3.0 m of stairs in 4.0 s does $60 \times 9.8 \times 3.0 \approx 1,760$ J of work at about 440 W. A muscle's greatest force depends

roughly on its cross-sectional area, about 20–30 N for every square centimeter, so training that thickens a muscle makes it stronger. But skill is different from strength: practice changes the *control* of the muscles, so the right fibers fire at the right moment with less wasted effort. Performance time on a new task often falls as a power of the number of practice trials, $T = T_1 N^{-\alpha}$, steeply at first and then slowly.

On the field. A wise athlete practices like Ericsson’s violinists: short, focused sessions on one weakness, with a coach’s eye or a video for feedback, and enough rest to recover. Hitting a hundred balls you already hit well feels good but teaches little; ten careful attempts at the shot you miss teach more. The learning curve also explains discouragement: early gains are fast, later ones are slow, and the slow ones are where the best players separate themselves.

Think it through. The psalmist wrote that we are “fearfully and wonderfully made.” Every unit of this course studies a body designed with levers, a center of mass and a chain of joints, and a nervous system that can learn. Practice is how we steward what we were given.

PICTURE STUDY



The Biglin Brothers Racing, Thomas Eakins, 1872 · Oil on canvas · National Gallery of Art, Washington, D.C.

Image: [Wikimedia Commons](#), public domain

John and Barney Biglin were professional rowers from New York. Thomas Eakins, himself a keen rower on the Schuylkill River in Philadelphia, painted them in a pair-oared contest in 1872. He made careful perspective drawings of the boat and oars first, and studied the rowers' motion as an engineer would. Eakins later taught anatomy and the study of movement to his art students.

Look closely

- Look at the two brothers' arms and oars. Are they at the same point in the stroke? What does that tell you about years of practice together?
- Notice which muscles are working: legs, back or arms? Find the clue in their posture.
- Find the other boat behind. How does Eakins show speed on a calm river?

Talk about it

1. Rowing is a kinetic chain repeated hundreds of times in a contest. Why would two rowers who are each strong, but not in time with each other, lose to a well-practiced pair?
2. What would deliberate practice look like for a pair of rowers? Name one weakness and one form of feedback.

Safety first. Juggle or toss only soft balls or rolled socks, in a clear space away from lamps and windows. Warm up wrists and shoulders. Practice in short sessions, and stop if your arms or hands become sore.

PROJECT

Your Learning Curve

You will learn a new motor skill from the beginning and record your progress session by session, practicing deliberately. At the end you will graph your learning curve and fit it with a power law.

You will need

- Three soft juggling balls or three pairs of rolled socks (or a soft ball and a small target for a non-dominant-hand toss)
- A stopwatch or phone timer
- A phone camera for feedback (optional)
- The scorebook, graph paper and a calculator

Steps

1. Choose a skill you cannot yet do: three-ball juggling (count consecutive catches), or tossing a soft ball into a bucket 3 m away with your non-dominant hand (count makes out of 20).
2. **Predict.** Write the score you expect after 10 sessions.
3. Session plan: 10 minutes a day for 10 days. Each session begins with a 1-minute warm-up of wrists and shoulders.
4. Test first: at the start of each session, do a fixed test (five attempts at juggling, recording the best run of catches; or 20 tosses, recording makes). Record it before practicing.
5. Name one specific weakness from yesterday's test (for example, "the second toss drifts forward") and write it down.
6. Practice only that weakness for 8 minutes, with feedback: watch a short slow-motion clip of yourself or have a partner watch one thing.
7. End each session by writing one sentence on what changed.
8. After 10 sessions, graph your test score against session number.
9. Plot the same data on a log-log graph, or use a spreadsheet trendline set to "power," and record the exponent.

10. **Decide.** Write your plan for the next 10 sessions: what you would practice, how you would get feedback, and when you would rest.

Tips

- Practice when you are fresh; tired practice builds sloppy habits.
- A plateau of two or three sessions is normal. Change the drill, not your goal.

Check your work

- ☐ I recorded a test score at the start of all 10 sessions.
- ☐ I named a specific weakness each session and practiced it with feedback.
- ☐ I graphed my learning curve and fit a power law.

SCOREBOOK

1. Practice log table: session, date, test score, weakness worked on, one-sentence note.
2. Learning-curve graph: score against session number, with a smooth curve drawn through the points.
3. Write one paragraph: which stage of learning (cognitive, associative or autonomous) were you in on day 1, and which on day 10?

KEY FORMULAS

$$W = Fd \quad W = mgh$$

$$P = \frac{W}{t} \quad P = Fv$$

$$T = T_1 N^{-\alpha}$$

From history. Ericsson taught for many years at Florida State University and died in 2020. Fitts and Posner's three stages appeared in their short book *Human Performance* (1967). Eakins painted rowing scenes many times, often from sketches made on the river.

WORKED EXAMPLES

Example 1. A 60 kg student runs up a flight of stairs 3.0 m high in 4.0 s. Find the work done against gravity and the average power.

Show solution

1. $W = mgh = 60 \times 9.8 \times 3.0 = 1,764 \text{ J}.$

2. $P = 1764/4.0 \approx 441 \text{ W}.$

Answer: About 1,760 J at about 440 W, roughly the power of four or five bright old-style light bulbs.

Example 2. Ericsson’s “best” violinists had about 7,410 hours of solo practice by age 18. If they began at age 6, what was their average weekly practice?

Show solution

1. Years: $18 - 6 = 12.$

2. Per year: $7410/12 \approx 618 \text{ hours}.$

3. Per week: $618/52 \approx 11.9 \text{ hours}.$

Answer: About 12 hours a week on average, rising from much less in early childhood to over 20 hours a week in their late teens.

Example 3. A student learning to juggle takes 60 s to complete a set drill on her first try. Her times follow $T = 60N^{-0.3}$. Find her time on the 10th and the 100th tries.

Show solution

1. $N = 10$: $10^{-0.3} \approx 0.501$, $T \approx 30 \text{ s}.$

2. $N = 100$: $100^{-0.3} \approx 0.251$, $T \approx 15 \text{ s}.$

Answer: About 30 s and 15 s. The first 10 tries halved her time; it took 90 more to halve it again.

PRACTICE

1. Easy How much work is done lifting a 20 N bag 1.5 m?

Show answer

$$W = 20 \times 1.5 = 30 \text{ J}.$$

2. **Easy** A lifter does 600 J of work in 1.2 s. Find the power.

Show answer

$$P = 600/1.2 = 500 \text{ W.}$$

3. **Easy** Name Fitts and Posner's three stages of learning a movement.

Show answer

Cognitive, associative and autonomous.

4. **Medium** A 50 kg student does a step-up onto a 0.40 m bench 20 times in 30 s. Find the total work against gravity and the average power.

Show answer

$$W = 20 \times 50 \times 9.8 \times 0.40 = 3,920 \text{ J}; P \approx 131 \text{ W.}$$

5. **Medium** A cyclist pushes with an average force of 25 N against air and road resistance while riding at 8.0 m/s. Find his power.

Show answer

$$P = Fv = 25 \times 8.0 = 200 \text{ W.}$$

6. **Medium** If a muscle can produce about 25 N per square centimeter of cross-section, what force can a muscle of 18 cm² produce?

Show answer

$$25 \times 18 = 450 \text{ N.}$$

7. **Medium** Give two differences between deliberate practice and simply playing.

Show answer

Deliberate practice targets a specific weakness at the edge of one's ability and includes immediate feedback (often from a teacher); playing mostly repeats what one already does well, with little feedback.

8. **Medium** Why did Ericsson object to the "10,000-hour rule"?

Show answer

The number was an average from one group at one age, not a threshold; and the kind of practice (deliberate, focused, with feedback) matters more than the total hours.

9. **Hard** Using $T = 40N^{-0.25}$, find the time on the 16th trial and the trial number at which the time first falls to 10 s.

Show answer

$$16^{-0.25} = 0.5, \text{ so } 20 \text{ s. } 40N^{-0.25} = 10 \Rightarrow N^{0.25} = 4 \Rightarrow N = 256.$$

10. **Hard** A 70 kg sprinter rises 0.05 m in each stride while running and takes 4.5 strides per second. What power goes into raising and lowering his body if the energy is not recovered?

Show answer

Per stride $70 \times 9.8 \times 0.05 \approx 34 \text{ J}$; $34 \times 4.5 \approx 154 \text{ W}$. (Tendons recover part of it like springs.)

11. **Hard** A student practices free throws 30 minutes a day, but shoots all of them from one spot without counting or checking. Rewrite the plan as deliberate practice.

Show answer

Answers vary: choose one specific fault (for example, a short shot), set a measurable target, shoot in sets of 10 with a count after each set, film or have a coach watch, change one thing at a time, and stop while still concentrating.

12. **Challenge** A team's practice log shows its players' times on a footwork drill: 20 s on day 1 and 15 s on day 8. Assuming $T = T_1 N^{-\alpha}$ with N the day number, find α and predict the time on day 27.

Show answer

$$15/20 = 8^{-\alpha}, \text{ so } \alpha = -\log(0.75)/\log 8 \approx 0.138. \text{ Day 27:}$$

$$20 \times 27^{-0.138} \approx 20 \times 0.634 \approx 12.7 \text{ s.}$$

COMMON MISTAKES

- Counting time spent rather than the quality of practice.
- Changing several things at once, so you cannot tell which helped.
- Confusing work (joules) with power (watts).

Make it a game • Three-Round Learning Curve. Choose a small skill, such as tossing a paper ball into a cup from across the room. Take ten tries per round. Between rounds, name one specific fix out loud and then practice with that one fix only. Chart your three scores on paper. Your parent guesses which round used deliberate practice, and you explain which stage of learning you were in.

Scripture. “I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well.” (Psalm 139:14, KJV)

Levers, a balance point and a chain of joints that a child can learn to use: the more closely we study the body, the more reason we find for thanks. Practice is how we take care of the gift.

UNIT 1

THE BODY AS A MACHINE

Before we study any one sport, we study the machine every sport uses. This unit starts with Newton's three laws and the ground that pushes back, then follows Giovanni Borelli in treating bones as levers, finds the center of mass that decides balance and made the Fosbury flop possible, traces the kinetic chain that whips speed from the legs to the hand, and ends with how muscles do work and how practice changes skill.

The projects measure your own body: the force of the floor in a jump, your arm's lever arms, your center of mass on a reaction board, the speed each link of the chain adds to a throw, and your own learning curve. The physics uses algebra, square roots and a little trigonometry.

PREREQUISITES

- Algebra I: solving linear equations, square roots and substituting into formulas
- Metric units: meters, kilograms, seconds
- Helpful: basic trigonometry (sine, cosine and tangent) for tilted levers and tipping angles

MASTERY CHECKLIST

- ☐ I can apply Newton's three laws to sport movements and compute forces with

$$F = ma.$$

- ☐ I can classify the levers of the body and compute a muscle force from the balance of torques.
- ☐ I can compute a center of mass, find my own with a reaction board, and explain stability.
- ☐ I can describe the kinetic chain and use

$$v = \text{with radians per second.}$$

$$\omega r$$

- ☐ I can compute work and power and explain what makes practice deliberate.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **OpenStax College Physics 2e: Forces and Torques in Muscles and Joints**: Free online textbook section with worked examples of muscle and joint forces. Extends Lessons 1.2 and 1.3. Ages 14+.
- **Khan Academy: Forces and Newton's laws of motion**: Free videos and practice problems on Newton's laws for Lesson 1.1.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

1.1	Newton's Laws in Sport	3 sessions of 50 minutes
1.2	Levers in the Body	3 sessions of 50 minutes
1.3	Center of Mass, Balance and the Base of Support	3 sessions of 50 minutes
1.4	The Kinetic Chain	3 sessions of 50 minutes
1.5	Muscles, Practice and Deliberate Practice	3 sessions of 50 minutes

UNIT 1 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$. Show your work for every calculation: write the formula, substitute with units, and give the answer with its unit. Answer the concept questions in complete sentences. The test is worth 100 points.

1. **5 pts**

State Newton's three laws of motion in your own words.

2. **6 pts**

A 75 kg sprinter accelerates from rest to 7.5 m/s in 2.5 s. Find the average acceleration and net force.

3. **7 pts**

A student jumps 0.45 m high (center of mass rise). Find her takeoff speed. If her push-off lasted 0.28 s and her mass is 52 kg, find the average floor force.

4. (6 pts)

Explain why a runner cannot start on slippery ice, using the third law.

5. (5 pts)

Classify each lever: (a) the triceps straightening the elbow, (b) rising onto your toes, (c) the quadriceps straightening the knee.

6. (8 pts)

A 4.0 kg weight is held 0.33 m from the elbow, forearm horizontal; the biceps attaches 0.044 m from the elbow. Find the biceps force, ignoring the forearm's weight, and the mechanical advantage.

7. (6 pts)

Why are most levers in the body third-class levers? What do they trade, and what do they gain?

8. (7 pts)

Masses of 30 kg, 20 kg and 10 kg sit at 0, 1.0 m and 2.0 m. Find the center of mass.

9. (7 pts)

A reaction board is 2.1 m long. A 56 kg student lies on it with her feet at the block, and the zeroed scale reads 26 kg. Find her center of mass from her feet and as a percentage of her 1.65 m height.

10. (6 pts)

Find the sideways tipping angle for a stance with feet 0.50 m apart and the center of mass 0.90 m high.

11. (6 pts)

Explain how the Fosbury flop allows a jumper to clear a bar higher than his center of mass rises.

12. (7 pts)

Convert a trunk rotation of $1,200^\circ$ per second to rad/s. If the shoulder is 0.20 m from the trunk's axis, how fast is it moving?

13. (6 pts)

Describe the proximal-to-distal sequence in a throw and explain why timing matters.

14. (6 pts)

A 55 kg student climbs a 4.0 m rope in 12 s. Find the work done against gravity and the average power.

15. (12 pts)

Short essay. In about 150 words, explain what Ericsson meant by deliberate practice and how you would use it to improve one skill in a sport you play. Include how you would measure progress.

ANSWER KEY

1. First: an object keeps its velocity unless a net force acts. Second: net force equals mass times acceleration. Third: forces come in equal and opposite pairs acting on different objects.
2. $a = 3.0 \text{ m/s}^2$; $F = 225 \text{ N}$.
3. $v = \sqrt{2(9.8)(0.45)} \approx 2.97 \text{ m/s}$; $a \approx 10.6 \text{ m/s}^2$; $F = 52(9.8 + 10.6) \approx 1,060 \text{ N}$.
4. To move forward, the runner must push backward on the ground and receive an equal forward push. On ice there is too little friction for the ground to supply a horizontal push, so no forward force acts.
5. (a) first class, (b) second class, (c) third class.
6. $F = \frac{39.2 \times 0.33}{0.044} \approx 294 \text{ N}$; $MA = 0.044/0.33 \approx 0.13$.
7. They trade force for speed and range: the muscle must pull much harder than the load, but the hand or foot moves much faster and farther than the muscle shortens.
8. $x = \frac{0 + 20 + 20}{60} \approx 0.67 \text{ m}$.
9. $x = \frac{26 \times 2.1}{56} = 0.975 \text{ m}$; about 59% of her height.
10. $\tan \theta = 0.25/0.90$, $\theta \approx 15.5^\circ$.
11. He arches over the bar so that different parts of his body cross it at different times; the arched body's center of mass lies below the body, so it can pass at or slightly beneath the bar while every part of the body passes over.
12. $\omega \approx 20.9 \text{ rad/s}$; $v \approx 4.2 \text{ m/s}$.
13. Segments reach peak speed from the center outward: hips, trunk, upper arm, forearm, hand. Each segment slows as the next speeds up, passing on its motion; if two turn together or out of order, the speed does not build up and the arm must work harder.
14. $W = 55 \times 9.8 \times 4.0 = 2,156 \text{ J}$; $P \approx 180 \text{ W}$.
15. Answers vary. A strong essay defines deliberate practice (targeted at a specific weakness, at the edge of ability, with immediate feedback, often designed by a coach), distinguishes it from repetition, describes a concrete plan, and names a measurable test (for example, makes out of 20) recorded over time.

PORTFOLIO PIECE: MY BODY MACHINE REPORT

Write a three-page illustrated report on your own body as a machine, using the measurements from this unit's projects. Include: your jump test with takeoff speed and floor force; a labelled diagram of your forearm as a lever with the biceps force for a 1 kg load; your center of mass in three positions from the reaction board; your throwing-distance results by style with estimated speeds; and your learning curve. For each, give the physics formula you used, one sentence on what surprised you, and one way the result could help you play a sport better or more safely.

LOOK FOR	WHAT IT MEANS
Measurements	All five measurements are present, with real data, repeated trials and units.
Physics	Each result is computed correctly from a stated formula, with work shown.
Diagrams	Clear, labelled diagrams of the lever, the center of mass and the kinetic chain.
Interpretation	Each result is connected to a specific improvement in technique or safety.

UNIT 2

BASEBALL AND SOFTBALL

Baseball is a laboratory of physics: a bat–ball collision lasting less than a millisecond, a spinning ball bending through the air, an arm whipping faster than almost any other human motion, and a fly ball that a fielder tracks with a simple rule of the eyes. This unit studies the swing and the sweet spot, the Magnus effect and Lyman Briggs’s 1959 measurements of the curveball, throwing mechanics and the Pitch Smart guidelines that protect young arms, the outfielder’s gaze heuristic, and Ted Williams’s science of hitting.

Fastpitch softball shares nearly all of this physics, and the projects work with either sport. You will measure bounces and a bat’s sweet spot, launch a Magnus glider, time your throws and keep a throwing log, test catching strategies on real fly balls, and map your own hitting zone.

PREREQUISITES

- Unit 1: Newton’s laws, levers, the kinetic chain and $v = \omega r$
- Algebra I: square roots and solving equations
- Trigonometry: sine, cosine and tangent for projectile motion

MASTERY CHECKLIST

- ☐ I can compute momentum, impulse and the coefficient of restitution, and use the batted-ball formula.
- ☐ I can explain the Magnus effect, predict the direction of a curve and use Briggs’s results.
- ☐ I can apply the Pitch Smart guidelines and explain why rest protects the arm.
- ☐ I can compute hang time, height and range of a fly ball and explain the gaze heuristic.
- ☐ I can compute a hitter’s time to react and explain Williams’s hitting zone and swing plane.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **Alan Nathan: The Physics of Baseball**: Free. A University of Illinois physicist's collection of articles and data on bats, balls, pitches and trajectories. Extends Lessons 2.1, 2.2 and 2.4. Some articles are written for physicists. Ages 14+.
- **MLB and USA Baseball: Pitch Smart guidelines**: Free. The official age-by-age pitch-count and rest tables used in Lesson 2.3. A parent should preview it, as the site carries advertising.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

2.1	The Batting Swing	3 sessions of 50 minutes
2.2	The Pitch and the Magnus Effect	3 sessions of 50 minutes
2.3	Throwing Mechanics and Arm Care	3 sessions of 50 minutes
2.4	Fielding and the Outfielder's Path	3 sessions of 50 minutes
2.5	Ted Williams and the Science of Hitting	3 sessions of 50 minutes

UNIT 2 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$ and $1 \text{ mph} = 0.447 \text{ m/s}$. Show your work for every calculation with units. Answer the concept questions in complete sentences. The test is worth 100 points.

1. **5 pts**

Find the momentum of a 0.19 kg softball moving at 30 m/s.

2. **6 pts**

A ball dropped from 1.20 m rebounds to 0.27 m. Find its coefficient of restitution.

3. **8 pts**

A 0.145 kg ball arrives at 38 m/s and leaves at 44 m/s in the opposite direction after 0.80 ms of contact. Find the change in momentum and the average force.

4. **6 pts**

Using $v = 0.2 v_{\text{pitch}} + 1.2 v_{\text{bat}}$, find the exit velocity for an 88 mph pitch and a 72 mph bat. Which matters more to the hitter, 5 mph of pitch speed or 5 mph of bat speed?

5. **5 pts**

Explain why hitting the ball off the end of the bat stings and produces a weaker hit.

6. **6 pts**

A right-handed pitcher's ball spins so that its front surface turns down (topspin). Which way does it break, and why?

7. **7 pts**

A pitch takes 0.55 s to reach the plate and spins at 1,500 rpm. How many turns does it make? Using Briggs's result that the curve is proportional to spin (17.5 in at 1,800 rpm), predict its curve.

8. **6 pts**

A pitch takes 0.42 s. How far would gravity alone make it fall? Why does a fastball with backspin seem to rise?

9. **6 pts**

Under Pitch Smart, how many rest days does a 13-year-old need after 40 pitches? After 70?

10. **6 pts**

Explain, using impulse, why a full follow-through protects a pitcher's shoulder.

11. **7 pts**

A fly ball is in the air for 5.0 s. Find its vertical launch speed and peak height, ignoring air resistance.

12. (7 pts)

A ball is hit at 35 m/s at 35° . Find its hang time and range without air. Will the real ball go farther or shorter?

13. (6 pts)

State the gaze heuristic and explain what a fielder should do if the gaze angle rises more and more slowly.

14. (6 pts)

A 92 mph pitch is released 16.8 m from the plate. A hitter's swing takes 0.15 s. By what time after release must he begin his swing?

15. (13 pts)

Short essay. In about 150 words, describe how physics can make a young baseball or softball player both better and safer. Use at least three ideas from this unit.

ANSWER KEY

1. $5.7 \text{ kg}\cdot\text{m/s}$.
2. $e = \sqrt{0.225} \approx 0.47$.
3. $\Delta p = 0.145 \times 82 \approx 11.9 \text{ kg}\cdot\text{m/s}$; $F \approx 14,900 \text{ N}$.
4. $17.6 + 86.4 = 104 \text{ mph}$. Bat speed: it is multiplied by 1.2, pitch speed by only 0.2.
5. Off the sweet spot, much of the collision's energy goes into vibrations of the bat, felt as a sting, leaving less energy for the ball.
6. Downward: the Magnus force points toward the side the front surface is turning, so topspin adds a downward force to gravity.
7. $25 \times 0.55 \approx 14$ turns; $17.5 \times 1500/1800 \approx 14.6 \text{ in}$.
8. $\frac{1}{2}(9.8)(0.42)^2 \approx 0.86 \text{ m}$. Backspin gives an upward force, so it falls less than the hitter expects.
9. Two (36–50); four (66+).
10. The arm's momentum after release must be removed. Stopping it over a longer time with a follow-through lowers the average force, $F = \Delta p / \Delta t$.
11. $v_y = 24.5 \text{ m/s}$; $H \approx 30.6 \text{ m}$.
12. $v_y \approx 20.1$, $v_x \approx 28.7 \text{ m/s}$; $T \approx 4.1 \text{ s}$; $R \approx 118 \text{ m}$. Shorter, because of drag.
13. Move so that the gaze angle to the ball rises at a steady rate. If it rises more and more slowly, the ball will land in front of him, so he should run in.
14. $v \approx 41.1 \text{ m/s}$; $t \approx 0.41 \text{ s}$; begin by about 0.26 s .
15. Answers vary. A strong essay uses specific ideas, such as bat speed and the sweet spot, spin and the Magnus effect, the kinetic chain and follow-through, pitch counts and rest, the gaze heuristic, and swing plane, and connects each to a concrete habit.

PORTFOLIO PIECE: A PHYSICS COACHING GUIDE FOR YOUNG PLAYERS

Write and illustrate a four-page coaching guide for a 10-year-old baseball or softball player, built on the physics and the data from this unit. Include one page each on hitting (sweet spot, bat speed and swing plane), pitching and throwing (the kinetic chain, the follow-through, pitch counts and rest), fielding (the first step and the gaze rule), and why balls curve. Each page must include one diagram, one number you measured yourself, one safety rule, and one sentence of physics explained simply. End with a one-paragraph note to parents on arm care.

LOOK FOR	WHAT IT MEANS
Correct physics	Each page explains a real principle correctly and simply.
Own data	Each page includes a measurement from the student’s own projects.
Safety	Clear, correct safety rules, including Pitch Smart limits and bat safety.
Clarity for a young reader	Plain language and clear diagrams a 10-year-old could follow.

2.1 THE BATTING SWING

OBJECTIVES

- Compute momentum and the average force in a bat–ball collision.
- Measure a coefficient of restitution and explain what it says about a ball or bat.
- Use the batted-ball-speed formula to show why bat speed and the sweet spot matter most.

Warm-up. Drop a tennis ball and a softball (or any two different balls) side by side from shoulder height onto a hard floor. Which bounces higher? Predict what fraction of the drop height each one returns to, then check against a tape measure.

WATCH

What makes the perfect swing in baseball?

Michigan Engineering • 3:38

<https://www.youtube.com/watch?v=uFAY8RwxFqc>

WHEN TO WATCH

After “how they figured it out.” Notice what the professor’s small sensor on the knob of the bat measures.

BACKUP VIDEO

The Science Of Hitting A Major League Fastball

Insider Science • 2:34

<https://www.youtube.com/watch?v=RENLMum5wz4>

Optional, after “on the field.” It shows how little time a hitter has, which you will study again in Lesson 2.5.

KEY TERMS

momentum

Mass times velocity, $p = mv$, in $\text{kg}\cdot\text{m/s}$.

impulse

Force times the time it acts; it equals the change in momentum, $F\Delta t = \Delta p$.

coefficient of restitution (COR)

The ratio of separation speed to approach speed in a collision; for a ball dropped on a hard floor,

$$e = \sqrt{h_{\text{up}}/h_{\text{down}}}.$$

sweet spot

The region of the barrel, about 13–18 cm from the end, where a hit sends the ball fastest and stings the hands least.

exit velocity

The speed of the ball just after it leaves the bat.

CORE IDEAS

The story. In 1987 the president of baseball’s National League, A. Bartlett Giamatti, a former president of Yale, asked a Yale physicist named Robert Adair to serve as the league’s “Physicist to the National League” and answer questions about bats and balls. Adair’s book *The Physics of Baseball* (1990) became a classic. A generation later, Alan Nathan, a physicist at the University of Illinois, measured thousands of bat–ball collisions in the laboratory and with stadium cameras. Today every major-league park tracks the speed of the bat and the ball for every swing.

How they figured it out. Hitters had always argued about heavy bats versus light bats and about where on the barrel to hit the ball. Physicists treated the swing as a collision. They fired baseballs from air cannons at bats held in clamps, filmed the collisions with high-speed cameras, and measured the speeds before and after. They found that the collision lasts less than a thousandth of a second, that the ball leaves much faster when it meets the bat in a narrow region near the end of the barrel, and that bat speed matters more than bat weight. Nathan summed up the results in a short formula for the speed of the batted ball.

The physics. Momentum is $p = mv$, and a force acting for a time changes it: $F\Delta t = \Delta p$. Because the contact time is so short, the average force on the ball is enormous. How “bouncy” the collision is depends on the coefficient of restitution e : a ball dropped onto a hard floor returns to the height $e^2 h$ (a major-league baseball has e of roughly 0.55 against a wooden wall). Nathan’s formula is $v_{\text{ball}} = q v_{\text{pitch}} + (1 + q) v_{\text{bat}}$, where q is about 0.2 for a wooden bat at its sweet spot. Notice that bat speed is multiplied by 1.2 but pitch speed by only 0.2: the hitter supplies most of the batted ball’s speed. Off the sweet spot, q falls because energy goes into vibrating the bat, which you feel as a sting.

On the field. Coaches now measure bat speed directly. A faster swing comes from the kinetic chain of Lesson 1.4: the stride, the hips turning ahead of the shoulders, and the hands staying inside the ball until late. A lighter bat can be swung faster and controlled better; a heavier one carries more momentum but is slower. Fastpitch softball works the same way, with a larger ball and a shorter distance. **The risk side:** a bat is a lever with a fast-moving end, and it can injure someone standing nearby, so the first rule of hitting practice is a clear circle.

Think it through. A good hitter does not try to hit the ball hard; he tries to meet it squarely on the sweet spot with a fast, controlled swing. The physics rewards precision more than effort.

PICTURE STUDY



Baseball Players Practicing, Thomas Eakins, 1875 · Watercolor on paper · Rhode Island School of Design Museum, Providence

Image: [Wikimedia Commons](#), public domain

Thomas Eakins painted two members of the Philadelphia Athletics practicing in 1875, the year before the National League began. Eakins loved to study the body in motion, and he painted the batter at the moment of waiting, weight back and bat ready, as the pitch is about to arrive.

Look closely

- Look at the batter's feet and knees. Where is his weight: on the back foot or the front?
- Look at the bat. How is it held, and how long is the lever from his hands to the end?
- Find the catcher. What does his posture tell you about how fast the pitch will arrive?

Talk about it

1. From this “loaded” position, describe the kinetic chain that would bring the bat to the ball.
2. Bats of the 1870s were heavy, often 40 ounces or more. Using the batted-ball formula, explain why modern hitters prefer lighter bats they can swing faster.

Safety first. Swing a bat only outdoors, in a clear circle at least twice the bat's length in every direction, with an adult watching and no one standing near. Use a plastic or foam ball off a tee. Warm up first, and wear athletic shoes. For the drop tests, keep fingers clear and drop balls only onto a hard floor away from glass.

PROJECT

Bounce, Sting and Sweet Spot

You will measure the coefficient of restitution of several balls, find the sweet spot of a bat by feel and sound, and compute how much exit velocity a hitter loses away from it.

You will need

- Three or four different balls (tennis ball, rubber ball, softball or baseball, foam ball)
- A tape measure taped vertically to a wall beside a hard floor
- A phone with slow-motion video (helpful)
- A wooden bat, or a broom handle as a substitute
- A small hammer or a second ball for tapping
- A pencil and masking tape for marking
- The scorebook and a calculator

Steps

1. **Predict.** Rank the balls from highest to lowest coefficient of restitution.
2. Drop each ball from 1.00 m beside the tape measure onto a hard floor. Film it, or have a partner watch, and record the height of the top of the first bounce. Do 5 drops per ball.
3. Compute the mean rebound height and $e = \sqrt{h_{\text{up}}/h_{\text{down}}}$ for each ball.
4. Repeat for one ball from 0.50 m and 1.50 m. Is e the same from each height?
5. Hold the bat loosely by the handle between your thumb and finger, barrel hanging down. Have a partner tap the barrel gently with the hammer every 2 cm from the end.
6. At each point, record how much vibration you feel (0 = none, 3 = strong) and whether the sound is a dull thud or a ringing tone.
7. Mark the point of least vibration with tape. Measure its distance from the end of the barrel.
8. Using $v = q(90) + (1 + q)(70)$, compute the exit velocity for $q = 0.20$ at your sweet spot and $q = 0.12$ near the end.

9. **Decide.** Write one sentence telling a young hitter where on the bat to aim and why, using your data.

Tips

- Read the rebound height at the bottom of the ball each time, the same way you measured the drop.
- The sweet spot is quiet: listen for the dull sound.

Check your work

- ☐ I measured five drops for each ball and computed e .
- ☐ I mapped vibration along the bat and found its sweet spot.
- ☐ I computed exit velocities on and off the sweet spot.

SCOREBOOK

1. Bounce table: ball, five rebound heights, mean, e .
2. Draw the bat to scale and shade a vibration map along its length; mark the sweet spot.
3. Draw a momentum diagram of the collision: arrows for the ball's momentum before and after, labelled with values.

KEY FORMULAS

$$p = mv \quad F \Delta t = \Delta p$$
$$e = \frac{\text{speed of separation}}{\text{speed of approach}} = \sqrt{\frac{h_{\text{up}}}{h_{\text{down}}}}$$
$$v_{\text{ball}} = q v_{\text{pitch}} + (1 + q) v_{\text{bat}}$$
$$1 \text{ mph} = 0.447 \text{ m/s}$$

From history. Wooden bats are usually made of ash, maple or birch. Major League Baseball's rules allow a bat up to 42 inches long and 2.61 inches thick, and a ball weighing 5 to 5¼ ounces.

WORKED EXAMPLES

Example 1. A pitch arrives at 90 mph and the bat's sweet spot is moving at 70 mph. Using $q = 0.2$, find the exit velocity. Repeat for a hit off the sweet spot, where $q = 0.1$.

Show solution

1. Sweet spot: $0.2(90) + 1.2(70) = 18 + 84 = 102$ mph.
2. Off the sweet spot: $0.1(90) + 1.1(70) = 9 + 77 = 86$ mph.

Answer: 102 mph on the sweet spot and 86 mph off it: a few centimeters on the barrel cost 16 mph.

Example 2. A baseball is dropped from 1.00 m onto concrete and rebounds to 0.30 m. Find its coefficient of restitution.

Show solution

1. $e = \sqrt{0.30/1.00} = \sqrt{0.30} \approx 0.55$.

Answer: About 0.55: the ball leaves the floor at 55% of the speed with which it hit.

Example 3. A 0.145 kg baseball arrives at 40 m/s and leaves the bat at 45 m/s in the opposite direction. The contact lasts 0.70 ms. Find the change in momentum and the average force.

Show solution

1. Taking the outgoing direction as positive:
 $\Delta p = 0.145(45) - 0.145(-40) = 0.145 \times 85 \approx 12.3 \text{ kg}\cdot\text{m/s}$.
2. $F = \frac{12.3}{0.00070} \approx 17,600 \text{ N}$.

Answer: About 12.3 kg·m/s and 17,600 N, the weight of a small car, for less than a thousandth of a second.

PRACTICE

1. Easy Find the momentum of a 0.145 kg baseball moving at 40 m/s.

Show answer

$$p = 5.8 \text{ kg}\cdot\text{m/s}.$$

2. Easy Convert 100 mph to meters per second.

Show answer

$$100 \times 0.447 = 44.7 \text{ m/s}.$$

3. Easy A ball dropped from 2.0 m rebounds to 0.50 m. Find e .

Show answer

$$e = \sqrt{0.25} = 0.50.$$

4. Medium Find the exit velocity for a 95 mph pitch and a 75 mph bat at the sweet spot ($q = 0.2$).

Show answer

$$19 + 90 = 109 \text{ mph}.$$

5. Medium A hitter adds 5 mph of bat speed. How much exit velocity does she gain at the sweet spot? How much would 5 mph more pitch speed add?

Show answer

$$\text{Bat: } 1.2 \times 5 = 6 \text{ mph; pitch: } 0.2 \times 5 = 1 \text{ mph}.$$

6. Medium A softball (0.19 kg) arrives at 25 m/s and leaves at 30 m/s in the opposite direction after 1.0 ms of contact. Find the average force.

Show answer

$$\Delta p = 0.19 \times 55 = 10.45 \text{ kg}\cdot\text{m/s}; F \approx 10,500 \text{ N}.$$

7. Medium Explain why a hit off the end of the bat or near the handle stings the hands.

Show answer

Away from the sweet spot, much of the collision's energy sets the bat vibrating; those vibrations travel to the hands (felt as a sting) and leave less energy for the ball.

8. **Medium** Who was named “Physicist to the National League,” and what book did he write?

Show answer

Robert Adair of Yale, author of *The Physics of Baseball* (1990).

9. **Hard** A ball with $e = 0.55$ is dropped from 1.50 m. How high is its first bounce and its second?

Show answer

$$0.55^2 \times 1.50 \approx 0.45 \text{ m}; 0.3025 \times 0.45 \approx 0.14 \text{ m}.$$

10. **Hard** What bat speed at the sweet spot is needed to give an exit velocity of 100 mph off an 85 mph pitch?

Show answer

$$100 = 17 + 1.2v, v \approx 69 \text{ mph}.$$

11. **Hard** Find the kinetic energy of a 0.145 kg ball leaving the bat at 45 m/s. If a 0.90 kg bat moves at 32 m/s, what is its kinetic energy (treat it as a point mass)?

Show answer

$$\text{Ball } \frac{1}{2}(0.145)(45^2) \approx 147 \text{ J}; \text{ bat } \frac{1}{2}(0.90)(32^2) \approx 461 \text{ J}.$$

12. **Challenge** Nathan shows that $q = \frac{e - r}{1 + r}$, where r is the ball’s mass divided by the bat’s “effective mass” at the impact point. With $e = 0.50$ and $r = 0.25$, find q and the exit velocity for a 90 mph pitch and a 70 mph bat. What happens to q if a lighter bat makes $r = 0.30$?

Show answer

$q = 0.25/1.25 = 0.20$; exit 102 mph. With $r = 0.30$: $q = 0.20/1.30 \approx 0.154$, so for the same bat speed the exit velocity falls; the lighter bat helps only if it lets the hitter swing faster.

COMMON MISTAKES

- Forgetting that the ball reverses direction, so the change in momentum adds the two speeds.
- Using $e = h_{\text{up}}/h_{\text{down}}$ without the square root.
- Thinking a heavier bat always hits farther; it does only if it does not slow the swing.

Make it a game • Rebound Estimation Duel. Collect three balls of different bounce. Each of you predicts how high each will rebound from a one-meter drop, and writes the guesses down. Drop and measure against a wall marked with tape. Closest guess wins a point. Then compute the coefficient of restitution for each ball as the square root of rebound height over drop height, and rank them.

2.2 THE PITCH AND THE MAGNUS EFFECT

OBJECTIVES

- Explain the Magnus effect and predict which way a spinning ball curves.
- Use Lyman Briggs’s 1959 results to compute the curve of a pitch from its spin.
- Compute flight times, spins in turns and gravity drop for a pitch.

Warm-up. Roll a soft ball off a table edge with no spin, then with backspin (pull your hand back as you release it), then with topspin. Watch where it lands each time. Write down which way the spin seemed to push the ball.

WATCH

What Is The Magnus Force?

Veritasium · 3:46

<https://www.youtube.com/watch?v=23f1jvGUWJs>

WHEN TO WATCH

Before “the physics” paragraph. Watch the spinning ball and say which way the air is deflected and which way the ball moves.

BACKUP VIDEO

Why Curveballs Are in the Eye of the Beholder

SciShow · 3:20

<https://www.youtube.com/watch?v=duKr7SQewtk>

Optional, after “on the field.” It explains why a curveball seems to “break” suddenly to a hitter.

KEY TERMS

Magnus effect

The sideways force on a spinning ball moving through air, toward the side where the ball’s surface moves backward relative to the air flow.

spin axis

The line about which a ball spins. Its direction decides which way the Magnus force points.

rpm

Turns per minute;

$1 \text{ rpm} = \frac{1}{60} \text{ turn per second.}$

backspin and topspin

Backspin: the top of the ball moves

backward, giving lift. Topspin: the top

moves forward, pushing the ball down.

wind tunnel

A tube in which air is blown past a

fixed object to measure the forces on it.

CORE IDEAS

The story. For a century people argued about whether a curveball really curves or only seems to. In 1959 Lyman Briggs, who had directed the National Bureau of Standards (now NIST) from 1933 to 1945, settled it. He had spent his career measuring things precisely, and he loved baseball. With pitchers Camilo Pascual and Pedro Ramos of the Washington Senators at Griffith Stadium, he fastened a light paper tape to a ball and counted how many twists it picked up on the way to the plate. Then he spun balls in a wind tunnel at the Bureau and measured how far they were pushed sideways. He reported that a curve could bend as much as about $17\frac{1}{2}$ inches over the distance to the plate.

How they figured it out. Isaac Newton had noticed in 1672 that a tennis ball struck with spin swerved in flight. The German scientist Heinrich Gustav Magnus explained the effect for spinning cylinders and spheres in 1852, while studying why spinning cannon shot drifted. Briggs measured it for real baseballs. His pitchers' balls turned 15 or 16 times on the way to the plate, about 1,600 rpm. In the wind tunnel, at spins up to 1,800 rpm and air speeds up to 150 feet per second, he found that the sideways push grew in direct proportion to the spin and to the square of the speed. A faster pitch is pushed harder but reaches the plate sooner, so the two effects nearly cancel: over 60 feet the curve depended mainly on the spin.

The physics. A spinning ball drags a thin layer of air around with it. On the side where the surface moves *with* the oncoming air, the flow stays attached longer and is deflected; by Newton's third law, the air pushes the ball the other way. The result: a ball curves toward the side where its surface is moving *backward* into the air flow, that is, in the direction the front of the ball is turning. Backspin gives an upward force (a fastball falls less than gravity alone would make it); topspin gives a

downward force (a curveball dives); sidespin bends the ball left or right. Over a time t a steady sideways acceleration a moves the ball $d = \frac{1}{2}at^2$. Briggs's 17.5 inches in 0.6 s means $a = 2d/t^2 \approx 2.5 \text{ m/s}^2$, about a quarter of g .

On the field. Today stadium tracking systems measure the spin rate and spin axis of every pitch. A fastball with more backspin falls less than the hitter expects and seems to “rise”; it does not rise, it simply drops less. A curveball thrown with topspin drops more than expected. Pitchers change the spin axis with the grip and the angle of the hand at release. The same physics bends a soccer ball (Unit 3), dips a topspin tennis forehand (Unit 4) and lifts a golf ball (Unit 5). **The risk side:** many young pitchers throw curveballs before their arms are mature and their mechanics sound; coaches and Pitch Smart recommend learning good fastball and change-up mechanics first.

Think it through. The ball does not curve because it is “thrown in a curve.” Once it leaves the hand, only gravity, drag and the Magnus force act on it. Everything the pitcher does happens before release.

PICTURE STUDY



Lyman J. Briggs and Ossie Bluege at Griffith Stadium, National Bureau of Standards photographer, 1957
· Photograph · Griffith Stadium, Washington, D.C.

Image: [Wikimedia Commons](#), public domain

This photograph from the National Bureau of Standards shows Lyman Briggs, then in his eighties and the Bureau's director emeritus, with Ossie Bluege, a former Washington Senators third baseman and manager who was then working for the club. They are preparing the tape method Briggs used to count how many times a pitched ball turned on its way to the plate.

Look closely

- Find the tape. How is it attached to the ball, and where will the rest of it lie during the pitch?
- Look at the two men's clothing and ages. What does the photograph suggest about who can do science?
- Look for the stadium in the background. Why do you think Briggs wanted real pitches from real pitchers, and not only a wind tunnel?

Talk about it

1. Briggs used two methods, the tape on the field and the wind tunnel in the laboratory. Why is it wise to measure the same thing in two different ways?
2. If the tape showed 16 twists over a pitch lasting 0.6 s, what spin rate in rpm did the ball have?

Safety first. Throw only soft or foam balls indoors and keep clear of windows, lamps and people. When launching the paper-cup glider, aim away from faces and keep the rubber bands short; never stretch a rubber band toward anyone.

PROJECT

The Magnus Glider and the Spinning Throw

You will build a Magnus glider from two paper cups, launch it with and without spin, and measure how far spin bends its path. Then you will test the direction rule with a soft ball.

You will need

- Two lightweight paper or foam cups and clear tape
- Four or five rubber bands looped into a chain
- A tape measure and masking tape for floor marks
- A soft foam ball
- A phone camera (helpful)
- The scorebook and a calculator

Steps

1. Tape the two cups bottom to bottom to make a spool.
2. Hold the end of the rubber-band chain against the spool's middle with your thumb, and wind the chain once around the waist of the spool so that it unrolls from the bottom.
3. **Predict.** When the spool is launched forward with the band pulling from underneath, it will spin with backspin. Predict whether it will rise, fall or fly level.
4. Stretch the band and release the spool from a fixed height (for example, standing on a mark with your hand at shoulder height). Record where it lands and sketch its path. Do 5 launches.
5. Now push the spool gently forward by hand with no spin from the same height and speed. Do 5 throws and record the landing points.
6. Wind the band the other way so that the spool gets topspin. Do 5 launches and record.
7. Turn the spool on its side (axis vertical) and launch it with sidespin. Which way does it curve? Measure the sideways distance from a straight line.

8. With the foam ball, throw 10 gentle pitches toward a partner 6 m away with sidespin, and have the partner mark where each crosses a line on the floor. Measure the average curve.
9. Use the direction rule (the ball curves the way its front surface turns) to explain every result.
10. **Decide.** Write how you would grip and release a soft ball to make it curve to your left, and test it.

Tips

- Launch from the same spot and height each time so that only the spin changes.
- Slow-motion video makes the spin direction easy to see.

Check your work

- ☐ I recorded 5 launches each with backspin, no spin, topspin and sidespin.
- ☐ I measured the sideways curve of the sidespin launches and the foam-ball pitches.
- ☐ I explained each result with the direction rule.

SCOREBOOK

1. Glider table: spin type, five landing distances, mean, path sketch (rise, fall, level, curve).
2. Draw a ball from above with sidespin, the air flowing past it, the deflected air and the Magnus force arrow.
3. Draw the path of a fastball with backspin and a curveball with topspin on the same side-view diagram, with a dashed line for a no-spin pitch.

KEY FORMULAS

$$d = \frac{1}{2}at^2 \quad t = \frac{D}{v}$$

$$\text{Briggs: } a \propto (\text{spin}) \times v^2$$

$$\text{turns} = \frac{\text{rpm}}{60} \times t$$

From history. Candy Cummings, a pitcher of the 1860s and 1870s, is traditionally credited with inventing the curveball and is in the National Baseball Hall of Fame. Briggs reported his results in the *American Journal of Physics* in 1959. He lived until 1963.

WORKED EXAMPLES

Example 1. Briggs's wind tunnel predicted a curve of 17.5 inches for a pitch at 100 ft/s spinning at 1,800 rpm over 60 feet. Find the flight time, the number of turns the ball makes, and the sideways acceleration in m/s^2 .

Show solution

1. Time: $t = 60/100 = 0.60 \text{ s}$.
2. Turns: $\frac{1800}{60} \times 0.60 = 18$.
3. Deflection in meters: $17.5 \times 0.0254 \approx 0.444 \text{ m}$.
4. $a = \frac{2d}{t^2} = \frac{2(0.444)}{0.36} \approx 2.5 \text{ m/s}^2$.

Answer: 0.60 s, 18 turns, and about 2.5 m/s^2 , roughly a quarter of the acceleration of gravity.

Example 2. At 100 ft/s, Briggs found that the curve is proportional to the spin. Using 17.5 inches at 1,800 rpm, predict the curve at 1,200 rpm and at 1,600 rpm.

Show solution

1. 1,200 rpm: $17.5 \times \frac{1200}{1800} \approx 11.7 \text{ in}$.
2. 1,600 rpm: $17.5 \times \frac{1600}{1800} \approx 15.6 \text{ in}$.

Answer: About 11.7 inches (matching Briggs's own table) and 15.6 inches.

Example 3. A fastball takes 0.45 s to reach the plate. How far would gravity alone make it drop? If backspin produces an upward acceleration of 3.0 m/s^2 , how far does it actually drop?

Show solution

1. Gravity alone: $\frac{1}{2}(9.8)(0.45)^2 \approx 0.99 \text{ m}$.
 2. Net downward acceleration: $9.8 - 3.0 = 6.8 \text{ m/s}^2$; drop
 $\frac{1}{2}(6.8)(0.45)^2 \approx 0.69 \text{ m}$.
-

Answer: About 0.99 m without spin and 0.69 m with backspin: the ball falls 30 cm less than the hitter's eyes expect, so it seems to rise.

PRACTICE

1. **Easy** Convert 2,400 rpm to turns per second.

Show answer

$$2400/60 = 40 \text{ turns per second.}$$

2. **Easy** A ball thrown by a right-handed pitcher spins so that its front surface turns toward first base (the pitcher's left). Which way does it curve?

Show answer

Toward first base, the pitcher's left: the ball curves in the direction its front surface is turning.

3. **Easy** What kind of spin makes a fastball fall less than gravity alone would?

Show answer

Backspin, which gives an upward Magnus force.

4. **Medium** A pitch travels 55 ft at 130 ft/s. Find the flight time.

Show answer

$$t \approx 0.42 \text{ s.}$$

5. **Medium** A curveball spinning at 2,500 rpm takes 0.50 s to reach the plate. How many turns does it make?

Show answer

$$\frac{2500}{60} \times 0.50 \approx 21 \text{ turns.}$$

6. **Medium** A ball experiences a sideways acceleration of 2.0 m/s^2 for 0.50 s . How far does it curve?

Show answer

$$d = \frac{1}{2}(2.0)(0.25) = 0.25 \text{ m.}$$

7. **Medium** How did Briggs measure the spin of a real pitch at Griffith Stadium?

Show answer

He fastened a light tape to the ball, laid the rest loosely along the ground toward the plate, and counted the twists in the tape after the catch.

8. **Medium** Explain in two sentences why a “rising fastball” does not really rise.

Show answer

A pitch thrown nearly level falls under gravity; backspin gives an upward force smaller than gravity, so the ball only falls less than expected. The hitter, expecting a normal drop, sees it arrive higher and perceives a rise.

9. **Hard** Briggs found the sideways acceleration proportional to spin times the square of speed. If a pitch at 100 ft/s has a sideways acceleration of 8.1 ft/s^2 , what would it be at 125 ft/s with the same spin? How long would the 125 ft/s pitch take over 60 ft , and how far would it curve?

Show answer

$$a = 8.1 \times 1.25^2 \approx 12.7 \text{ ft/s}^2; t = 0.48 \text{ s}; d = \frac{1}{2}(12.7)(0.48)^2 \approx 1.46 \text{ ft} \approx 17.5 \text{ in.}$$

The curve is about the same: speed cancels out.

10. **Hard** A curveball has topspin that adds a downward acceleration of 4.0 m/s^2 . Over 0.50 s , how much farther does it drop than a ball with no spin?

Show answer

$$\frac{1}{2}(4.0)(0.25) = 0.50 \text{ m more drop.}$$

11. **Hard** Why does a ball thrown with a spin axis tilted halfway between vertical and horizontal curve less sideways than one spinning about a vertical axis?

Show answer

The Magnus force is perpendicular to both the motion and the spin axis; tilting the axis turns part of the force up or down, so only part of it pushes sideways.

12. **Challenge** Show that if sideways acceleration is $a = k\omega v^2$ and the pitch covers distance D at constant speed v , then the curve d does not depend on v . What does it depend on?

Show answer

$t = D/v$, so $d = \frac{1}{2}k\omega v^2(D/v)^2 = \frac{1}{2}k\omega D^2$. It depends only on the spin and the distance (and on k , which reflects the ball and the air).

COMMON MISTAKES

- Getting the direction backward: the ball moves toward the side where its surface moves backward into the air, the way its front is turning.
- Thinking the ball keeps curving because of the throwing motion; after release only gravity, drag and the Magnus force act.
- Forgetting to convert inches to meters, or rpm to turns per second.

Make it a game • Curve Caller. Your parent describes a spinning ball without showing it: backspin, topspin, or spin clockwise seen from above, plus its direction of travel. You shout which way the Magnus force pushes and where the ball curves. A wrong call costs a point. Then reverse it. For a bonus, explain in one sentence what Lyman Briggs measured in his wind tunnel in 1959.

2.3 THROWING MECHANICS AND ARM CARE

OBJECTIVES

- Describe the phases of a pitch and the loads on the shoulder and elbow.
- Apply the Pitch Smart guidelines to compute rest days and plan a season.
- Measure throwing speed from timing and distance and keep a throwing log.

Warm-up. Stand 5 m from a partner and play catch with a soft ball for three minutes, gradually stepping back. Count your throws. Then write: how did your arm feel at the start, and how did it feel at the end? What did you do to warm up?

WATCH

Youth Baseball Pitch Count Guidelines // 4 Vital Pitch Count Topics to Save Your Arm

Building Better Baseball • 7:19

https://www.youtube.com/watch?v=wDRXffx_Vgo

WHEN TO WATCH

After “the physics” paragraph. Write down each guideline the coach names and compare it with the table in this lesson.

Note: The video’s description invites coaches to an email sign-up; it is not needed.

BACKUP VIDEO

The Simplest Arm Care Program For Youth Baseball

Coach Dan Blewett • 5:54

<https://www.youtube.com/watch?v=awSMT7PlZ5A>

Optional, before the project. A short band routine for the shoulder; do it only with a light band and a parent’s approval.

KEY TERMS

pitch count

The number of pitches a pitcher throws in a game or day; the main measure of workload in youth baseball.

Pitch Smart

Guidelines on pitch counts and rest days published by Major League Baseball and USA Baseball in 2014.

arm cocking and acceleration

The phases in which the arm rotates back to its maximum external rotation and then whips forward to release.

torque at the elbow

The twisting load on the elbow as the forearm lags behind the upper arm during the throw.

fatigue

Loss of muscle force and control after repeated effort; it changes mechanics and raises injury risk.

CORE IDEAS

The story. Walter Johnson pitched for the Washington Senators for 21 seasons, from 1907 to 1927, and won 417 games. Batters feared his fastball, yet his motion was smooth, sidearm and nearly effortless, and he pitched for two decades. In the twenty-first century, doctors noticed something troubling: more and more teenage pitchers needed surgery on their elbows. In November 2014 Major League Baseball and USA Baseball, advised by physicians and researchers including those at the American Sports Medicine Institute, published *Pitch Smart*, age-based limits on pitches and rest.

How they figured it out. Researchers at ASMI filmed pitchers with high-speed motion capture and computed the forces in their joints. In a 1995 study, Glenn Fleisig and his colleagues found that, in experienced adult pitchers, the elbow carries a twisting load of about 64 newton-meters near the moment of greatest arm cocking, and the shoulder must hold the arm in its socket against a pull greater than the pitcher's body weight at release. Other studies followed young pitchers for years. They found that the strongest predictors of injury were *too much pitching*: high pitch counts, pitching while fatigued, pitching for several teams, and pitching all year round. Good mechanics lowered the loads, but no mechanics could make unlimited throwing safe.

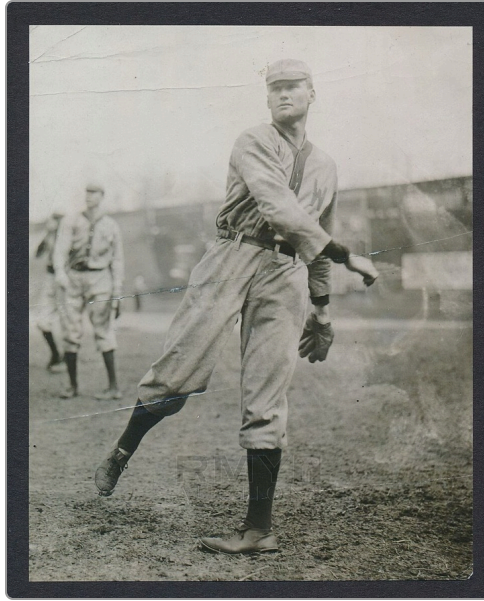
The physics. A pitch has phases: windup, stride, arm cocking, arm acceleration, deceleration and follow-through. During arm cocking the trunk rotates forward while the arm is still back, so the forearm lags and the elbow is twisted, like a door pushed open past its stop. In arm acceleration, which lasts only a few hundredths of a second, the shoulder rotates inward at up to about 7,000° per second. After release, the arm is moving very fast with no ball to push, and the muscles of the back of the

shoulder must stop it: the follow-through spreads that braking over a longer time and distance, lowering the force, just as $F = \Delta p / \Delta t$ predicts. Fatigued muscles cannot share the load, so more of it falls on ligaments and tendons.

On the field. Pitch Smart sets a daily maximum of 95 pitches for ages 13–16 and 105 for ages 17–18, with required rest days that rise with the count. For ages 13–14, 1–20 pitches need no rest day, 21–35 need one, 36–50 two, 51–65 three, and 66 or more four. No pitcher should pitch on three consecutive days, and the guidelines recommend months off from competitive pitching each year. Softball pitchers throw underhand with a windmill motion, which loads the shoulder differently, but they too need rest and a careful count. **The risk side:** a sore arm is not toughness; it is a warning. The high-percentage choice is to rest.

Think it through. A wise player plays the long game. Walter Johnson pitched for 21 seasons; a young pitcher who throws too much at 13 may not pitch at 17. Counting pitches is a way of caring for the body you were given.

PICTURE STUDY



Walter Johnson Warming Up, American Press Association, 1911 · Photograph · Washington, D.C.

Image: [Wikimedia Commons](#), public domain

Walter Johnson, called “the Big Train,” pitched 21 seasons for Washington and was one of the first five players chosen for the National Baseball Hall of Fame in 1936. He was known for his sportsmanship as well as his speed. This press photograph shows him warming up in 1911, early in his long career.

Look closely

- Look at his arm angle. Is he throwing over the top or from the side?
- Find his feet and trunk. Can you see the stride and the turn of the body that begin the kinetic chain?
- Look at his expression and posture. Does the motion look strained or easy?

Talk about it

1. Johnson warmed up before pitching. What does a warm-up do for the muscles and joints before the loads of a pitch?
2. Johnson pitched until he was 39. What habits would help a young pitcher today to pitch for many years?

Safety first. This is the most important safety lesson in the unit. Warm up before every throw, start short and move back gradually, and never throw hard when your arm is tired or sore. Follow the Pitch Smart limits for your age and never pitch on three days in a row. Pain in the shoulder or elbow is a signal to stop and tell a parent, not something to throw through.

PROJECT

Throwing Log and Speed Test

You will measure your throwing speed with a phone or stopwatch, keep a two-week throwing log with counts and rest days, and see how fatigue changes your accuracy.

You will need

- A soft ball or tennis ball (a baseball only outdoors with a glove and a parent present)
- A partner with a glove
- A tape measure and cones
- A phone with slow-motion video, or a stopwatch
- A target (a box or a taped square on a fence, about 50 cm on a side)
- The scorebook and a calculator

Steps

1. Warm up: arm circles, then 20 easy throws starting at 5 m and moving back to 15 m.
2. Measure a 15 m throwing distance with the tape and mark it with cones.
3. **Predict.** Estimate your throwing speed in mph.
4. Make 5 firm (not maximum) throws to your partner. Film each one from the side so that release and catch are both visible, and count frames (or use the stopwatch) to find the flight time.
5. Compute each speed $v = d/t$ and convert to mph. Find the mean.
6. Accuracy and fatigue: throw 30 throws at the target from 10 m in sets of 10, with 1 minute's rest between sets. Record hits in each set and rate your arm's tiredness (1 to 5) after each set. Stop at once if anything hurts.
7. Keep a throwing log for two weeks: date, number of throws, how hard (easy, medium, firm), arm feeling, and rest day or not. Apply the Pitch Smart table for your age to any day you throw more than 20 firm throws.
8. At the end of two weeks, total your throws and count your rest days.

9. **Decide.** Write your own arm-care rules for a season: warm-up, counts, rest days and what you will do if your arm is sore.

Tips

- At 240 frames per second, 180 frames is 0.75 s.
- Firm throws, not all-out throws, give reliable speeds and protect the arm.

Check your work

- ☐ I measured five throwing speeds and computed the mean in m/s and mph.
- ☐ I recorded accuracy and tiredness for three sets.
- ☐ I kept a two-week log and wrote my arm-care rules.

SCOREBOOK

1. Speed table: throw, frames (or time), seconds, speed (m/s), speed (mph).
2. Fatigue graph: hits per set and tiredness rating per set on the same axes.
3. Copy the Pitch Smart rest table for your age neatly, and use it to plan a two-game week.

KEY FORMULAS

$$v = \frac{d}{t}$$
$$F_{\text{avg}} = \frac{\Delta p}{\Delta t} = \frac{m \Delta v}{\Delta t}$$
$$KE = \frac{1}{2}mv^2$$

From history. Walter Johnson's 110 shutouts remain the major-league record. The American Sports Medicine Institute was founded in Birmingham, Alabama, in 1987 by the orthopedic surgeon James Andrews and colleagues.

WORKED EXAMPLES

Example 1. Under Pitch Smart, how many rest days does a 14-year-old need after throwing 58 pitches? And a 16-year-old after 80 pitches (bands for ages 15–16: 1–30 none, 31–45 one, 46–60 two, 61–75 three, 76 or more four)?

Show solution

1. 14-year-old: 58 is in the 51–65 band, so three days of rest.
 2. 16-year-old: 80 is in the 76+ band, so four days of rest.
-

Answer: Three days and four days.

Example 2. A partner stands 15.0 m away. Slow-motion video shows a throw takes 0.75 s from release to catch. Estimate the average speed in m/s and mph.

Show solution

1. $v = 15.0/0.75 = 20$ m/s.
 2. $20/0.447 \approx 45$ mph.
-

Answer: About 20 m/s, or 45 mph. (The ball is a little faster at release and slower at the catch.)

Example 3. After release the hand and forearm, with an effective mass of about 1.5 kg, are moving at about 25 m/s. Compare the average braking force if the arm stops in 0.05 s with no follow-through and in 0.20 s with a full follow-through.

Show solution

1. Momentum: $1.5 \times 25 = 37.5$ kg·m/s.
 2. No follow-through: $37.5/0.05 = 750$ N.
 3. Full follow-through: $37.5/0.20 \approx 190$ N.
-

Answer: About 750 N against 190 N: a full follow-through cuts the braking force to a quarter. *Illustrative values.*

PRACTICE

1. **Easy** What is the Pitch Smart daily maximum for a 13-year-old? For a 17-year-old?

Show answer

95 pitches; 105 pitches.

2. **Easy** A 13-year-old throws 30 pitches. How many rest days are required?

Show answer

One (21–35 band).

3. **Easy** Name the six phases of a pitch.

Show answer

Windup, stride, arm cocking, arm acceleration, deceleration, follow-through.

4. **Medium** A throw covers 18 m in 0.80 s. Find the average speed in m/s and mph.

Show answer

$22.5 \text{ m/s} \approx 50 \text{ mph}$.

5. **Medium** Find the kinetic energy of a 0.145 kg baseball at 35 m/s.

Show answer

$\frac{1}{2}(0.145)(35^2) \approx 89 \text{ J}$.

6. **Medium** A 14-year-old pitches 45 pitches on Saturday. On what day may he next pitch?

Show answer

Two rest days (36–50 band): Sunday and Monday; he may pitch again on Tuesday.

7. **Medium** Give three workload habits that research links to youth arm injuries.

Show answer

Any three: high pitch counts, pitching while fatigued, pitching all year with no months off, pitching for several teams at once, pitching on consecutive days, also catching between pitching appearances.

8. **Medium** Why can good mechanics not make unlimited pitching safe?

Show answer

Even with good mechanics the elbow and shoulder carry large loads on every pitch; tissues need time to recover, and fatigue changes mechanics, so the total number of pitches still matters.

9. **Hard** The ball is accelerated from about 2 m/s to 38 m/s in 0.05 s. Find the average force on the 0.145 kg ball.

Show answer

$$F = 0.145 \times 36/0.05 \approx 104 \text{ N.}$$

10. **Hard** A 15-year-old pitcher wants to pitch on Saturday and again on Tuesday. What is the largest number of pitches he may throw on Saturday (bands for 15–16: 1–30 none, 31–45 one, 46–60 two, 61–75 three)?

Show answer

He has Sunday and Monday as rest days (two days), so he may throw at most 60 pitches on Saturday.

11. **Hard** Explain with impulse why a pitcher's follow-through protects the shoulder.

Show answer

The arm's momentum must be removed after release. A long follow-through spreads the braking over more time and distance, so the average force ($\Delta p / \Delta t$) on the muscles and joint is smaller.

12. **Challenge** A youth team plays games on Saturday and Wednesday every week. Using the 13–14 table (21–35 one day, 36–50 two, 51–65 three, 66+ four), design a two-pitcher plan that covers two games a week with the most total pitches while letting each pitcher pitch in at most one game a week. Then explain why a team with three pitchers is safer.

Show answer

Each pitcher pitches one game a week and so has at least 3 days before the next game; each may throw up to 95 pitches (the daily max), with four rest days, and both games are covered. A three-pitcher plan lets the team keep counts lower, rotate when a pitcher is tired, and avoid the temptation to stretch a pitcher in a close game.

COMMON MISTAKES

- Counting only game pitches and forgetting warm-up and practice throws.
- Treating soreness as a sign of hard work rather than a signal to rest.
- Using maximum-effort throws for every test; firm throws are safer and more consistent.

Make it a game • Spot the Overuse. Take a pitcher who has thrown 62 pitches. From memory, write a week-long plan with throwing days and rest days that follows the Pitch Smart guidelines. Your parent then adds one flaw, such as a short rest or a spike in pitch count, and you hunt for it. Check your answer against the guideline table. Swap and repeat with a different pitcher.

Scripture. “A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished.” (Proverbs 22:3, KJV)

Prudence sees a danger coming and takes cover. Counting pitches and resting a tired arm is not weakness; it is foresight.

2.4 FIELDING AND THE OUTFIELDER'S PATH

OBJECTIVES

- Compute the hang time, height and range of a fly ball with projectile equations, and explain how air resistance changes them.
- Explain the gaze heuristic and show that, without air resistance, the tangent of the gaze angle rises at a steady rate for a fielder at the landing spot.
- Test catching strategies with real fly balls.

Warm-up. Toss a soft ball straight up as high as you safely can and time how long it is in the air. From the time alone, estimate how high it went. (Hint: it spends half the time going up.)

WATCH

The Calculus of Catching Fly Balls | World Science Festival

World Science Festival · 5:43

<https://www.youtube.com/watch?v=-J1qryj6kdg>

WHEN TO WATCH

After “how they figured it out.” Listen for the difference between computing the landing point and keeping a simple rule with the eyes.

BACKUP VIDEO

How To Play the Outfield with Gold Glover Jason Heyward

Chicago Cubs · 5:52

<https://www.youtube.com/watch?v=TFaCkLLUKJA>

Optional, before the project. A major-league outfielder shows his first step, footwork and communication.

KEY TERMS

projectile

An object moving freely under gravity (and air resistance) after launch.

hang time

The time a fly ball spends in the air.

gaze heuristic

A rule of thumb for catching: run so that the angle of your gaze up to the ball keeps rising at a steady rate.

drag

The force of air resistance, which grows with speed and shortens the flight of a fly ball.

CORE IDEAS

The story. Tris Speaker, the center fielder of the Boston Red Sox and later Cleveland, played so close to the infield that he sometimes took part in plays at second base, yet he ran back to catch balls hit over his head. How could anyone know, a second after the crack of the bat, where a ball would land 4 seconds later? In 1968 a physicist named Seville Chapman published a short paper, “Catching a Baseball,” in the *American Journal of Physics*. He suggested the fielder does not compute anything; he watches.

How they figured it out. One idea was that fielders estimate the landing point, like a computer solving equations, and run straight to it. But video shows outfielders do not run straight to the spot; they often run on gentle curves and arrive just in time, still moving. Chapman showed that, in the ideal case without air, a fielder standing at the landing point sees the tangent of the ball’s elevation angle rise at a perfectly steady rate. If the angle rises faster and faster, the ball will land behind him; if it rises more slowly, in front. In 1995 Michael McBeath, Dennis Shaffer and Mary Kaiser published a study in *Science* showing that fielders also keep the ball moving along a straight line in their view. The psychologist Gerd Gigerenzer later called such rules the “gaze heuristic.”

The physics. Ignoring air, a ball launched at speed v and angle θ has horizontal speed $v_x = v \cos \theta$ and vertical speed $v_y = v \sin \theta$. It rises for v_y/g and falls for the same time, so the hang time is $T = 2v_y/g$, the peak height $H = v_y^2/2g$, and the range $R = v_x T$. For a fielder at the landing point, the ball’s height is $y = v_y t - \frac{1}{2}gt^2$ and its horizontal distance from him is $v_x(T - t)$. Their ratio simplifies to $\tan \alpha = \frac{g}{2v_x} t$, which rises steadily with time. Real fly balls feel drag, which shortens the range a great deal (for example, a drive that would carry about 140 m in a vacuum may travel only about 110 m), but the gaze rule still works because the fielder keeps adjusting.

On the field. Good outfielders take a quick first step back or in, keep their eyes on the ball and head steady, and run on the balls of their feet so the ball does not seem to bounce in their vision. They catch on the run and communicate loudly. The same

rule helps a dog catch a disc and a pilot judge a landing. **The risk side:** eyes on the ball means eyes off the fence and your teammates; collisions are the main danger in fielding, which is why fielders call for the ball and learn the warning track.

Think it through. A rule of thumb can beat a complicated calculation when there is little time and the world keeps changing. The fielder's brain does not need the range formula; it needs to keep one angle behaving.

PICTURE STUDY



Tris Speaker, Boston, Bain News Service, 1912 · Glass-plate negative photograph · Library of Congress, Washington, D.C.

Image: [Wikimedia Commons](#), public domain

Tris Speaker played center field from 1907 to 1928 and is in the National Baseball Hall of Fame. He was famous for playing unusually shallow, trusting his reading of the ball and his first step to catch anything hit over his head. The Bain News Service photographed him in 1912, the year Boston won the World Series.

Look closely

- Speaker is posed as a batter here. Look at his stance and shoes. What do they suggest about how quickly he could start running?
- Outfield gloves of his day were small, thin leather gloves. How would that change catching a long fly ball compared with today?
- Imagine the field behind him. Where would you stand in center field if you trusted your first step as he did?

Talk about it

1. Speaker played shallow to catch the many short hits of his era. What is the risk of that choice, and what skill reduces the risk?
2. How would the gaze heuristic help a fielder like Speaker on a ball hit over his head?

Safety first. Use a soft ball or tennis ball for fly balls, never a hard baseball without a glove and experience. Practice in an open field with no fences, trees or other players nearby, and call “mine!” loudly. Never look up while running toward another person. Wear athletic shoes, drink water, and use sun protection outdoors.

PROJECT

Hang Time and the Gaze Rule

With a partner tossing high fly balls, you will measure hang times, compute launch speeds and heights, and test whether the gaze heuristic helps you catch more balls.

You will need

- A tennis ball or soft ball (and a glove if you have one)
- A stopwatch or phone timer
- A partner who can toss high fly balls (underhand or with a soft racket)
- Cones and a tape measure
- An open field with a parent present
- The scorebook and a calculator

Steps

1. Mark your starting spot with a cone. Your partner stands 15–20 m away and tosses high fly balls to various spots within about 8 m of you.
2. **Predict.** Which method will give more catches: running straight to where you first think the ball will land, or the gaze rule?
3. Method A (guess and go): as soon as the ball is tossed, guess the landing spot, run there, then look up. 10 tosses. Record catches.
4. Method B (gaze rule): watch the ball from the start and move so that it rises steadily in your view, never speeding up or stalling. 10 tosses. Record catches.
5. Alternate methods in sets of 5 so that tiredness and practice affect both equally. Do 20 tosses of each in total.
6. Have a third person (or the tosser) time the hang time of 10 tosses with the stopwatch.
7. For each timed toss, compute the vertical launch speed $v_y = gT/2$ and peak height $H = gT^2/8$.
8. Record whether you ran straight or curved with each method.

9. **Decide.** Write which method you will use, supported by your catch percentages, and explain it with the physics.

Tips

- Call “mine!” on every ball, even in practice.
- Keep your head steady and run on the balls of your feet.

Check your work

- ☐ I recorded 20 tosses with each method and the catch rate of each.
- ☐ I timed 10 hang times and computed launch speeds and heights.
- ☐ I wrote a decision based on my data.

SCOREBOOK

1. Catch table: method, set, tosses, catches, percent.
2. Hang-time table: toss, T , v_y , H .
3. Draw a side view of a fly ball and a fielder at the landing spot, with gaze lines at 1-second intervals; label each angle.

KEY FORMULAS

$$\begin{aligned}v_x &= v \cos \theta & v_y &= v \sin \theta \\T &= \frac{2v_y}{g} & H &= \frac{v_y^2}{2g} & R &= v_x T = \frac{v^2 \sin 2\theta}{g} \\ \tan \alpha &= \frac{g}{2v_x} t \quad (\text{fielder at the landing point, no air})\end{aligned}$$

From history. McBeath, Shaffer and Kaiser published “How Baseball Outfielders Determine Where to Run to Catch Fly Balls” in *Science* in 1995. Speaker’s 792 career doubles are still the major-league record.

WORKED EXAMPLES

Example 1. A fly ball is in the air for 4.0 s. Ignoring air resistance and assuming it lands at the height it was hit, find its initial vertical speed and its peak height.

Show solution

1. $v_y = gT/2 = 9.8 \times 2.0 = 19.6 \text{ m/s.}$

2. $H = \frac{19.6^2}{2 \times 9.8} = 19.6 \text{ m.}$

Answer: 19.6 m/s upward and a peak 19.6 m high, about six stories.

Example 2. A fly ball has $v_x = 20 \text{ m/s}$. For a fielder standing at the landing point, find the gaze angle at $t = 1, 2$ and 3 s .

Show solution

1. Rate: $\frac{g}{2v_x} = \frac{9.8}{40} = 0.245 \text{ per second.}$

2. $t = 1: \tan \alpha = 0.245, \alpha \approx 13.8^\circ.$

3. $t = 2: \tan \alpha = 0.490, \alpha \approx 26.1^\circ.$

4. $t = 3: \tan \alpha = 0.735, \alpha \approx 36.3^\circ.$

Answer: The tangent rises by the same 0.245 each second, so the fielder sees a steady climb and knows he is in the right place.

Example 3. A ball has a hang time of 4.5 s. A center fielder reacts in 0.5 s and runs at 7.0 m/s. How far can he run before it lands? If he must cover 30 m, can he reach it?

Show solution

1. Running time: $4.5 - 0.5 = 4.0 \text{ s.}$

2. Distance: $7.0 \times 4.0 = 28 \text{ m.}$

Answer: He can cover 28 m; 30 m is just out of reach unless he reacts faster or dives. A quicker first step is worth more than a faster top speed.

PRACTICE

1. Easy A ball is tossed straight up and is in the air for 2.0 s. Find its launch speed and maximum height.

Show answer

$$v = 9.8 \text{ m/s}; H = 4.9 \text{ m}.$$

2. Easy State the gaze heuristic in one sentence.

Show answer

Run so that the angle of your gaze up to the ball keeps rising at a steady rate (neither speeding up nor slowing down).

3. Easy Who published “Catching a Baseball” in 1968?

Show answer

The physicist Seville Chapman, in the *American Journal of Physics*.

4. Medium A ball is hit at 30 m/s at 40° . Find v_x and v_y .

Show answer

$$v_x \approx 23.0 \text{ m/s}, v_y \approx 19.3 \text{ m/s}.$$

5. Medium For the ball in problem 4, find the hang time, peak height and range without air.

Show answer

$$T \approx 3.94 \text{ s}, H \approx 19.0 \text{ m}, R \approx 90.6 \text{ m}.$$

6. Medium Without air, which launch angle gives the greatest range? Why do real long fly balls leave the bat at a lower angle, about $25\text{--}35^\circ$?

Show answer

45° . Drag shortens high, slow-falling flights most, and backspin lift helps lower drives, so the best angle for distance in air is lower.

7. Medium A fielder sees the gaze angle rising faster and faster. Where will the ball land, and what should he do?

Show answer

Behind him; he should run back (away from home plate).

8. **Hard** A ball with $v_x = 25$ m/s lands at the fielder. Find the rate at which $\tan \alpha$ rises and the angle 3.5 s after the hit.

Show answer

Rate $9.8/50 = 0.196$ per second; $\tan \alpha = 0.686$, $\alpha \approx 34.4^\circ$.

9. **Hard** A fly ball would travel 140 m in a vacuum but goes 110 m in air. By what percent did drag shorten it?

Show answer

$30/140 \approx 21\%$.

10. **Hard** A softball outfielder stands 60 m from home. A ball is hit with hang time 3.6 s toward a spot 75 m from home. She reacts in 0.4 s. How fast must she run?

Show answer

15 m in 3.2 s: ≈ 4.7 m/s.

11. **Hard** Explain why outfielders run on the balls of their feet and keep their heads steady.

Show answer

A bouncing head makes the ball appear to jump in the visual field, spoiling the angle-tracking that the gaze heuristic depends on.

12. **Challenge** Derive $\tan \alpha = \frac{g}{2v_x}t$ from $y = v_y t - \frac{1}{2}gt^2$, the horizontal distance $v_x(T - t)$, and $T = 2v_y/g$.

Show answer

$$\tan \alpha = \frac{t(v_y - \frac{1}{2}gt)}{v_x(T - t)}. \text{ Since } v_y = \frac{1}{2}gT, v_y - \frac{1}{2}gt = \frac{1}{2}g(T - t), \text{ so}$$
$$\tan \alpha = \frac{t \cdot \frac{1}{2}g(T - t)}{v_x(T - t)} = \frac{g}{2v_x}t.$$

COMMON MISTAKES

- Using the total hang time for the rise; the ball rises for only half of it.
- Using degrees in a calculator set to radians, or the reverse.
- Taking eyes off the ball to look at the landing spot.

Make it a game • Gaze Rule Catch. Outdoors, have your parent lob a soft ball high and far. You must keep the angle of your gaze to the ball rising at a steady rate while you move, then catch it. Before each toss, estimate the hang time by counting seconds. Score a point for a catch and a point for a guess within one second. Play to ten.

2.5 TED WILLIAMS AND THE SCIENCE OF HITTING

OBJECTIVES

- Compute the time a hitter has to see, decide and swing for baseball and fastpitch softball pitches.
- Explain Ted Williams's hitting-zone chart and his rule "get a good ball to hit."
- Explain why a slight upward swing that matches the pitch's downward path gives a larger margin for timing error.

Warm-up. Have a partner hold a ruler vertically with its zero end between your open thumb and finger, then drop it without warning. Catch it and read the distance it fell. Do it 5 times. You will turn these distances into reaction times in the project.

WATCH

Ted Williams talks about swing, hitting approach in extensive interview | Bob Wolff Film Collection

National Baseball Hall of Fame and Museum · 7:51

<https://www.youtube.com/watch?v=-5dx5bGvnE0>

WHEN TO WATCH

After "the story." Listen for what Williams says about waiting for his pitch.

Note: An old television film; it opens with a short 1950s shaving-cream advertisement.

BACKUP VIDEO

A Deeper Look at Ted Williams' Swing

MLB Network · 2:12

<https://www.youtube.com/watch?v=XIUqqG-dXP0>

Optional, after "the physics." A former player shows Williams's hip turn and slight upswing.

KEY TERMS

reaction time

The time between a signal (seeing the ball) and the start of a response (beginning the swing).

hitting zone

Williams's name for the part of the strike zone where a hitter makes his best contact.

swing plane

The tilted plane in which the bat moves through the zone.

on-base percentage

The fraction of plate appearances in which a batter reaches base by a hit, walk or hit by pitch.

CORE IDEAS

The story. On the last day of the 1941 season, Ted Williams of the Boston Red Sox was batting .3996, which would have been rounded to .400. His manager, Joe Cronin, offered to let him sit out the doubleheader and keep the mark. Williams refused, played both games, got six hits in eight times at bat, and finished at .406. No major-league hitter has batted .400 since. Thirty years later, with the writer John Underwood, Williams published *The Science of Hitting* (1971), one of the most studied books on the subject.

How they figured it out. Williams studied hitting the way a scientist studies a problem. He divided the strike zone into 77 baseball-sized cells, seven wide and eleven high, and wrote in each the average he believed he could hit on pitches there: about .400 in the heart of his zone, and as low as about .230 on the low outside corner. His first rule was “get a good ball to hit.” He also argued, against much coaching of his day, for a slight upward swing, because the pitch arrives on a downward path. Modern tracking has confirmed both ideas: hitters do best on pitches in their own zone, and a swing that matches the pitch’s path makes solid contact more likely.

The physics. A 90 mph pitch (40.2 m/s) released about 16.8 m (55 ft) from the plate arrives in $t = 16.8/40.2 \approx 0.42$ s. A swing takes about 0.15 s, and the brain needs time to see and decide, so a hitter must commit before the ball is halfway there. In fastpitch softball the pitcher’s circle is only 43 feet from the plate, so a 65 mph pitch reaches the plate in about the same time as a 95 mph baseball pitch. Pitches descend at roughly 5–10° as they reach the plate. A level swing crosses the ball’s path at only one point, so a small timing error means a miss or a weak hit; a swing tilted slightly upward along the pitch’s path stays in line with the ball for several centimeters, so the same timing error still produces solid contact. Being early or late by 7 ms means the ball has moved $40 \times 0.007 \approx 0.28$ m, a large error unless bat and ball share a path.

On the field. Good hitters learn their own hitting zones and are patient with pitches outside them; this also raises on-base percentage, and Williams's career on-base percentage of .482 is the highest in major-league history. Hitters train their timing by facing many pitches, and their swing plane by hitting off tees at different heights.

The risk side: a hitter who swings at everything gives the pitcher control; one who never swings is called out on strikes. Discipline is choosing well, not refusing to choose.

Think it through. Williams worked at hitting relentlessly, yet his greatest strength was judgment: knowing which pitches to leave alone. Skill and wisdom work together.

PICTURE STUDY



Ted Williams, Billy Kane and Joe Cronin, Unknown photographer, 1941 · Press photograph · Boston, Massachusetts

Image: [Wikimedia Commons](#), public domain

In 1941, the summer he batted .406, Ted Williams posed with his manager, Joe Cronin, and a young fan, Billy Kane, who had come all the way from Maine hoping to meet him. Williams was 22 years old and already one of the most famous hitters in the game.

Look closely

- Look at Williams's build: tall and slender. Where do you think the speed of his swing came from, if not from bulk?
- Look at the faces. What do they suggest about how the players treated a young fan?
- Compare Williams's and Cronin's uniforms with a modern uniform.

Talk about it

1. Williams said that hitting a baseball is the hardest thing to do in sport. Using this lesson's numbers, explain why.
2. Williams studied his own hitting like a scientist. What would you record if you studied your own swing that way?

Safety first. Swing a bat only outdoors, in a clear circle at least twice the bat's length in every direction, with an adult watching and no one standing near. Use a plastic or foam ball off a tee. Warm up first, and wear athletic shoes.

PROJECT

Your Own Hitting-Zone Chart

Following Williams, you will map the parts of your strike zone where you make your best contact, measure your reaction time, and compute how much time you would have against real pitches.

You will need

- A batting tee (or a tall bucket with a cone on top)
- A plastic or foam bat and plastic or foam balls
- A 30 cm ruler
- Tape and cardboard to mark nine tee positions (three heights $\times$ inside, middle, outside)
- An open outdoor space with an adult watching
- The scorebook and a calculator

Steps

1. Reaction test: do 10 ruler drops (catch with your batting-side hand) and convert each distance to a time with $t = \sqrt{2d/g}$. Find your mean reaction time.
2. Mark out a strike zone by your batting stance: three heights (knees, belt, chest) and three positions (inside, middle, outside), nine cells in all.
3. **Predict.** Shade the cells where you expect to hit best.
4. Warm up with 10 easy swings, outdoors, in a clear circle.
5. Hit 6 balls from the tee in each of the nine cells, in a random order of cells. Score each contact: 3 for a line drive, 2 for a fly or hard grounder, 1 for weak contact, 0 for a miss.
6. Compute the average score for each cell and write it in a 3×3 chart. Color the chart from best to worst.
7. Repeat the middle-belt cell with a level swing and with a slight upswing, 10 balls each, and compare scores.
8. Use your reaction time and a swing time of 0.15 s to compute how much time you would have to judge a 60 mph and a 90 mph pitch from 16.8 m.

9. **Decide.** Write your own “good ball to hit” rule: which cells you would swing at with no strikes, and which you would leave alone.

Tips

- Random order matters: if you hit all six balls in one cell in a row, you will improve during the set and spoil the comparison.
- Keep the scoring honest; have a partner judge if you can.

Check your work

- ☐ I measured my mean reaction time from 10 drops.
- ☐ I hit 6 balls in each of nine cells and made a colored zone chart.
- ☐ I compared a level swing with a slight upswing and wrote my own hitting rule.

SCOREBOOK

1. Reaction table: drop, distance (m), time (s); mean.
2. Your 3×3 hitting-zone chart with average scores and colors, in the style of Williams’s chart.
3. Side-view sketch of a pitch descending at 8° with a level swing and an 8° upswing; mark where each meets the ball.

KEY FORMULAS

$$t = \frac{d}{v}$$

$$\text{ruler drop: } t = \sqrt{\frac{2d}{g}}$$

$$\text{OBP} = \frac{H + BB + HBP}{AB + BB + HBP + SF}$$

From history. Williams played for the Red Sox from 1939 to 1960 and finished with 521 home runs and a .344 career batting average. Fastpitch softball, invented in Chicago in 1887, is played on a field with a 43-foot pitching distance at the high-school and college levels.

WORKED EXAMPLES

Example 1. A 95 mph baseball pitch is released 16.8 m from the plate. A 65 mph fastpitch softball pitch is released 11.3 m from the plate. Compare their flight times.

Show solution

1. Baseball: $95 \times 0.447 \approx 42.5 \text{ m/s}$; $t = 16.8/42.5 \approx 0.40 \text{ s}$.

2. Softball: $65 \times 0.447 \approx 29.1 \text{ m/s}$; $t = 11.3/29.1 \approx 0.39 \text{ s}$.

Answer: About 0.40 s and 0.39 s: a fast softball pitch gives the hitter as little time as a 95 mph fastball.

Example 2. A ruler dropped from a partner's fingers falls 0.18 m before a student catches it. Find the reaction time. If a 90 mph pitch takes 0.42 s and the swing takes 0.15 s, how much time is left to see and decide after allowing for that reaction time?

Show solution

1. $t = \sqrt{2(0.18)/9.8} \approx 0.19 \text{ s}$.

2. Time left: $0.42 - 0.15 - 0.19 = 0.08 \text{ s}$.

Answer: About 0.19 s of reaction time, leaving only about 0.08 s of extra viewing: the hitter must decide while the ball is still far away.

Example 3. In 1941 Williams had 185 hits in 456 at bats, with 147 walks, 3 times hit by a pitch, and no sacrifice flies counted. Find his batting average and his on-base percentage.

Show solution

1. Average: $185/456 \approx .406$.

2. OBP: $\frac{185 + 147 + 3}{456 + 147 + 3} = \frac{335}{606} \approx .553$.

Answer: Batting average .406 and on-base percentage .553: he reached base in more than half his plate appearances.

PRACTICE

1. **Easy** How long does an 80 mph pitch (35.8 m/s) take to travel 16.8 m?

Show answer

$$\approx 0.47 \text{ s.}$$

2. **Easy** What was Williams's first rule of hitting?

Show answer

"Get a good ball to hit."

3. **Easy** A ruler falls 0.10 m before it is caught. Find the reaction time.

Show answer

$$t = \sqrt{0.2/9.8} \approx 0.14 \text{ s.}$$

4. **Medium** Williams's chart had 77 cells, 7 wide and 11 high. If a strike zone is 43 cm wide and 64 cm high, about how big is each cell?

Show answer

$$43/7 \approx 6.1 \text{ cm by } 64/11 \approx 5.8 \text{ cm, a little smaller than a baseball (7.4 cm).}$$

5. **Medium** A batter is 5 ms late on a 90 mph pitch. How far has the ball traveled past the planned contact point?

Show answer

$$40.2 \times 0.005 \approx 0.20 \text{ m.}$$

6. **Medium** Why does a slight upward swing help a hitter whose timing is not perfect?

Show answer

The bat travels along the ball's descending path for a stretch, so contact still happens on the barrel if the swing is a little early or late.

7. **Medium** Why does refusing to swing at pitches outside one's zone raise on-base percentage?

Show answer

Pitches outside the zone that are not swung at are often called balls, leading to walks, and swings are saved for pitches the hitter can hit hard.

8. **Medium** In what year did Williams bat .406, and what did he refuse to do on the last day?

Show answer

1941; he refused to sit out to protect a .400 average and played both games.

9. **Hard** A softball hitter's reaction time is 0.20 s and her swing takes 0.14 s. For a pitch that takes 0.39 s, how much time does she have to judge the pitch? What fraction of the flight is that?

Show answer

$0.39 - 0.20 - 0.14 = 0.05$ s, about 13% of the flight.

10. **Hard** A batter has 150 hits, 60 walks, 5 hit-by-pitches and 4 sacrifice flies in 500 at bats. Find his batting average and on-base percentage.

Show answer

Average .300; OBP $\frac{215}{569} \approx .378$.

11. **Hard** A pitch descends at 8° as it reaches the plate. How much lower is the ball 0.30 m farther along its path? A bat barrel is about 6.6 cm thick. Explain what this means for a level swing that meets the ball 0.30 m too early.

Show answer

$0.30 \tan 8^\circ \approx 0.042$ m, about 4.2 cm. A level bat aimed at the right height would meet the ball 4.2 cm above its center, more than half the barrel's thickness, giving a weak grounder or a miss. A bat moving upward along the pitch's path would still meet it squarely.

12. **Challenge** A hitter needs 0.15 s to swing and 0.10 s of processing before he can begin. Pitches arrive at 0.40 s. If he must decide by the time the ball has traveled what fraction of the way, and why do pitchers try to make different pitches look the same for that long?

Show answer

He must commit at $0.40 - 0.25 = 0.15$ s, when the ball has covered $0.15/0.40 \approx 37.5\%$ of the distance. Pitchers make fastballs, curves and change-ups look alike early (same arm angle and release), so the differences show only after the hitter has committed.

COMMON MISTAKES

- Forgetting to convert mph to m/s before dividing a distance in meters.
- Thinking a patient hitter never swings; patience means swinging at the right pitches.
- Taking the full 60 ft 6 in as the flight distance; the pitcher releases about 5–6 ft in front of the rubber.

Make it a game • Decision Clock. Your parent calls out a pitch speed and the distance to the plate. You race to compute how many seconds the hitter has before the ball arrives, and then subtract a pretend 0.2 seconds for reaction. Then sketch a strike-zone grid from memory and mark the cells where Ted Williams hit best. Say his rule aloud: get a good ball to hit.

Scripture. “And whatsoever ye do, do it heartily, as to the Lord, and not unto men;” (Colossians 3:23, KJV)

Williams brought his whole mind to a game. A Christian brings his whole heart to every task, in sport or study, not for applause but as service to the Lord.

UNIT 2

BASEBALL AND SOFTBALL

Baseball is a laboratory of physics: a bat–ball collision lasting less than a millisecond, a spinning ball bending through the air, an arm whipping faster than almost any other human motion, and a fly ball that a fielder tracks with a simple rule of the eyes. This unit studies the swing and the sweet spot, the Magnus effect and Lyman Briggs’s 1959 measurements of the curveball, throwing mechanics and the Pitch Smart guidelines that protect young arms, the outfielder’s gaze heuristic, and Ted Williams’s science of hitting.

Fastpitch softball shares nearly all of this physics, and the projects work with either sport. You will measure bounces and a bat’s sweet spot, launch a Magnus glider, time your throws and keep a throwing log, test catching strategies on real fly balls, and map your own hitting zone.

PREREQUISITES

- Unit 1: Newton’s laws, levers, the kinetic chain and $v = \omega r$
- Algebra I: square roots and solving equations
- Trigonometry: sine, cosine and tangent for projectile motion

MASTERY CHECKLIST

- ☐ I can compute momentum, impulse and the coefficient of restitution, and use the batted-ball formula.
- ☐ I can explain the Magnus effect, predict the direction of a curve and use Briggs’s results.
- ☐ I can apply the Pitch Smart guidelines and explain why rest protects the arm.
- ☐ I can compute hang time, height and range of a fly ball and explain the gaze heuristic.
- ☐ I can compute a hitter’s time to react and explain Williams’s hitting zone and swing plane.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **Alan Nathan: The Physics of Baseball**: Free. A University of Illinois physicist's collection of articles and data on bats, balls, pitches and trajectories. Extends Lessons 2.1, 2.2 and 2.4. Some articles are written for physicists. Ages 14+.
- **MLB and USA Baseball: Pitch Smart guidelines**: Free. The official age-by-age pitch-count and rest tables used in Lesson 2.3. A parent should preview it, as the site carries advertising.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

2.1 The Batting Swing	3 sessions of 50 minutes
2.2 The Pitch and the Magnus Effect	3 sessions of 50 minutes
2.3 Throwing Mechanics and Arm Care	3 sessions of 50 minutes
2.4 Fielding and the Outfielder's Path	3 sessions of 50 minutes
2.5 Ted Williams and the Science of Hitting	3 sessions of 50 minutes

UNIT 2 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$ and $1 \text{ mph} = 0.447 \text{ m/s}$. Show your work for every calculation with units. Answer the concept questions in complete sentences. The test is worth 100 points.

1. **5 pts**

Find the momentum of a 0.19 kg softball moving at 30 m/s.

2. **6 pts**

A ball dropped from 1.20 m rebounds to 0.27 m. Find its coefficient of restitution.

3. **8 pts**

A 0.145 kg ball arrives at 38 m/s and leaves at 44 m/s in the opposite direction after 0.80 ms of contact. Find the change in momentum and the average force.

4. **6 pts**

Using $v = 0.2 v_{\text{pitch}} + 1.2 v_{\text{bat}}$, find the exit velocity for an 88 mph pitch and a 72 mph bat. Which matters more to the hitter, 5 mph of pitch speed or 5 mph of bat speed?

5. **5 pts**

Explain why hitting the ball off the end of the bat stings and produces a weaker hit.

6. **6 pts**

A right-handed pitcher's ball spins so that its front surface turns down (topspin). Which way does it break, and why?

7. **7 pts**

A pitch takes 0.55 s to reach the plate and spins at 1,500 rpm. How many turns does it make? Using Briggs's result that the curve is proportional to spin (17.5 in at 1,800 rpm), predict its curve.

8. **6 pts**

A pitch takes 0.42 s. How far would gravity alone make it fall? Why does a fastball with backspin seem to rise?

9. **6 pts**

Under Pitch Smart, how many rest days does a 13-year-old need after 40 pitches? After 70?

10. **6 pts**

Explain, using impulse, why a full follow-through protects a pitcher's shoulder.

11. **7 pts**

A fly ball is in the air for 5.0 s. Find its vertical launch speed and peak height, ignoring air resistance.

12. (7 pts)

A ball is hit at 35 m/s at 35° . Find its hang time and range without air. Will the real ball go farther or shorter?

13. (6 pts)

State the gaze heuristic and explain what a fielder should do if the gaze angle rises more and more slowly.

14. (6 pts)

A 92 mph pitch is released 16.8 m from the plate. A hitter's swing takes 0.15 s. By what time after release must he begin his swing?

15. (13 pts)

Short essay. In about 150 words, describe how physics can make a young baseball or softball player both better and safer. Use at least three ideas from this unit.

ANSWER KEY

1. $5.7 \text{ kg}\cdot\text{m/s}$.
2. $e = \sqrt{0.225} \approx 0.47$.
3. $\Delta p = 0.145 \times 82 \approx 11.9 \text{ kg}\cdot\text{m/s}$; $F \approx 14,900 \text{ N}$.
4. $17.6 + 86.4 = 104 \text{ mph}$. Bat speed: it is multiplied by 1.2, pitch speed by only 0.2.
5. Off the sweet spot, much of the collision's energy goes into vibrations of the bat, felt as a sting, leaving less energy for the ball.
6. Downward: the Magnus force points toward the side the front surface is turning, so topspin adds a downward force to gravity.
7. $25 \times 0.55 \approx 14$ turns; $17.5 \times 1500/1800 \approx 14.6 \text{ in}$.
8. $\frac{1}{2}(9.8)(0.42)^2 \approx 0.86 \text{ m}$. Backspin gives an upward force, so it falls less than the hitter expects.
9. Two (36–50); four (66+).
10. The arm's momentum after release must be removed. Stopping it over a longer time with a follow-through lowers the average force, $F = \Delta p / \Delta t$.
11. $v_y = 24.5 \text{ m/s}$; $H \approx 30.6 \text{ m}$.
12. $v_y \approx 20.1$, $v_x \approx 28.7 \text{ m/s}$; $T \approx 4.1 \text{ s}$; $R \approx 118 \text{ m}$. Shorter, because of drag.
13. Move so that the gaze angle to the ball rises at a steady rate. If it rises more and more slowly, the ball will land in front of him, so he should run in.
14. $v \approx 41.1 \text{ m/s}$; $t \approx 0.41 \text{ s}$; begin by about 0.26 s .
15. Answers vary. A strong essay uses specific ideas, such as bat speed and the sweet spot, spin and the Magnus effect, the kinetic chain and follow-through, pitch counts and rest, the gaze heuristic, and swing plane, and connects each to a concrete habit.

PORTFOLIO PIECE: A PHYSICS COACHING GUIDE FOR YOUNG PLAYERS

Write and illustrate a four-page coaching guide for a 10-year-old baseball or softball player, built on the physics and the data from this unit. Include one page each on hitting (sweet spot, bat speed and swing plane), pitching and throwing (the kinetic chain, the follow-through, pitch counts and rest), fielding (the first step and the gaze rule), and why balls curve. Each page must include one diagram, one number you measured yourself, one safety rule, and one sentence of physics explained simply. End with a one-paragraph note to parents on arm care.

LOOK FOR	WHAT IT MEANS
Correct physics	Each page explains a real principle correctly and simply.
Own data	Each page includes a measurement from the student’s own projects.
Safety	Clear, correct safety rules, including Pitch Smart limits and bat safety.
Clarity for a young reader	Plain language and clear diagrams a 10-year-old could follow.

UNIT 3

SOCCER

The world's most popular game is a game of collisions and spin. This unit studies the impulse of the instep drive, the spinning-ball physics behind Roberto Carlos's 1997 free kick, the cushioned first touch that absorbs momentum, the friction and balance of cutting and the FIFA 11+ program that protects knees, and the physics behind the youth heading guidelines.

Projects measure your own shot speed and accuracy, the bend of your curled kicks, your first touch off a wall, your balance and landing before and after three weeks of the 11+, and heading technique learned safely with a balloon. Heading in this course is taught only with a balloon or a very soft foam ball.

PREREQUISITES

- Unit 1: Newton's laws, center of mass and the kinetic chain
- Unit 2: momentum, impulse, coefficient of restitution and the Magnus effect
- Algebra I and basic trigonometry

MASTERY CHECKLIST

- ☐ I can compute the impulse and force of a kick and explain how technique raises ball speed.
- ☐ I can explain why a spinning ball bends and why its curve sharpens as it slows.
- ☐ I can explain cushioning with the impulse-momentum relation and compute stiff and soft receptions.
- ☐ I can compute the friction and lean needed to cut, and explain how the 11+ protects the knee.
- ☐ I can explain the youth heading guidelines with the physics of head acceleration.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **The IFAB: Laws of the Game, Law 2 (The Ball)**: Free. The official specification of the ball's size, mass and pressure used in Lessons 3.1–3.3, from the body that writes soccer's rules.
- **U.S. Soccer: Recognize to Recover**: Free. U.S. Soccer's player-health program, with guidance on heading, injury prevention and warm-ups for Lessons 3.4 and 3.5. For parents and coaches.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

3.1	The Instep Drive: The Physics of the Kick	3 sessions of 50 minutes
3.2	Bending It: Spin and the Famous Free Kick	3 sessions of 50 minutes
3.3	First Touch: Absorbing Momentum	3 sessions of 50 minutes
3.4	Balance, Cutting and Protecting the Knee	3 sessions of 50 minutes
3.5	Heading: Physics and Safety Rules	3 sessions of 50 minutes

UNIT 3 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$ and a ball mass of 0.43 kg unless told otherwise. Show your work for every calculation with units. Answer the concept questions in complete sentences. The test is worth 100 points.

1. **6 pts**

A ball is kicked from rest to 26 m/s in 0.010 s. Find the impulse and average force.

2. **6 pts**

A foot moving at 19 m/s sends the ball off at 1.3 times its speed. Find the ball's speed in km/h and its time to travel 20 m.

3. (6 pts)

Explain two ways a locked ankle and the knee over the ball improve an instep drive.

4. (6 pts)

A right-footer curls the ball with the inside of the foot. Which way does it spin (seen from above) and which way does it bend?

5. (8 pts)

A ball moving at 27 m/s feels a sideways force of 2.9 N. Find its radius of curvature, then the radius at 18 m/s with the same force. Explain the result.

6. (5 pts)

What did Dupeux and his colleagues show in “The spinning ball spiral” (2010)?

7. (7 pts)

A ball arriving at 16 m/s is stopped in 0.012 s and, with a cushioned touch, in 0.090 s. Find both average forces.

8. (6 pts)

With an effective coefficient of restitution of 0.15, a pass at 13 m/s rebounds at what speed? How far does it roll on grass that slows it at 0.8 m/s^2 ?

9. (7 pts)

A 65 kg player runs at 6.0 m/s. Find the tightest turn radius with $\mu = 0.8$ and the sideways force needed on a 4.0 m radius.

10. (6 pts)

Find the lean angle for a 5.0 m/s turn on a 4.0 m radius.

11. (6 pts)

Describe the knee position the FIFA 11+ teaches for landing and cutting, and explain why it protects the knee.

12. (6 pts)

Summarize the 2008 Norwegian trial of the 11+ honestly, including its limitation.

13. (5 pts)

State U.S. Soccer's heading guidance for players 10 and under and for ages 11–13.

14. (7 pts)

Illustrative. A ball gives a head an impulse of $6.0 \text{ N}\cdot\text{s}$ over 0.010 s . Find the head's average acceleration in g for effective masses of 5.0 kg and 15 kg .

15. (13 pts)

Short essay. In about 150 words, explain how the same physical idea, impulse and contact time, appears in the instep drive, the first touch and heading. Show how a player uses it differently in each.

ANSWER KEY

1. $11.2 \text{ N}\cdot\text{s}$; $\approx 1,120 \text{ N}$.
2. $24.7 \text{ m/s} \approx 89 \text{ km/h}$; 0.81 s .
3. The locked ankle raises the effective mass of the foot, so more speed goes to the ball; the knee over the ball keeps contact through or above center, so the shot stays low.
4. Counterclockwise from above; it bends from right to left.
5. $r \approx 108 \text{ m}$; $r \approx 48 \text{ m}$. The slowing ball curves more sharply because $r = mv^2/F$ falls with the square of speed.
6. That a spinning ball slowed by drag keeps its spin while losing speed, so its path tightens from a curve toward a spiral, explaining the late bend of long, hard-struck free kicks.
7. $6.88/0.012 \approx 573 \text{ N}$; $6.88/0.090 \approx 76 \text{ N}$.
8. 1.95 m/s ; $\approx 2.4 \text{ m}$.
9. $r_{\min} \approx 4.6 \text{ m}$; $F = 65 \times 36/4.0 = 585 \text{ N}$ (more than $\mu mg \approx 510 \text{ N}$, so the player would slip).
10. $\tan \theta \approx 0.64$, $\theta \approx 33^\circ$.
11. Knees bent and over the toes, not collapsing inward, with the trunk over the feet. It lets the large leg and hip muscles share the load and avoids twisting and inward loads on the ligaments.
12. In a season-long trial of 1,892 girls from 125 clubs, teams using the 11+ had about a third fewer injuries overall and nearly half as many severe injuries; the reduction in leg injuries alone was not statistically certain.
13. No heading for 10 and under; for 11–13, heading only in practice, with at most about 30 minutes of heading training and 15–20 headers per player per week.
14. $\approx 12 g$ and $\approx 4 g$.
15. Answers vary. A strong essay explains $F\Delta t = \Delta p$ and shows that in the kick the player wants a large impulse delivered with a fast, firm foot; in the first touch he lengthens contact time to lower force and rebound; in heading a firm neck raises the effective mass so the head's velocity changes little, and safety rules limit repeated impacts.

PORTFOLIO PIECE: A SOCCER PLAYER'S PHYSICS AND SAFETY HANDBOOK

Create an illustrated handbook of at least four pages for a youth soccer team. Include: how to hit a powerful, accurate shot (with your own measured speeds); how to bend the ball (with your measured bends); how to take a good first touch (with your wall-test results); how to warm up and land safely (the 11+, with your before-and-after balance data); and the heading guidelines explained with physics. Each page must have a labelled diagram, one formula explained in plain words, and one practical tip. End with a one-page warm-up card a coach could pin to a bulletin board.

LOOK FOR	WHAT IT MEANS
Physics	Correct, clearly explained physics on every page, with formulas used properly.
Own data	Real measurements from the unit's projects, honestly reported.
Safety	Accurate heading guidance and injury-prevention advice, without medical claims.
Usefulness	A handbook and warm-up card a youth team could actually use.

3.1 THE INSTEP DRIVE: THE PHYSICS OF THE KICK

OBJECTIVES

- Use impulse and momentum to compute the force of a kick and the effect of contact time.
- Explain why foot speed, a locked ankle and solid contact give a faster ball.
- Measure ball speed from video and compare kicking techniques.

Warm-up. Roll a soccer ball gently against a wall with the inside of your foot, then tap it with your toe, then kick it with your laces (the top of the foot), each with the same small swing. Which surface sends it fastest? Which feels most controlled?

WATCH

The Ultimate Guide to Shooting with Power and Accuracy in Football

Kreider Academy · 6:23

https://www.youtube.com/watch?v=vZ1G5mCAf_c

WHEN TO WATCH

After “the physics” paragraph. For each coaching point, say which physical quantity it improves: foot speed, contact or direction.

BACKUP VIDEO

Biomechanics of Kicking a Soccer Ball

Chris Hale · 5:24

<https://www.youtube.com/watch?v=PQjoSNaFf5c>

Optional, after the worked examples. A student’s slow-motion study of the phases of the instep kick, a model for your own project.

KEY TERMS

instep drive

A powerful kick struck with the laces (the top of the foot) with the ankle locked and toe pointed down.

impulse

Average force times contact time, equal to the change in momentum:

$$F\Delta t = m\Delta v.$$

contact time

How long the foot and ball touch, about a hundredth of a second in a hard kick.

effective mass

The part of the leg's mass that acts in the collision; it rises when the ankle is locked firm.

plant foot

The supporting foot, placed beside the ball, which sets the direction and height of the kick.

CORE IDEAS

The story. The modern rules of association football were written in London in 1863, and for decades players kicked a heavy leather ball that soaked up water in the rain. Steve Bloomer of Derby County, England's greatest goal-scorer of the 1890s and 1900s, was famous for his sudden, low shots struck before a goalkeeper could set himself. A century later, sport scientists began filming kicks with cameras running thousands of frames per second. Researchers such as Takeshi Asai at the University of Tsukuba in Japan measured how the foot and ball deform and how long they touch.

How they figured it out. High-speed film showed that the ball flattens against the foot and that the contact lasts only about a hundredth of a second (roughly 8–12 ms). The ball leaves faster than the foot was moving, typically 1.2 to 1.4 times the foot speed, because the ball is light and springy and the leg is heavy. The films also showed why technique matters: if the ankle is loose, the foot bends back on contact, acts like a lighter object, and the ball leaves slower. A locked ankle and a firm, straight foot make the foot and leg act as one heavy striking mass.

The physics. The kick is a collision. The impulse on the ball equals its change in momentum: $F\Delta t = m\Delta v$. A 0.43 kg ball kicked from rest to 25 m/s in 0.010 s receives an average force of $0.43 \times 25/0.010 \approx 1,080$ N, more than the weight of a large adult. The ball's speed depends mostly on the foot's speed, which comes from the kinetic chain (Lesson 1.4): a long last stride, the hip and thigh swinging first, then the knee snapping straight just before contact. Striking through the ball's center sends it straight; striking below center lifts it; striking off center adds spin. The plant foot beside the ball, toes pointed at the target, keeps the hips square and the ball low.

On the field. Coaches teach “laces, ankle locked, knee over the ball, follow through.” Each is physics: the laces give a large, firm contact surface; the locked ankle raises the effective mass; the knee over the ball keeps the contact point above the ball’s center so the shot stays low; the follow-through keeps the foot fast through the whole contact. **The risk side:** the same large forces act on the foot and ankle. Kicking a heavy or wet ball with a loose ankle or with the toe can bruise or sprain, and a hard kick near other players can hurt them. Power should never come before control and safety.

Think it through. A shot that is a little slower but on target scores more often than a rocket over the bar. The physics of power and the physics of accuracy must be learned together.

PICTURE STUDY



Steve Bloomer, William W. Winter, c. 1896 · Photograph · Derby, England

Image: [Wikimedia Commons](#), public domain

Steve Bloomer played for Derby County and Middlesbrough and scored 28 goals in 23 matches for England between 1895 and 1907. The Derby photographer William Winter made this portrait of him in his England shirt and cap, the cap given to every player chosen for his country, which is why international appearances are still called “caps.”

Look closely

- Look at Bloomer’s build. He was slight, not heavy. What does that suggest about where the power of a shot comes from?
- Find the cap and the badge. What do they tell you about the honor of playing for one’s country?
- Imagine the leather ball and boots of his time. How would a heavy, wet ball change the impulse needed for a shot?

Talk about it

1. Bloomer was known for shooting early and low. Using this lesson’s physics, explain why a low shot struck quickly is hard to save.
2. What can a light, quick player do to kick the ball hard without great size?

Safety first. Warm up with jogging and leg swings before kicking. Kick only outdoors or against a sturdy wall with no windows, wear athletic shoes (never kick a hard ball barefoot), and make sure no one is in the line of the ball. Drink water and use sun protection outdoors. Stop if anything hurts, and tell a parent.

PROJECT

Measuring Your Shot

You will measure the speed of your instep drive with a phone or stopwatch, compare it with an inside-of-the-foot pass and a loose-ankle kick, and record accuracy at the same time.

You will need

- A soccer ball (size 4 or 5)
- A wall with no windows, a goal, or a target made from two cones 2 m apart
- A tape measure and cones
- A phone with slow-motion video, or a stopwatch and a partner
- The scorebook and a calculator

Steps

1. Mark a kicking spot 11 m from the wall or goal.
2. Warm up: jog, leg swings, and 10 gentle passes.
3. **Predict.** Estimate your shot speed in km/h and your accuracy (hits out of 10) for each kick type.
4. Kick type A: 10 inside-of-the-foot passes as firmly as you can while keeping control.
5. Kick type B: 10 instep drives with the ankle locked, toe down, knee over the ball.
6. Kick type C: 5 instep drives with the ankle deliberately relaxed (gently; stop if it hurts).
7. Film each kick from the side, or have a partner time from contact to the ball reaching the wall. Count frames to find each flight time.
8. Compute each speed $v = d/t$ and convert to km/h. Record hits on target.
9. Find the mean speed and hit rate for each kick type.
10. If you have slow-motion video, count the frames the foot and ball are in contact for a few kicks and estimate the contact time.

11. **Decide.** Write when you would use each kick in a game, using both speed and accuracy, and estimate the force of your best shot with $F = m\Delta v/\Delta t$.

Tips

- At 240 frames per second, 3 frames is 0.0125 s.
- Measure the distance the ball actually traveled, not just the distance to the goal line.

Check your work

- ☐ I measured speed and accuracy for at least 25 kicks of three types.
- ☐ I computed mean speeds in m/s and km/h.
- ☐ I estimated the force of my best shot and wrote a decision using both speed and accuracy.

SCOREBOOK

1. Kick table: type, trial, flight time, speed (m/s), speed (km/h), on target?
2. Draw the instep drive at contact in side view: label the plant foot, knee over the ball, locked ankle, contact point and follow-through.
3. Bar graph of mean speed and hit rate for each kick type.

KEY FORMULAS

$$F\Delta t = m\Delta v$$

$$v_{\text{ball}} \approx (1.2 \text{ to } 1.4) \times v_{\text{foot}}$$

$$v = \frac{d}{t} \quad 1 \text{ m/s} = 3.6 \text{ km/h}$$

From history. The Football Association adopted its first laws in 1863; the size of the ball (27–28 inches around) was fixed in 1872. Today's size-5 ball is 68–70 cm around and weighs 410–450 g at the start of a match.

WORKED EXAMPLES

Example 1. A 0.43 kg ball is kicked from rest to 25 m/s with a contact time of 0.010 s. Find the impulse and the average force.

Show solution

1. Impulse: $m\Delta v = 0.43 \times 25 = 10.75 \text{ N}\cdot\text{s}$.
2. Force: $F = 10.75/0.010 \approx 1,080 \text{ N}$.

Answer: About 10.8 N·s and 1,080 N.

Example 2. A player's foot reaches 18 m/s at contact. If the ball leaves at 1.3 times the foot speed, find its speed in m/s and km/h, and the time it takes to cross the 16.5 m penalty area.

Show solution

1. $v = 1.3 \times 18 = 23.4 \text{ m/s}$, $23.4 \times 3.6 \approx 84 \text{ km/h}$.
2. $t = 16.5/23.4 \approx 0.71 \text{ s}$.

Answer: 23.4 m/s (about 84 km/h); it crosses the area in about 0.7 s.

Example 3. With a loose ankle, the same swing gives the ball only 1.1 times the foot speed. How much slower is the ball, and how much longer does it take to travel 20 m?

Show solution

1. Locked: $1.3 \times 18 = 23.4 \text{ m/s}$; loose: $1.1 \times 18 = 19.8 \text{ m/s}$.
2. Times: $20/23.4 \approx 0.85 \text{ s}$ and $20/19.8 \approx 1.01 \text{ s}$.

Answer: About 3.6 m/s slower and 0.16 s later, enough time for a goalkeeper to move about a meter.

PRACTICE

1. Easy Find the momentum of a 0.43 kg ball moving at 20 m/s.

Show answer

8.6 kg·m/s.

2. Easy Convert 30 m/s to km/h.

Show answer

108 km/h.

3. Easy Name three coaching points for the instep drive and the physics behind each.

Show answer

Laces (a large, firm surface), locked ankle (a higher effective mass), knee over the ball and follow-through (a low shot and a fast foot through contact). Others are acceptable with reasons.

4. Medium A ball is kicked from rest to 22 m/s in 0.009 s. Find the average force.

Show answer

$$F = 0.43 \times 22/0.009 \approx 1,050 \text{ N.}$$

5. Medium A shot travels 18 m in 0.75 s. Find its average speed in m/s and km/h.

Show answer

$$24 \text{ m/s} = 86.4 \text{ km/h.}$$

6. Medium If the same impulse is delivered over 0.012 s instead of 0.008 s, how does the average force change?

Show answer

It falls to $8/12 = \frac{2}{3}$ of its former value.

7. Medium Why does a ball leave the foot faster than the foot was moving?

Show answer

The ball is light and springy, and the leg is much heavier; in such a collision the light object rebounds from the heavy one at more than the heavy one's speed.

8. Medium Why does a player place the knee over the ball for a low drive?

Show answer

It keeps the foot's contact through or slightly above the ball's center, so the impulse has little upward component and the ball stays low.

9. **Hard** A goalkeeper can react in 0.25 s and then move 1.0 m in 0.35 s. A shot is struck from 11 m. What is the slowest shot speed that beats him if it is aimed 1.0 m to his side?

Show answer

He needs 0.60 s; the shot must arrive sooner: $v > 11/0.60 \approx 18.3$ m/s.

10. **Hard** A ball rebounding off a wall arrives at 15 m/s and leaves at 9 m/s, with 0.010 s of contact. Find the average force of the wall.

Show answer

$$\Delta p = 0.43 \times 24 = 10.3 \text{ kg}\cdot\text{m/s}; F \approx 1,030 \text{ N}.$$

11. **Hard** A ball is kicked at 20 m/s at 30° above the ground. Find its hang time and range, ignoring air resistance.

Show answer

$$v_y = 10, v_x \approx 17.3 \text{ m/s}; T \approx 2.04 \text{ s}; R \approx 35.3 \text{ m}.$$

12. **Challenge** In a collision between a foot of effective mass M moving at V and a ball of mass m at rest, with coefficient of restitution e , the ball leaves at $v = \frac{M(1+e)}{M+m}V$. With $m = 0.43$ kg, $e = 0.5$, find v/V for $M = 1.5$ kg (loose ankle) and $M = 3.0$ kg (locked ankle).

Show answer

$$M = 1.5: \frac{1.5(1.5)}{1.93} \approx 1.17; M = 3.0: \frac{3.0(1.5)}{3.43} \approx 1.31. \text{ Locking the ankle raises the ball's speed by about 12\% for the same swing.}$$

COMMON MISTAKES

- Using the distance to the goal line when the ball traveled at an angle.
- Leaning back, which puts the contact below center and sends the ball high.
- Kicking with the toe, which gives a small, unstable contact and poor control.

Make it a game • Coach for a Minute. You are the coach. For sixty seconds, explain why contact time, foot speed and a locked ankle change how fast a kicked ball leaves. Your parent listens and sneaks in one false claim for you to catch. Then work the numbers together: a 0.43 kg ball leaves at 25 m/s after 0.01 seconds of contact. What is the average force? Check against your formulas.

3.2 BENDING IT: SPIN AND THE FAMOUS FREE KICK

OBJECTIVES

- Explain how sidespin produces a Magnus force that bends a soccer ball.
- Explain why a slowing, spinning ball curves more and more sharply (the spinning-ball spiral).
- Measure the bend of your own curved kicks.

Warm-up. Kick a ball with the inside of your foot, wrapping your foot around the right side of the ball as you kick, and watch its path. Then kick it squarely through the center. Draw both paths from above.

WATCH

Football physics: The "impossible" free kick - Erez Garty

TED-Ed · 3:33

<https://www.youtube.com/watch?v=m57cimnJ7fc>

WHEN TO WATCH

After “the story” paragraph. Watch for the moment the ball seems to change direction.

BACKUP VIDEO

Deconstructing Roberto Carlos free kick technique vs France (1997)

3CB Performance · 2:52

<https://www.youtube.com/watch?v=rK4daWiB2Nc>

Optional, after “the physics.” A slow-motion look at his run-up, foot contact and spin.

KEY TERMS

sidespin

Spin about a vertical axis; it bends the ball left or right.

spin parameter

The ratio of the ball’s surface speed from spin to its forward speed; the larger it is, the sharper the curve.

Magnus force

The sideways force on a spinning ball moving through air (Lesson 2.2).

radius of curvature

The radius of the circle that best fits a curved path at one point; a smaller radius means a sharper bend.

CORE IDEAS

The story. On June 3, 1997, in Lyon, at a pre-tournament match called Le Tournoi de France, Brazil's left back Roberto Carlos placed the ball for a free kick about 35 m from the French goal. He ran a long way back, then struck the ball with the outside of his left foot. It flew so far to the right of the defensive wall that a ball boy beside the goal ducked, then it bent sharply left and went in off the post. The French goalkeeper, Fabien Barthez, did not move. Many people thought it was luck, or impossible.

How they figured it out. The Magnus effect explained the bend, but not why this ball seemed to curve *more* sharply near the end. In 2010 a team of French physicists led by Guillaume Dupeux and Christophe Clanet fired small spinning balls into water and published “The spinning ball spiral” in the *New Journal of Physics*. They showed that a spinning ball slowed by drag keeps most of its spin while it loses forward speed, so the spin parameter grows, and the path tightens from a curve into a spiral. On a short kick the effect is too small to notice; from 35 m, struck hard with great spin, the ball reaches the goal before it finishes its spiral, and the last part of the bend is the sharpest.

The physics. The Magnus force on a spinning ball points toward the side its front surface is turning (Lesson 2.2). A curving path needs a sideways force toward the center of the curve: $F = \frac{mv^2}{r}$, so $r = \frac{mv^2}{F}$. If the Magnus force stays roughly constant while drag slows the ball, v falls and r shrinks: the curve sharpens. Drag itself depends strongly on speed; at very high speeds the air flow around a ball changes in a way that sharply lowers the drag (the “drag crisis”), and as the ball slows through that range the drag rises suddenly. Striking the ball off center with the inside or outside of the foot gives sidespin; striking straight through the center with little spin gives the wobbling “knuckleball,” whose path is hard to predict.

On the field. Players bend corner kicks toward or away from the goal, curl free kicks around walls, and bend long passes into a teammate's path. A right-footed player curling with the inside of the foot gives the ball spin that bends it from right to left; using the outside of the foot bends it the other way. **The risk side:** a bending ball is harder to control and harder for a teammate to receive; a wise player uses spin when it helps and a simple pass when it does not.

Think it through. Roberto Carlos's kick looked like a miracle of luck, but physicists showed it was the predictable result of speed, spin and distance. Skill is often what looks like luck to someone who does not understand it.

PICTURE STUDY



Portrait of Heinrich Gustav Magnus, Eduard Magnus, 1841 · Oil on canvas · Berlin

Image: [Wikimedia Commons](#), public domain

Heinrich Gustav Magnus (1802–1870) was a German chemist and physicist who taught at the University of Berlin. In 1852 he explained why spinning cylinders and cannon shot are pushed sideways by the air, the effect that now bears his name. His older brother Eduard, a well-known portrait painter, painted him in 1841.

Look closely

- Look at Magnus's face and expression. What kind of person might patiently test a spinning cylinder in a stream of air?
- Notice the simple dark background. Where does the painter want you to look?
- This is a painting of one brother by another. What details suggest the painter knew his subject well?

Talk about it

1. Magnus studied cannon shot, but his effect now explains free kicks, curveballs and golf drives. Why do discoveries in one field so often help in another?

2. If you could show Magnus a video of Roberto Carlos's free kick, how would you explain it to him in his own terms?

Safety first. Warm up with jogging and leg swings before kicking. Kick only outdoors or against a sturdy wall with no windows, wear athletic shoes (never kick a hard ball barefoot), and make sure no one is in the line of the ball. Drink water and use sun protection outdoors. Stop if anything hurts, and tell a parent. When practicing curved kicks, make sure the whole area the ball might bend into is clear.

PROJECT

Measuring the Bend

You will kick curved balls past a pole and measure how far they bend, then compare inside-of-foot curls, outside-of-foot curls and straight kicks.

You will need

- A soccer ball
- Cones, a tall pole or a broom stuck upright in a bucket
- A tape measure and string
- A phone camera on a high point, or a partner to mark landing spots
- An open field and a parent present
- The scorebook and a calculator

Steps

1. Lay a straight string line 20 m long on the ground from your kicking spot. Put a pole 10 m along the line to act as the “wall.”
2. **Predict.** Estimate how many meters to one side of the line your curled kick will cross the 20 m mark.
3. Straight kicks: 5 instep or inside-foot kicks aimed straight along the line, striking through the center. Measure how far from the line each crosses the 20 m mark.
4. Inside curls: aim 2 m to the right of the pole (for a right-footer) and wrap the inside of your foot around the ball. 10 kicks. Measure where each crosses the 20 m mark.
5. Outside curls (optional and harder): 10 kicks with the outside of the foot, aiming to the left of the pole.
6. For each kick, record whether it bent around the pole without hitting it.
7. Find the mean sideways bend for each kick type: the difference between where you aimed and where it crossed.
8. Film a few curled kicks from above (a parent on a balcony or a high step) and trace the path frame by frame. Does the bend look the same all the way, or sharper at the end?

9. **Decide.** Write when in a game a curled kick is the better choice and when a simple straight pass is wiser, using your accuracy data.

Tips

- Measure the sideways distance at right angles to the string.
- Contact the ball off center with a smooth wrap of the foot rather than a swipe.

Check your work

- ☐ I measured the bend of at least 15 kicks of two or more types.
- ☐ I recorded how many went around the “wall.”
- ☐ I compared the bend at the start and end of the path and wrote a decision.

SCOREBOOK

1. Bend table: kick type, aim point, crossing point at 20 m, bend (m), around the pole?
2. Draw an overhead map of the field with the paths of your three best curled kicks.
3. Draw a spinning ball from above with its spin direction, its velocity and the Magnus force.

KEY FORMULAS

$$F_c = \frac{mv^2}{r} \quad r = \frac{mv^2}{F}$$

$$\text{spin parameter} = \frac{R\omega}{v}$$

$$\omega = 2\pi f$$

From history. The ball in Lyon in 1997 was struck from about 35 m; the match ended 1–1. Magnus was also a celebrated teacher whose students included several leading German physicists of the next generation.

WORKED EXAMPLES

Example 1. A 0.43 kg ball moving at 30 m/s feels a sideways Magnus force of 3.0 N. Find the radius of its curved path. What is the radius when drag has slowed it to 20 m/s, if the force is unchanged?

Show solution

1. At 30 m/s: $r = \frac{0.43 \times 900}{3.0} = 129 \text{ m.}$
 2. At 20 m/s: $r = \frac{0.43 \times 400}{3.0} \approx 57 \text{ m.}$
-

Answer: 129 m at first and about 57 m later: the curve becomes more than twice as sharp as the ball slows. *Illustrative values.*

Example 2. A ball of radius 0.11 m spins at 8 turns per second while moving at 30 m/s. Find its spin parameter. What is it when the ball has slowed to 20 m/s, still spinning at 8 turns per second?

Show solution

1. $\omega = 2\pi(8) \approx 50.3 \text{ rad/s; surface speed } R\omega \approx 5.5 \text{ m/s.}$
 2. At 30 m/s: $5.5/30 \approx 0.18$. At 20 m/s: $5.5/20 \approx 0.28$.
-

Answer: The spin parameter rises from about 0.18 to 0.28 as the ball slows, which is why the bend grows.

Example 3. A 35 m free kick is struck at 30 m/s and arrives at the goal at an average of 25 m/s. How long does the goalkeeper have? If the ball's bend moves it 3 m sideways in the last 0.4 s, what average sideways speed did it gain?

Show solution

1. Time: $35/25 = 1.4 \text{ s.}$
 2. Sideways: $3/0.4 = 7.5 \text{ m/s}$ on average over the last 0.4 s.
-

Answer: About 1.4 s in all, but the ball's direction changes most in the last fraction of a second, when the goalkeeper has least time to react.

PRACTICE

1. **Easy** A right-footed player strikes the ball with the inside of the foot, wrapping around its right side. Which way does it bend?

Show answer

From right to left (counterclockwise spin seen from above).

2. **Easy** Where and when did Roberto Carlos take his famous free kick?

Show answer

Lyon, France, on June 3, 1997, against France.

3. **Easy** Convert 6 turns per second to radians per second.

Show answer

$$12\pi \approx 37.7 \text{ rad/s.}$$

4. **Medium** Find the centripetal force needed for a 0.43 kg ball at 25 m/s to curve on a radius of 80 m.

Show answer

$$F = 0.43 \times 625/80 \approx 3.4 \text{ N.}$$

5. **Medium** A ball spins at 10 turns per second with radius 0.11 m. Find its surface speed.

Show answer

$$R\omega = 0.11 \times 62.8 \approx 6.9 \text{ m/s.}$$

6. **Medium** Why does a spinning ball curve more sharply as it slows down?

Show answer

It keeps most of its spin but loses speed, so the spin parameter grows and, with the sideways force nearly steady, the radius mv^2/F shrinks.

7. **Medium** What is a knuckleball in soccer, and why is it hard to save?

Show answer

A shot struck hard with almost no spin. Small, shifting forces from the air make it wobble or dip unpredictably.

8. **Hard** A ball moving at 28 m/s curves on a radius of 100 m. What sideways force acts on it? If that force stays the same, what will the radius be at 18 m/s?

Show answer

$$F = 0.43 \times 784/100 \approx 3.37 \text{ N}; r = 0.43 \times 324/3.37 \approx 41 \text{ m}.$$

9. **Hard** A corner kick travels 30 m in 1.5 s. If its bend displaces it 2.0 m sideways with constant sideways acceleration, find that acceleration.

Show answer

$$a = 2d/t^2 = 4.0/2.25 \approx 1.8 \text{ m/s}^2.$$

10. **Hard** Why did the Dupeux team fire balls into water rather than air?

Show answer

In water the forces are much larger relative to the ball's mass, so the full spiral appears within a short, easily filmed distance; the same physics then scales to a soccer ball in air over long distances.

11. **Challenge** A ball of mass 0.43 kg feels a sideways force $F = kv$ with $k = 0.10 \text{ N}\cdot\text{s}/\text{m}$. Show that the radius of curvature is $r = mv/k$, and find it at 30 m/s and 15 m/s.

Show answer

$mv^2/r = kv \Rightarrow r = mv/k$. 30 m/s: 129 m; 15 m/s: 64.5 m. Even with a force that weakens as the ball slows, the curve still tightens.

COMMON MISTAKES

- Mixing up the direction of spin and bend: the ball bends the way its front surface turns.
- Assuming the curve has the same radius all the way; a slowing ball curves more sharply.
- Hitting the ball too hard to control; spin needs a clean, off-center contact more than raw power.

Make it a game • Draw the Bend. Draw the view from above of a free kick: the ball, the wall, the goal, and the curved path. Mark the sidespin direction with a small arrow. Your parent guesses the direction of the bend and where the Magnus force pushes. Then draw the later part of the path as sharper, and label why a slowing, spinning ball curves more. Switch and draw again.

3.3 FIRST TOUCH: ABSORBING MOMENTUM

OBJECTIVES

- Use the impulse–momentum relation to explain why “giving” with the ball lowers the force and the rebound.
- Compute the force and rebound speed for stiff and soft receptions.
- Measure your own first touch and improve it with deliberate practice.

Warm-up. Toss a raw egg (over grass) or a water balloon gently to a partner, who catches it first with stiff hands and then by drawing the hands back as it arrives. Why does one way work better? (Use a soft ball instead if you prefer.)

WATCH

The SECRET to a SOFT touch to control ANY pass

Unisport · 5:19

<https://www.youtube.com/watch?v=J91H3MOFZuY>

WHEN TO WATCH

After “the physics” paragraph. Listen for the coach’s phrase about “cushioning” and connect it to contact time.

BACKUP VIDEO

The Art of First Touch in Soccer | 5 Techniques to MASTER

Kreider Academy · 7:24

<https://www.youtube.com/watch?v=2eLMBfXa0KE>

Optional, before the project, for five receiving techniques to practice.

KEY TERMS

first touch

A player’s first contact when receiving the ball, which decides how well it is controlled.

cushioning

Moving the receiving surface back with the ball to lengthen the contact time.

impulse–momentum relation

$F\Delta t = \Delta p$: the same change in momentum needs less force if it takes longer.

rebound speed

The speed of the ball just after it leaves the receiving surface.

CORE IDEAS

The story. On March 2, 2002, at St James’ Park in Newcastle, Arsenal’s Dennis Bergkamp received a hard pass with his back to goal and a defender close behind. With a single touch he flicked the ball one way around the defender, spun the other way, met the ball on the far side and scored. Coaches still show the goal to young players, not for its flair but for its first touch: Bergkamp did not stop the ball and then decide; his first contact already put it where he needed it.

How they figured it out. Coaches long told players to have “soft feet,” and Newton’s second law explains why. Every pass arrives with momentum mv . To control the ball, the player must change that momentum. If the receiving foot is rigid, the contact is short and the ball bounces away fast, often out of reach. If the foot moves back with the ball as it arrives, the contact lasts longer, the force is smaller, and the ball leaves slowly, staying close. High-speed video shows that skilled players begin withdrawing the foot just before contact and keep the ankle relaxed but steady.

The physics. The impulse–momentum relation $F\Delta t = m\Delta v$ says that the same change in momentum can be produced by a large force for a short time or a small force for a long time. A 0.43 kg ball arriving at 15 m/s and stopped completely has a momentum change of 6.45 kg·m/s. Stopped in 0.010 s, the average force is about 645 N and the ball rebounds; stopped in 0.10 s, the force is about 65 N. In collision terms, cushioning lowers the effective coefficient of restitution between foot and ball: a rigid foot returns a large share of the ball’s speed, a giving foot very little. The same idea explains why a goalkeeper draws in a shot, why a catcher’s mitt is padded, and why we bend our knees when we land.

On the field. A good first touch does three things: it slows the ball, it moves the ball away from pressure, and it sets up the next action. Players choose the surface (inside of the foot, sole, thigh, chest) that offers the largest, softest contact for the ball’s height and speed. Sometimes they want a firmer touch that redirects the ball into space rather than deadening it: physics lets them choose how much momentum to remove. **The risk side:** a poor first touch is one of the most common ways to lose the

ball, and a hard ball received stiffly on the chest or thigh can sting or bruise. Practice with softer balls first.

Think it through. In many parts of life, as in soccer, a gentle response to a hard thing is the stronger one: “A soft answer turneth away wrath” (Proverbs 15:1). The physics of cushioning is a fair picture of it.

PICTURE STUDY



France against Switzerland, Unknown photographer, February 1905 · Photograph · Paris, France

Image: [Wikimedia Commons](#), public domain

This photograph shows Switzerland's first international match, played against France in Paris in February 1905. The players wore heavy boots and the leather ball grew heavier as it soaked up water from the muddy field. Controlling such a ball took real skill.

Look closely

- Find the ball. Which player is closest, and is he about to receive it, pass it or shoot?
- Look at the field. How would mud change the way a ball rolls and bounces after a first touch?
- Look at the spacing of the players. How much time would a player have to control the ball before an opponent arrived?

Talk about it

1. A wet leather ball weighed noticeably more than a modern one. How does extra mass change the momentum a player must absorb on the first touch?
2. Why is a good first touch even more valuable when opponents are close?

Safety first. Practice receiving passes with a properly inflated ball on grass or against a sturdy rebound wall with no windows. Receive high balls on the thigh or chest only with a soft ball until your technique is sound; never receive a hard ball on the face or head. Warm up first, and stop if anything hurts.

PROJECT

Wall Work: Measuring Your First Touch

You will measure how far the ball ends up from your foot after receiving passes off a wall, with stiff and cushioned touches, then improve with ten days of deliberate practice.

You will need

- A soccer ball
- A sturdy wall with no windows (or a rebounder)
- A tape measure, chalk or cones
- A phone camera (helpful)
- The scorebook

Steps

1. Stand 6 m from the wall. Mark a 1 m circle around your receiving spot with chalk or cones, and rings at 2 m and 3 m.
2. Warm up with 20 easy passes against the wall.
3. **Predict.** Estimate what fraction of balls you will keep inside the 1 m circle with each technique.
4. **Stiff touch:** 10 firm passes off the wall, received with a firm, unmoving inside of the foot. Record which ring each ball stops in (1 m, 2 m, 3 m or outside).
5. **Cushioned touch:** 10 passes received by drawing the foot back as the ball arrives. Record.
6. **Redirect touch:** 10 passes received with a touch that moves the ball 1–2 m to the side into a target square. Record hits.
7. **Score:** 3 points for inside 1 m, 2 for 2 m, 1 for 3 m, 0 outside. Find each technique's mean score.
8. Practice deliberately for 10 minutes a day for ten days, focusing on one weakness each day (weaker foot, faster passes, the sole, the thigh with a soft ball). Test with 10 cushioned touches at the start of each day.
9. Graph your daily test score.

10. **Decide.** Write which receiving surface and touch you will use for a fast pass with an opponent close behind, and why.

Tips

- Pass harder to make the test harder as you improve, and say so in your log.
- Film a few touches from the side in slow motion to see when your foot starts to move back.

Check your work

- ☐ I recorded 30 touches of three kinds on the first day.
- ☐ I practiced and tested for ten days and graphed my scores.
- ☐ I explained my best technique with impulse and momentum.

SCOREBOOK

1. Touch table: technique, ring for each of 10 balls, total score, mean.
2. Learning curve: daily test score over ten days.
3. Two force–time sketches: a tall, narrow spike for a stiff touch and a low, wide hump for a cushioned touch, with equal areas. Label the area as the impulse.

KEY FORMULAS

$$F_{\text{avg}} = \frac{m \Delta v}{\Delta t}$$

$$v_{\text{rebound}} = e v_{\text{arrive}} \quad (\text{for a stationary, rigid surface})$$

From history. Early footballs were made of leather panels laced around an inflated bladder; synthetic, water-resistant balls became standard in the 1980s. Bergkamp's goal at Newcastle came in a Premier League season his club finished as champions.

WORKED EXAMPLES

Example 1. A 0.43 kg ball arrives at 15 m/s. Find the average force needed to stop it in 0.010 s and in 0.10 s.

Show solution

1. $\Delta p = 0.43 \times 15 = 6.45 \text{ kg}\cdot\text{m/s}$.

2. $6.45/0.010 = 645 \text{ N}$; $6.45/0.10 \approx 65 \text{ N}$.

Answer: 645 N with a stiff touch and about 65 N with a cushioned touch: ten times less.

Example 2. A rigid foot gives an effective coefficient of restitution of 0.6; a cushioned foot gives 0.15. For a pass arriving at 12 m/s, find the rebound speed in each case, and how far the ball rolls if it slows at 0.8 m/s^2 on grass.

Show solution

1. Rigid: $0.6 \times 12 = 7.2 \text{ m/s}$; roll $\frac{7.2^2}{2(0.8)} \approx 32 \text{ m}$.

2. Cushioned: $0.15 \times 12 = 1.8 \text{ m/s}$; roll $\frac{1.8^2}{1.6} \approx 2.0 \text{ m}$.

Answer: The stiff touch sends the ball about 32 m away; the cushioned touch keeps it within about 2 m. *Illustrative values.*

Example 3. A player wants to redirect a 10 m/s pass sideways at 4 m/s into space, with no forward speed left. Find the change in momentum (a vector) and its size.

Show solution

1. Before: $4.3 \text{ kg}\cdot\text{m/s}$ forward. After: $0.43 \times 4 = 1.72 \text{ kg}\cdot\text{m/s}$ sideways.

2. The change has components 4.3 backward and 1.72 sideways:

$$|\Delta p| = \sqrt{4.3^2 + 1.72^2} \approx 4.63 \text{ kg}\cdot\text{m/s}.$$

Answer: About $4.6 \text{ kg}\cdot\text{m/s}$, directed mostly backward and partly sideways; the foot must meet the ball at an angle and give with it.

PRACTICE

1. **Easy** A ball with momentum $5.0 \text{ kg}\cdot\text{m/s}$ is stopped in 0.050 s . Find the average force.

Show answer

100 N .

2. **Easy** Name three body surfaces used to receive the ball, from low to high.

Show answer

Sole or inside of the foot, thigh, chest (others acceptable).

3. **Easy** Why does drawing the foot back with the ball make the touch softer?

Show answer

It lengthens the contact time, so the same change in momentum needs a smaller force, and less speed is returned to the ball.

4. **Medium** A 0.43 kg ball arrives at 20 m/s and is stopped in 0.080 s . Find the average force.

Show answer

$8.6/0.080 \approx 108 \text{ N}$.

5. **Medium** With an effective coefficient of restitution of 0.2 , how fast does a 14 m/s pass rebound from a stationary foot?

Show answer

2.8 m/s .

6. **Medium** A ball rebounds from a first touch at 3.0 m/s and slows at 0.75 m/s^2 on grass. How far does it roll?

Show answer

$9/1.5 = 6.0 \text{ m}$.

7. **Medium** Who scored the famous first-touch goal at Newcastle in 2002, and what made the first touch so effective?

Show answer

Dennis Bergkamp; his first contact moved the ball around the defender into the space he wanted, so he did not need a second touch to set it up.

8. **Hard** A goalkeeper catches a 0.43 kg shot at 25 m/s. With stiff arms the catch takes 0.015 s; drawing the ball in takes 0.060 s. Compare the average forces.

Show answer

$$10.75/0.015 \approx 717 \text{ N against } 10.75/0.060 \approx 179 \text{ N.}$$

9. **Hard** A ball arrives at 12 m/s and the player wants it to stop within 1.5 m of his foot on grass that slows it at 0.8 m/s^2 . What is the largest rebound speed allowed, and the largest effective coefficient of restitution?

Show answer

$$v = \sqrt{2(0.8)(1.5)} \approx 1.55 \text{ m/s}; e \leq 1.55/12 \approx 0.13.$$

10. **Hard** Explain why a chest trap is done by leaning back slightly and drawing the chest in as the ball arrives.

Show answer

Leaning back sends the rebound upward and down in front of the player rather than away; drawing the chest in lengthens the contact time and lowers the force and rebound speed.

11. **Challenge** A foot moving backward at speed u meets a ball arriving at v . Relative to the foot the ball arrives at $v - u$ and leaves (relative to the foot) at $e(v - u)$. Show that the ball's rebound speed relative to the ground is $e(v - u) - u$ and find the foot speed that leaves the ball dead for $e = 0.5$, $v = 12 \text{ m/s}$.

Show answer

Relative to the ground the ball leaves forward at $e(v - u)$ measured from a foot that is itself moving back at u , so its ground speed away from the foot is $e(v - u) - u$. Set to zero: $0.5(12 - u) = u \Rightarrow u = 4 \text{ m/s}$.

COMMON MISTAKES

- Moving the foot back too early or too late; the give must begin as the ball arrives.
- Thinking a soft touch means a lazy foot; the foot is relaxed but controlled.
- Forgetting that momentum is a vector when the ball is redirected.

Make it a game • Soft Hands, Hard Hands. Toss a soft ball against a wall and catch the rebound twice: once with stiff hands, and once pulling your hands back to give. Mark with tape how far the ball rebounds each time. Score one point for each round where your prediction matched the result. Then explain aloud, using impulse and momentum, why giving with the ball lowers the force on your hands.

3.4 BALANCE, CUTTING AND PROTECTING THE KNEE

OBJECTIVES

- Compute the centripetal force and friction needed to change direction, and explain why players lean and decelerate before cutting.
- Describe the knee as a hinge held by ligaments and explain the safe landing and cutting position.
- Carry out the FIFA 11+ warm-up and measure your balance and landing control.

Warm-up. Jog five steps, then plant one foot and cut sharply to the side. Repeat while bending your knees more. Then try a cut while landing with your knee drifting inward, slowly and gently, and notice how unstable it feels. Which way felt strongest?

WATCH

FIFA 11+ Injury Prevention Program (Plus FREE Handouts)

E3 Rehab · 11:33

<https://www.youtube.com/watch?v=X5YyunLZzBc>

WHEN TO WATCH

Before the project. Follow along with the running exercises and note the coaching cue for keeping the knee over the toes.

Note: The video's description invites viewers to an email newsletter; it is not needed.

KEY TERMS

cutting

A sharp change of direction while running.

coefficient of friction

The ratio of the largest sideways grip force to the normal force pressing the shoe on the ground, μ .

centripetal force

The inward force needed to make a body follow a curved path, $F = mv^2/r$.

ligament

A tough band that ties bone to bone and keeps a joint stable; the knee has four main ones.

FIFA 11+

A 20-minute warm-up of running, strength, jumping and balance exercises designed to reduce soccer injuries.

CORE IDEAS

The story. In the early 2000s, FIFA's medical research center (F-MARC), working with the Oslo Sports Trauma Research Center in Norway and the Santa Monica Orthopaedic and Sports Medicine Research Foundation in California, set out to design a warm-up that would prevent the most common soccer injuries, especially to the knee and ankle. The result, called the FIFA 11+, was tested in Norway in a season-long trial with 1,892 girls aged 13 to 17 from 125 clubs. Torbjørn Soligard and his colleagues published the results in the *British Medical Journal* in 2008.

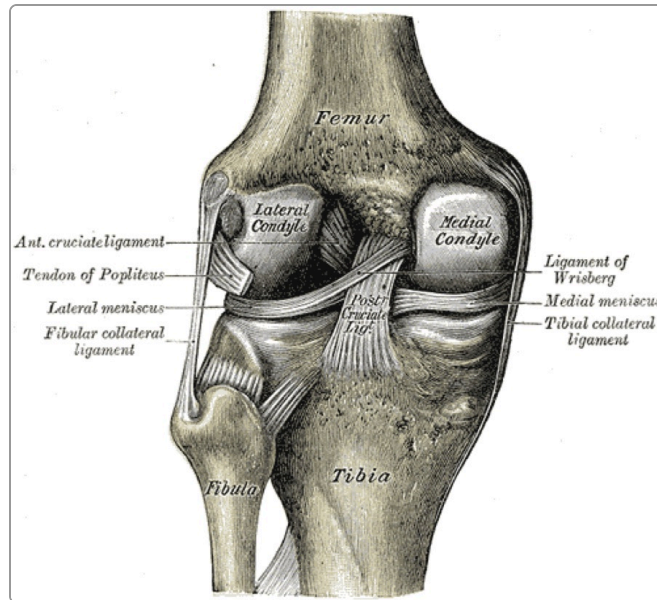
How they figured it out. Half the clubs used the 11+ before every practice; the other half warmed up as usual. Over eight months, the 11+ teams had about a third fewer injuries overall and nearly half as many severe injuries. (The drop in leg injuries alone was smaller and might have been chance, a reminder to read a study carefully.) Researchers had already found that many serious knee injuries in soccer happen without contact, when a player lands, stops or cuts with the knee collapsing inward and the body leaning back. The 11+ trains the opposite: strong hips and hamstrings, balance on one leg, and landing with the knee over the toes.

The physics. To change direction, a runner needs a sideways force. Turning on a curve of radius r at speed v takes $F = \frac{mv^2}{r}$, and that force can come only from friction between shoe and ground, at most μmg . So the sharpest turn possible is $r_{\min} = \frac{v^2}{\mu g}$. At 6 m/s with $\mu = 0.8$, that is $36/7.8 \approx 4.6$ m: a sharp cut at full speed is impossible, so players slow down first. They also lean into the turn so that the ground's push (straight up and sideways) passes through their center of mass and does not tip them over: the lean angle satisfies $\tan \theta = \frac{v^2}{rg}$. The knee is mainly a hinge; it handles large forces well along its bending direction, but twisting and inward (valgus) loads strain its ligaments. A low center of mass, a bent knee and the knee kept over the toes let the strong muscles share the load.

On the field. The 11+ takes about 20 minutes and uses only a ball and cones: running exercises, then strength, jumping and balance exercises in three levels, then fast running. Coaches who use it at least twice a week see the benefit. Good players decelerate with short steps before cutting, bend their knees, and keep their eyes up. **The risk side:** the most dangerous moments are the ordinary ones: a sudden stop, a cut on a slippery field, an awkward landing when tired. Proper shoes for the surface, a good warm-up and rest when fatigued are the high-percentage habits.

Think it through. Prevention is invisible: no one sees the injury that did not happen. That is why it takes wisdom, and patience, to do the warm-up every time.

PICTURE STUDY



Left Knee-Joint from Behind, Showing Interior Ligaments, Henry Vandyke Carter, for Gray's *Anatomy*, 1858 · Wood engraving · Published in London

Image: [Wikimedia Commons](#), public domain

Henry Gray, a young London surgeon, wrote *Anatomy, Descriptive and Surgical* in 1858, and his colleague Henry Vandyke Carter drew its illustrations. Carter's engravings were so clear that the book, now called *Gray's Anatomy*, is still published. This one shows a knee from behind, opened to reveal the ligaments that hold it together.

Look closely

- Find the femur above and the tibia below. Which way can this joint bend easily?
- Find the two cruciate (crossed) ligaments in the middle. Why might crossing them help stop the bones from sliding forward and back?
- Find the two menisci, the curved cushions between the bones. What job do they do when you land?
- Find the collateral ligaments on each side. What kind of load would stretch them?

Talk about it

1. The knee bends well but resists twisting and inward collapse poorly. Which exercise in the 11+ protects against each?

2. Carter drew this by careful observation, and surgeons still rely on drawings like it. Why is accurate drawing a form of science?

Safety first. Do every exercise on grass or a non-slip floor in athletic shoes, with space around you. Land softly with knees bent and pointing over the toes, never collapsing inward. Progress slowly from level 1 to level 3, rest between sets, and stop if any joint hurts. This lesson is about prevention; it is not medical advice, and an injury should be seen by a doctor.

PROJECT

The 11+ for Three Weeks: Balance and Landing Test

You will test your single-leg balance and landing control, do the FIFA 11+ warm-up (or its home version) three times a week for three weeks, and test again.

You will need

- A soccer ball and 6–12 cones (or shoes as markers)
- A stopwatch
- A phone camera on a stand
- A mirror or partner
- A flat, non-slip surface or grass
- The scorebook

Steps

1. Single-leg balance test: stand on one leg, hands on hips, other foot off the ground, and time how long you hold it without moving the standing foot (stop at 60 s). Three trials each leg, eyes open; then three trials each leg, eyes closed.
2. Landing test: stand on a low step (about 30 cm), drop off and land on both feet, then immediately jump straight up. Film from the front. Do 5 landings.
3. In the video, freeze each landing at the lowest point. Check: are your knees over your toes, or do they move inward? Score each landing 2 (knees over toes), 1 (slightly inward) or 0 (clearly inward).
4. **Predict.** Write how much you expect your balance times and landing scores to improve in three weeks.
5. Learn the 11+ from the video: the running exercises, the strength, jumping and balance exercises at level 1, and the final running. Do it three times a week for three weeks, moving to level 2 when level 1 feels easy and controlled.
6. Log each session: date, level, exercises done, and any discomfort.
7. After three weeks, repeat both tests exactly as before.

8. Compare before and after: mean balance time for each leg and condition, and total landing score.
9. **Decide.** Write whether the 11+ is worth 20 minutes before each practice for you, using your data, and what you would tell a younger player about cutting and landing.

Tips

- Quality matters more than speed: slow, controlled reps build the habit.
- Film from the same spot and height before and after.

Check your work

- ☐ I tested balance and landing before and after three weeks.
- ☐ I logged nine 11+ sessions.
- ☐ I compared my results and wrote a decision.

SCOREBOOK

1. Balance table: leg, eyes open or closed, three times, mean, before and after.
2. Landing score table before and after, with one sketch of a good landing (knees over toes) and one of a poor landing (knees inward).
3. Free-body diagram of a player leaning into a cut: weight, normal force, friction, and the resultant through the center of mass.

KEY FORMULAS

$$F_c = \frac{mv^2}{r} \leq \mu mg$$

$$r_{\min} = \frac{v^2}{\mu g}$$

$$\tan \theta_{\text{lean}} = \frac{v^2}{rg}$$

From history. The 11+ grew from an earlier, shorter program called “The 11,” introduced by F-MARC in 2003. Gray’s *Anatomy* has been revised continually since 1858 and remains a standard reference.

WORKED EXAMPLES

Example 1. A 60 kg player running at 5.0 m/s cuts on a curve of radius 3.0 m. Find the sideways force needed and the smallest coefficient of friction that provides it.

Show solution

$$1. F = \frac{60 \times 25}{3.0} = 500 \text{ N.}$$
$$2. \mu \geq \frac{F}{mg} = \frac{500}{588} \approx 0.85.$$

Answer: 500 N, needing a friction coefficient of at least about 0.85: good shoes on dry grass, but not on wet grass.

Example 2. On wet grass the coefficient of friction falls to about 0.5. What is the tightest turn radius at 5.0 m/s? How fast can a player go around a 3.0 m radius?

Show solution

$$1. r_{\min} = \frac{25}{0.5 \times 9.8} \approx 5.1 \text{ m.}$$
$$2. v_{\max} = \sqrt{\mu gr} = \sqrt{0.5 \times 9.8 \times 3.0} \approx 3.8 \text{ m/s.}$$

Answer: About 5.1 m; on a 3.0 m turn the player must slow to about 3.8 m/s or slip.

Example 3. Find the lean angle for a player turning at 5.0 m/s on a radius of 3.0 m.

Show solution

$$1. \tan \theta = \frac{25}{3.0 \times 9.8} \approx 0.85, \theta \approx 40^\circ \text{ from vertical.}$$

Answer: About 40° , a dramatic lean; in practice players slow down and cut with a smaller lean.

PRACTICE

1. Easy Find the centripetal force on a 50 kg runner at 4.0 m/s on a 4.0 m radius.

Show answer

200 N.

2. Easy Name two things the FIFA 11+ trains that protect the knee.

Show answer

Any two: hip and hamstring strength, single-leg balance, landing with the knee over the toes, controlled jumping, cutting technique.

3. Easy In the 2008 Norwegian trial, about how much did the 11+ reduce injuries overall and severe injuries?

Show answer

About a third fewer injuries overall and nearly half as many severe injuries.

4. Medium Find the tightest turn radius at 7.0 m/s with $\mu = 0.9$.

Show answer

$$49/8.82 \approx 5.6 \text{ m.}$$

5. Medium What is the greatest speed for a 2.0 m radius cut with $\mu = 0.8$?

Show answer

$$\sqrt{0.8 \times 9.8 \times 2.0} \approx 4.0 \text{ m/s.}$$

6. Medium Find the lean angle for 4.0 m/s on a 2.0 m radius.

Show answer

$$\tan \theta = 16/19.6 \approx 0.82, \theta \approx 39^\circ.$$

7. Medium Why should a player slow down with short steps before a sharp cut?

Show answer

The force needed grows with the square of speed; slowing first keeps the needed friction within what the shoes can provide and lowers the load on the knee.

8. Medium Why was it important that the Norwegian trial compared clubs using the 11+ with clubs that did not?

Show answer

Without a comparison group, a drop in injuries could have come from other causes (weather, chance, a different season); the comparison isolates the warm-up's effect.

9. **Hard** A 55 kg player decelerates from 6.0 m/s to 2.0 m/s in 0.50 s before a cut. Find the average braking force and the friction coefficient it requires.

Show answer

$$a = 8.0 \text{ m/s}^2; F = 440 \text{ N}; \mu \geq 440/539 \approx 0.82.$$

10. **Hard** Two players turn on the same 3.0 m radius, one at 4 m/s and one at 6 m/s. By what factor is the force on the faster player larger?

Show answer

$$(6/4)^2 = 2.25 \text{ times.}$$

11. **Hard** Explain, with the center of mass, why landing with the body leaning back and the knee straight is risky.

Show answer

With the center of mass behind the foot and the knee straight, the ground force passes behind the knee and the bones and ligaments take the load instead of the bent-knee muscles; the knee can also shift and twist.

12. **Challenge** Show that the lean angle needed for a turn equals the angle whose tangent is the friction coefficient being used, $\tan \theta = F/(mg)$, and find the largest lean possible with $\mu = 0.85$.

Show answer

The ground pushes up with mg and sideways with $F = mv^2/r$; the total force must point along the body through the center of mass, so $\tan \theta = F/mg = v^2/rg$. The largest is $\theta = \tan^{-1} 0.85 \approx 40^\circ$.

COMMON MISTAKES

- Thinking stronger players do not need a warm-up; the 11+ trained high-level players too.
- Letting the knees fall inward on squats and landings.
- Treating a study's secondary results as certain without reading its main result.

Make it a game • Cut, Lean or Tall Tale. Your parent states three claims about cutting and the knee: two true, one tall tale. Topics include centripetal force, friction needed to turn, why players lean, and the safe landing position from the FIFA 11+. You name the tall tale and correct it. Swap roles. Each correct catch earns a point. First to five wins. Bonus point for naming the ligament role.

Scripture. “A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished.” (Proverbs 22:3, KJV)

The 11+ is foresight in practice: twenty minutes of preparation against a danger that most players never see coming.

3.5 HEADING: PHYSICS AND SAFETY RULES

OBJECTIVES

- Use momentum to explain why a firm neck and good technique lower the acceleration of the head when a ball is headed.
- State U.S. Soccer’s heading guidelines for youth players and explain the reasons for them.
- Practice heading technique safely with a balloon and measure what changes.

Warm-up. Hold a light balloon and drop it in front of your face. Watch how slowly it falls compared with a ball. Then tap it upward with your forehead, eyes open, three times in a row. Where on your head did the best touches land?

WATCH

Protecting the Brain | Cincinnati Children's

Cincinnati Children's • 3:21

<https://www.youtube.com/watch?v=JMzBE4742As>

WHEN TO WATCH

After “how they figured it out.” Listen for what the researchers measure and why they study young players.

Note: A hospital research feature; part of it shows a protective collar being tested, which is not an endorsement of any product.

BACKUP VIDEO

Heading Drills HD

Lexington United Soccer Club • 10:08

<https://www.youtube.com/watch?v=N1SSYAbalN8>

Optional, before the project, to see the eyes-open, forehead-contact technique taught to young teen players with light balls.

KEY TERMS

header

Playing the ball with the forehead.

head acceleration

How quickly the head's velocity changes when struck; it is what researchers measure to judge the severity of a head impact.

effective mass

The mass that takes part in a collision; a firm neck links the head to the trunk and raises it.

subconcussive impact

A blow to the head that causes no obvious symptoms, studied because many such blows over time may matter.

CORE IDEAS

The story. Heading has been part of soccer since its earliest days, and great headers of the ball have long been admired. But doctors and researchers grew concerned about repeated blows to the developing brains of children. In November 2015 U.S. Soccer announced new guidance for youth players, which took effect in 2016: **no heading for players 10 and under**, and for players aged 11 to 13, heading limited to practice, with no more than about 30 minutes of heading training a week and no more than 15 to 20 headers per player per week. England's Football Association issued similar guidance in 2020.

How they figured it out. Researchers fit players with small sensors behind the ear or in mouthguards and recorded every impact to the head in practices and games. They found that most headers produce modest accelerations, but that collisions (head to head, head to ground, head to elbow) during heading duels cause most of the serious head injuries in soccer. Studies of young players also suggested that a child's head is relatively heavy and the neck relatively weak, so the head is accelerated more by the same ball. Because researchers are still learning what many small impacts do over years, the rules take the cautious path for children.

The physics. When a ball strikes the head, it changes momentum, and an equal and opposite impulse acts on the head. The head's change in velocity is $\Delta v_{\text{head}} = \frac{\Delta p}{M_{\text{eff}}}$, where M_{eff} is the effective mass that moves with the head. A loose neck lets the head move almost alone (about 4–5 kg in an adult); a firm neck, braced with the trunk,

links the head to much more of the body, so the same impulse gives the head a smaller change in velocity and a smaller acceleration. Meeting the ball with the flat, strong forehead, eyes open and mouth closed, spreads the force and lets the player control it; being struck on the top or side of the head is worse. A balloon has a mass of only a few grams, so its momentum, and the impulse it delivers, is tiny: it lets you learn the technique with almost no load.

On the field. Safe heading habits are: eyes open, mouth closed, contact on the forehead at the hairline, neck firm and the movement coming from the trunk and legs, arms used for balance but never as elbows into opponents, and no heading of hard-kicked balls. Many coaches now teach young players to receive high balls on the chest or thigh instead. **The risk side:** the danger in heading comes mostly from collisions in the air. A wise player chooses not to contest a header he cannot win cleanly, and every player should report any headache or dizziness at once.

Think it through. The rules for children are stricter than for adults, not because heading is forbidden, but because children's bodies are still growing. Caring for the body includes accepting limits for a season of life.

PICTURE STUDY



An Association Football Match, Arthur Thiele, c. 1905 · Color postcard · Germany

Image: [Wikimedia Commons](#), public domain

Arthur Thiele was a German illustrator famous for lively, humorous postcards. Around 1905 he drew this football match, with players jostling under a high ball in front of the goal. It shows the moment that heading guidelines worry about most: several players competing for one ball in the air.

Look closely

- Find the ball. How many players are trying to reach it?
- Look at the player kicking high. Where is his foot compared with the other players' heads?
- Look at the arms and elbows. Which movements would be dangerous in a real contest for the ball?
- Find the goalkeeper. What is he doing, and what should he do?

Talk about it

1. Using this lesson, explain why collisions, more than the ball, cause most serious head injuries in heading play.
2. If you were coaching these players, what two rules would you give them for contesting a high ball safely?

Safety first. Heading in this lesson is done only with a balloon or a very soft foam ball, never with a regular soccer ball. Follow U.S. Soccer's guidance: no heading at all for players 10 and under, and only limited heading in practice for ages 11–13. Never head a ball that is kicked hard, never jump to head near another player, and stop at once and tell a parent if you feel a headache, dizziness or any change after a blow to the head.

PROJECT

Balloon Heading: Technique Without the Load

You will learn and score heading technique with a balloon, measure how long you can keep it up, and compute the momentum you are handling compared with a real ball.

You will need

- Several balloons (or a very soft foam ball)
- A kitchen scale
- A tape measure and a phone camera
- A partner
- A room cleared of breakable objects, or a calm outdoor space
- The scorebook and a calculator

Steps

1. Weigh a balloon on the kitchen scale (or weigh five together and divide). Record its mass in kilograms.
2. Drop the balloon from 2.0 m and time its fall with video. Compute its average falling speed and its momentum.
3. **Predict.** How many consecutive forehead taps can you make before the balloon touches the floor?
4. Technique check: have your partner film you from the side for 10 headers of a balloon tossed gently from 2 m away. Score each: eyes open (1), mouth closed (1), forehead contact (1), neck firm with the movement from the trunk (1). Total out of 4.
5. Keep-up test: tap the balloon upward with your forehead as many times as you can. Three trials; record the best.
6. Practice for 10 minutes on three different days, focusing on the lowest-scoring technique point.
7. Repeat the technique check and keep-up test.
8. Compute the momentum of a regular ball (use 0.43 kg) arriving at 8 m/s and compare it with your balloon's.

9. Write U.S. Soccer's heading guidance in your own words and explain each part with the physics of this lesson.
10. **Decide.** Write what you would tell a 9-year-old teammate who wants to head the ball in a game, and what you would tell a 13-year-old.

Tips

- Keep your eyes on the balloon all the way to your forehead; this is the hardest habit to learn and the most important.
- Do not let anyone kick or throw a real ball at your head in this project.

Check your work

- ☐ I measured the balloon's mass, speed and momentum and compared it with a real ball.
- ☐ I scored my technique before and after practice.
- ☐ I wrote the heading guidance and explained it with physics.

SCOREBOOK

1. Technique table: header number, eyes open, mouth closed, forehead, firm neck, total; before and after.
2. Momentum comparison: a bar chart (on a log scale if you can) of balloon, foam ball and regular ball momentum.
3. Side-view sketch of good heading posture: label the forehead contact point, the firm neck, the trunk movement and the eyes.

KEY FORMULAS

$$\Delta v_{\text{head}} = \frac{\Delta p_{\text{ball}}}{M_{\text{eff}}}$$

$$a_{\text{avg}} = \frac{\Delta v}{\Delta t} \quad 1 g = 9.8 \text{ m/s}^2$$

From history. U.S. Soccer's youth heading guidance was announced in November 2015 and took effect in 2016. In 2020 England's Football Association removed heading from training for primary-school children and limited it for older youth.

WORKED EXAMPLES

Example 1. Illustrative. A 0.43 kg ball arrives at 12 m/s and leaves the head at 6 m/s in the opposite direction. Contact lasts 0.010 s. Find the head's average acceleration if the effective mass is 5 kg (loose neck) and 15 kg (firm neck and trunk), in m/s^2 and in g .

Show solution

1. $\Delta p = 0.43 \times (12 + 6) = 7.74 \text{ kg}\cdot\text{m/s}$.
2. Loose: $\Delta v = 7.74/5 \approx 1.55 \text{ m/s}$; $a \approx 155 \text{ m/s}^2 \approx 16 g$.
3. Firm: $\Delta v = 7.74/15 \approx 0.52 \text{ m/s}$; $a \approx 52 \text{ m/s}^2 \approx 5 g$.

Answer: About 16 g with a loose neck and about 5 g with a firm neck: a firm neck cuts the head's acceleration to about a third.

Example 2. Compare the momentum of a 0.43 kg ball at 12 m/s with that of a 3 g balloon at 3 m/s.

Show solution

1. Ball: $0.43 \times 12 = 5.16 \text{ kg}\cdot\text{m/s}$.
2. Balloon: $0.003 \times 3 = 0.009 \text{ kg}\cdot\text{m/s}$.
3. Ratio: $5.16/0.009 \approx 570$.

Answer: The ball carries about 570 times the momentum of the balloon, which is why the balloon is safe for learning technique.

Example 3. A 12-year-old follows U.S. Soccer's guidance of at most 20 headers a week, with light balls in practice only. Over a 30-week season, how many headers is that at most? How does that compare with a player who heads 10 balls a day, 5 days a week, for the same season?

Show solution

1. $20 \times 30 = 600$.
2. $10 \times 5 \times 30 = 1,500$.

Answer: At most 600 against 1,500: the guideline cuts the yearly total by at least 60%.

PRACTICE

1. **Easy** At what age does U.S. Soccer's guidance say players should not head the ball at all?

Show answer

10 and under.

2. **Easy** List four habits of safe heading technique.

Show answer

Eyes open, mouth closed, contact on the forehead, neck firm with the movement from the trunk and legs (also: no elbows, no heading hard-kicked balls).

3. **Easy** Find the momentum of a 0.43 kg ball at 8.0 m/s.

Show answer

3.44 kg·m/s.

4. **Medium** A ball gives a 0.010 s impulse of 5.0 N·s to a head of effective mass 5.0 kg. Find the change in velocity and the average acceleration in g .

Show answer

$$\Delta v = 1.0 \text{ m/s}; a = 100 \text{ m/s}^2 \approx 10 g.$$

5. **Medium** Repeat problem 4 with an effective mass of 12 kg.

Show answer

$$\Delta v \approx 0.42 \text{ m/s}; a \approx 42 \text{ m/s}^2 \approx 4.3 g.$$

6. **Medium** Why is a child's head accelerated more than an adult's by the same ball?

Show answer

A child's head is relatively large and heavy compared with a weaker neck, so it is less firmly linked to the trunk; the effective mass is smaller and the same impulse produces a larger change in velocity.

7. **Medium** According to research, what causes most serious head injuries during heading play?

Show answer

Collisions during heading duels: head to head, head to elbow or head to ground, rather than the ball itself.

8. **Medium** Why do the guidelines limit heading for ages 11–13 to practice?

Show answer

In practice the ball speed, number of headers and contact with other players can be controlled, while games bring hard-kicked balls and aerial collisions.

9. **Hard** A ball at 15 m/s rebounds from a head at 5 m/s. For a firm neck with effective mass 15 kg and a contact time of 0.012 s, find the head's average acceleration in g .

Show answer

$$\Delta p = 0.43 \times 20 = 8.6; \Delta v \approx 0.57 \text{ m/s}; a \approx 48 \text{ m/s}^2 \approx 4.9 g.$$

10. **Hard** In a collision, a 4.5 kg head moving at 2.0 m/s strikes another player's 4.5 kg head at rest, and afterward both move together at 1.0 m/s. If the collision lasts 0.005 s, find the average acceleration of each head in g . Compare with problem 4.

Show answer

Each head changes velocity by 1.0 m/s in 0.005 s: $a = 200 \text{ m/s}^2 \approx 20 g$. That is about twice the header in problem 4: head-to-head contact, short and uncushioned, is far more severe than heading the ball.

11. **Hard** Explain why a player who “attacks” the ball with a firm neck and a step forward may receive a smaller head acceleration than one who lets the ball hit him.

Show answer

The firm neck and braced trunk raise the effective mass, so the head's velocity changes less; moving to meet the ball also lets the player control the contact on the forehead.

12. **Challenge** A balloon of mass 3.0 g falls at a steady 2.5 m/s, while a soccer ball dropped from 2.0 m reaches about 6.3 m/s. Compute both momenta and explain, with numbers, why balloon practice teaches technique while carrying almost no load.

Show answer

Balloon: $0.0075 \text{ kg} \cdot \text{m/s}$; ball: $0.43 \times 6.3 \approx 2.7 \text{ kg} \cdot \text{m/s}$, about 360 times as much. The balloon moves slowly enough to practice eyes-open forehead contact and body movement, while the impulse on the head is negligible.

COMMON MISTAKES

- Closing the eyes at contact; it leads to mistimed contact on the top of the head.
- Letting the neck go loose, which lowers the effective mass and raises the head's acceleration.
- Thinking the guidelines ban heading forever; they set age-appropriate limits.

Make it a game • Team Doctor Press Conference. Your parent plays a reporter and asks about heading in youth soccer. You are the team doctor with sixty seconds to answer. Cover how a firm neck and good technique change head acceleration, then the guidelines for youth players, and why they exist. Your parent counts facts: one point for each correct physics idea or rule. Beat your own count on a second round.

UNIT 3

SOCCER

The world's most popular game is a game of collisions and spin. This unit studies the impulse of the instep drive, the spinning-ball physics behind Roberto Carlos's 1997 free kick, the cushioned first touch that absorbs momentum, the friction and balance of cutting and the FIFA 11+ program that protects knees, and the physics behind the youth heading guidelines.

Projects measure your own shot speed and accuracy, the bend of your curled kicks, your first touch off a wall, your balance and landing before and after three weeks of the 11+, and heading technique learned safely with a balloon. Heading in this course is taught only with a balloon or a very soft foam ball.

PREREQUISITES

- Unit 1: Newton's laws, center of mass and the kinetic chain
- Unit 2: momentum, impulse, coefficient of restitution and the Magnus effect
- Algebra I and basic trigonometry

MASTERY CHECKLIST

- ☐ I can compute the impulse and force of a kick and explain how technique raises ball speed.
- ☐ I can explain why a spinning ball bends and why its curve sharpens as it slows.
- ☐ I can explain cushioning with the impulse-momentum relation and compute stiff and soft receptions.
- ☐ I can compute the friction and lean needed to cut, and explain how the 11+ protects the knee.
- ☐ I can explain the youth heading guidelines with the physics of head acceleration.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **The IFAB: Laws of the Game, Law 2 (The Ball)**: Free. The official specification of the ball's size, mass and pressure used in Lessons 3.1–3.3, from the body that writes soccer's rules.
- **U.S. Soccer: Recognize to Recover**: Free. U.S. Soccer's player-health program, with guidance on heading, injury prevention and warm-ups for Lessons 3.4 and 3.5. For parents and coaches.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

3.1 The Instep Drive: The Physics of the Kick	3 sessions of 50 minutes
3.2 Bending It: Spin and the Famous Free Kick	3 sessions of 50 minutes
3.3 First Touch: Absorbing Momentum	3 sessions of 50 minutes
3.4 Balance, Cutting and Protecting the Knee	3 sessions of 50 minutes
3.5 Heading: Physics and Safety Rules	3 sessions of 50 minutes

UNIT 3 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$ and a ball mass of 0.43 kg unless told otherwise. Show your work for every calculation with units. Answer the concept questions in complete sentences. The test is worth 100 points.

1. **6 pts**

A ball is kicked from rest to 26 m/s in 0.010 s. Find the impulse and average force.

2. **6 pts**

A foot moving at 19 m/s sends the ball off at 1.3 times its speed. Find the ball's speed in km/h and its time to travel 20 m.

3. (6 pts)

Explain two ways a locked ankle and the knee over the ball improve an instep drive.

4. (6 pts)

A right-footer curls the ball with the inside of the foot. Which way does it spin (seen from above) and which way does it bend?

5. (8 pts)

A ball moving at 27 m/s feels a sideways force of 2.9 N. Find its radius of curvature, then the radius at 18 m/s with the same force. Explain the result.

6. (5 pts)

What did Dupeux and his colleagues show in “The spinning ball spiral” (2010)?

7. (7 pts)

A ball arriving at 16 m/s is stopped in 0.012 s and, with a cushioned touch, in 0.090 s. Find both average forces.

8. (6 pts)

With an effective coefficient of restitution of 0.15, a pass at 13 m/s rebounds at what speed? How far does it roll on grass that slows it at 0.8 m/s^2 ?

9. (7 pts)

A 65 kg player runs at 6.0 m/s. Find the tightest turn radius with $\mu = 0.8$ and the sideways force needed on a 4.0 m radius.

10. (6 pts)

Find the lean angle for a 5.0 m/s turn on a 4.0 m radius.

11. (6 pts)

Describe the knee position the FIFA 11+ teaches for landing and cutting, and explain why it protects the knee.

12. (6 pts)

Summarize the 2008 Norwegian trial of the 11+ honestly, including its limitation.

13. (5 pts)

State U.S. Soccer's heading guidance for players 10 and under and for ages 11–13.

14. (7 pts)

Illustrative. A ball gives a head an impulse of $6.0 \text{ N}\cdot\text{s}$ over 0.010 s . Find the head's average acceleration in g for effective masses of 5.0 kg and 15 kg .

15. (13 pts)

Short essay. In about 150 words, explain how the same physical idea, impulse and contact time, appears in the instep drive, the first touch and heading. Show how a player uses it differently in each.

ANSWER KEY

1. $11.2 \text{ N}\cdot\text{s}$; $\approx 1,120 \text{ N}$.
2. $24.7 \text{ m/s} \approx 89 \text{ km/h}$; 0.81 s .
3. The locked ankle raises the effective mass of the foot, so more speed goes to the ball; the knee over the ball keeps contact through or above center, so the shot stays low.
4. Counterclockwise from above; it bends from right to left.
5. $r \approx 108 \text{ m}$; $r \approx 48 \text{ m}$. The slowing ball curves more sharply because $r = mv^2/F$ falls with the square of speed.
6. That a spinning ball slowed by drag keeps its spin while losing speed, so its path tightens from a curve toward a spiral, explaining the late bend of long, hard-struck free kicks.
7. $6.88/0.012 \approx 573 \text{ N}$; $6.88/0.090 \approx 76 \text{ N}$.
8. 1.95 m/s ; $\approx 2.4 \text{ m}$.
9. $r_{\min} \approx 4.6 \text{ m}$; $F = 65 \times 36/4.0 = 585 \text{ N}$ (more than $\mu mg \approx 510 \text{ N}$, so the player would slip).
10. $\tan \theta \approx 0.64$, $\theta \approx 33^\circ$.
11. Knees bent and over the toes, not collapsing inward, with the trunk over the feet. It lets the large leg and hip muscles share the load and avoids twisting and inward loads on the ligaments.
12. In a season-long trial of 1,892 girls from 125 clubs, teams using the 11+ had about a third fewer injuries overall and nearly half as many severe injuries; the reduction in leg injuries alone was not statistically certain.
13. No heading for 10 and under; for 11–13, heading only in practice, with at most about 30 minutes of heading training and 15–20 headers per player per week.
14. $\approx 12 g$ and $\approx 4 g$.
15. Answers vary. A strong essay explains $F\Delta t = \Delta p$ and shows that in the kick the player wants a large impulse delivered with a fast, firm foot; in the first touch he lengthens contact time to lower force and rebound; in heading a firm neck raises the effective mass so the head's velocity changes little, and safety rules limit repeated impacts.

PORTFOLIO PIECE: A SOCCER PLAYER'S PHYSICS AND SAFETY HANDBOOK

Create an illustrated handbook of at least four pages for a youth soccer team. Include: how to hit a powerful, accurate shot (with your own measured speeds); how to bend the ball (with your measured bends); how to take a good first touch (with your wall-test results); how to warm up and land safely (the 11+, with your before-and-after balance data); and the heading guidelines explained with physics. Each page must have a labelled diagram, one formula explained in plain words, and one practical tip. End with a one-page warm-up card a coach could pin to a bulletin board.

LOOK FOR	WHAT IT MEANS
Physics	Correct, clearly explained physics on every page, with formulas used properly.
Own data	Real measurements from the unit's projects, honestly reported.
Safety	Accurate heading guidance and injury-prevention advice, without medical claims.
Usefulness	A handbook and warm-up card a youth team could actually use.

UNIT 4

TENNIS AND VOLLEYBALL

Two net games, one physics. This unit studies the tennis serve as a kinetic chain and the narrow window over the net, topspin and the forehand, the split step and reaction time, the volleyball forearm pass as a reflection off a tilted platform, and the spike and jump serve, with the history of William G. Morgan's game of 1895.

The projects measure your serve speed and accuracy, the margin topspin gives your forehand, your reaction time and first step, your passing angle and accuracy, and your approach jump. Every project works at home with a soft ball, a wall and a phone camera; a trip to a court is optional and supervised.

PREREQUISITES

- Units 1–3: the kinetic chain, projectile motion, the Magnus effect, impulse and the coefficient of restitution
- Algebra I and right-triangle trigonometry
- Vectors in two dimensions (helpful for the reflection problems)

MASTERY CHECKLIST

- ☐ I can explain the serve as a kinetic chain and use the court's geometry to explain the need for spin.
- ☐ I can show with projectile calculations why topspin keeps a hard shot in the court.
- ☐ I can measure reaction time and explain the split step.
- ☐ I can find the platform angle that sends a pass to a target using the law of reflection.
- ☐ I can compute jump height, hang time and the steepest angle of a spike over the net.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **Rod Cross: Physics of Tennis and Other Sports**: Free. A University of Sydney physicist's articles on rackets, strings, spin and bounce, with high-speed photographs. Extends Lessons 4.1 and 4.2. Some articles are technical. Ages 14+.
- **International Volleyball Hall of Fame**: Free. The Holyoke museum's site, with the history of William G. Morgan and the early game for Lessons 4.4 and 4.5.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

4.1 The Tennis Serve as a Kinetic Chain	3 sessions of 50 minutes
4.2 Topspin and the Forehand	3 sessions of 50 minutes
4.3 Footwork, the Split Step and Reaction Time	3 sessions of 50 minutes
4.4 The Volleyball Pass: Platform Angle and Reflection	3 sessions of 50 minutes
4.5 The Spike and the Jump Serve	3 sessions of 50 minutes

UNIT 4 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$. Show your work for every calculation with units. Answer the concept questions in complete sentences. The test is worth 100 points.

1. 6 pts

A racket center 1.45 m from the shoulder axis turns at 29 rad/s. Find its speed. If the ball leaves at 1.4 times that speed, find the ball speed in km/h.

2. 7 pts

Using the straight-line serve model, find how high a serve from a 2.9 m contact point crosses the net when aimed at the service line. Does it clear the 0.914 m net?

3. 6 pts

Explain why most second serves are hit with spin.

4. 6 pts

Find the surface speed of a ball of radius 3.35 cm spinning at 2,800 rpm.

5. 9 pts

A ball is hit from 1.0 m at 24 m/s, 12° above horizontal. Find where it lands with no spin and with topspin adding 5.0 m/s^2 downward. Which lands in a 23.77 m court from the baseline?

6. (5 pts)

A ruler falls 0.15 m before it is caught. Find the reaction time.

7. (6 pts)

Find the air time of a 6.0 cm split-step hop, and explain why the split step should land as the opponent strikes the ball.

8. (6 pts)

A serve takes 0.55 s to reach a returner whose reaction time is 0.20 s. If she accelerates at 6.0 m/s^2 after reacting, how far can she move before the ball arrives?

9. (8 pts)

A serve arrives descending at 40° toward a passer, who wants it to rise at 60° toward the net. Find the angle of the platform's normal above horizontal and the slope of the forearms.

10. (7 pts)

A pass leaves at 7.5 m/s and 70° . Find its peak height and flight time to the same height.

11. (5 pts)

Who invented volleyball, where and when, and what was it first called?

12. (7 pts)

A player jumps 0.45 m. Find her takeoff speed and hang time.

13. (8 pts)

From a contact point 3.05 m high and 1.0 m from a 2.43 m net, find the steepest straight-line hit and how far beyond the net it lands.

14. (14 pts)

Short essay. In about 150 words, compare the tennis forehand and the volleyball spike as uses of the kinetic chain and spin. Include one calculation from your own project data.

ANSWER KEY

1. 42 m/s ; $58.9 \text{ m/s} \approx 212 \text{ km/h}$.
2. $2.9 \times 0.350 \approx 1.02 \text{ m}$; yes, by about 10 cm.
3. A flat serve has a tiny window over the net and into the box; spin curves the ball down, letting it cross higher and still land in, which lowers the risk of a double fault.
4. $\omega \approx 293 \text{ rad/s}$; $v \approx 9.8 \text{ m/s}$.
5. $v_x \approx 23.5$, $v_y \approx 4.99$. No spin: $t \approx 1.19 \text{ s}$, $x \approx 28 \text{ m}$ (out). Topspin:
 $1 + 4.99t - 7.4t^2 = 0 \Rightarrow t \approx 0.84 \text{ s}$, $x \approx 19.6 \text{ m}$ (in).
6. $\approx 0.17 \text{ s}$.
7. $2\sqrt{0.12/9.8} \approx 0.22 \text{ s}$. Landing then lets the player push off in the right direction immediately, with stretched, ready muscles; landing early leaves him flat and still, landing late leaves him in the air.
8. $\frac{1}{2}(6.0)(0.35)^2 \approx 0.37 \text{ m}$.
9. The normal bisects: $\phi = (40^\circ + 60^\circ)/2 = 50^\circ$; forearms slope 40° below horizontal.
10. $v_y \approx 7.05$; $H \approx 2.54 \text{ m}$; $T \approx 1.44 \text{ s}$.
11. William G. Morgan, at the Holyoke, Massachusetts, YMCA in 1895; mintonette.
12. 2.97 m/s ; 0.61 s .
13. $\tan \theta = 0.62$, $\theta \approx 32^\circ$; lands $3.05/0.62 \approx 4.9 \text{ m}$ from contact, about 3.9 m beyond the net.
14. Answers vary. A strong essay describes both as proximal-to-distal chains (legs, hips, trunk, shoulder, elbow, wrist), explains how each produces topspin (low-to-high racket path; wrist snap over the ball) and why topspin brings the ball down into the court, and includes a correct calculation from the student's measurements.

PORTFOLIO PIECE: A NET-GAMES PHYSICS NOTEBOOK

Prepare an illustrated report of four to six pages on the physics of tennis and volleyball, built around your own measurements. Include your serve speeds and contact height with the straight-line net calculation; your flat and topspin forehand margins; your reaction time and split-step test; your passing angles and accuracy; and your approach jump with the steepest angles you could hit. For each, give the formula, your data, one graph or diagram, and a one-sentence coaching tip. End with a comparison of tennis and volleyball: what physics they share, and what is different.

LOOK FOR	WHAT IT MEANS
Measurements	All five measurements present with repeated trials and units.
Physics and mathematics	Correct formulas and calculations, including the reflection and net-geometry problems.
Diagrams and graphs	Clear, labelled, to-scale diagrams and at least two graphs.
Comparison and coaching	A thoughtful comparison of the two sports and practical coaching tips drawn from the data.

4.1 THE TENNIS SERVE AS A KINETIC CHAIN

OBJECTIVES

- Describe the serve as a kinetic chain from the legs to the racket and compute racket speed with $v = \omega r$.
- Use the geometry of the court to explain why a flat serve needs a high contact point.
- Measure your own serve's speed and accuracy.

Warm-up. Without a racket, throw a soft ball high over a fence or into a far corner of the yard with an overhand throw. Then throw it with your feet together and no body turn. Compare the distances. How is a tennis serve like a throw?

WATCH

How To Master The Serve Kinetic Chain

TPA tennis · 8:29

<https://www.youtube.com/watch?v=r4L8afIM6Eg>

WHEN TO WATCH

After “the physics” paragraph. As the coach builds the serve link by link, name each segment and its order.

Note: The coach mentions his paid lessons and newsletter; neither is needed.

KEY TERMS

serve

The overhead stroke that starts each point, tossed and struck from behind the baseline into the diagonal service box.

pronation

The inward turning of the forearm just before contact, which squares the racket face and adds speed.

trophy position

The coiled position of the serve, knees bent, racket back and tossing arm up, before the upward drive.

contact height

The height above the court at which the racket strikes the ball.

CORE IDEAS

The story. Lawn tennis was first played at Wimbledon in 1877, and early servers often struck the ball underhand or at shoulder height. By 1912 a young Californian named Maurice McLoughlin, the “California Comet,” had won the U.S. championship with a serve so fast that writers called it the “cannonball.” He reached the Wimbledon final in 1913. McLoughlin did not have a stronger arm than everyone else; he had learned to throw his whole body up into the ball.

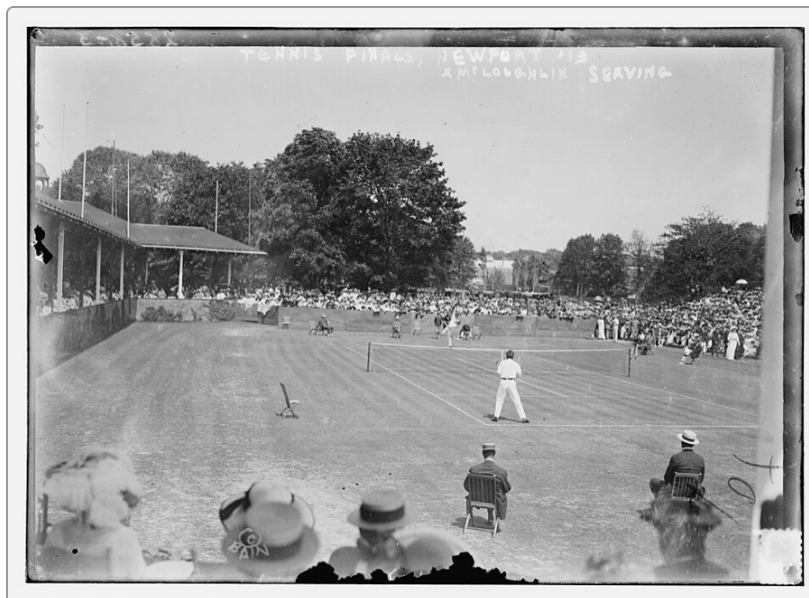
How they figured it out. Coaches long said the serve is “like throwing a ball,” and biomechanists confirmed it with high-speed film and motion capture. Researchers such as Bruce Elliott in Australia measured each segment’s speed and found the same proximal-to-distal sequence as in pitching (Lesson 1.4): the legs drive up from bent knees, the hips and trunk rotate and tilt, the upper arm rotates inward, the forearm pronates, and the racket head is whipped through the ball. The inward rotation of the upper arm and the pronation of the forearm, coming last, contribute much of the final racket speed, but only because the legs and trunk have already set the whole arm moving.

The physics. At contact, the racket head moves at $v = \omega r$, where r is its distance from the turning axis; a long arm plus a racket of about 0.69 m makes r large. A good serve’s strings move at 35–45 m/s, and the light ball leaves at roughly 1.3 to 1.5 times the racket speed. Geometry adds a second lesson. The net is 0.914 m high at the center and 11.89 m from the baseline; the service line is 6.40 m beyond the net. A straight line from a contact point 2.8 m high to the service line crosses the net only about 7 cm above it. Gravity bends the path downward, and the ball must also fall into the box, so a hard flat serve has a tiny window. That is why servers reach up to hit as high as possible, and why most serves carry spin.

On the field. Good servers toss the ball to the same spot every time, bend the knees into the trophy position, drive up and out, and let the arm whip through relaxed. Most players hit their first serve harder and flatter and their second serve with more spin and margin. **The risk side:** the serve is the most repeated overhead motion in tennis, and the shoulder and elbow carry heavy loads. Weak legs or a missing trunk rotation make the arm do too much, as in a poorly thrown pitch. Warm up, build up the number of serves gradually, and rest a sore shoulder.

Think it through. The serve is the only stroke in tennis that a player controls completely. Physics rewards the server who uses that control: same toss, same rhythm, whole-body chain.

PICTURE STUDY



Tennis Finals, Newport, 1913: McLoughlin Serving, Bain News Service, 1913 · Glass-plate negative photograph · Newport, Rhode Island (Library of Congress)

Image: [Wikimedia Commons](#), public domain

The U.S. national championships were played on the grass courts of a private club in Newport, Rhode Island, from 1881 until 1914. This Bain News Service photograph shows the 1913 final, with Maurice McLoughlin serving. Spectators in straw hats sit around the court, and a line judge watches from a chair.

Look closely

- Find McLoughlin. Is he at the start of his motion, reaching up, or following through?
- Look at the court surface. How would grass change the bounce of a hard serve?
- Find the line judge. Why would a fast serve make judging the line difficult?

Talk about it

1. McLoughlin served with a wooden racket and a heavy, loosely strung ball by modern standards. What would limit his serve speed compared with a player today?
2. From the far baseline, the returner had well under half a second. What does that say about how he must prepare?

Safety first. Warm up the shoulders, wrists and legs before swinging. Indoors, use only a foam ball or a balloon and a light or toy racket, in a clear space away from lamps, windows and people. Outdoors, keep a clear circle around anyone swinging a racket, wear athletic shoes, drink water and use sun protection. A parent supervises any trip to a public court.

PROJECT

Serve Speed and Accuracy

At a court with a parent, or against a wall outdoors, you will measure the speed of your serves from video, record how many land in, and compare a flat serve with a spin serve.

You will need

- A tennis racket and at least 10 tennis balls
- A tennis court with a parent present, or a practice wall with a chalk line at net height (0.91 m)
- A phone with slow-motion video and a stand
- A tape measure
- The scorebook and a calculator

Steps

1. Warm up: arm circles, shoulder stretches, then 10 easy serves at half speed.
2. **Predict.** Estimate your flat-serve speed in km/h and how many of 20 will land in.
3. Place the phone on a stand to the side of the court, about level with the net, so that it sees both your contact and the bounce. Record in slow motion.
4. Hit 20 flat first serves into one service box. Record in or out for each.
5. Hit 20 second serves with as much spin as you can make (brush up and across the ball). Record in or out.
6. For 5 serves of each kind, count frames from contact to the bounce and measure the distance (about 18–19 m from the baseline to the service box). Compute each average speed and convert to km/h.
7. Have your partner measure your contact height: reach up with the racket as at contact and measure from the court to the strings.
8. Use the straight-line model to find how far above the net your flat serve would pass if aimed at the service line from your contact height.
9. **Decide.** Write your plan for first and second serves using your in-percentages and speeds.

Tips

- Video at 240 frames per second: count frames carefully from the first frame of contact to the first frame of the bounce.
- Keep the toss the same each time; a wandering toss changes everything.

Check your work

- ☐ I recorded 20 flat and 20 spin serves, in or out.
- ☐ I measured 10 speeds and my contact height.
- ☐ I wrote a first- and second-serve plan based on my data.

SCOREBOOK

1. Serve table: type, serve number, in or out, frames to bounce, speed (m/s and km/h).
2. Side-view diagram of the court to scale (1 cm = 2 m): your contact height, the net, the service line, and the straight-line serve path.
3. A five-frame stick-figure sequence of your serve with the moving link labelled in each frame.

KEY FORMULAS

$$v = \omega r$$

$$v_{\text{ball}} \approx (1.3 \text{ to } 1.5) v_{\text{racket}}$$

$$y_{\text{net}} = h \left(1 - \frac{11.89}{18.29} \right) \quad (\text{straight-line serve to the service line})$$

From history. The U.S. championships moved from Newport to the West Side Tennis Club in Forest Hills, New York, in 1915. Modern rules set the ball's mass at 56.0 to 59.4 grams and the court at 23.77 m long.

WORKED EXAMPLES

Example 1. A server's arm and racket together reach 1.5 m from the shoulder to the center of the strings, and the whole lever turns at 28 rad/s at contact. Find the string speed. If the ball leaves at 1.4 times that speed, what is its speed in km/h?

Show solution

1. $v = 28 \times 1.5 = 42 \text{ m/s}$.

2. Ball: $1.4 \times 42 \approx 59 \text{ m/s} \approx 212 \text{ km/h}$.

Answer: Strings at 42 m/s; the ball at about 59 m/s, or 212 km/h.

Illustrative values.

Example 2. A flat serve is hit in a straight line from a contact height h to land on the service line, 18.29 m from the baseline. The net is 11.89 m from the baseline and 0.914 m high. How high does the line cross the net if $h = 2.8 \text{ m}$? If $h = 2.5 \text{ m}$?

Show solution

1. Fraction of the drop remaining at the net: $1 - \frac{11.89}{18.29} \approx 0.350$.

2. $h = 2.8$: $2.8 \times 0.350 \approx 0.98 \text{ m}$, about 7 cm above the net.

3. $h = 2.5$: $2.5 \times 0.350 \approx 0.875 \text{ m}$, below the 0.914 m net.

Answer: From 2.8 m the straight path barely clears; from 2.5 m it hits the net. Gravity curves the real path downward, making the window even smaller, so shorter players must use spin.

Example 3. A serve leaves the racket at 50 m/s and slows to an average of 44 m/s over the 18.3 m to the bounce. How long does the returner have before the bounce? Find the ball's momentum at 50 m/s (mass 0.057 kg) and the average force if the strings deliver it in 0.0045 s.

Show solution

1. Time: $18.3/44 \approx 0.42$ s.
2. Momentum: $0.057 \times 50 = 2.85$ kg·m/s.
3. Force: $2.85/0.0045 \approx 630$ N.

Answer: About 0.42 s to the bounce, 2.85 kg·m/s of momentum, and an average force of about 630 N.

PRACTICE

1. Easy Convert 180 km/h to m/s.

Show answer

50 m/s.

2. Easy List the links of the serve's kinetic chain in order.

Show answer

Legs, hips, trunk, upper arm (inward rotation), forearm (pronation), wrist and racket.

3. Easy Who was called the "California Comet," and why?

Show answer

Maurice McLoughlin, U.S. champion in 1912 and 1913, for his very fast "cannonball" serve.

4. Medium A racket center 1.4 m from the shoulder axis turns at 30 rad/s. Find its speed.

Show answer

42 m/s.

5. **Medium** A tennis ball of 0.058 kg leaves the racket at 55 m/s. Find its momentum and kinetic energy.

Show answer

$$3.19 \text{ kg}\cdot\text{m/s}; \approx 88 \text{ J.}$$

6. **Medium** Using the straight-line model, what is the lowest contact height that clears the 0.914 m net on a serve to the service line?

Show answer

$$h = 0.914/0.350 \approx 2.61 \text{ m.}$$

7. **Medium** Why is a second serve usually hit with more spin and less speed?

Show answer

A second fault loses the point, so the server trades speed for a larger margin: spin curves the ball down into the box and lets it cross higher over the net.

8. **Medium** Why can poor leg drive lead to a sore shoulder in servers?

Show answer

Without the legs and trunk, the shoulder and arm must produce most of the racket speed alone, carrying larger loads in smaller tissues.

9. **Hard** A ball struck horizontally at 50 m/s from 2.8 m: how far does gravity alone pull it down by the time it reaches the net 11.89 m away? Where is it then?

Show answer

$t = 0.238 \text{ s}$; drop $\frac{1}{2}(9.8)(0.238)^2 \approx 0.28 \text{ m}$; height about 2.52 m, far above the net, and it would land long. A flat serve must be hit slightly downward.

10. **Hard** A serve at 200 km/h covers 18.3 m to the bounce at an average of 90% of that speed. Find the time.

Show answer

$$v = 55.6 \times 0.9 \approx 50 \text{ m/s}; t \approx 0.37 \text{ s.}$$

11. **Hard** Estimate the average force on a 0.057 kg ball taken from 0 to 55 m/s in 0.0045 s, and compare it with the ball's weight.

Show answer

$$F \approx 697 \text{ N, about 1,250 times the ball's weight of } 0.56 \text{ N.}$$

12. **Challenge** In the straight-line model, a server wants the ball to cross the net with at least 15 cm to spare and land 1.0 m inside the service line (17.29 m from the baseline). Find the minimum contact height.

Show answer

Fraction at the net: $1 - 11.89/17.29 \approx 0.312$. Need $0.312 h \geq 1.064$, so $h \geq 3.41$ m: impossible for nearly every player, which is why safe serves use spin to curve down into the box.

COMMON MISTAKES

- Forgetting that the ball slows down, so the average speed over the court is less than the speed off the racket.
- Serving with the arm alone and no leg drive.
- Assuming a harder serve is always better; a serve that misses the box scores nothing.

Make it a game • Racket Speed Duel. Measure your arm plus a pretend racket length, about 1.2 meters is typical. Each of you guesses the racket-tip speed for an angular velocity your parent names, then computes it with v equals ω times r . Closest guess wins. Then both of you shadow-serve with no racket and mark with tape the highest point you can reach on your toes.

4.2 TOPSPIN AND THE FOREHAND

OBJECTIVES

- Explain how a low-to-high racket path puts topspin on the ball and how topspin produces a downward Magnus force.
- Show with projectile calculations why topspin lets a player hit harder and higher over the net yet still land in.
- Measure the effect of topspin on your own forehands.

Warm-up. Hold a racket (or a book) and drop a ball onto it. Brush the strings upward across the back of the ball as it bounces. Watch the ball spin. Which way is it spinning, and which way does it curve as it falls?

WATCH

Science Xplained: Topspin Doctor: How Physics Serves Tennis

Yale University · 2:40

<https://www.youtube.com/watch?v=VXWbDd7UftU>

WHEN TO WATCH

After “how they figured it out.” Listen for how the strings help make spin.

BACKUP VIDEO

The Secret Physics of Tennis: What Pros Don't Tell You!

STEMbite · 2:22

<https://www.youtube.com/watch?v=uiJ5ir2aGqM>

Optional, after the worked examples. A physics teacher looks closely at the strings and the ball.

KEY TERMS

topspin

Spin in which the top of the ball moves forward in the direction of travel; the Magnus force then pushes the ball down.

racket path

The direction the racket head moves through contact; low-to-high produces topspin.

string bed

The woven strings of a racket, which grip and push the ball during contact.

margin

The safety room by which a shot clears the net and lands inside the lines.

CORE IDEAS

The story. In 1905 May Sutton, an 18-year-old Californian, became the first American to win the women's singles at Wimbledon. Players there noticed her unusual forehand: she swung up and over the ball, so it dipped and kicked high. A century later, the coach and writer John Yandell filmed professionals with high-speed cameras and counted the turns of the ball; Rafael Nadal's forehand was measured at an average of about 3,200 rpm, far more than the players of earlier decades. Heavy topspin had become the foundation of modern tennis.

How they figured it out. Players learned by experience that brushing up the back of the ball made it dip, but physicists explained why. Rod Cross of the University of Sydney and others filmed the ball on the strings and found that the strings stretch sideways along the ball's surface during the 4–5 ms of contact and then snap back, adding spin. Modern polyester strings slide and snap back more than older strings, which helps explain why spin rates rose after the late 1990s. In the air, the spinning ball is pushed downward by the Magnus effect (Lesson 2.2).

The physics. A racket moving up and forward at contact gives the ball forward speed and, by friction and the snapback of the strings, topspin. With topspin, the Magnus force adds to gravity, so the ball's downward acceleration is greater than g . A shot can then be hit faster and aimed higher over the net, because it curves down sooner. Take a ball hit at 25 m/s, 10° above horizontal, from 1.0 m high. With no spin it lands about 26.5 m away, beyond the 23.77 m court. With topspin adding 5 m/s^2 downward, it lands about 18.8 m away, comfortably inside, and still crosses the net at about 1.4 m. After the bounce, topspin makes the ball kick forward and high, pushing the opponent back.

On the field. Players hit topspin forehands with a racket path that starts below the ball and finishes high over the opposite shoulder, a relaxed wrist and a full body turn (the kinetic chain again). They aim well above the net, for margin, and let the spin bring the ball down. Flatter shots go faster for the same swing but leave less room for error. **The risk side:** spin costs some speed, and a ball hit with too little pace and

too much spin can sit up for the opponent. Wise players vary spin and speed by the situation: more margin when defending, more pace when attacking.

Think it through. Topspin is a way of making a risky shot safe: it lets a player swing freely and still keep the ball in. Margin, not maximum speed, wins most points.

PICTURE STUDY



May Sutton, Bowden Brothers, c. 1905 · Photograph · England

Image: [Wikimedia Commons](#), public domain

May Sutton (1886–1975) was born in England and grew up in California, where she learned the game on hard courts. She won the U.S. championship in 1904 and Wimbledon in 1905 and 1907. The London photographers Bowden Brothers took this picture during her years at Wimbledon, when women played in long dresses.

Look closely

- Look at the racket held high. Is this the start or the finish of a stroke? Where would the racket have started?
- Look at her clothing. How would a long dress change footwork and the kinetic chain?
- Look at the grass court and the net behind. How would grass change the bounce of a topspin ball?

Talk about it

1. Sutton learned on hard courts in California, where the ball bounced higher. Why might that have taught her to swing up through the ball?
2. She won twice at Wimbledon against players who hit flatter. What does physics say about the advantage of topspin?

Safety first. Warm up the shoulders, wrists and legs before swinging. Indoors, use only a foam ball or a balloon and a light or toy racket, in a clear space away from lamps, windows and people. Outdoors, keep a clear circle around anyone swinging a racket, wear athletic shoes, drink water and use sun protection. A parent supervises any trip to a public court.

PROJECT

Spin and Margin: Flat versus Topspin

You will hit flat and topspin forehands against a wall or on a court, measure where they cross a line at net height and where they land, and compute your in-percentage for each.

You will need

- A tennis racket and soft or regular tennis balls
- A practice wall with a chalk line 0.91 m high (net height), or a court with a parent present
- Chalk or tape, a tape measure
- A phone with slow motion
- A partner to feed balls (optional)
- The scorebook

Steps

1. Warm up with 20 easy forehands.
2. At a wall, mark the net line (0.91 m) and a second line 1.5 m high. Stand 8–10 m back.
3. **Predict.** Write which kind of forehand you expect to keep in play more often.
4. Hit 20 flat forehands (racket path level). For each, record whether it struck the wall above the net line and how high (below 0.91, 0.91–1.5, above 1.5).
5. Hit 20 topspin forehands (low-to-high path, finishing over the opposite shoulder). Record the same.
6. On a court (optional, with a parent), hit 20 of each from the baseline and record in, out long, or net.
7. Film 5 of each in slow motion from the side. Watch the racket path and the ball's spin. Estimate the racket path angle from the video.
8. Compute the percentage of each type that cleared the net line and (on a court) landed in.

9. **Decide.** Write when you would choose a topspin forehand and when a flatter one, using your percentages.

Tips

- Topspin comes from the path, not from flicking the wrist.
- Count carefully: honest records are worth more than good-looking ones.

Check your work

- ☐ I hit and recorded 20 flat and 20 topspin forehands.
- ☐ I estimated my racket path angle from video.
- ☐ I compared percentages and wrote a decision.

SCOREBOOK

1. Margin table: shot type, number above the net line, number above 1.5 m, number in (on a court), percentages.
2. Side-view drawing of a flat and a topspin trajectory from the baseline, both clearing the net, with landing points.
3. Draw a ball on the strings with the racket moving up and forward; show the direction of spin it receives.

KEY FORMULAS

$$\begin{aligned}\omega &= 2\pi \times \frac{\text{rpm}}{60} & v_{\text{surface}} &= \omega R \\ y &= y_0 + v_y t - \frac{1}{2}(g + a_M)t^2 & x &= v_x t \\ v_x &= v \cos \theta & v_y &= v \sin \theta\end{aligned}$$

From history. May Sutton later played under her married name, May Sutton Bundy, and was elected to the International Tennis Hall of Fame. Rod Cross's experiments on strings and spin are described on his University of Sydney web pages.

WORKED EXAMPLES

Example 1. A forehand spins at 3,200 rpm. The ball's radius is 3.35 cm. Find its angular velocity and the speed of a point on its surface.

Show solution

1. $\omega = 2\pi \times 3200/60 \approx 335 \text{ rad/s}$.

2. $v = \omega R = 335 \times 0.0335 \approx 11.2 \text{ m/s}$.

Answer: About 335 rad/s; the surface moves at about 11 m/s relative to the center.

Example 2. A ball is hit from 1.0 m high at 25 m/s, 10° above horizontal. Find where it lands with no spin, and with topspin that adds 5.0 m/s^2 downward. Find its height at the net, 11.89 m away, in each case.

Show solution

1. $v_x = 25 \cos 10^\circ \approx 24.6$, $v_y = 25 \sin 10^\circ \approx 4.34 \text{ m/s}$.

2. No spin: $1 + 4.34t - 4.9t^2 = 0 \Rightarrow t \approx 1.075 \text{ s}$; $x \approx 26.5 \text{ m}$ (out).

3. Topspin: $1 + 4.34t - 7.4t^2 = 0 \Rightarrow t \approx 0.764 \text{ s}$; $x \approx 18.8 \text{ m}$ (in).

4. At the net, $t = 11.89/24.6 \approx 0.483 \text{ s}$: no spin $y \approx 1.95 \text{ m}$; topspin $y \approx 1.37 \text{ m}$.

Answer: Without spin the ball lands 2.7 m long; with topspin it lands 5 m inside the baseline and still clears the net by almost half a meter.

Example 3. At contact the racket moves at 30 m/s along a path tilted 25° upward. Find its forward and upward components.

Show solution

1. Forward: $30 \cos 25^\circ \approx 27.2 \text{ m/s}$.

2. Upward: $30 \sin 25^\circ \approx 12.7 \text{ m/s}$.

Answer: The forward 27 m/s drives the ball; the upward 13 m/s brushes the back of the ball and produces topspin.

PRACTICE

1. **Easy** Convert 2,400 rpm to turns per second and to rad/s.

Show answer

40 turns per second; $\approx 251 \text{ rad/s}$.

2. **Easy** Which way does the Magnus force push a ball with topspin?

Show answer

Downward (toward the ground), adding to gravity.

3. **Easy** In what year did May Sutton win Wimbledon, and what was notable about it?

Show answer

1905; she was the first American to win the Wimbledon singles title.

4. **Medium** A ball of radius 0.0335 m spins at 2,000 rpm. Find its surface speed.

Show answer

$\omega \approx 209 \text{ rad/s}$; $v \approx 7.0 \text{ m/s}$.

5. **Medium** A racket moves at 28 m/s at 30° upward. Find its upward component.

Show answer

14 m/s.

6. **Medium** Why do topspin hitters aim higher over the net than flat hitters?

Show answer

Topspin makes the ball dive sooner, so a higher path still lands in; the extra height gives a safety margin over the net.

7. **Medium** What did high-speed films show about the strings during contact, and why does it add spin?

Show answer

The strings stretch sideways along the ball and snap back before it leaves, rotating the ball further.

8. **Hard** A ball leaves at 20 m/s horizontally from 1.2 m. How far does it travel before landing with no spin? With topspin adding 4.0 m/s² downward?

Show answer

No spin: $t = \sqrt{2.4/9.8} \approx 0.495$ s, $x \approx 9.9$ m. Topspin: $t = \sqrt{2.4/13.8} \approx 0.417$ s, $x \approx 8.3$ m. (Both would land before the net from the baseline: the ball must be hit upward.)

9. **Hard** A ball hit at 22 m/s at 12° above horizontal from 1.0 m: find its height at the net 11.89 m away, with no spin.

Show answer

$$v_x \approx 21.5, v_y \approx 4.57; t \approx 0.553 \text{ s}; y = 1 + 2.53 - 1.50 \approx 2.03 \text{ m}.$$

10. **Hard** A rally ball's topspin gives it 4.0 m/s² of extra downward acceleration. Over a 0.8 s flight, how much farther does it drop than a ball with no spin?

Show answer

$$\frac{1}{2}(4.0)(0.64) = 1.28 \text{ m}.$$

11. **Hard** Give one advantage and one cost of heavy topspin.

Show answer

Advantage: margin (high over the net, still lands in) and a high bounce. Cost: some forward speed is used for spin, so the shot may be slower and can sit up if it lacks depth.

12. **Challenge** For the ball in worked example 2, find the extra downward acceleration a_M that would make it land exactly on the baseline, 23.77 m away.

Show answer

$$t = 23.77/24.6 \approx 0.966 \text{ s}. 0 = 1 + 4.34(0.966) - \frac{1}{2}(9.8 + a_M)(0.966)^2:$$
$$\frac{1}{2}(9.8 + a_M)(0.933) = 5.19, \text{ so } 9.8 + a_M \approx 11.1 \text{ and } a_M \approx 1.3 \text{ m/s}^2.$$

COMMON MISTAKES

- Thinking topspin makes a ball faster; it makes it dive and bounce higher, at some cost in pace.
- Flicking the wrist instead of using a low-to-high path.
- Forgetting to include the Magnus acceleration in the vertical equation.

Make it a game • Margin Mapper. On paper, draw the side view of a tennis court with the net and baseline. Sketch one flat shot and one topspin shot hit at the same speed. Mark the margin over the net and the margin long. Your parent guesses which path is topspin by looking at the Magnus force drawn as a downward arrow. Swap and repeat with a lob.

4.3 FOOTWORK, THE SPLIT STEP AND REACTION TIME

OBJECTIVES

- Measure reaction time with a ruler drop and compute it from $d = \frac{1}{2}gt^2$.
- Explain the split step with the time of a small hop and the stretch of the leg muscles.
- Compute the time a returner has against a serve and plan the first steps.

Warm-up. Stand facing a partner, feet still. Your partner points left or right without warning, and you take one quick shuffle step that way. Then repeat while doing a small hop just as your partner points. Which felt quicker?

WATCH

(Tennis Footwork) Why Split Stepping Is So Important

2MinuteTennis · 8:24

<https://www.youtube.com/watch?v=C6l6EVJW8yc>

WHEN TO WATCH

After “the physics” paragraph. Note when the coach says the split step should land.

KEY TERMS

reaction time

The delay between a signal and the start of a response, typically about 0.2 s for a simple visual signal.

split step

A small hop taken as the opponent strikes the ball, landing with the feet apart, ready to push off in any direction.

stretch-shortening cycle

A muscle that is stretched just before it contracts pushes harder than one that starts from rest.

anticipation

Reading the opponent’s body and racket before contact to predict where the ball will go.

CORE IDEAS

The story. In the 1880s William Renshaw won Wimbledon seven times by rushing the net and volleying, and his rivals had to learn to move quickly enough to pass him. A century later, the best returners of serve stood a meter behind the baseline

against serves arriving in under half a second, and still hit them back. Coaches noticed that every great player did the same thing just before the opponent struck the ball: a small hop, landing with the feet apart. They called it the split step.

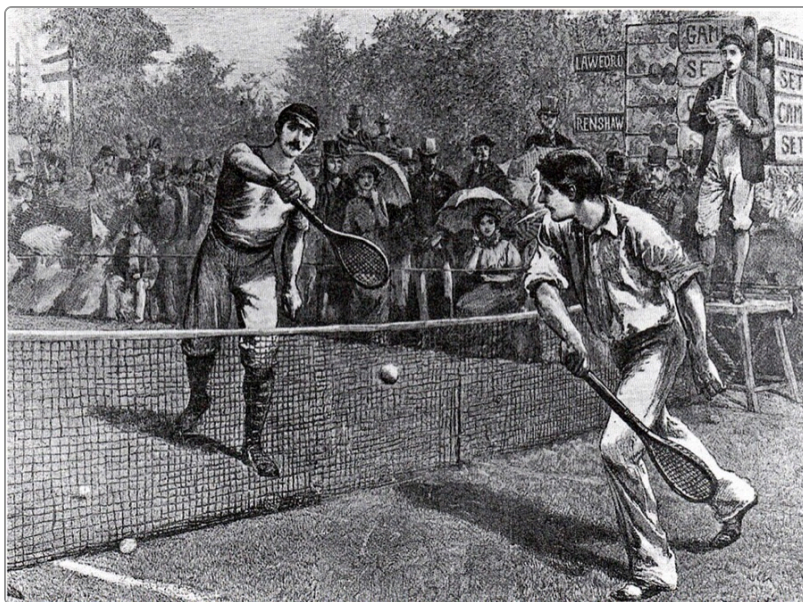
How they figured it out. Psychologists had long measured reaction time: a person who sees a light and presses a button takes about 0.2 s, and when there are two choices (left or right) it takes longer. Sport scientists filmed returners and found that experts start their split step as the server swings and land at about the moment of contact, or just after, when they can see which way the ball is going. Experts also read the opponent's toss, shoulders and racket to anticipate the direction before contact. The split step does not make the brain faster; it makes the body ready to use the brain's answer at once.

The physics. You can measure reaction time with a falling ruler. A ruler dropped from rest falls $d = \frac{1}{2}gt^2$, so $t = \sqrt{2d/g}$: a catch after 0.20 m means 0.20 s. A small split-step hop of height h keeps the player in the air for $t = 2\sqrt{2h/g}$; a 5 cm hop lasts about 0.20 s, close to a reaction time. On landing, the legs' muscles and tendons are stretched like springs (the stretch-shortening cycle), so the first push-off is quicker and stronger than from a standing start. With the feet apart and the center of mass low (Lesson 1.3), the player can push sideways at once.

On the field. Players split step before every shot the opponent hits, at the baseline and at the net. Returners use a slightly bigger, earlier split against a fast server, and many take a step forward into it. Volleyball passers, soccer goalkeepers and baseball infielders use the same move: infielders take a small step as the pitch reaches the plate. **The risk side:** a split step taken too early leaves the player standing flat when the ball is struck; too late, and he is still in the air when he needs to move. Ankles are at risk on uneven ground, so keep hops small and landings soft.

Think it through. Readiness is a habit, not a reaction. The player who prepares before the ball is struck is the one who seems to have more time.

PICTURE STUDY



Lawford against Renshaw at Wimbledon, Arthur Hopkins, 1881 · Wood engraving · All England Club, Wimbledon (printed in a London illustrated weekly, August 6, 1881)

Image: [Wikimedia Commons](#), public domain

A London illustrated weekly newspaper printed this engraving by Arthur Hopkins in August 1881, showing Herbert Lawford and William Renshaw at Wimbledon. Renshaw won the championship that year, the first of his seven titles, and his attacking play at the net forced his opponents to move faster than tennis players ever had.

Look closely

- Look at the two players' feet. Which player is balanced and ready, and which is stretching?
- Find the ball. How much time does the player at the net have to react to it?
- Look at the scoreboard and the crowd. What do they tell you about tennis in 1881?

Talk about it

1. Renshaw's volleying left his opponents little time. How would a split step have helped them?
2. Players of 1881 wore long trousers and leather shoes on grass. How would that affect their footwork compared with today?

Safety first. Do footwork drills on a dry, non-slip floor or court in athletic shoes, with space around you. Keep hops small and land on the balls of the feet with knees bent. Warm up the ankles first, and stop if an ankle or knee hurts.

PROJECT

Reaction, Split Step and First Step

You will measure your reaction time with a ruler, then time your first step to a ball with and without a split step, to see whether the split step really helps you.

You will need

- A 30 cm ruler
- A partner
- Cones placed 2 m to your left and right
- A phone with slow motion or a stopwatch
- A soft ball
- The scorebook and a calculator

Steps

1. Ruler test: do 10 drops with your dominant hand and 10 with the other. Convert each to a time with $t = \sqrt{2d/g}$, and find the means.
2. **Predict.** Will the split step make you reach a cone faster? By how much?
3. Set up: you stand in a ready position between two cones 2 m to each side. Your partner, facing you, holds a soft ball in each hand and drops one without warning.
4. Without a split step: from a still ready position, run and touch the cone on the side of the dropped ball. Film from the side. Do 10 trials.
5. With a split step: hop lightly as your partner raises the balls, land as one is released, and run to the cone. Do 10 trials.
6. From the video, count frames from release to your first foot movement, and from release to touching the cone. Convert to seconds.
7. Find the mean times for each method. Did the split step help? By how much?
8. Repeat 5 trials with the split step deliberately early (landing well before the release). Compare.
9. **Decide.** Write your rule for timing the split step, with your numbers.

Tips

- Keep the partner's release random, and do not watch his eyes (or do, and see whether it helps you anticipate).
- Alternate methods in sets of five so that tiredness affects both equally.

Check your work

- ☐ I measured 20 ruler drops.
- ☐ I timed 10 trials with and 10 without a split step, plus 5 early splits.
- ☐ I wrote a timing rule based on my data.

SCOREBOOK

1. Reaction table: hand, drop, distance, time; means.
2. Timing table: method, trial, frames to first movement, frames to the cone, seconds.
3. A timeline from the opponent's swing to your contact, marking the split step, reaction, first step and swing.

KEY FORMULAS

$$t = \sqrt{\frac{2d}{g}} \quad (\text{ruler drop})$$

$$t_{\text{air}} = 2\sqrt{\frac{2h}{g}} \quad (\text{hop of height } h)$$

$$d = \frac{1}{2}at^2 \quad (\text{start from rest})$$

From history. William Renshaw and his twin brother Ernest dominated the early years of Wimbledon; the twins also won the men's doubles together several times. Reaction-time research began in the nineteenth century with astronomers who noticed that observers differed in how quickly they recorded a star crossing a line.

WORKED EXAMPLES

Example 1. A ruler falls 0.18 m before a student catches it. Find her reaction time.

Show solution

$$1. t = \sqrt{2(0.18)/9.8} = \sqrt{0.0367} \approx 0.19 \text{ s.}$$

Answer: About 0.19 s.

Example 2. How long is a player in the air during a split-step hop 5.0 cm high? What hop height gives 0.25 s in the air?

Show solution

1. $t = 2\sqrt{2(0.050)/9.8} = 2(0.101) \approx 0.20 \text{ s}.$

2. For 0.25 s: half the time, 0.125 s, is the fall: $h = \frac{1}{2}(9.8)(0.125)^2 \approx 0.077 \text{ m}.$

Answer: About 0.20 s for a 5 cm hop; a 7.7 cm hop gives 0.25 s.

Example 3. A serve takes 0.60 s to reach a returner standing 1 m behind the baseline. Her reaction time is 0.20 s. After reacting, she accelerates sideways at 6.0 m/s^2 . How far can she move before the ball arrives? How far if a poor start costs her another 0.10 s?

Show solution

1. Time to move: $0.60 - 0.20 = 0.40 \text{ s}; d = \frac{1}{2}(6.0)(0.40)^2 = 0.48 \text{ m}.$

2. With 0.30 s: $d = \frac{1}{2}(6.0)(0.30)^2 = 0.27 \text{ m}.$

Answer: About 0.48 m against 0.27 m: a tenth of a second lost at the start costs almost half the reach. With a racket and outstretched arm adding about 1.5 m of reach, that difference decides many returns. *Illustrative values.*

PRACTICE

1. Easy A ruler falls 0.12 m before it is caught. Find the reaction time.

Show answer

$\approx 0.16 \text{ s}.$

2. Easy What is a split step, and when should it land?

Show answer

A small hop landing with the feet apart, timed to land about when the opponent strikes the ball.

3. Easy How many Wimbledon singles titles did William Renshaw win?

Show answer

Seven.

4. Medium How far would a ruler fall in 0.25 s?

Show answer

$$\frac{1}{2}(9.8)(0.0625) \approx 0.31 \text{ m.}$$

5. Medium Find the air time of a 3.0 cm hop.

Show answer

$$2\sqrt{0.06/9.8} \approx 0.16 \text{ s.}$$

6. Medium A 160 km/h serve covers 24 m to the returner at an average of 38 m/s. How long does the returner have?

Show answer

$$\approx 0.63 \text{ s.}$$

7. Medium Why does landing from a split step help a player push off faster?

Show answer

Landing stretches the leg muscles and tendons, which then contract more forcefully (the stretch-shortening cycle); the player also lands balanced with feet apart and knees bent, ready to push sideways.

8. Medium Why is a choice between left and right slower than a simple reaction to a light?

Show answer

The brain must identify which response is needed before starting it, which adds processing time.

9. **Hard** A player reacts in 0.22 s and accelerates at 5.0 m/s^2 . How long after the opponent's contact can he reach a ball 1.2 m to his side (counting his body only)?

Show answer

$$1.2 = \frac{1}{2}(5.0)t^2 \Rightarrow t \approx 0.69 \text{ s; total} \approx 0.91 \text{ s.}$$

10. **Hard** A returner splits too early and lands 0.15 s before contact; her muscles lose the benefit of the stretch, and her push-off acceleration falls from 6.0 to 4.5 m/s^2 . In 0.40 s of movement, how much less ground does she cover?

Show answer

$$\frac{1}{2}(6.0)(0.16) - \frac{1}{2}(4.5)(0.16) = 0.48 - 0.36 = 0.12 \text{ m.}$$

11. **Hard** Estimate your total time to return a serve that takes 0.55 s, if your reaction time is 0.20 s and your swing takes 0.25 s. What must you do to have time?

Show answer

Reaction plus swing is 0.45 s, leaving only 0.10 s for moving; you must shorten the backswing (a compact block), anticipate from the server's toss and motion, and split step on time.

12. **Challenge** A player in the air during a split step cannot push off. Show that landing exactly when the opponent hits, rather than 0.10 s after, gains reach equal to $\frac{1}{2}a[(T - t_r)^2 - (T - t_r - 0.10)^2]$ and evaluate it for $T = 0.60$ s, $t_r = 0.20$ s, $a = 6.0$ m/s².

Show answer

Moving time is $T - t_r$ if she lands on time and 0.10 s less if late.

$$\frac{1}{2}(6.0)(0.40^2 - 0.30^2) = 3.0(0.16 - 0.09) = 0.21 \text{ m.}$$

COMMON MISTAKES

- Using centimeters in $t = \sqrt{2d/g}$ instead of meters.
- Hopping too high, which keeps you in the air too long.
- Splitting too early and landing flat-footed and still.

Make it a game • Ruler Drop Duel. Your parent holds a ruler at the top while your fingers wait open. Drop it without warning and catch it. Record the centimeters. Do ten trials, then compute your reaction time from d equals one half g t squared. Beat your own average on a second set of ten. Then try again after a small split-step hop and compare.

Scripture. “Let thine eyes look right on, and let thine eyelids look straight before thee.” (Proverbs 4:25, KJV)

Watching the ball and the opponent, ready before the moment comes, is a small picture of a wise life: eyes forward, prepared, not distracted.

4.4 THE VOLLEYBALL PASS: PLATFORM ANGLE AND REFLECTION

OBJECTIVES

- Explain the forearm pass as a reflection, with the angle of incidence equal to the angle of reflection about the platform's normal.
- Find the platform angle needed to send a ball to a target, and compute the pass's height and flight time.
- Measure your own passing accuracy and platform angles.

Warm-up. Bounce a soft ball against a tilted book held at different angles and watch where it goes. Can you tilt the book so that the ball comes straight back to you? So that it goes up and to the side?

WATCH

Passing FUNDAMENTALS - How to PASS Volleyball Tutorial (part 1/6)

Elevate Yourself • 7:02

<https://www.youtube.com/watch?v=gOgfoEGUDCA>

WHEN TO WATCH

Before “the physics” paragraph. Pay attention to the ready posture and how the coach forms and angles the platform.

Note: The description links to the channel's paid jump-training programs; they are not needed.

BACKUP VIDEO

Dominate Volleyball Passing: Master Angles & Footwork

Coach Chijo • 6:37

<https://www.youtube.com/watch?v=12v03fGkHI4>

Optional, before the project. A coach drills a young player in angling the platform toward the target from different positions.

KEY TERMS

forearm pass

Receiving the ball on the flat surface of both forearms held together, used to pass a serve to the setter.

platform

The flat surface formed by the forearms held together with the thumbs side by side.

normal

The line perpendicular to a surface at the point of contact.

law of reflection

For a smooth bounce, the angle of incidence equals the angle of reflection, both measured from the normal.

CORE IDEAS

The story. On February 9, 1895, at the YMCA in Holyoke, Massachusetts, the physical director William G. Morgan introduced a new indoor game for businessmen who found basketball too rough. He stretched a tennis net 6 feet 6 inches high across the gym and had players bat a ball back and forth over it. He called it mintonette. When he showed it at the YMCA training school in Springfield the next year, a teacher named Alfred Halstead noticed the players “volleying” the ball and suggested a new name: volley ball. Morgan had studied at that same school, where he had met James Naismith, the inventor of basketball.

How they figured it out. Early players struck the ball with open hands. As the game spread through YMCAs and around the world, players found that hard-driven serves were easier to control on the forearms than on the hands. By the middle of the twentieth century the forearm pass, or “bump,” was standard. Coaches learned that the best passers barely swing their arms at all: they move their feet to get behind the ball and simply angle the platform toward the setter. That is physics. A ball that strikes a firm, flat surface leaves as if reflected in a mirror.

The physics. For a smooth bounce off a flat surface, the angle between the incoming path and the surface’s normal equals the angle between the outgoing path and the normal. So the normal of the platform must point halfway between the direction the ball came from and the direction it should go: it bisects them. If a serve arrives descending at 30° and the passer wants the ball to rise at 70° toward the setter, the platform’s normal must point 50° above horizontal, so the forearms slope down at 40° below horizontal. The speed of the pass depends on the ball’s incoming speed, on

how bouncy the collision is (its coefficient of restitution), and on whether the arms move: against a hard serve the passer “gives” slightly (Lesson 3.3); against a slow ball she lifts a little with the legs. Once launched, the pass follows projectile motion: rise $v_y^2/2g$, flight time $2v_y/g$.

On the field. Passers stand in a balanced, low ready position (Lesson 1.3), move their feet to the ball, form a flat platform early, and angle it toward the target, keeping the shoulders turned toward the setter. Coaches say “angle, don’t swing.” The ideal pass rises a few meters, high enough for the setter to get under it, and lands just off the net. **The risk side:** a swung pass multiplies errors, because any error in timing changes the ball’s speed and direction; a steady platform makes the reflection predictable.

Think it through. The best passers make the hardest serves look easy because they let physics do the work: they get in position early and present the right angle. Preparation turns a difficult problem into a simple one.

PICTURE STUDY



Women Playing Volleyball at the University of Washington, Webster & Stevens, c. 1923 · Glass-plate negative photograph · Museum of History & Industry, Seattle

Image: [Wikimedia Commons](#), public domain

The Seattle photographers Webster & Stevens took this picture of two University of Washington students in about 1923. Volleyball had spread quickly through YMCAs, colleges and schools. Here one student tosses the ball while the other reaches with straight arms and hands together, an early form of the forearm pass.

Look closely

- Look at the receiving player's arms. Are they together and straight? At what angle are they held?
- Look at her feet and knees. Is she balanced low, or reaching?
- Find the net, the wall bars and the wooden floor. What else was this gym used for?

Talk about it

1. If the ball is tossed gently toward her and she wants it to go straight up, how should she angle her arms?
2. Compare her posture with the ready position in this lesson's video. What has changed in a hundred years, and what has stayed the same?

Safety first. Use a soft volleyball, a beach ball or a balloon indoors, with a clear space and nothing breakable nearby. Warm up first. Land from any jump on both feet with bent knees, on a non-slip floor or grass, never near furniture or walls. Stop if anything hurts.

PROJECT

Platform Angle and Passing Accuracy

You will measure how well you pass to a target, measure your platform angles from video, and test the law of reflection with a ball and a board.

You will need

- A soft volleyball, a beach ball or a balloon
- A partner to toss
- A hula hoop or a 1 m chalk circle as a target
- A phone with slow motion and a stand
- A board or large book, a protractor
- The scorebook and a calculator

Steps

1. Reflection test: tilt a board at a measured angle (use the protractor) and drop or toss a ball onto it from a fixed direction. Record where it goes. Try four angles. Does the outgoing angle match the law of reflection? (A real ball also loses speed and can pick up spin, so expect small differences.)
2. Warm up with 20 easy passes to yourself.
3. **Predict.** How many of 20 passes will land in the target circle 3 m away?
4. Your partner tosses 20 balls to you from 4 m away. Pass each to the target 3 m to your side. Record hits (in the circle), near misses (within 1 m) and misses.
5. Film 5 passes from the side. Freeze the frame at contact and measure the angle of your forearms to the horizontal with a protractor on the screen.
6. Measure the incoming and outgoing angles of the ball on the same frames, and check whether the platform's normal bisects them.
7. Practice "angle, don't swing" for 10 minutes, then repeat the 20-pass test.
8. Compare your scores before and after.
9. **Decide.** Write the two coaching cues that helped you most, explained with physics.

Tips

- Keep your thumbs together and level, and your elbows locked, so the platform stays flat.
- Move your feet first; the platform angle comes second.

Check your work

- ☐ I tested reflection at four board angles.
- ☐ I measured platform angles on 5 filmed passes.
- ☐ I recorded 20 passes before and 20 after practice.

SCOREBOOK

1. Reflection table: board angle, incoming direction, predicted outgoing direction, measured outgoing direction.
2. Passing table: pass number, hit, near or miss; before and after.
3. Diagram of one filmed pass: incoming path, outgoing path, platform line and its normal, with the angles marked.

KEY FORMULAS

$$\theta_{\text{in}} = \theta_{\text{out}} \quad (\text{measured from the normal})$$

$$\hat{n} \propto \hat{u}_{\text{out}} - \hat{u}_{\text{in}}$$

$$H = \frac{v_y^2}{2g} \quad T = \frac{2v_y}{g} \quad R = v_x T$$

From history. Halstead's name "volley ball" was used for decades before the two words were joined. The set-and-spike attack is said to have developed among players in the Philippines around 1916. The International Volleyball Hall of Fame is in Holyoke.

WORKED EXAMPLES

Example 1. A serve arrives descending at 30° below horizontal, moving toward the passer. She wants it to leave rising at 70° above horizontal, back toward the net. Find the direction of the platform's normal and the slope of her forearms.

Show solution

1. Unit vectors (forward toward the net is $+x$, up is $+y$): incoming
 $\hat{u}_{\text{in}} = (-\cos 30^\circ, -\sin 30^\circ) = (-0.866, -0.500)$; outgoing
 $\hat{u}_{\text{out}} = (\cos 70^\circ, \sin 70^\circ) = (0.342, 0.940)$.
2. Normal direction: $\hat{u}_{\text{out}} - \hat{u}_{\text{in}} = (1.208, 1.440)$.
3. Angle above horizontal: $\tan^{-1}(1.440/1.208) \approx 50^\circ$.
4. The forearms are perpendicular to the normal: they slope $90^\circ - 50^\circ = 40^\circ$ below horizontal.

Answer: The normal points 50° above horizontal toward the net; the forearms slope down about 40° from the elbows to the hands.

Example 2. A pass leaves the platform at 7.0 m/s , 70° above horizontal. Find its peak height above the platform, its time to return to platform height, and the horizontal distance it travels in that time.

Show solution

1. $v_y = 7.0 \sin 70^\circ \approx 6.58$, $v_x = 7.0 \cos 70^\circ \approx 2.39 \text{ m/s}$.
2. $H = 6.58^2/19.6 \approx 2.2 \text{ m}$; $T = 2(6.58)/9.8 \approx 1.34 \text{ s}$; $R \approx 2.39 \times 1.34 \approx 3.2 \text{ m}$.

Answer: It rises about 2.2 m , stays in the air about 1.3 s , and travels about 3.2 m : a good pass to a setter a few meters away.

Example 3. A serve arrives at 14 m/s. If the passer holds her arms still and the ball leaves at 7.0 m/s, what is the effective coefficient of restitution? If she lifts her arms toward the ball, will the pass go faster or slower?

Show solution

1. $e \approx 7.0/14 = 0.50$.
2. Moving the platform toward the ball raises the approach speed and adds the platform's own speed, so the ball leaves faster.

Answer: About 0.50. Swinging the arms makes the pass faster and harder to control; against a hard serve the passer holds still or gives slightly.

PRACTICE

1. **Easy** State the law of reflection.

Show answer

The angle of incidence equals the angle of reflection, both measured from the normal to the surface.

2. **Easy** Where and when was volleyball invented, and what was it first called?

Show answer

At the YMCA in Holyoke, Massachusetts, in 1895, by William G. Morgan; it was called mintonette.

3. **Easy** Why do coaches say “angle, don’t swing”?

Show answer

A steady, well-angled platform reflects the ball predictably; swinging adds speed and timing errors.

4. **Medium** A ball arrives straight down (90° below horizontal) and must leave straight up. What is the platform's normal?

Show answer

Straight up: the platform is horizontal.

5. **Medium** A ball arrives descending at 20° toward the passer and should leave rising at 60° toward the net. Find the angle of the normal above horizontal.

Show answer

$$\hat{u}_{\text{out}} - \hat{u}_{\text{in}} = (0.5 + 0.940, 0.866 + 0.342) = (1.440, 1.208); \text{ angle } \tan^{-1}(1.208/1.440) \approx 40^\circ.$$

6. **Medium** A pass leaves vertically at 6.0 m/s. How high does it rise and how long is it in the air?

Show answer

$$H \approx 1.84 \text{ m}; T \approx 1.22 \text{ s}.$$

7. **Medium** A volleyball (0.27 kg) arrives at 15 m/s and leaves at 6 m/s in the opposite direction. Find the change in momentum.

Show answer

$$0.27 \times 21 \approx 5.7 \text{ kg}\cdot\text{m/s}.$$

8. **Hard** A pass leaves at 8.0 m/s and 65° . Find its peak height, flight time to the same height, and horizontal travel.

Show answer

$$v_y \approx 7.25, v_x \approx 3.38; H \approx 2.68 \text{ m}; T \approx 1.48 \text{ s}; R \approx 5.0 \text{ m}.$$

9. **Hard** A setter stands 4.0 m in front of the passer. The pass must travel 4.0 m horizontally and return to the passer's platform height. If it leaves at 70° , what launch speed is needed?

Show answer

$$R = v^2 \sin 140^\circ / g; v = \sqrt{4.0 \times 9.8 / 0.643} \approx 7.8 \text{ m/s}.$$

10. **Hard** Explain why the passer turns her shoulders toward the setter rather than only tilting her arms.

Show answer

Turning the shoulders points the platform's normal sideways toward the setter as well as up, so the reflection sends the ball in the right horizontal direction; it also keeps the platform flat and stable.

11. **Challenge** A ball arrives descending at angle α below horizontal, moving toward the passer, and should leave rising at angle β above horizontal toward the net. Explain why the platform's normal must point at $\phi = (\alpha + \beta)/2$ above horizontal, check it against worked example 1, and find the forearm slope for $\alpha = 25^\circ$, $\beta = 75^\circ$.

Show answer

Reverse the incoming direction: it points up toward the net at α above horizontal. The law of reflection says the normal makes equal angles with this reversed direction and with the outgoing direction, so it lies exactly between them: $\phi = (\alpha + \beta)/2$. Example 1: $(30^\circ + 70^\circ)/2 = 50^\circ$, as found. For 25° and 75° : $\phi = 50^\circ$, so the forearms slope 40° below horizontal.

COMMON MISTAKES

- Measuring angles from the surface instead of from the normal.
- Swinging the arms at a hard serve, which sends the ball too far.
- Forgetting the passer's feet: the best angle cannot be reached from the wrong position.

Make it a game • Bank Shot Targets. Place a small cup on the floor and roll a soft ball so it bounces off the wall and into the cup. Before each roll, predict the aim point on the wall using equal angles about the wall's normal. Mark and measure. One point for each cup landing. Then explain how a volleyball platform follows the same reflection rule.

4.5 THE SPIKE AND THE JUMP SERVE

OBJECTIVES

- Compute takeoff speed, jump height and hang time for a spike approach.
- Use the geometry of the net to show why contact height decides how steeply a ball can be hit.
- Describe the spike as a kinetic chain and measure your own jump and arm swing.

Warm-up. Stand next to a wall and mark your standing reach. Jump once from standing and once after a two- or three-step approach, marking the highest touch each time. Which is higher, and by how much?

WATCH

Spiking Arm Swing Technique (Part 1 of 2) | Volleyball Tutorial

Elevate Yourself • 9:31

<https://www.youtube.com/watch?v=u-WhjYYocBs>

WHEN TO WATCH

After “the physics” paragraph. Name each part of the arm swing as the coach shows it, and connect it to the kinetic chain.

Note: Near the end the video advertises the channel’s paid jump-training programs; they are not needed.

KEY TERMS

spike

A hard, downward hit of the ball from above the net, usually after a running approach and jump.

hang time

The time an athlete is in the air during a jump, $T = 2v/g$.

approach

The two to four steps before a spike that turn running speed into upward speed.

jump serve

A serve tossed high and struck at the top of a jump, like a spike from behind the end line.

CORE IDEAS

The story. William G. Morgan's first net in 1895 was 6 feet 6 inches (1.98 m) high, and his players simply batted the ball back and forth. As the game spread, players learned to set the ball high near the net so that a teammate could jump and hit it downward. Today the net is 2.43 m high for men and 2.24 m for women, and the best attackers hit the ball well over a meter above it. The jump serve, a spike from behind the end line, became common in the 1980s.

How they figured it out. Coaches noticed that players jumped higher after a short run than from standing, and sport scientists measured why. In the last two steps of the approach, the player plants both feet ahead of the body, swings both arms back and then up hard, and drives the body upward; the plant converts some of the horizontal speed into vertical speed, and the stretched leg muscles push harder (the stretch-shortening cycle of Lesson 4.3). In the air, the spike is a kinetic chain like a serve or a throw: the trunk rotates and bends, the shoulder rotates inward, the elbow straightens and the wrist snaps over the ball to add topspin.

The physics. The takeoff speed decides the jump: $h = \frac{v^2}{2g}$ and $T = \frac{2v}{g}$. A 0.50 m jump needs a takeoff speed of about 3.1 m/s and gives about 0.64 s in the air. Contact height decides the angle. A straight hit from contact height H at distance d from the net must pass above the net's height N , so its steepest downward slope is $(H - N)/d$. A player who contacts the ball 2.75 m high and 1.0 m from a 2.24 m net can hit down at about 27° and land the ball about 4.4 m beyond the net; against a 2.43 m net the same contact allows only about 18° , and the ball lands about 7.6 m beyond, near the back of the 9 m court. Topspin from the wrist snap pulls the ball down sooner (Lesson 4.2). The ball's speed comes from the hand's speed and the collision, as in a kick (Lesson 3.1).

On the field. Hitters time the approach so that they reach the top of the jump as the ball arrives, swing with a high elbow and contact the ball in front of the hitting shoulder at full reach. Many matches are decided by the attackers who can hit at sharp angles over the blockers. **The risk side:** landing is where most volleyball injuries happen, especially ankle sprains from landing on another player's foot under the net, and knee strain from landing stiff-legged. Land on both feet, knees bent, and stay on your own side of the center line.

Think it through. A few centimeters of extra jump, gained by technique, change what angles are possible. The physics rewards patient practice of the approach more than raw strength.

PICTURE STUDY



William G. Morgan, Physical Director of the Holyoke YMCA, Holyoke YMCA, published in the Holyoke Transcript, 1897 · Photograph · Holyoke, Massachusetts

Image: [Wikimedia Commons](#), public domain

William G. Morgan (1870–1942) studied at the YMCA training school in Springfield, where James Naismith had invented basketball in 1891, and became the physical director of the YMCA in Holyoke. This portrait, published in 1897, shows him a couple of years after he invented mintonette, the game that became volleyball. He wanted a vigorous game that older men could play without the hard contact of basketball.

Look closely

- Look at Morgan's face and dress. What kind of job and community does the portrait suggest?
- Morgan was in his mid-twenties when he invented the game. What does that say about who can invent things?
- Imagine the gymnasium behind him. What equipment would he have had to borrow from other sports?

Talk about it

1. Morgan designed volleyball to avoid physical contact between opponents. How does the net change the physics of the game compared with basketball?
2. If Morgan saw a modern jump serve, what would most surprise him?

Safety first. Use a soft volleyball, a beach ball or a balloon indoors, with a clear space and nothing breakable nearby. Warm up first. Land from any jump on both feet with bent knees, on a non-slip floor or grass, never near furniture or walls. Stop if anything hurts. Practice the approach and jump without a net and without a partner close by. Never spike a ball toward anyone, and land on both feet facing forward.

PROJECT

Approach, Jump and Reach

You will measure your standing, standing-jump and approach-jump reach, compute takeoff speeds and hang times, and work out what angles you could hit over a net from your reach.

You will need

- A wall and chalk or sticky notes, or a reach board
- A tape measure
- A phone with slow-motion video
- A soft volleyball or beach ball (optional)
- A non-slip floor or grass
- The scorebook and a calculator

Steps

1. Warm up: jog, skips, leg swings and 5 easy jumps.
2. Measure your standing reach (feet flat, arm fully up).
3. **Predict.** Estimate how much higher you will reach with a three-step approach than from standing.
4. Standing jump: 5 jumps with an arm swing, touching the wall at the top. Record each reach.
5. Approach jump: practice the three-step approach (for a right-hander: right, left, right-left plant), swinging both arms back on the plant and up on takeoff. 5 jumps, touching the wall. Record.
6. Film one jump of each kind from the side and count the frames in the air. Compute hang time and compare with $T = 2\sqrt{2h/g}$.
7. For each kind, compute the mean jump height, the takeoff speed $v = \sqrt{2gh}$, and the contact height.
8. Using your best approach reach, find the steepest straight-line hit 1.0 m from a 2.24 m net and from a 2.43 m net.

9. Optional: with a soft ball and a partner tossing, practice the arm swing against a wall, contacting the ball in front of the hitting shoulder.
10. **Decide.** Write which part of the approach helped your jump most, and set a jump goal for four weeks of practice.

Tips

- Plant both feet, heels first, slightly ahead of your body.
- Land on both feet with knees bent every time.

Check your work

- ☐ I measured standing reach and 10 jumps of two kinds.
- ☐ I computed takeoff speeds and hang times and checked one with video.
- ☐ I computed my steepest angles over both net heights.

SCOREBOOK

1. Jump table: kind, trial, reach, jump height, takeoff speed, hang time.
2. Side-view sketch to scale of the net, your contact point and the steepest hit for both net heights.
3. Stick-figure sequence of your approach and arm swing in five frames.

KEY FORMULAS

$$v = \sqrt{2gh} \quad T = \frac{2v}{g}$$

$$\tan \theta_{\max} = \frac{H - N}{d}$$

$$v_{\text{ball}} = \frac{M(1 + e)}{M + m} V$$

From history. A hard downward hit developed by Filipino players is often named as an early form of the spike. Volleyball became an Olympic sport at the 1964 Games in Tokyo. Morgan is honored in the International Volleyball Hall of Fame in Holyoke.

WORKED EXAMPLES

Example 1. A student jumps 0.50 m after a three-step approach. Her standing reach (with arm fully raised) is 2.25 m. Find her takeoff speed, hang time and highest contact point. How far above a 2.24 m net is it?

Show solution

1. $v = \sqrt{2(9.8)(0.50)} \approx 3.13 \text{ m/s}$; $T = 2(3.13)/9.8 \approx 0.64 \text{ s}$.
2. Contact: $2.25 + 0.50 = 2.75 \text{ m}$, which is 0.51 m above the net.

Answer: 3.1 m/s, 0.64 s, and a contact point 0.51 m above a women's net.

Example 2. From a contact point 2.75 m high and 1.0 m back from the net, find the steepest straight-line hit that clears a 2.24 m net, and where it lands. Repeat for a 2.43 m net.

Show solution

1. Women's net: slope $0.51/1.0 = 0.51$, angle $\tan^{-1} 0.51 \approx 27^\circ$. Lands $2.75/0.51 \approx 5.4 \text{ m}$ from contact, 4.4 m beyond the net.
2. Men's net: slope 0.32, angle $\approx 18^\circ$. Lands $2.75/0.32 \approx 8.6 \text{ m}$ from contact, 7.6 m beyond the net.

Answer: About 27° (landing 4.4 m past the net) and about 18° (landing 7.6 m past). Gravity and topspin curve the ball down further, giving a little more room.

Example 3. The hand (effective mass 3.0 kg) moves at 15 m/s when it strikes a 0.27 kg volleyball, with a coefficient of restitution of 0.60. Find the ball's speed.

Show solution

1. $v = \frac{3.0(1.60)}{3.27}(15) \approx 22 \text{ m/s}$, about 79 km/h.

Answer: About 22 m/s.

PRACTICE

1. Easy Find the takeoff speed for a 0.40 m jump.

Show answer

2.8 m/s.

2. Easy What are the standard net heights for men and women?

Show answer

2.43 m for men and 2.24 m for women.

3. Easy How high was Morgan's first net in 1895?

Show answer

6 feet 6 inches, about 1.98 m.

4. Medium Find the hang time for a jump with a takeoff speed of 3.5 m/s, and the jump height.

Show answer

$T \approx 0.71 \text{ s}$; $h = 12.25/19.6 \approx 0.63 \text{ m}$.

5. Medium A player's standing reach is 2.40 m and she jumps 0.55 m. How far above a 2.24 m net is her contact?

Show answer

0.71 m.

6. Medium From a contact 3.20 m high and 0.80 m from a 2.43 m net, find the steepest straight-line angle.

Show answer

$\tan \theta = 0.77/0.80$, $\theta \approx 44^\circ$.

7. Medium Why does a hitter jump higher after an approach than from standing?

Show answer

The approach provides horizontal speed that the plant partly converts to vertical speed, the arm swing adds upward momentum, and the quick stretch of the leg muscles before takeoff makes them push harder.

8. Medium Name two ways to land safely after a spike.

Show answer

On both feet with knees bent; on your own side of the center line, away from other players' feet.

9. **Hard** A ball spiked at 25 m/s from 2.9 m travels 7.0 m to the floor. Roughly how long does a defender have? (Use the straight-line distance and ignore slowing.)

Show answer

Path length $\sqrt{7.0^2 + 2.9^2} \approx 7.6$ m; $t \approx 0.30$ s.

10. **Hard** With hand mass 3.5 kg, ball mass 0.27 kg and $e = 0.6$, what hand speed gives a 25 m/s spike?

Show answer

$$V = 25 \times \frac{3.77}{3.5 \times 1.6} \approx 16.8 \text{ m/s.}$$

11. **Hard** Explain why taller players and better jumpers have an advantage at the net, using the angle formula.

Show answer

A higher contact point increases $H - N$, so the ball can be hit more steeply over the net and still land in, and it can be hit over blockers.

12. **Challenge** A hitter jumps 0.60 m. How long after takeoff does she reach the top of her jump? A set reaches its peak 1.20 s after it leaves the setter's hands, and the hitter wants to meet it there at the top of her jump. How long after the set leaves the setter's hands should she take off?

Show answer

$v = \sqrt{2(9.8)(0.60)} \approx 3.43$ m/s; time to the top $3.43/9.8 = 0.35$ s. Take off at $1.20 - 0.35 = 0.85$ s after the set leaves the setter. Her approach steps must begin earlier still, which is why hitters start moving as the setter receives the pass.

COMMON MISTAKES

- Measuring jump height from the floor instead of from standing reach.
- Using the full hang time in $h = v^2/2g$ instead of the takeoff speed.
- Swinging the arm late, after the top of the jump.

Make it a game • Vertical Record Chase. Mark your standing reach on a wall with tape. Take three approach jumps and mark the highest touch each time. Compute your jump height, takeoff speed with v equals the square root of two $g h$, and hang time. Your parent records the best height as your personal record. Beat it on a second set after a good warm-up, and explain why contact height matters at the net.

Scripture. “Whatsoever thy hand findeth to do, do it with thy might;” (Ecclesiastes 9:10, KJV)

A spike rewards full commitment: a half-hearted approach and swing produce neither height nor speed. The Preacher’s counsel applies to every task God gives us.

UNIT 4

TENNIS AND VOLLEYBALL

Two net games, one physics. This unit studies the tennis serve as a kinetic chain and the narrow window over the net, topspin and the forehand, the split step and reaction time, the volleyball forearm pass as a reflection off a tilted platform, and the spike and jump serve, with the history of William G. Morgan's game of 1895.

The projects measure your serve speed and accuracy, the margin topspin gives your forehand, your reaction time and first step, your passing angle and accuracy, and your approach jump. Every project works at home with a soft ball, a wall and a phone camera; a trip to a court is optional and supervised.

PREREQUISITES

- Units 1–3: the kinetic chain, projectile motion, the Magnus effect, impulse and the coefficient of restitution
- Algebra I and right-triangle trigonometry
- Vectors in two dimensions (helpful for the reflection problems)

MASTERY CHECKLIST

- ☐ I can explain the serve as a kinetic chain and use the court's geometry to explain the need for spin.
- ☐ I can show with projectile calculations why topspin keeps a hard shot in the court.
- ☐ I can measure reaction time and explain the split step.
- ☐ I can find the platform angle that sends a pass to a target using the law of reflection.
- ☐ I can compute jump height, hang time and the steepest angle of a spike over the net.

OPTIONAL BOOKS AND GAMES FOR THIS UNIT

- **Rod Cross: Physics of Tennis and Other Sports**: Free. A University of Sydney physicist's articles on rackets, strings, spin and bounce, with high-speed photographs. Extends Lessons 4.1 and 4.2. Some articles are technical. Ages 14+.
- **International Volleyball Hall of Fame**: Free. The Holyoke museum's site, with the history of William G. Morgan and the early game for Lessons 4.4 and 4.5.

Not required. Every project in this unit works without them. School Launch has no ties to these authors, publishers or companies.

LESSONS IN THIS UNIT

4.1 The Tennis Serve as a Kinetic Chain	3 sessions of 50 minutes
4.2 Topspin and the Forehand	3 sessions of 50 minutes
4.3 Footwork, the Split Step and Reaction Time	3 sessions of 50 minutes
4.4 The Volleyball Pass: Platform Angle and Reflection	3 sessions of 50 minutes
4.5 The Spike and the Jump Serve	3 sessions of 50 minutes

UNIT 4 TEST

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$. Show your work for every calculation with units. Answer the concept questions in complete sentences. The test is worth 100 points.

1. 6 pts

A racket center 1.45 m from the shoulder axis turns at 29 rad/s. Find its speed. If the ball leaves at 1.4 times that speed, find the ball speed in km/h.

2. 7 pts

Using the straight-line serve model, find how high a serve from a 2.9 m contact point crosses the net when aimed at the service line. Does it clear the 0.914 m net?

3. 6 pts

Explain why most second serves are hit with spin.

4. 6 pts

Find the surface speed of a ball of radius 3.35 cm spinning at 2,800 rpm.

5. 9 pts

A ball is hit from 1.0 m at 24 m/s, 12° above horizontal. Find where it lands with no spin and with topspin adding 5.0 m/s^2 downward. Which lands in a 23.77 m court from the baseline?

6. (5 pts)

A ruler falls 0.15 m before it is caught. Find the reaction time.

7. (6 pts)

Find the air time of a 6.0 cm split-step hop, and explain why the split step should land as the opponent strikes the ball.

8. (6 pts)

A serve takes 0.55 s to reach a returner whose reaction time is 0.20 s. If she accelerates at 6.0 m/s^2 after reacting, how far can she move before the ball arrives?

9. (8 pts)

A serve arrives descending at 40° toward a passer, who wants it to rise at 60° toward the net. Find the angle of the platform's normal above horizontal and the slope of the forearms.

10. (7 pts)

A pass leaves at 7.5 m/s and 70° . Find its peak height and flight time to the same height.

11. (5 pts)

Who invented volleyball, where and when, and what was it first called?

12. (7 pts)

A player jumps 0.45 m. Find her takeoff speed and hang time.

13. (8 pts)

From a contact point 3.05 m high and 1.0 m from a 2.43 m net, find the steepest straight-line hit and how far beyond the net it lands.

14. (14 pts)

Short essay. In about 150 words, compare the tennis forehand and the volleyball spike as uses of the kinetic chain and spin. Include one calculation from your own project data.

ANSWER KEY

1. 42 m/s ; $58.9 \text{ m/s} \approx 212 \text{ km/h}$.
2. $2.9 \times 0.350 \approx 1.02 \text{ m}$; yes, by about 10 cm.
3. A flat serve has a tiny window over the net and into the box; spin curves the ball down, letting it cross higher and still land in, which lowers the risk of a double fault.
4. $\omega \approx 293 \text{ rad/s}$; $v \approx 9.8 \text{ m/s}$.
5. $v_x \approx 23.5$, $v_y \approx 4.99$. No spin: $t \approx 1.19 \text{ s}$, $x \approx 28 \text{ m}$ (out). Topspin:
 $1 + 4.99t - 7.4t^2 = 0 \Rightarrow t \approx 0.84 \text{ s}$, $x \approx 19.6 \text{ m}$ (in).
6. $\approx 0.17 \text{ s}$.
7. $2\sqrt{0.12/9.8} \approx 0.22 \text{ s}$. Landing then lets the player push off in the right direction immediately, with stretched, ready muscles; landing early leaves him flat and still, landing late leaves him in the air.
8. $\frac{1}{2}(6.0)(0.35)^2 \approx 0.37 \text{ m}$.
9. The normal bisects: $\phi = (40^\circ + 60^\circ)/2 = 50^\circ$; forearms slope 40° below horizontal.
10. $v_y \approx 7.05$; $H \approx 2.54 \text{ m}$; $T \approx 1.44 \text{ s}$.
11. William G. Morgan, at the Holyoke, Massachusetts, YMCA in 1895; mintonette.
12. 2.97 m/s ; 0.61 s .
13. $\tan \theta = 0.62$, $\theta \approx 32^\circ$; lands $3.05/0.62 \approx 4.9 \text{ m}$ from contact, about 3.9 m beyond the net.
14. Answers vary. A strong essay describes both as proximal-to-distal chains (legs, hips, trunk, shoulder, elbow, wrist), explains how each produces topspin (low-to-high racket path; wrist snap over the ball) and why topspin brings the ball down into the court, and includes a correct calculation from the student's measurements.

PORTFOLIO PIECE: A NET-GAMES PHYSICS NOTEBOOK

Prepare an illustrated report of four to six pages on the physics of tennis and volleyball, built around your own measurements. Include your serve speeds and contact height with the straight-line net calculation; your flat and topspin forehand margins; your reaction time and split-step test; your passing angles and accuracy; and your approach jump with the steepest angles you could hit. For each, give the formula, your data, one graph or diagram, and a one-sentence coaching tip. End with a comparison of tennis and volleyball: what physics they share, and what is different.

LOOK FOR	WHAT IT MEANS
Measurements	All five measurements present with repeated trials and units.
Physics and mathematics	Correct formulas and calculations, including the reflection and net-geometry problems.
Diagrams and graphs	Clear, labelled, to-scale diagrams and at least two graphs.
Comparison and coaching	A thoughtful comparison of the two sports and practical coaching tips drawn from the data.

MIDTERM EXAM

Covers Units 1–3. Time: 100 minutes.

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$, $1 \text{ mph} = 0.447 \text{ m/s}$, a baseball of 0.145 kg and a soccer ball of 0.43 kg unless told otherwise. Show the formula, the substitution with units and the answer for every calculation. Answer the concept questions in complete sentences. The exam is worth 100 points.

1. **3 pts**

State Newton's third law and use it to explain how a sprinter moves forward.

2. **4 pts**

A 68 kg runner accelerates from rest to 6.8 m/s in 2.0 s . Find the average net force.

3. **5 pts**

A 58 kg student jumps 0.48 m high with a push-off lasting 0.29 s . Find the takeoff speed and the average floor force.

4. **4 pts**

A 3.0 kg weight is held 0.34 m from the elbow, the biceps attaching 0.045 m from it, forearm horizontal. Find the biceps force (ignore the forearm's weight).

5. **3 pts**

Classify the lever in (a) a calf raise and (b) the biceps bending the elbow, and say which favors speed.

6. **4 pts**

Masses of 40 kg at 0 , 25 kg at 1.2 m and 15 kg at 2.0 m . Find the center of mass.

7. **4 pts**

Find the sideways tipping angle for feet 0.56 m apart and the center of mass 0.92 m high.

8. **4 pts**

Convert $6,500^\circ$ per second to rad/s and find the speed of a point 0.32 m from the axis.

9. **4 pts**
Explain the proximal-to-distal sequence and why skipping a link (such as the stride) is both slower and riskier.
10. **3 pts**
A 52 kg student climbs 3.2 m of stairs in 3.6 s. Find the average power.
11. **4 pts**
Using $v = 0.2 v_{\text{pitch}} + 1.2 v_{\text{bat}}$, find the exit velocity for an 85 mph pitch and a 68 mph bat.
12. **4 pts**
A ball dropped from 1.50 m rebounds to 0.42 m. Find its coefficient of restitution.
13. **4 pts**
A baseball arrives at 36 m/s and leaves at 42 m/s in the opposite direction after 0.75 ms. Find the average force.
14. **4 pts**
Using Briggs's result that the curve is proportional to spin (17.5 in at 1,800 rpm), predict the curve at 1,350 rpm. How many turns does the ball make in 0.55 s at that spin?
15. **3 pts**
Which way does a ball with backspin curve, and why does a backspin fastball seem to rise?
16. **4 pts**
Under Pitch Smart, a 14-year-old throws 62 pitches on Monday. How many rest days are required, and on what day may he next pitch? (Bands for 13–14: 21–35 one day, 36–50 two, 51–65 three, 66+ four.)
17. **4 pts**
A fly ball is in the air 4.6 s. Find its vertical launch speed and peak height (no air resistance).

18. (4 pts)

For a fielder at the landing point, show that $\tan \alpha$ rises at the rate $g/2v_x$ and evaluate it for $v_x = 24 \text{ m/s}$.

19. (4 pts)

A 90 mph pitch is released 16.8 m from the plate. Find the flight time. If a hitter needs 0.15 s to swing and 0.20 s to react, how much time remains to judge the pitch?

20. (4 pts)

A soccer ball is kicked from rest to 27 m/s in 0.011 s. Find the average force.

21. (4 pts)

A ball arrives at 15 m/s and is stopped by a first touch in 0.012 s and in 0.10 s. Find both forces.

22. (4 pts)

A ball at 26 m/s feels a sideways force of 3.1 N. Find its radius of curvature now and at 18 m/s if the force is unchanged.

23. (4 pts)

A 62 kg player cuts at 5.5 m/s on a 3.5 m radius. Find the force needed and the minimum friction coefficient.

24. (3 pts)

State U.S. Soccer's youth heading guidance and give one physics reason for it.

25. (8 pts)

Short essay. In about 150 words, explain how impulse and momentum appear in baseball and soccer, using one example where a player wants a large force and one where he wants a small force.

ANSWER KEY

1. For every force there is an equal and opposite force on the other object. The sprinter pushes backward on the ground, and the ground pushes forward on the sprinter.
2. $a = 3.4 \text{ m/s}^2$; $F \approx 231 \text{ N}$.
3. $v \approx 3.07 \text{ m/s}$; $a \approx 10.6 \text{ m/s}^2$; $F = 58(9.8 + 10.6) \approx 1,180 \text{ N}$.
4. $F = \frac{29.4 \times 0.34}{0.045} \approx 222 \text{ N}$.
5. (a) second class; (b) third class, which favors speed.
6. $x = \frac{0 + 30 + 30}{80} = 0.75 \text{ m}$.
7. $\tan \theta = 0.28/0.92$, $\theta \approx 17^\circ$.
8. $\approx 113 \text{ rad/s}$; $\approx 36 \text{ m/s}$.
9. Segments peak in order from the center outward, each slowing as the next speeds up, so speed builds link by link. Skipping a link breaks the chain, lowering speed and forcing the small distal segments to make up the difference with larger loads.
10. $P = 52 \times 9.8 \times 3.2/3.6 \approx 453 \text{ W}$.
11. $17 + 81.6 \approx 99 \text{ mph}$.
12. $e = \sqrt{0.28} \approx 0.53$.
13. $\Delta p = 0.145 \times 78 \approx 11.3$; $F \approx 15,100 \text{ N}$.
14. $17.5 \times 0.75 \approx 13.1 \text{ in}$; $22.5 \times 0.55 \approx 12.4 \text{ turns}$.
15. Upward (the Magnus force is up). It falls less than gravity alone would make it, so it arrives higher than the hitter expects.
16. Three rest days (Tuesday, Wednesday, Thursday); he may pitch again on Friday.
17. $v_y \approx 22.5 \text{ m/s}$; $H \approx 25.9 \text{ m}$.
18. Using $y = \frac{1}{2}gt(T - t)$ and horizontal distance $v_x(T - t)$, $\tan \alpha = \frac{g}{2v_x}t$; rate $9.8/48 \approx 0.20$ per second.
19. $t \approx 0.42 \text{ s}$; about 0.07 s .
20. $\approx 1,060 \text{ N}$.
21. $\approx 538 \text{ N}$ and $\approx 65 \text{ N}$.
22. $\approx 94 \text{ m}$ and $\approx 45 \text{ m}$.
23. $F \approx 536 \text{ N}$; $\mu \geq 0.88$.

24. No heading for 10 and under; limited heading in practice only for ages 11–13. A child’s relatively heavy head and weaker neck give a smaller effective mass, so the same impulse produces a larger head acceleration.
25. Answers vary. A strong essay states $F\Delta t = \Delta p$, gives an example of a large force in a short time (bat–ball collision, instep drive) and of a small force over a longer time (first touch, follow-through, catching), with correct reasoning about contact time.

FINAL EXAM

Covers Units 1–6. Time: 120 minutes.

Calculators are allowed. Use $g = 9.8 \text{ m/s}^2$, $1 \text{ mph} = 0.447 \text{ m/s}$, a baseball of 0.145 kg and a soccer ball of 0.43 kg unless told otherwise. Show the formula, the substitution with units and the answer for every calculation. Answer the concept questions in complete sentences. The exam is worth 100 points.

1. **3 pts**

A 72 kg sprinter receives an average net forward force of 288 N. Find the acceleration and the speed after 1.5 s.

2. **4 pts**

Your head's 50 N weight acts 2.5 cm in front of the joint at the top of the spine; neck muscles attach 5.0 cm behind. Find the muscle force and the class of lever.

3. **4 pts**

A reaction board is 2.0 m long. A 64 kg student lies on it (feet at the block) and the zeroed scale reads 30 kg. Find the center of mass.

4. **4 pts**

Explain why a high jumper using the Fosbury flop can clear a bar while raising the center of mass less than with older styles.

5. **3 pts**

Convert $1,100^\circ$ per second to rad/s.

6. **4 pts**

Using $T = 50N^{-0.3}$, find the time on the 20th practice trial.

7. **4 pts**

A pitch at 92 mph and a bat at 74 mph meet at the sweet spot ($q = 0.2$). Find the exit velocity.

8. **4 pts**

A fastball takes 0.40 s; backspin gives an upward acceleration of 3.5 m/s^2 . How far does it drop, compared with 0.78 m for no spin?

9. (3 pts)

Name three workload habits that protect a young pitcher's arm.

10. (4 pts)

A ball is hit at 32 m/s at 30° (no air). Find hang time and range.

11. (4 pts)

A ball arrives at 13 m/s and the receiving foot's effective coefficient of restitution is 0.12. Find the rebound speed and roll distance on grass slowing it at 0.8 m/s^2 .

12. (4 pts)

Find the tightest turn radius at 6.5 m/s with $\mu = 0.85$, and the lean angle on that turn.

13. (4 pts)

Illustrative. A ball gives a head an impulse of $7.0 \text{ N}\cdot\text{s}$ in 0.010 s . Find the head acceleration in g for effective masses of 5 kg and 14 kg.

14. (4 pts)

In the straight-line serve model, find the height at which a serve from a 2.7 m contact point crosses the net when aimed at the service line. Does it clear 0.914 m?

15. (5 pts)

A forehand leaves 1.0 m high at 26 m/s, 9° above horizontal. Find where it lands with topspin adding 5.0 m/s^2 downward. Is it in a 23.77 m court?

16. (3 pts)

A ruler falls 0.16 m before it is caught. Find the reaction time.

17. (4 pts)

A serve arrives descending at 35° and a pass should rise at 65° toward the net. Find the platform normal's angle above horizontal.

18. (4 pts)

From a contact point 2.85 m high, 1.0 m from a 2.24 m net, find the steepest straight-line hit and where it lands beyond the net.

19. (4 pts)

A 0.20 kg clubhead at 48 m/s strikes a 0.0459 kg ball with $e = 0.83$. Find the ball speed.

20. (4 pts)

A green reads 9 feet (2.74 m); the Stimp meter releases at 1.83 m/s. Find the deceleration and the starting speed for a 2.5 m putt to finish 0.43 m past.

21. (4 pts)

A bowling ball slides without spin at 7.8 m/s on a dry lane ($\mu = 0.20$). Find the time until it rolls without slipping.

22. (4 pts)

In a 240 fps video, an elbow angle opens from 95° to 165° in 6 frames. Find the angular velocity in rad/s.

23. (4 pts)

A 52 kg student lands from 0.45 m and stops in 0.30 m. Find the average ground force in body weights.

24. (4 pts)

A cyclist produces 180 W at 22% efficiency for one hour. Find the heat produced and the sweat needed to remove it all by evaporation ($L_v = 2.4 \text{ MJ/kg}$).

25. (7 pts)

Short essay. In about 200 words, choose one sport from this course and explain how three physical principles (from different units) govern its key skill, and one safety rule that follows from the physics. Close with a sentence on what it means to care for the body as a gift.

ANSWER KEY

1. $a = 4.0 \text{ m/s}^2$; $v = 6.0 \text{ m/s}$.
2. 25 N; first class.
3. $x = 30 \times 2.0/64 \approx 0.94 \text{ m}$.
4. The arched body crosses the bar a part at a time; its center of mass lies below the body and can pass at or below the bar.
5. $\approx 19.2 \text{ rad/s}$.
6. $20^{-0.3} \approx 0.407$; $T \approx 20.4 \text{ s}$.
7. $18.4 + 88.8 \approx 107 \text{ mph}$.
8. $\frac{1}{2}(6.3)(0.16) \approx 0.50 \text{ m}$, about 28 cm less.
9. Any three: follow pitch-count and rest-day limits, never pitch on three consecutive days, take months off from pitching each year, do not pitch through fatigue or pain, avoid pitching for several teams at once.
10. $T \approx 3.27 \text{ s}$; $R \approx 90.5 \text{ m}$.
11. 1.56 m/s ; $\approx 1.5 \text{ m}$.
12. $r \approx 5.1 \text{ m}$; $\tan \theta = 0.85$, $\theta \approx 40^\circ$.
13. $\approx 14 g$ and $\approx 5 g$.
14. $2.7 \times 0.350 \approx 0.945 \text{ m}$; yes, by about 3 cm.
15. $v_x \approx 25.7$, $v_y \approx 4.07$; $1 + 4.07t - 7.4t^2 = 0 \Rightarrow t \approx 0.74 \text{ s}$; $x \approx 19 \text{ m (in)}$.
16. $\approx 0.18 \text{ s}$.
17. $(35^\circ + 65^\circ)/2 = 50^\circ$.
18. $\tan \theta = 0.61$, $\theta \approx 31^\circ$; lands $2.85/0.61 \approx 4.7 \text{ m}$ from contact, 3.7 m beyond the net.
19. $\frac{1.83}{1.23} \times 48 \approx 71.4 \text{ m/s}$.
20. $a \approx 0.61 \text{ m/s}^2$; $v_0 = \sqrt{2(0.61)(2.93)} \approx 1.89 \text{ m/s}$.
21. $t = 2(7.8)/(7 \times 0.20 \times 9.8) \approx 1.14 \text{ s}$.
22. $70^\circ/0.025 \text{ s} = 2,800^\circ/\text{s} \approx 49 \text{ rad/s}$.
23. $mgh \approx 229 \text{ J}$; $229/0.30 + 510 \approx 1,273 \text{ N}$, about 2.5 body weights.
24. Body 818 W; heat 638 W; $2.30 \text{ MJ} \Rightarrow \approx 0.96 \text{ kg}$.
25. Answers vary. A strong essay names three distinct principles correctly (for example the kinetic chain, the Magnus effect and impulse), applies each

accurately to the chosen skill with numbers where possible, gives a physics-based safety rule, and reflects sincerely on stewardship of the body.