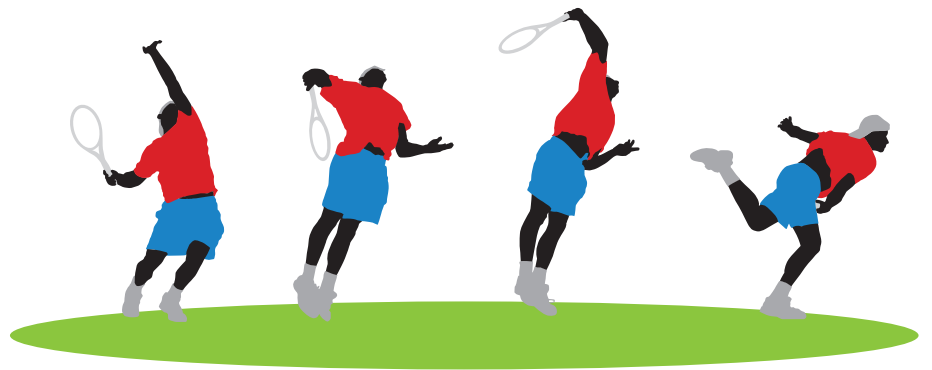
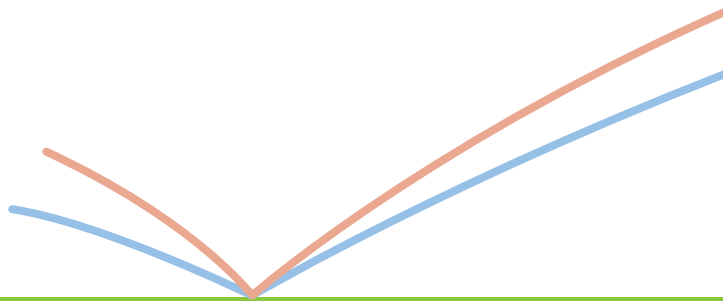


tennis science

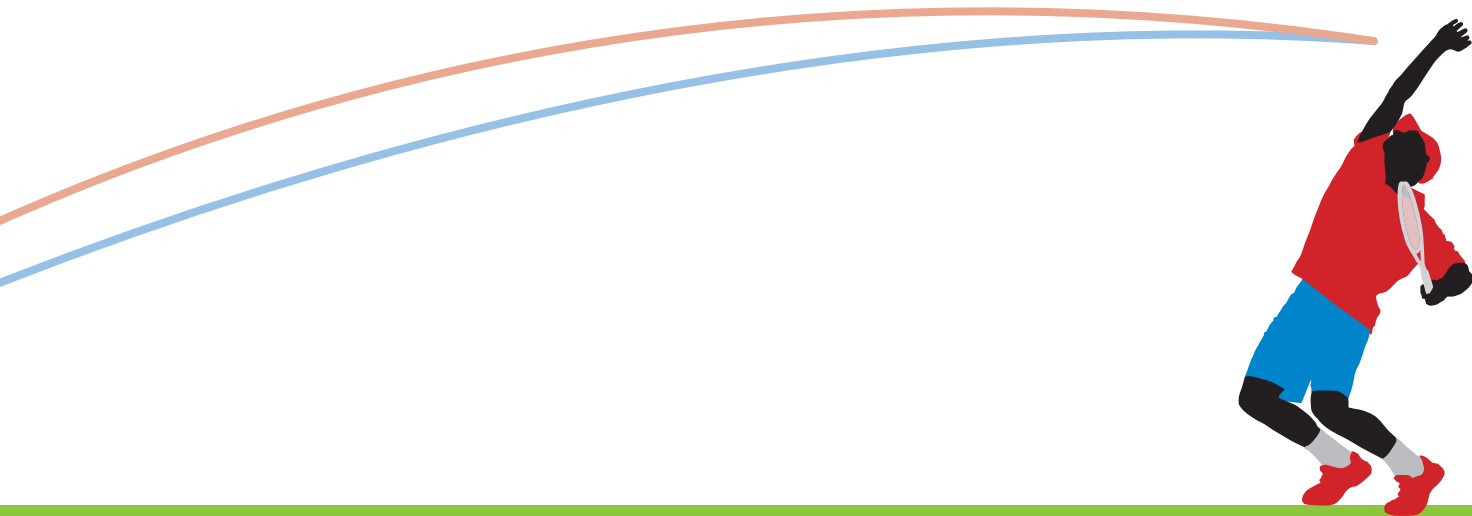




tennis science

Edited by MACHAR REID, BRUCE ELLIOTT & MIGUEL CRESPO

how player and racket work together



THE UNIVERSITY OF CHICAGO PRESS

Chicago and London

Machar Reid is the innovation catalyst at Tennis Australia.

Bruce Elliott is a senior research fellow in biomechanics at the School of Sport Science, Exercise, and Health at the University of Western Australia.

Miguel Crespo is a research officer at the International Tennis Federation Development Department, Spain.

The University of Chicago Press, Chicago 60637

© The Ivy Press Limited 2015

All rights reserved. Published 2015.

Printed in China

24 23 22 21 20 19 18 17 16 15 1 2 3 4 5

ISBN-13: 978-0-226-13640-0 (cloth)

ISBN-13: 978-0-226-13962-3 (e-book)

DOI: 10.7208/chicago/9780226139623.001.0001

Library of Congress Cataloging-in-Publication Data

Elliott, Bruce, 1945— author.

Tennis science : how player and racket work together / Machar Reid, Bruce Elliott, and Miguel Crespo.

pages cm

Includes bibliographical references and index.

ISBN 978-0-226-13640-0 (cloth : alkaline paper) — ISBN 0-226-13640-X (cloth : alkaline paper) — ISBN 978-0-226-13962-3 (e-book) —

ISBN 0-226-13962-X (e-book) 1. Tennis. 2. Sports sciences. I. Reid, Machar, author. II. Crespo, Miguel, author. III. Title.

GV995.E383 2015

796.342—dc23

2014037019

This book was conceived, designed, and produced by

Ivy Press

210 High Street, Lewes

East Sussex BN7 2NS

United Kingdom

www.ivypress.co.uk

Creative Director Michael Whitehead

Publisher Susan Kelly

Editorial Director Tom Kitch

Commissioning Editor Emma Shackleton

Senior Project Editor Caroline Earle

Designer JC Lanaway

Copy Editor Rob Yarham

Illustrator Nick Rowland

Additional illustrations Robert Brandt

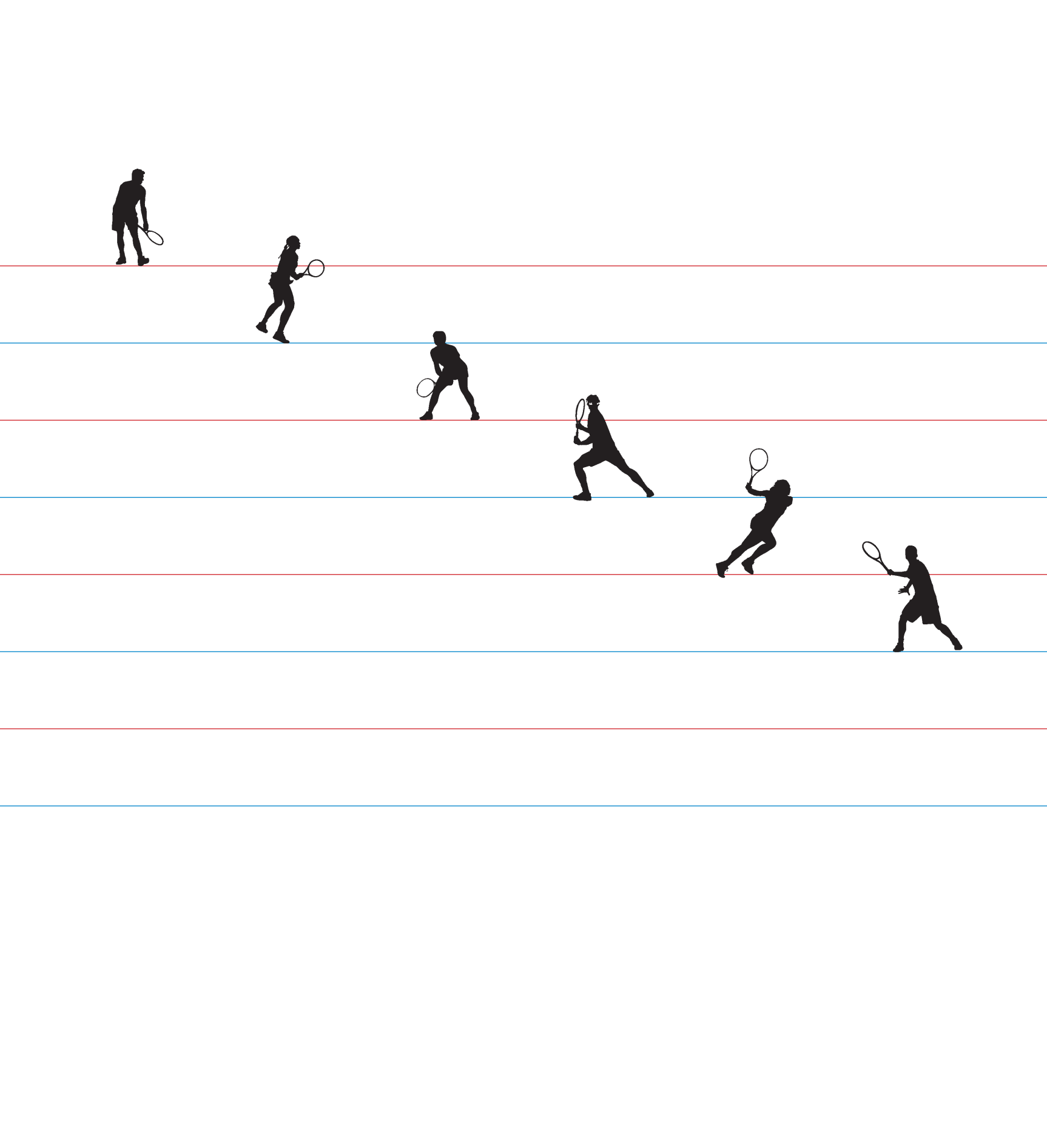
Cover illustration: Nick Rowland; photo: Anthony Lee/Getty Images.

Note from the publisher

Information given in this book is not intended to be taken as a replacement for medical advice. Any person with a condition requiring medical attention should consult a qualified medical practitioner or therapist.

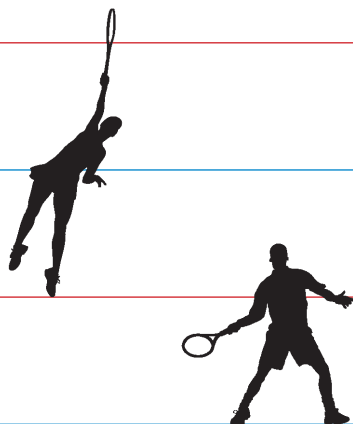






Contents

	Introduction	8
CHAPTER ONE	learning the game Machar Reid, Miguel Crespo, and Damian Farrow	12
CHAPTER TWO	technique Bruce Elliott and Machar Reid	32
CHAPTER THREE	performance analysis and game intelligence Michael Bane, Bruce Elliott, and Machar Reid	54
CHAPTER FOUR	the mental edge Miguel Crespo and Paul Lubbers	74
CHAPTER FIVE	physical development Mark Kovacs, Rob Duffield, and Aaron Kellett	94
CHAPTER SIX	nutrition and recovery Shona Halson and Louise Burke	116
CHAPTER SEVEN	staying healthy Todd Ellenbecker and W. Ben Kibler	136
CHAPTER EIGHT	equipment and technology Duane Knudson	156
	Notes	178
	Glossary	184
	Notes on contributors	189
	Index	190
	Table of measurements	192
	Acknowledgments	192



Introduction

Tennis is a popular lifetime activity for millions of players worldwide. Part of the sport's appeal is that it challenges both the mind and body—the fittest player or the one with the best strokes does not always win. Playing on different surfaces—hard courts, clay, grass, and artificial grass—with their wide range of characteristics adds to the difficulty for developing high-performance players. In addition, tennis is played outdoors and indoors, requiring players to master hitting the ball with power, topspin, or backspin in diverse environmental conditions. Furthermore, tennis makes great physical demands on players during matchplay, which typically lasts between two and four hours—one match at Wimbledon in 2010 between John Isner and Nicolas Mahut lasted an incredible 11 hours, 5 minutes. Therefore, understanding the scientific basis that underlies important aspects of tennis can provide a crucial contribution to help develop a high-performance player, but also to assist a recreational player to improve and extract even greater enjoyment from the game.

Roger Federer is arguably the greatest male tennis player of all time. At different stages of his career, Federer has relied on various aspects of science to hone his game to ever more impressive levels. He developed his technical skills as a young player in Switzerland, where a strong belief in footwork, full-body coordination, and fitness was an integral part of the learning process. He has subsequently concentrated on physical preparation—a key factor in his relatively injury-free career—and has developed a mental toughness that has been severely tested in epic battles with leading competitors, such as Rafael Nadal.

While Roger Federer's natural athleticism has always been clear to see, the behind-the-scenes study and hard work that have led to his development into one of the all-time greats of the game certainly owe an enormous amount to tennis science.

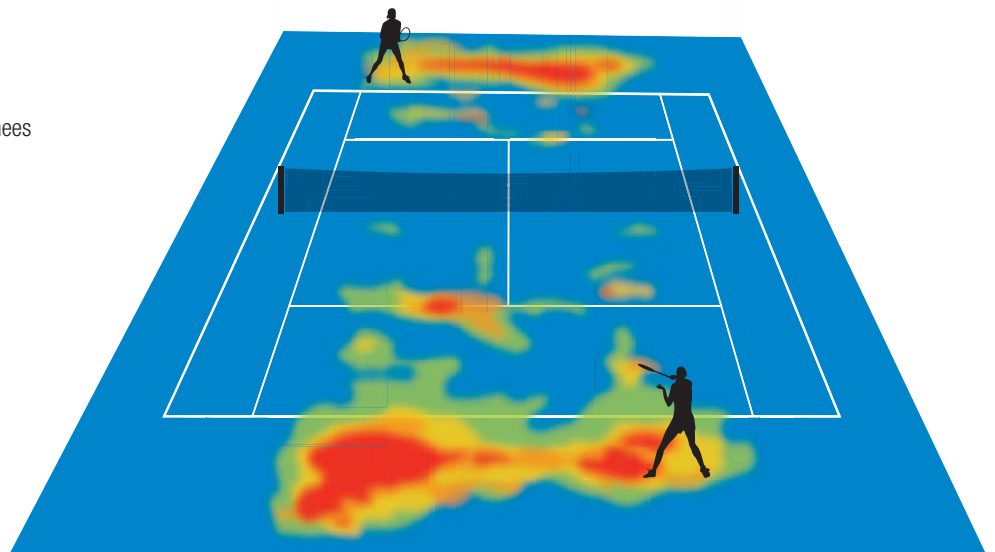
► **Science behind success** Professional tennis players such as Roger Federer have turned increasingly to science to help them understand every aspect of the game and give them an edge out on the court. Psychology, physiology, nutrition, materials science, and biomechanics all play their part in the tennis player's quest to maximize their chances of success.





Developed with the involvement of world authorities on the science of the game, *Tennis Science* employs a unique approach to studying the sport, by answering a series of intriguing and important questions from both a scientific and a popular point of view.

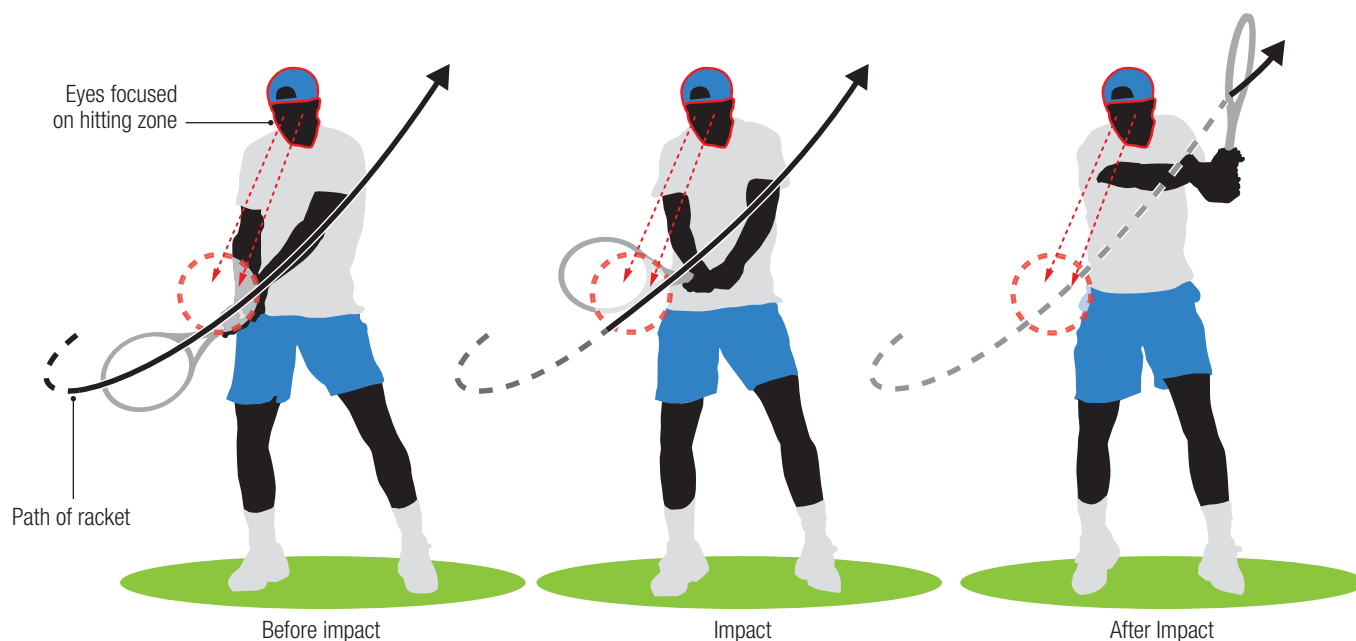
Each chapter covers a different scientific discipline. Chapter 1, *Learning the Game*, addresses skill acquisition and development, including the best ways to learn to play and how best to practice. Learning how to make effective tennis strokes is dealt with in Chapter 2, *Technique*. Chapter 3, *Performance Analysis and Game Intelligence* analyzes the data behind the players who succeed in becoming successful professionals, as well as game tactics. In Chapter 4, *The Mental Edge*, we look at the important role of psychology in playing tennis, such as how to master self-doubt. Today's game requires



a very high level of physical performance as well, so Chapter 5, *Physical Development*, delves into the science behind the fitness and strength of tennis players. Chapter 6, *Nutrition and Recovery*, covers the crucial subjects of consuming the correct food and fluids, and regenerating the body for repeated play. The sport's heavy physical demands inevitably lead to injury, so Chapter 7, *Staying Healthy*, addresses the best ways of preventing or minimizing the risks of injury. Finally, no book on the science of tennis would be complete without a discussion of how developments in equipment have changed the way the game is played, and this is presented in Chapter 8, *Equipment and Technology*.

Each chapter includes a detailed look at how equipment—such as video analysis and Hawk-Eye—has impacted tennis science, and we learn how the professional sport has benefited directly from the science in action.

◀▼ **Graphically speaking** The graphics and illustrations in the book will introduce you to the science that has developed over many years of tennis play, from the fundamentals of physics and body biomechanics involved during a tennis stroke to the latest developments in tennis equipment and movement-tracking technology.





Learning is commonly understood to permeate the careers of most tennis players rather than simply occur at a discrete moment in time, or stop soon after players are able to execute the game's basic skills. When conceptualized in this way, learning can be appreciated as a dynamic process, in which every interaction with the coach and the environment has the potential to shape progress. Individual idiosyncrasies, resulting from differences in physical size and learning styles, can also influence the ways in which players digest information, respond to coach instructions, process feedback and ultimately improve. This chapter therefore considers the growing body of evidence that allows us to explore the interaction between player and coach.

chapter one

learning the game

Machar Reid, Miguel Crespo, and Damian Farrow



What factors influence learning a skill during practice?

A coach's decision on how to structure practice depends upon factors such as the age and experience of the learner, as well as the complexity of the skill to be learned. Interestingly, research examining how to most effectively structure practice to improve player learning has provided some counterintuitive findings that challenge the accepted coaching practice of “drilling” or “grooving” a stroke—using large numbers of repetitions and minimal variation.

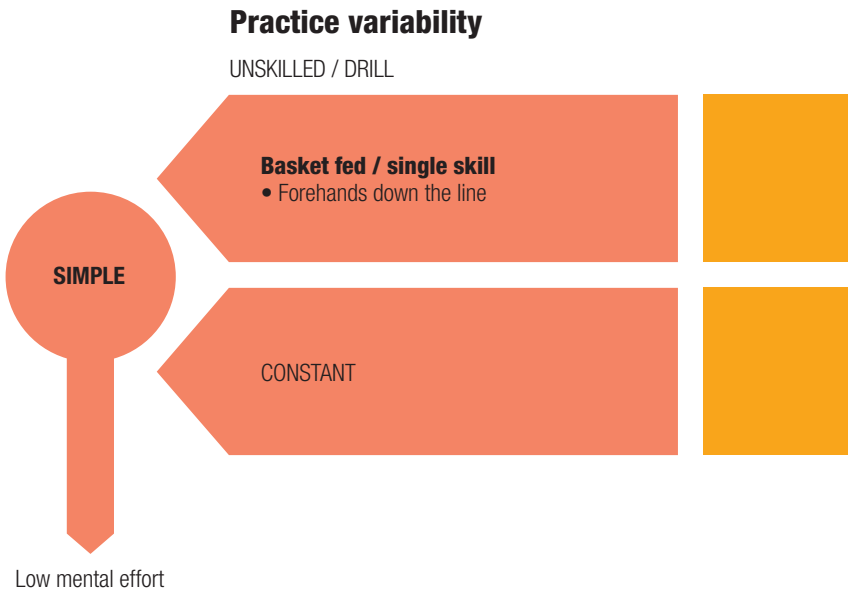
One way of structuring practice is to address the amount of mental effort needed to perform a skill. Low variability or blocked practice—repeating the same shot multiple times before doing the same with a different shot—means that a learner’s mental effort to produce each shot is low (also known as low contextual interference). High variability or random practice—varying the shots—means that greater mental effort is required (known as high contextual interference). For example, if a flat tennis serve is practiced and then another flat tennis serve is hit from the same position, the mental effort for the second serve is not as demanding as the first. However, if the player were asked to hit a groundstroke instead of repeating the serve, they would use more mental effort to generate the new movement sequence.

► **Varying practice** *The skill level of the performer and the difficulty of the task to be practiced are two important factors that influence a coach’s decision about how much practice variability to expose the learner to. In general terms, it is evident that traditional approaches to tennis coaching typically err on the side of less variability, providing a more manageable challenge for the learner. Interestingly, research evidence tends to suggest a more aggressive approach to practice variability is more effective.² In this diagram illustrating the objective of increasing the forehand racket velocity, the coach increases the variability—and contextual interference—as the player’s skill level improves.*

What type of practice will best improve my tennis?

Research into the contextual interference phenomenon reveals that practicing a number of shots in a random manner leads to improved retention of the practiced skills, compared with practicing each task separately for a block of trials. For example, blocked practice would involve practicing one skill (such as the forehand groundstroke) constantly for a period, and then following that with practicing a different skill (such as the backhand groundstroke). In comparison, random practice would involve practicing both skills randomly in the same block of practice attempts: for instance, hitting two backhands, then a forehand, then another backhand, and so on. At the end of practice, an equal number of forehand and backhand groundstrokes would have been performed by the learner.

Researchers have found that random practice does not improve the player’s ability to perform the skills initially, but enhances their retention later on, as well as improving performance of the skills in more varied game situations.¹



Practice guidelines

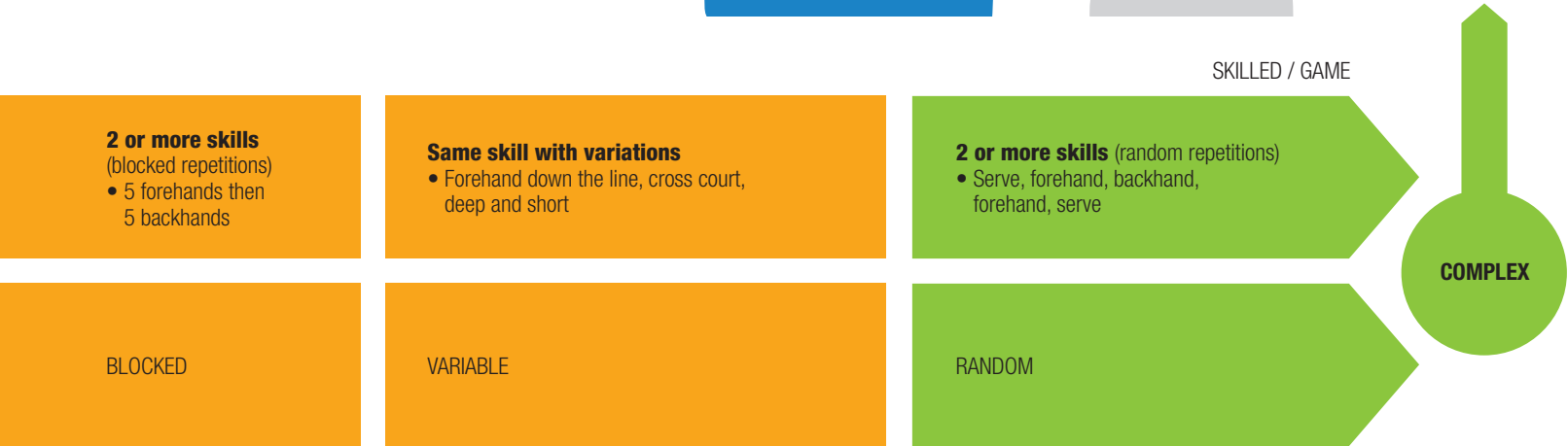
Skill level	Beginner	Intermediate	Advanced
Practice	Blocked	Blocked/random	Random
Interference/mental effort	Low	Medium/high	High

▲ **Skill level and practice** The amount of practice variability will be significantly reduced for children and beginners learning tennis. It is important to give young learners plenty of repeat trials in the form of blocked practice, with opportunities to either reinforce a desirable outcome or correct an error from the previous practice attempt. A basic movement pattern must be established before variations of that pattern or changing environmental conditions are experienced. Equally, a more skilled performer may also need to practice in a more blocked manner when re-learning a skill or making a modification to an existing skill. The table provides general guidelines.

Mental focus



▼ **Mental effort** The more mental effort a player is forced to use when practicing a skill, or a combination of skills, the greater their chance of retaining those skills.



Do tennis skills benefit from task decomposition?

Should I practice parts of a stroke separately?

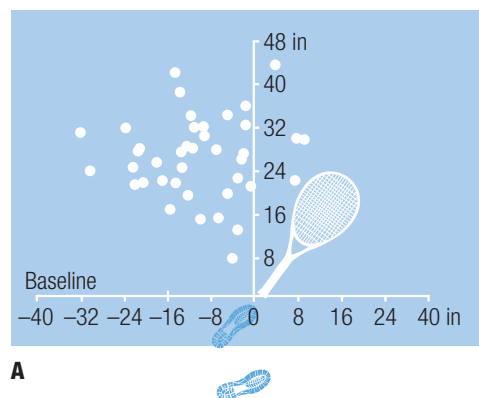
Many tennis coaches structure entire practice sessions around refining the mechanical consistency of their players' strokes, hoping to achieve the perfect, repeatable stroke. However, achieving this “stroke nirvana” is highly unlikely (and even undesirable). Furthermore, the practice methods that coaches regularly employ to achieve this are often counterproductive.

Players, at all levels of the game, have been instructed by coaches to break down a skill and rehearse it in its component parts. In coaching science, such an approach is termed “task decomposition.” Perhaps the most commonly performed example of task decomposition in tennis is that which sees the ball toss and racket swing of the serve practiced independently of each other. This is done to enhance the movement consistency of the individual component parts, under the assumption that any improvements are carried over when the parts are reassembled and the whole skill is rehearsed. However, in sports like tennis, which involve lots of interceptive skills that rely on strong connections between perception and action for effective performance, the efficacy of this type of

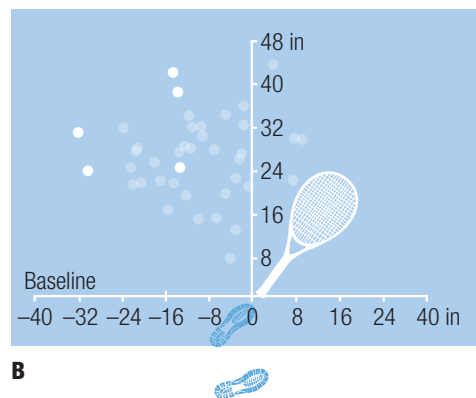
practice has been challenged. The notion of perception–action coupling can be traced back to the work of James Gibson, in the late 1970s, who described a reciprocal relationship between how we process sensory information and produce related actions.¹

Recent research has investigated the kinematic effects of breaking down the serve, by separating the ball toss from the racket swing.² The results were contrary to what many coaches might expect and, most importantly, intend. Players tossed the ball significantly higher (on average, 9 in or 22.5 cm) when the toss was rehearsed independently from the racket swing, resulting in an increase of approximately 10% in toss time (from ball release to “impact”). Furthermore, players were no better equipped to achieve a stable or consistent toss without ball impact—if anything, the consistency of their toss deteriorated. Rehearsing the swing without the toss also appeared to disturb the link between perception and action that is critical to serving success. Specifically, players changed their timing and reduced the velocity of their racket swing at impact by about 22%.

Ball toss landing positions



Extrapolated landing positions for the ball toss for 8 players (5 serves per player)

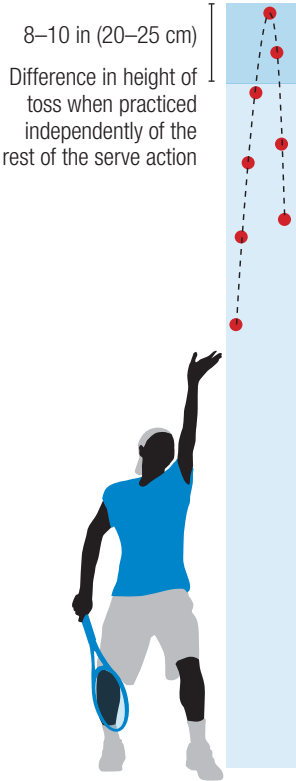


Extrapolated landing positions for the ball toss for 1 player (which spans an area larger than a racket face)

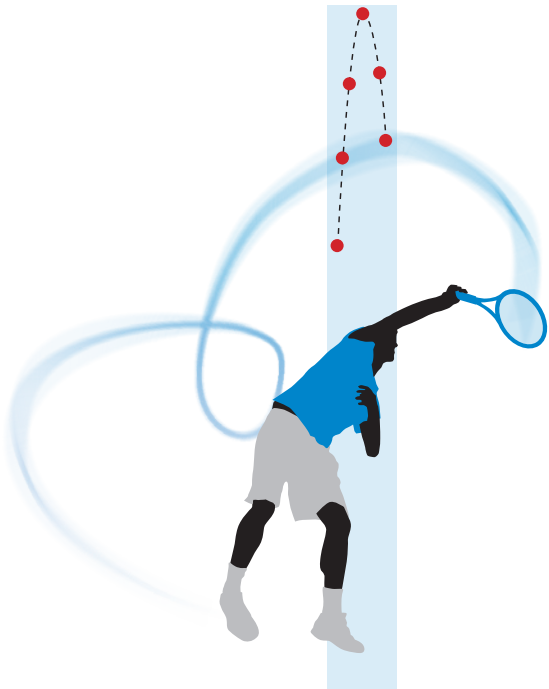
◀ **Landing locations** When trying to develop a consistent ball toss, players are sometimes asked to practice landing their ball toss on a racket placed on a position just over the baseline in front of the front foot. In a study by Whiteside and colleagues,³ eight professional players hit a combined total of 40 successful serves to a target placed at the “T” of the deuce court. Graph **A** shows the extrapolated landing positions of the ball had the serves not been hit, illustrating just how misguided this common placement of the racket is. However, even in adjusting this placement (to the left and forward), there is no guarantee that the target is more realistic given the variability inherent in the tossing action (shown in graph **B**).

► **Breaking down** Coaches and players need to be mindful of the kinematic changes that can occur as a result of task decomposition and skill interventions more generally. Given that players typically toss the ball higher when practicing the serve independent of the swing, there are occasions when this may be beneficial if changes to the timing of the action (through a higher toss) are needed. More commonly, though, players may need to be instructed to consciously toss the ball lower or find other ways to preserve the connection between perception and action when rehearsing the toss.

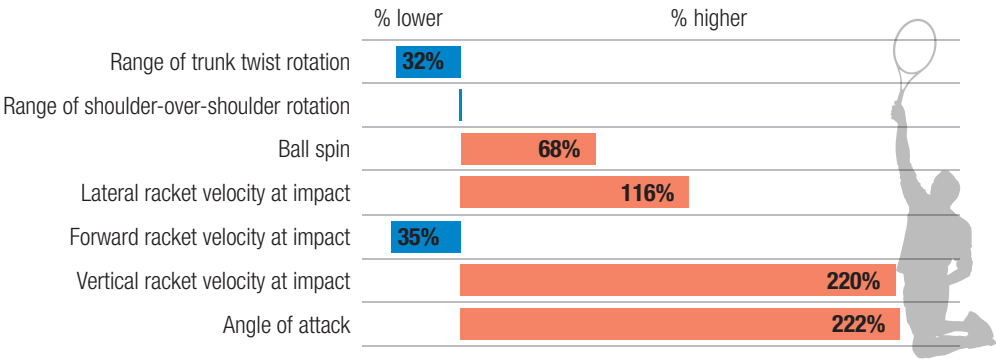
Serve stroke action decomposed



Practicing the toss



Knee serve practice



◀ **Knee serve** Consistent with coaching convention, some skills can be “decomposed” or constrained more readily than others. For example, asking players to serve from their knees (blocking knee and ankle extension) has been shown to increase vertical racket velocity and ball spin.⁴ However, whether those increases are transferred to the skill when the whole stroke action is “reassembled” remains unclear.

▲ **Kinematics** The table shows the effects of the knee serve, as a practice intervention, on the body and racket kinematics that the exercise is intended to target (as compared to the kinematics of a normal serve). The knee serve does appear to reduce trunk rotation about the twist axis, as expected. However, this does not lead to a concurrent and subsequent increase in shoulder-over-shoulder rotation. It also produces greater ball spin through a more vertical swing path at impact, which is accompanied by significantly lower forward racket velocities.

How does learning transfer affect tennis skills?

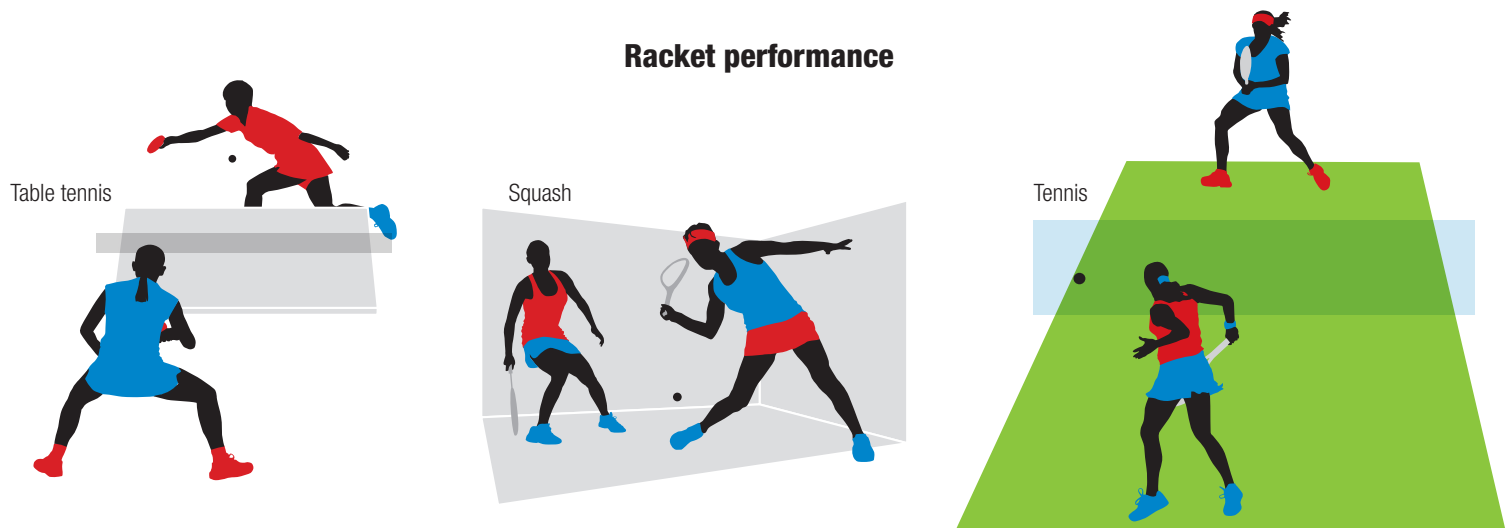
Will playing other sports improve my tennis?

In the world of sport, fundamental motor skills such as throwing, jumping, and catching—often learned in early childhood—are presumed to be the building blocks for more specific sports skills. For instance, the overhand throw and side-arm strike are purported to benefit the tennis-specific skills of the serve and groundstrokes respectively. There have always been anecdotes about tennis players benefiting from playing squash, golf, or even soccer, as these sports contain movement patterns or thought processes that may improve tennis performance through what is known as “learning transfer.” However, there is a distinct lack of empirical data to support such assertions.

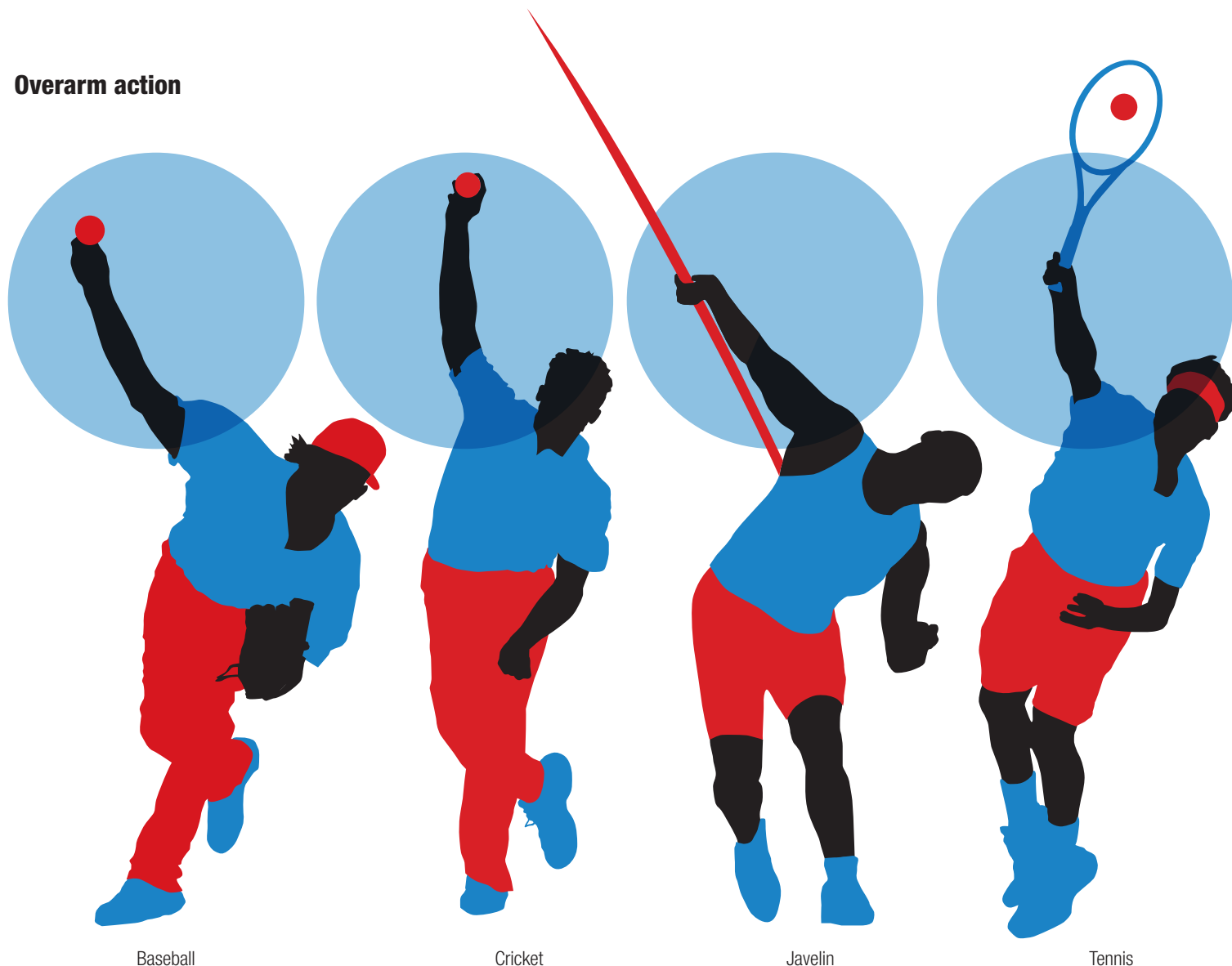
So how do a tennis player’s previous experiences influence the learning of a new tennis skill? There does indeed appear to be a positive transfer of learning between activities involving similar motor tasks, the underlying reasons for which are the physical similarity of the skills (for instance, overhand throwing and serving) and the processing requirements of the two tasks.

With this understanding in mind, coaches and commentators often note how players with good “throwing arms” have a head start when it comes to developing prowess in the serve. The inference is that there is a mechanical similarity between the two tasks that allows players with good throwing technique to develop more competent service actions. Independent biomechanical assessments of the two skills suggest that they do indeed share a number of important mechanical similarities, such as transverse plane trunk rotation and upper arm external and internal rotation during the respective wind-up and forwardswing phases. While these linkages are borne out by independent samples of expert throwers and tennis players, more recent work has compared the kinematics of the throw and serve within an expert tennis-playing population.¹ This suggests that the skills share a similar sequence of proximal–distal joint rotations and enjoy moderately positive associations between the speed of transverse plane trunk rotation and ball velocity. Interestingly, the magnitude of peak upper arm internal rotation velocity was quite different, suggesting that this correspondence may not be as definitive as supposed.

Racket performance



Overarm action



Baseball

Cricket

Javelin

Tennis

◀ **Racket games** Competitors in one racket sport occasionally participate in another as a form of recreation or with a specific performance motive in mind. In essence, however, any benefit is likely to be limited—with some potential for positive transfer in cognitive and perceptual skill, but not necessarily in movement kinematics.

▲ **Learning transfer** There is evidence to suggest that there may be some positive transfer of learning between overhand throwing and the development of the tennis serve. However, the benefits of this are likely to predominantly exist in the early stages of learning when a player is first developing the tennis serve action. As skill level develops, the specificity of the serve action is likely to reduce any further transfer. Athletes involved in overarm throwing and hitting sports all arrive in similar positions

of maximum external rotation of the upper arm, which enables these athletes to produce the forceful internal rotation movement about the shoulder that is so important to generating high ball speed (see Chapter 2, page 48).

Additionally, as highlighted above, overarm throwing and tennis hitting actions are characterized by similar alignments between the upper arm and trunk at impact and release—these alignments have been shown to produce favorable velocity and joint loading profiles.

Does court size affect learning?

What size court should a young player use?

A standard singles tennis court is 78 ft (23.77 m) long, 27 ft (8.23 m) wide, and with a net height of 3 ft (0.91 m). These dimensions are fixed in the rules of tennis, and were historically derived with the adult game in mind. Logically, it stands to reason that, as players mature, the court size and net height should take account of changes in the players' physical stature. In other words, if standard singles courts are constructed for the typical adult—an average height of 5 ft 9 in (1.76 m) if male and 5 ft 4 in (1.62 m) if female¹—then children should play on courts that are smaller in size and with lower nets.

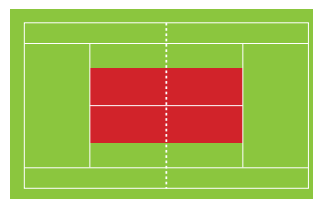
In recent times, the game has enthusiastically tried to embrace this notion, yet the recommended dimensions of the court and net remain arbitrary or loosely based on anthropometric differences. For example, the International Tennis Federation (ITF) recommends that children aged between five and eight play on courts measuring 36 × 20 ft (10.97 × 6.00 m) and with net heights of 2 ft 8 in (80 cm), before progressing to courts 60 × 27 ft (18.23 × 8.23 m), with net heights between 2 ft 8 in and 3 ft (80–91 cm) at the age of eight to 10. Interestingly, different scaling factors are applied to the size of the court as compared with the height of the net.

► **Court short** Most children of eight years old or less will find it difficult to play properly on a full-size court—rallies tend to be much shorter and play will occur well within the court area, and require more running to cover the court area. A typical crosscourt groundstroke from the baseline travels a longer distance toward the opposite corner as the court size increases. The recommended dimensions for court sizes to be used for Tennis10s (the ITF's modified program for tennis for players under the age of 10) for each age group are shown on the right.

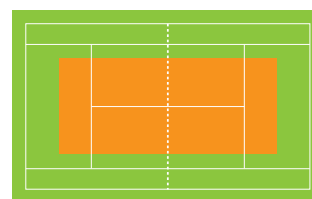
Without much evidence to support scaling recommendations, Timmerman et al.² used a scaling ratio (based on a comparison of the average time between shots hit by adults against 10-year-old boys) to assess the effect on the characteristics of matchplay of a court and net that were 76% of the size of the standard court and net. When playing with just the lower net, the children hit more shots from a comfortable height, played more volleys, and hit more winners, but committed more errors than with a standard net. When both the net and court were reduced in size, the tempo of the rallies was closer to that of the adult game. In conclusion, this study suggests that net height may be underestimated, as compared with racket length or ball compression, as a factor in helping young players to learn the game.

▼ **Court guidelines** It is worth noting that one of the limitations of the dimensions of these modified courts is that they fail to account for variation in physical stature that can be observed in two children of the same age, as well as differences in skill level. For these reasons, the guidelines are just that.

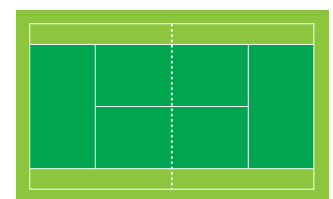
Junior courts



Ages 5–8: Red court
30 × 20 ft
(10.97 × 6.00 m)

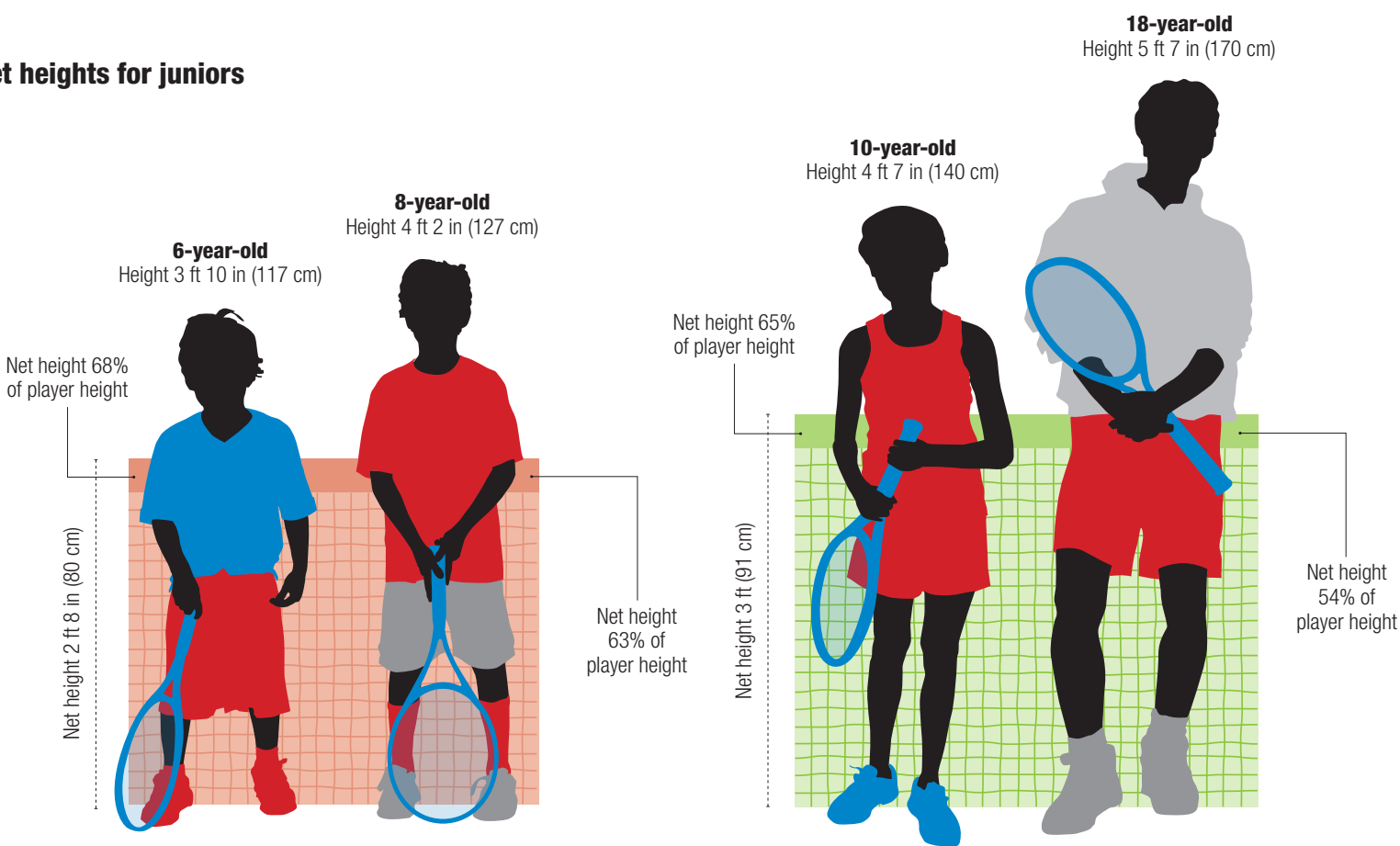


Ages 8–10: Orange court
59 × 21 ft
(17.98 × 6.4 m)



Ages 10 and over: Green/full court
78 × 27 ft
(23.77 × 8.23 m)

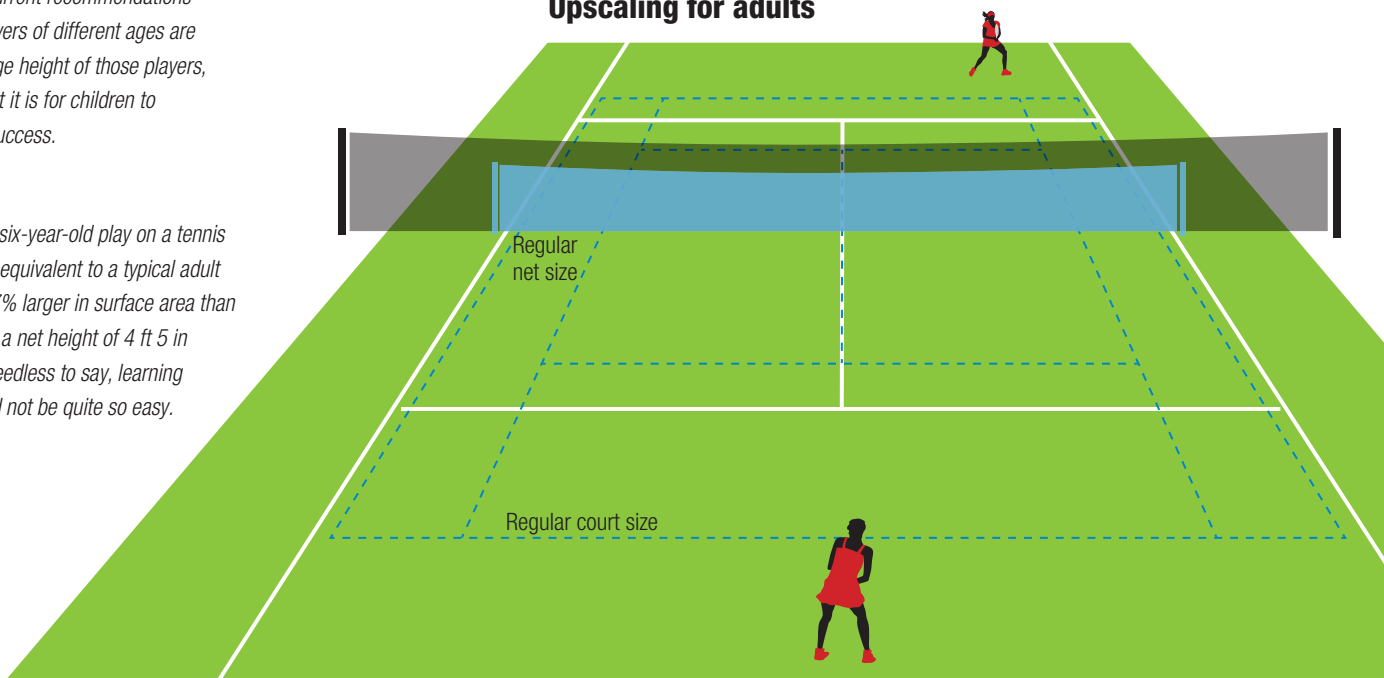
Net heights for juniors



▲ **Net gains** When the current recommendations regarding net height for players of different ages are plotted relative to the average height of those players, it highlights just how difficult it is for children to achieve immediate hitting success.

► **Child's play** Having a six-year-old play on a tennis court with a standard net is equivalent to a typical adult playing on a court that is 47% larger in surface area than the standard court and with a net height of 4 ft 5 in (134 cm) vs 3 ft (91 cm). Needless to say, learning and playing the game would not be quite so easy.

Upscaling for adults



equipment: scaling

Most tennis fans will be familiar with one of the following programs—Play and Stay, Quickstart, Hot Shots, Tennis10s, or Mini-Tennis—if not by name, then almost certainly in concept. All of these forms of tennis rely on modifying the equipment to better meet the needs of children. They also serve to enhance their learning, increasing their enjoyment of the game and their desire to play it in the future.

In many respects, the concept of scaling equipment is not new—children and parents have effectively used modified net heights and court sizes in their driveways, on streets, and in their backyards for generations. Intriguingly, though, despite recent efforts by the sport's governing bodies to provide age-appropriate guidelines for equipment selection and court and net size to accompany these youth programs, there

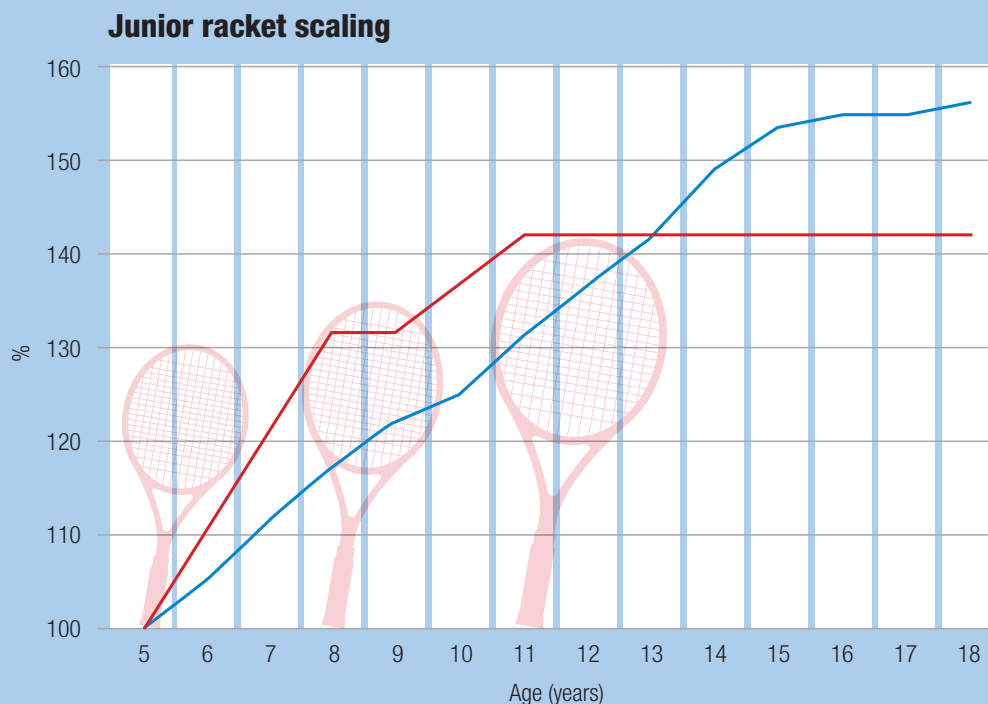
remains a lack of underpinning empirical rationale to guide what is appropriate for the individual learner. (See pages 20–21 for a more detailed examination of the effects of scaling the net and court dimensions in helping young players to learn tennis.)

What we do know from the limited research conducted is that scaled court and ball combinations do provide novice players, aged eight years and under, with significantly more hitting opportunities (and therefore practice volume) than when no scaling is used at all. For example, it has been demonstrated that children engage in longer rallies when playing with equipment and in conditions that are more age-appropriate. Overwhelmingly, these modified conditions result in a more positive learning experience for the children, who report being more engaged and enjoy playing more than when involved in non-scaled, adult conditions.

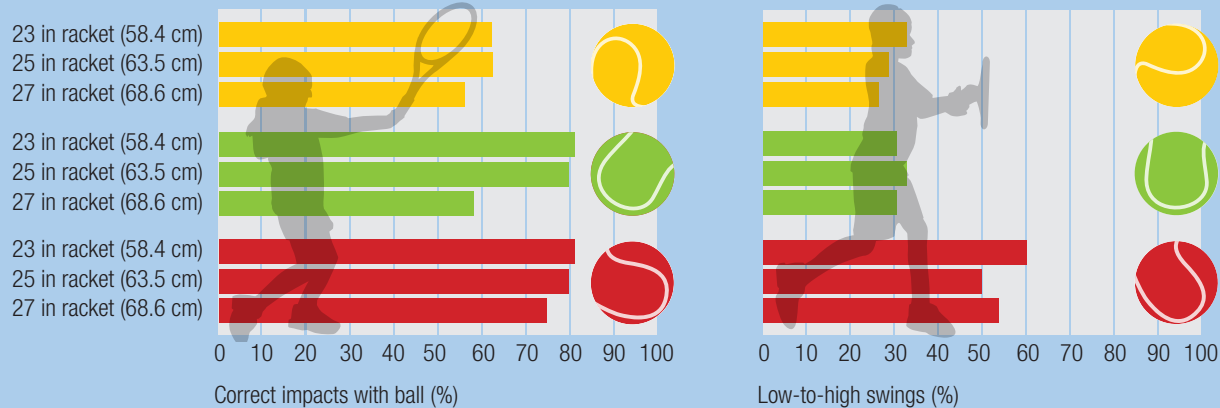
► **Player age and racket size** This graph plots the increase in racket length and player height over time—and relative to the length of the racket and height of the player at the age of five. As depicted here, existing attempts to link racket length to the increase in age (and logically growth in height and strength) of young players appear too simplistic. There is an almost linear increase in height from age five through 18, and yet young tennis players generally graduate to adult-size rackets by the age of 11.

— Recommended length of racket
(as a percentage of recommended length at 5 years)

— Height of player
(as a percentage of height at 5 years)



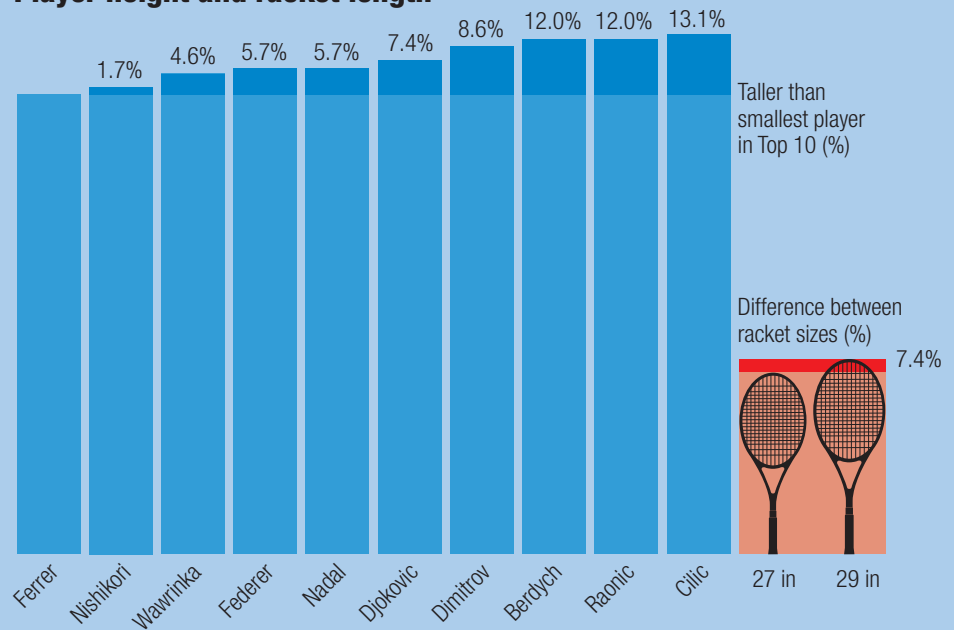
Scaling for performance



- Yellow ball: regular tennis ball
- Green ball: 75% compression of regular ball
- Red ball: 25% compression of regular ball

▲ **Hitting performance** Hitting performances for children aged six to eight years were best when a modified racket of length 23 in or 25 in (58.4 cm or 63.5 cm), relative to a normal racket of 27 in (68.6 cm), was used in combination with the lowest compression ball (25% of the compression of a normal tennis ball, and 10% larger). Using the lowest compression ball also promoted two technique benefits: swinging the racket from low to high and striking the ball in front and to the side of the body.¹

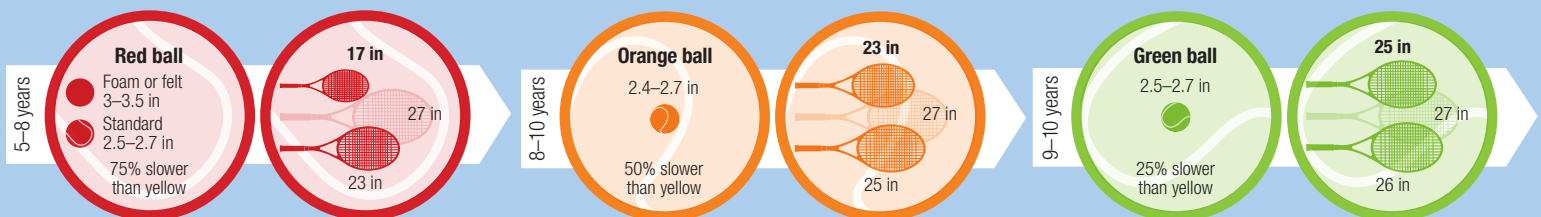
Player height and racket length



Tennis10s scaling

▼ **Tennis10s** This graphic provides an overview of equipment scaling for the three different stages of the Tennis10s program for youngsters, as they progress toward the use of the adult yellow ball. The detailed guidelines provide recommended play options for each age group, including parameters for ball, racket, net, and court.²

▲ **One size for all?** Player anthropometry—height, body composition, lever lengths, and so on, as well as strength and game style—should logically affect the characteristics of racket choice. Looking at the heights of the Top 10 male players, it stands to reason that each player would not use the same length of racket. Interestingly, while the variation in player height here is in excess of 13%, convention dictates that there is only a 7.4% variation in the length of rackets used, from 27 inches (68.6 cm) to 29 inches (73.7 cm), by players from the age of 11 or 12.



Can augmented feedback expedite learning?

How can what I see or hear improve my skills?

Tennis coaching is big business and with good reason. Learning to play tennis requires not only plenty of practice but expert advice, especially if a young player is hoping to move beyond junior or amateur level. Coaches use instructional feedback as the major tool for guiding their students. However, research has demonstrated that this feedback is not as simple as a coach simply appraising the technique of a player after each shot.

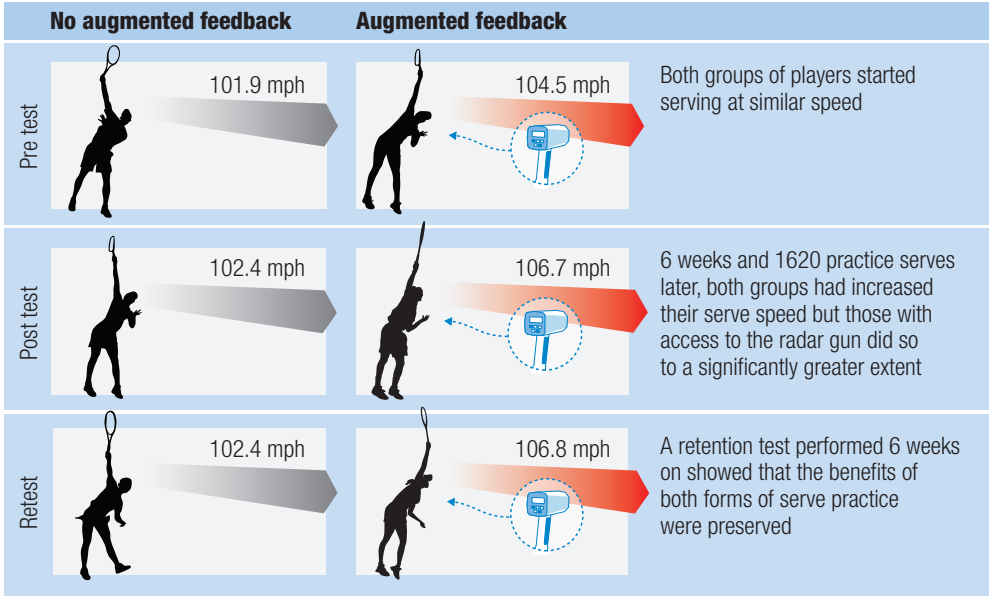
Feedback can take many forms. “Intrinsic” feedback is the information available to a player simply through the execution of a skill or stroke—their own experience of playing a shot. While much can be learned from the player’s ability to analyze this intrinsic information, it is argued that in most instances so-called “augmented” feedback can speed up the learning process. Augmented feedback is additional to the intrinsic information. For such augmented feedback to be effective, it needs to add extra information to what the player already possesses.

In the context of tennis, intrinsic feedback includes the sound or feel of the ball hitting the strings (did the racket twist or vibrate on contact?) and, most informatively, the flight of the ball (did it spin as planned and land in or out of the court?). Alternatively, verbal prompts from the coach about a specific aspect of a player’s technique (for example, leg drive or swing plane), or a radar gun providing information about the speed of the serve, are examples of augmented feedback. It is worth noting that, if a player were able to correctly predict the speed of their serve, the type of augmented feedback a radar gun provides would be redundant.

While there is general agreement that augmented feedback can supplement intrinsic feedback, there are still a number of key questions that research is yet to address. What type of feedback content is most useful? Does it matter when the feedback is provided? How capable are players of using this augmented information to change performance?

► **Predicting ball speed** In a clever study, Moran, Murphy, and Marshall¹ demonstrated that high-level national junior tennis players were unable to accurately determine if their serve was faster or slower than a previous serve. This highlights that the intrinsic feedback information provided by ball flight and speed was insufficient to guide learning, and so augmented information was required. In a follow-up experiment, the authors demonstrated that when a group of players was provided with feedback from a radar gun about their service speed, they were able to significantly improve their service speed relative to another group of players who did not receive this augmented feedback.

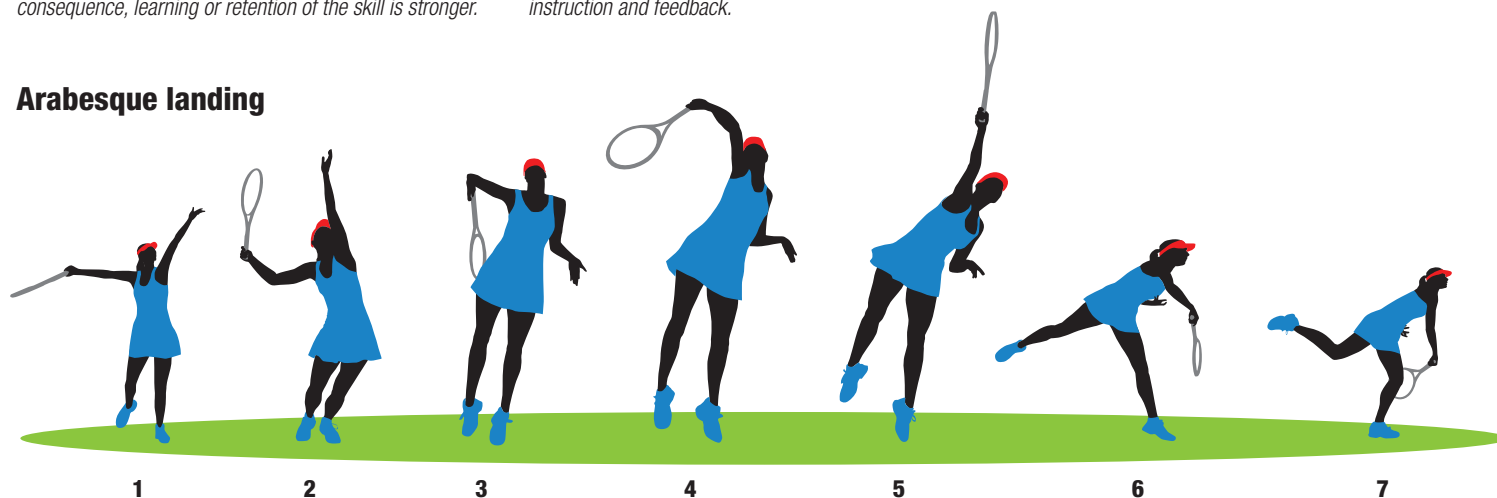
Radar gun feedback



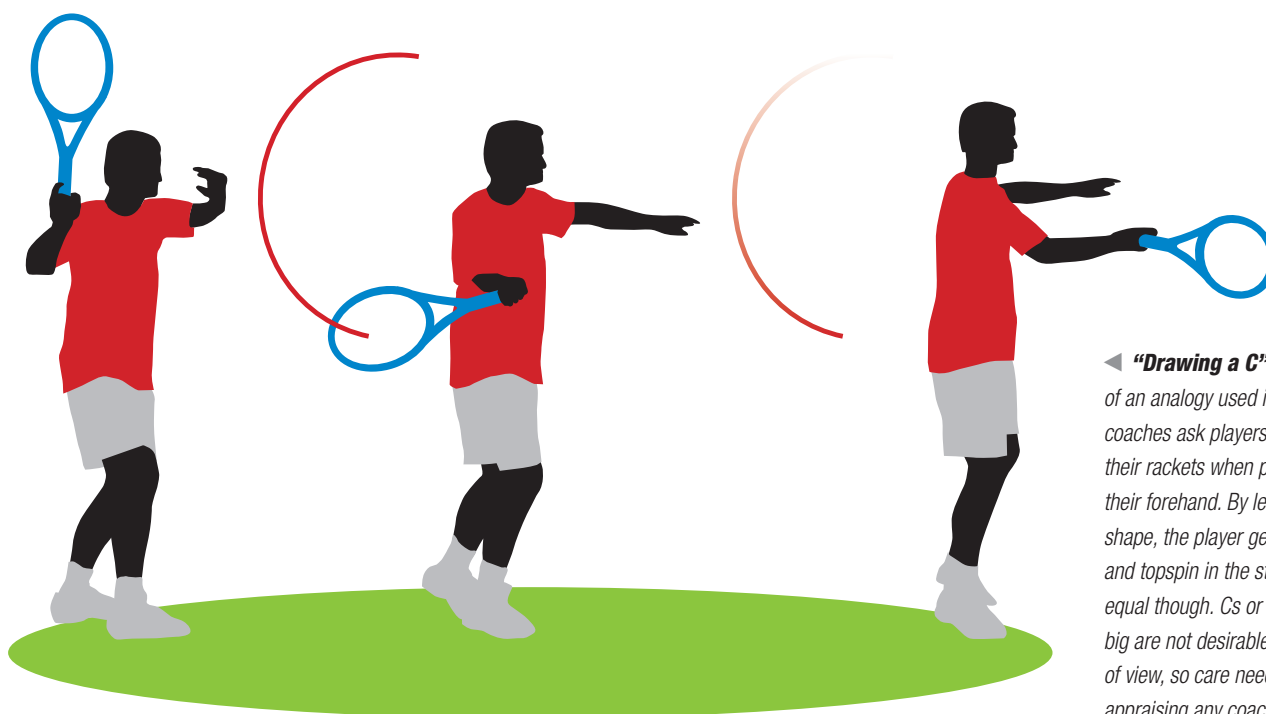
▼ **Coaching by analogy** Research has demonstrated that if a coach asks a player to imitate certain actions or commonly observed movements (such as from other sports) related to the technique they are seeking to teach the player, there are learning benefits. It has been suggested that using an analogy to describe a skill can summarize much of the technical information so that the learner can digest the instruction more easily. As a consequence, learning or retention of the skill is stronger.

Reid and Gibling² recently demonstrated that when tennis players are instructed to land in an arabesque when serving (as in the ballet dancing move, in **6–7** below), they implicitly adjust their preceding kinematics (the leg drive and angular velocity of lateral trunk rotation, in **1–5**). Liao and Masters³ found that learning in this way can produce more pressure-resistant motor performances than when players receive more traditional coaching instruction and feedback.

Arabesque landing



C-shape swing



◀ **“Drawing a C”** Another common example of an analogy used in tennis instruction is when coaches ask players to “draw the letter C” with their rackets when preparing to impact the ball with their forehand. By learning to swing with this C shape, the player generally develops more power and topspin in the stroke. Not all “Cs” are created equal though. Cs or looped backswings that are too big are not desirable from a stroke production point of view, so care needs to be taken in offering and appraising any coaching analogies.

As we have read, the speed with which individuals learn the skills of the game can be affected by a variety of factors, often relating to the individual (such as their morphology), the learning environment (such as the court surface or typical weather conditions experienced during training), or the task or skill being learned.¹

It is no coincidence that elite tennis player preparation focuses on “practicing with a purpose.” Indeed, the widely acclaimed work of Chase and Simon² and Ericsson,³ among others, has illustrated the importance of deliberate practice in the success of elite performers across many disciplines in sports and industry. In a practical sense, purposeful or deliberate practice underlines the need for a coach to structure learning or the task so that it is individualized to the athlete’s needs; is designed by a coach to improve specific aspects of an individual’s performance; involves significant repetition and successive refinement; provides feedback to guide the athlete’s successive practice repetitions; requires mental effort by the athlete; and is at a level of challenge appropriate to the current skills of the athlete.

Practice needs to be deliberate and the drills (or tasks) need to reflect this. It then follows that being clear in what you hope to achieve, and structuring practice accordingly, is essential for developing an individual’s game. Pete Sampras, in his formative years, was instructed by his coach to perform a drill that involved tossing the ball up to serve, but was only told where to direct his serve by his coach at the top of the toss. This helped Sampras learn to hit different serves without adjusting the toss, and ensured that the direction of his serve was harder for an opponent to read, giving Sampras an advantage. The left-handed Australian, Wayne Arthurs, recalled introducing as much challenge, or variability, into his serving practice as possible. This helped Arthurs to develop one of the most robust and skillful serves in the game. In both cases, the objectives were clear and the characteristics of the task being practiced helped to produce effective learning outcomes. The message to those learning the sport is simple: practice purposefully to achieve specific outcomes.

► **Practicing advantage** *Pete Sampras’ coach successfully focused practice drills on the objective of disguising the direction of the serve—which meant that Sampras’ opponents found it much harder to return his serve.*



What information do players use to predict serve location?

How can I return serve like a skilled player?

Many elite players, particularly in the men's game, are able to direct serves in excess of 124 mph (200 km/h) to all parts of the service box. This obviously presents a considerable challenge to their opponents, standing some 78 ft (24 m) away, who have approximately one third of a second to assess the ball's flight and then execute a well-timed return.

This battle between the server and returner has attracted the interest of researchers for more than 20 years. Various researchers have focused on what information (or cues) returners can use prior to the third of a second of ball flight to help determine the serve's likely direction—logically allowing for an improved motor response. Skilled players have been shown to use two forms of advance information: firstly, situational probability information, such as strategic insights based on known preferences of the server; secondly, the mechanics of the service action.

In other words, skilled players are sensitive to tactical patterns that occur throughout the game. Awareness of these specific event probabilities buys the returners additional time to prepare a response. Indeed, in an attempt to analyze this phenomenon,

Farrow and Reid¹ presented skilled and less-skilled tennis players with video sequences of a simulated match where the direction and type of serve in the first point of each game were controlled (to the “T” on the deuce court), while the serve direction of all other points was randomly assigned. Skilled players picked up this cue by the end of the first set, while less-skilled players were unable to detect it at all.

The biomechanical elements of the server's action are also thought to provide the type of anticipatory information that has been shown to help skilled players accurately predict service direction some 300 milliseconds before the ball is struck. The location or height of the ball toss and the angle of the racket during its forwardswing to impact seem to provide the most information.

▼ **Reading the serve** *With so little time available to respond to the serve, players need to extract every bit of information that they can to most effectively return serve. While in some instances, players are known to call upon situational probability information to predict serve location, often players will also do something as simple as adjusting their position on return to buy themselves more time to perceive and respond. Here, we see the average return of serve position of 16 of the game's best male and female players during a recent Australian Open tournament.*

Return of serve location



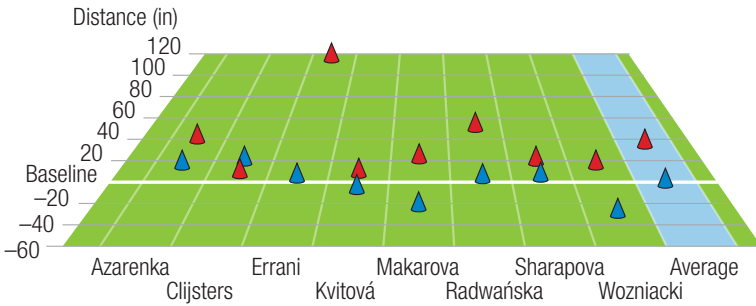
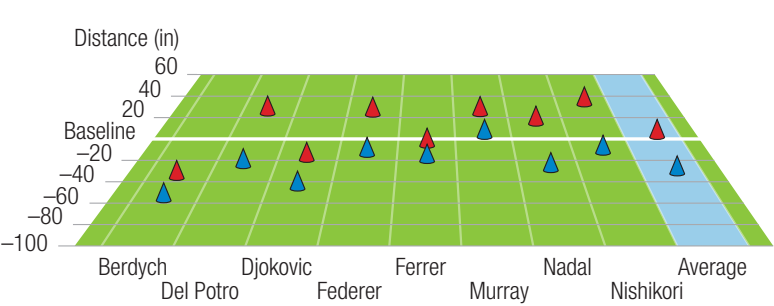
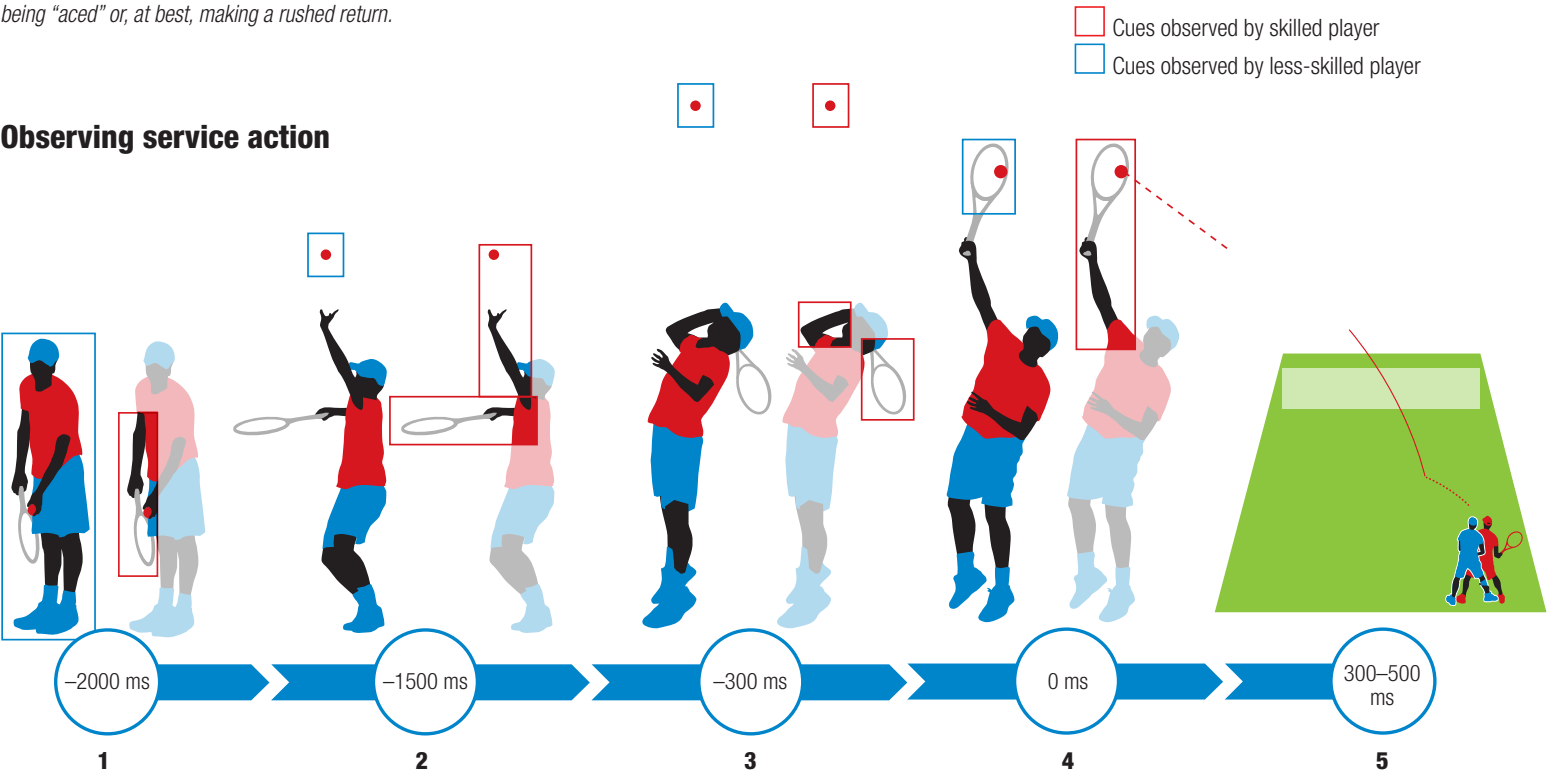
Average contact point of these players on return of opponents' serves

▲ Average first serve return position ▲ Average second serve return position

▼ **Anticipation** Highly skilled players can generally interpret where the ball is going to be hit based on the mechanics of their opponent's service action. These players often pick up cues well before the racket meets the ball, providing them with more time to plan their serve return. In contrast, less-skilled players are reliant on ball flight information and consequently are left with little time to prepare an appropriate response, resulting in these being "aced" or, at best, making a rushed return.

Highly skilled players access information to help predict serve location from the movement of the server's racket and arm (red boxes in the sequence below) with the 300 milliseconds before impact up until impact particularly informative (3–4). On the other hand, less-skilled players almost exclusively track the ball toss (blue boxes) and have no systematic search pattern, so assume less favorable positions to return the ball (blue player in step 5).

Observing service action



Average contact point when opponents return these players' serves

How does an experienced coach analyze technique?

How can I see what a tennis coach sees?

It is human nature to want to see the world through other people's eyes. The emergence of technologies such as compact sports video cameras have made this easier to achieve than ever before. In the world of science, we have been able to record and understand what people are looking at for some time. Commonly referred to as eye-movement recording, the procedure involves using pairs of customized spectacles, which project a low intensity infra-red light onto the eye via a reflective lens linked to a series of small cameras, to very precisely record the visual gaze behavior of the viewer.

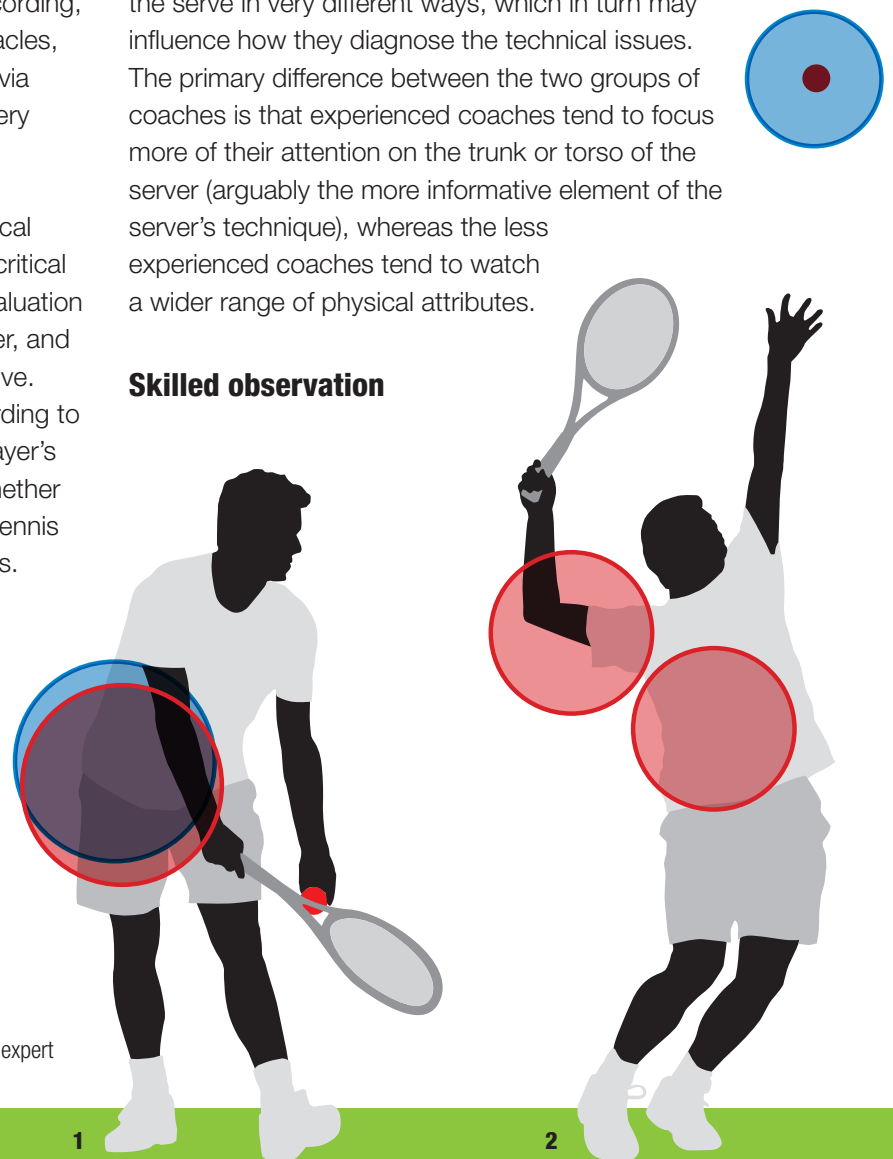
A tennis coach's ability to accurately perceive the technical strengths and weaknesses of their students is clearly a critical skill in helping a player to improve. A coach's correct evaluation and diagnosis can increase the learning rate of the player, and ensure that their stroke production is efficient and effective. Recent research has begun to use eye-movement recording to analyze what a tennis coach sees when appraising a player's technique. In particular, the research has focused on whether highly experienced tennis coaches look at and analyze tennis serves in a different manner to less experienced coaches.

Results demonstrated that, not surprisingly, experienced coaches were better at evaluating the serve by identifying significantly more technical weaknesses than the less experienced coaches. Analysis of some aspects of visual search behavior—the number and duration of fixations, and the number of areas of the service action that were visually sampled, for example—showed no clear differences

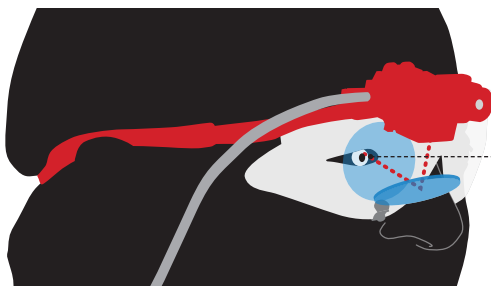
between the experienced or less experienced coaches. However, when the search priorities (areas of the service action viewed) of the coaches were examined during the evolution of the service action, some interesting differences emerged: experienced and less experienced coaches viewed the serve in very different ways, which in turn may influence how they diagnose the technical issues. The primary difference between the two groups of coaches is that experienced coaches tend to focus more of their attention on the trunk or torso of the server (arguably the more informative element of the server's technique), whereas the less experienced coaches tend to watch a wider range of physical attributes.

Skilled observation

- Expert coach
- Novice coach
- Both novice and expert



Eye-tracking technology



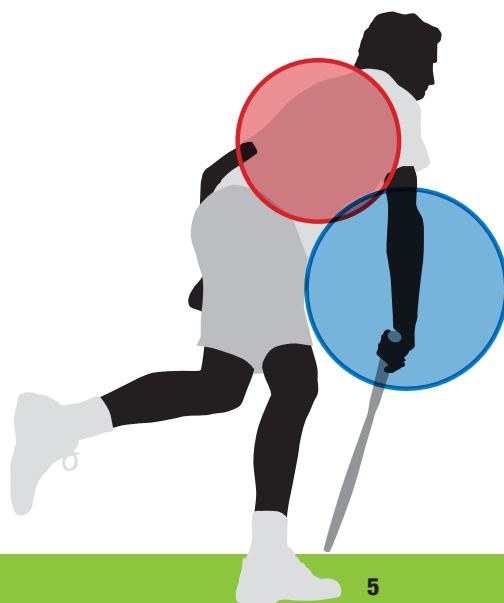
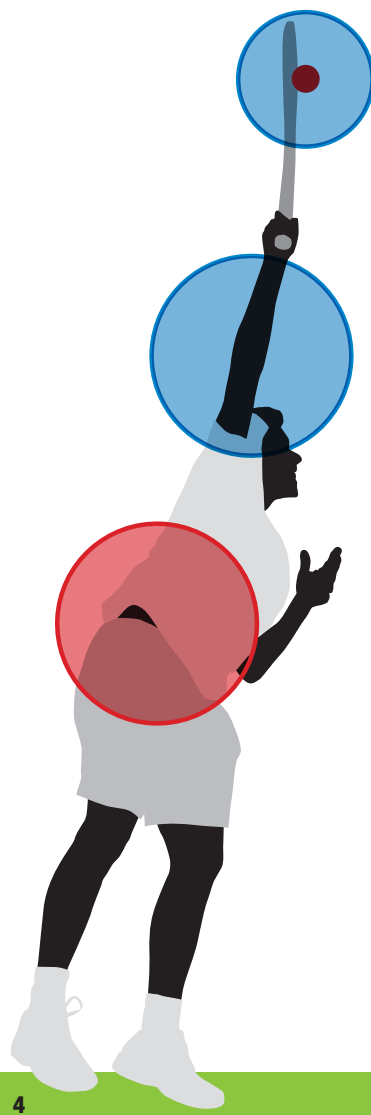
Sensors detect movement of the coach's irises



Sensor data is collated for analysis

▲ **Mobile eye recorder** Eye-tracking technology allows the scientist to record information such as where the coach looks at the various phases of the serve, the duration of time spent looking at the various features, and the order in which the technique was searched (search order). A fixation, which is the maintenance of steady gaze on a location for a minimum of 80–150 milliseconds, is considered a definitive “look” at an object. This enables the viewer to stabilize an informative area of a scene or object on the eye so that complex processing can occur.

▼ **Coaching attention** The most pronounced difference in visual search behavior between experienced and less-experienced tennis coaches is the greater amount of time that the experienced coaches spend watching the torso during each phase of the service action. A distinct difference in search priority is also evident in the follow-through phase (4–5), when less-experienced coaches prioritize the hitting arm and ball, while experienced coaches continue to watch the proximal location of the torso—the torso forms the foundation of the movement sequence underlying the overarm hitting action of the serve.¹ The vantage point of a coach influences the efficacy of any on-court analysis, particularly from a technical perspective. For example, when it comes to the serve, coaches are recommended to appraise a player's leg drive from behind the player but a player's shoulder-over-shoulder rotation from side-on. Knowing where to position oneself to see what one needs to see is likely to be another quality that differentiates highly skilled from lesser-skilled coaches.²





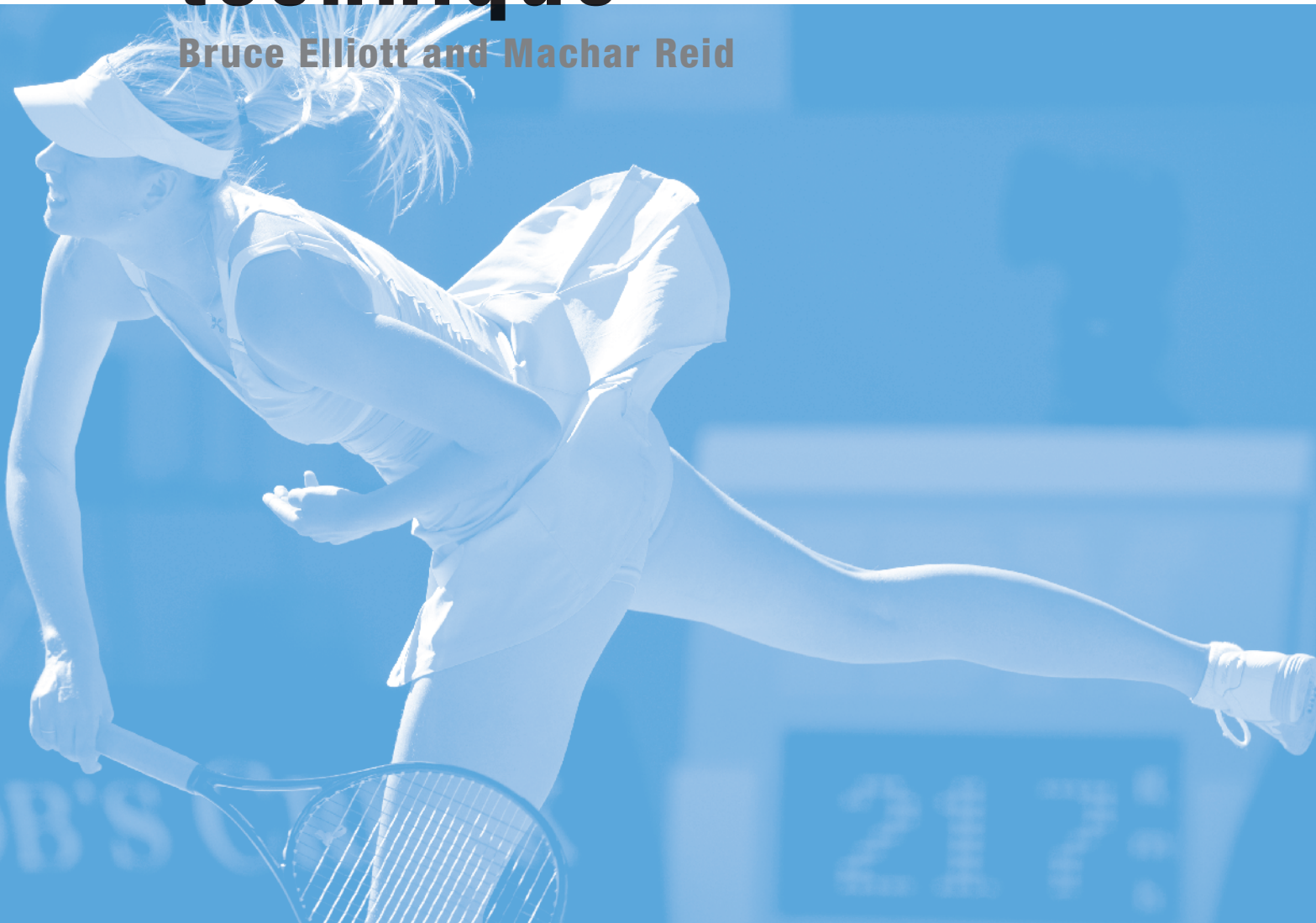
We marvel at how professional tennis players are able to meet the physical and mental demands of play and still hit the ball so powerfully. All players begin the road to technical mastery through a combination of talent, good coaching, and hard work. Many books relate science to each of the game's strokes.^{1,2} This chapter takes a global approach and sets out to explain the science behind all aspects of stroke production, and the role it plays in enabling players to hit the ball with controlled power.

Remember that approximately 75% of the speed of the outgoing ball is determined by racket speed and 25% comes from the incoming speed of the ball.³ On slower surfaces, such as clay, a player must be able to generate even more racket speed to hit the ball with the same pace. The ability of a player to generate racket speed lies at the heart of a power game.

chapter two

technique

Bruce Elliott and Machar Reid



What is elastic energy?

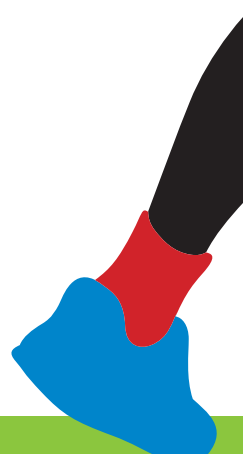
How can a spring improve my game?

When a spring is compressed it stores energy. The same theory of the storage and use of elastic energy can be applied to a tennis player's movements. During stretching, when the rate of stretch is controlled, the muscles and tendons store energy (typically during a backswing). On reversing the movement during the shortening phase (the forwardswing), the stretched muscles and tendons recoil and a portion of the stored energy is recovered.^{1,2} Science indicates that 10 to 20% of additional speed is achieved following a muscle pre-stretch.

In addition, energy is lost if there is a pause between the stretching and shortening phases. For example, during a service backswing, energy is stored in the internal rotator muscle group at the shoulder as the upper arm externally rotates. The majority of this energy helps with the speed of the upper arm's subsequent internal rotation if the pause between backswing and forwardswing is minimal. If a player pauses for 1 second, then 50% of the energy is lost, and after 4 seconds all of the benefit is removed. The recovery of stored energy occurs quickly and is therefore a major advantage in the early part of the forwardswing phase of a stroke. It is of even greater benefit to young children, who often find the inertia (swing weight) of the racket difficult to overcome.

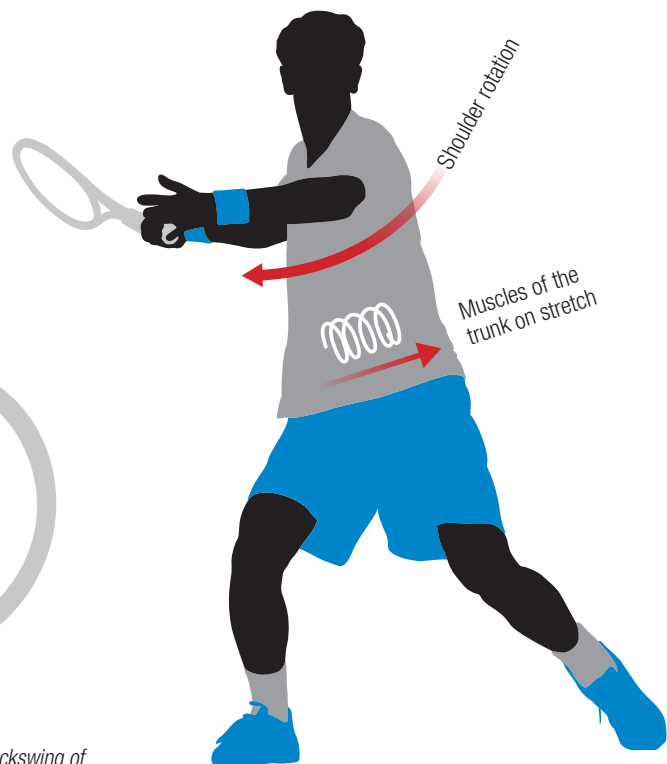
Almost all aspects of the tennis stroke may be enhanced through the use of this source of "free" energy. However, a player needs to feel the tension in the stretched muscle to be sure that energy is being stored. In the serve, there are many examples of how elastic energy may be used to enhance performance, but none is as important as the energy stored in the internal rotator muscle group previously mentioned. Science has shown that upper arm internal rotation plays the most important role in generating racket head speed, accounting for approximately 40% of the racket's speed at impact in high-performance male players (see pages 138–139). By extension, it would seem that such high-speed movements are only possible with the aid of elastic energy.³

► **The "split step"** The small jump, known as the "split step," is an integral part of the preparation for many strokes, and is used prior to movement in general play from the baseline, during a service return, or in preparation for a volley. All of these movements rely on energy stored in the quadriceps muscle group (on the front of the thigh), to assist movement to the ball. In the "split step" shown here, the quadriceps muscles are stretched to control knee flexion, with gravity and possibly minor hamstring activity acting together to create this movement. Without this activity by the quadriceps the player would drop to the ground. The quadriceps then contract (shorten) to create the extension of the knee (as the lower limb straightens) and the stored elastic energy assists this muscle action in moving the player to the ball.

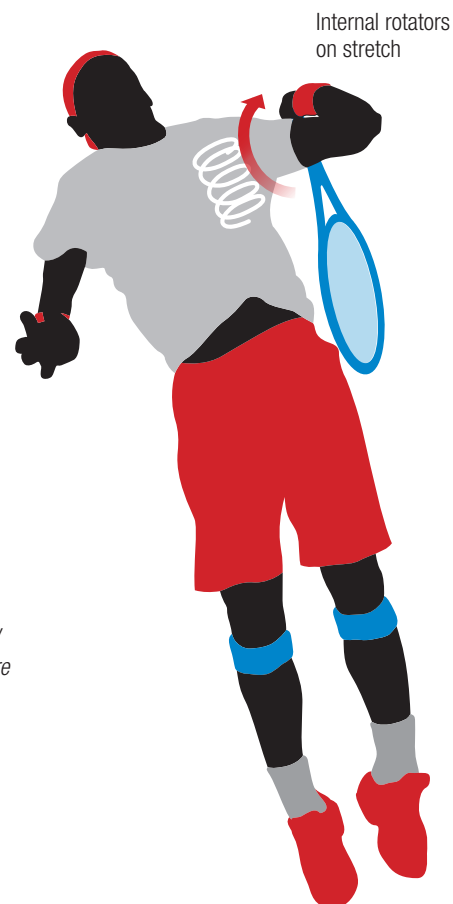




Energy release



► **Trunk muscles** In the backswing of groundstrokes and the serve, the greater rotation of the shoulders relative to the hips creates what is described as a separation angle, typically of 20° to 30° . The separation angle places the muscles of the player's trunk on stretch, which causes energy to be stored. This stored energy then assists the trunk to rotate during the forwardswing.



► **Internal rotators** The shoulder rotation that permits the racket to be moved "down and away" from the body in the backswing is partly stopped by the internal rotator muscles. The internal rotators are thus put on stretch—storing energy. During the forwardswing to the ball, this energy is used in the generation of racket speed. This process is shown here in the service action.

How do the eyes track the ball? → Do I really see ball impact?

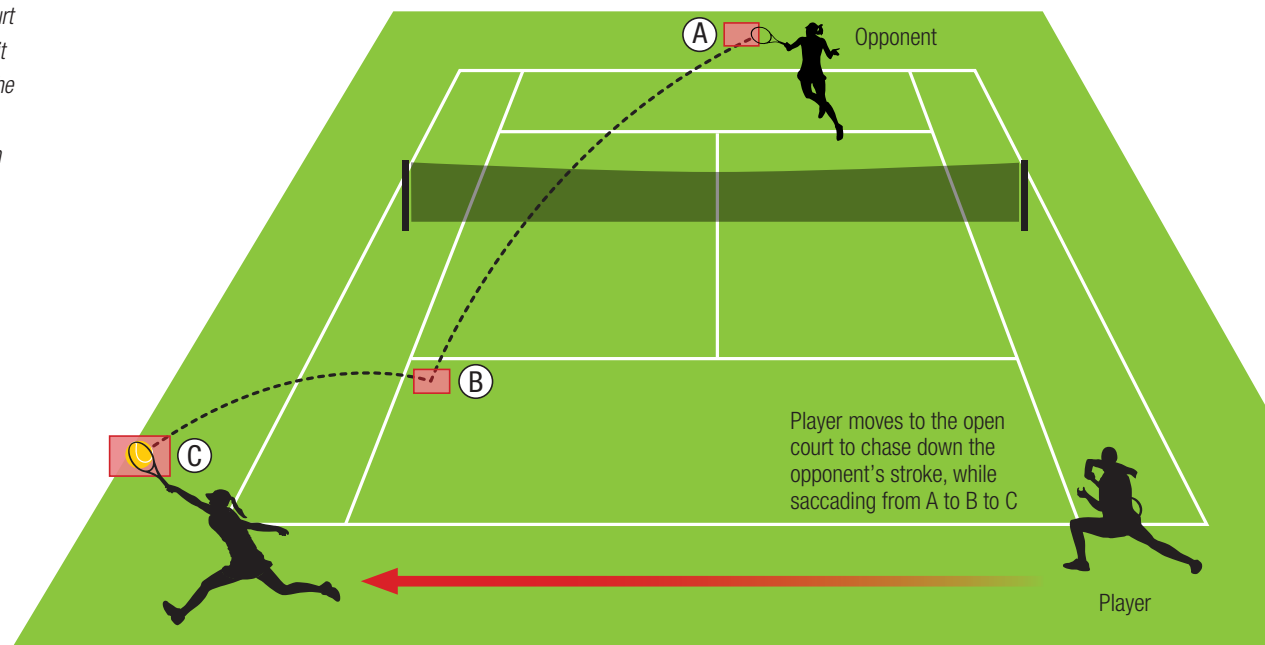
Does a player actually see the ball impact the strings? The ball moves too quickly for a player's eyes to track it to the point of impact, which is very brief (approximately 5 milliseconds). However, were the ball to be moving considerably slower it would be a different story, as individuals can track slow-moving objects such as a ball rolling slowly across the floor using what is known as "smooth-pursuit tracking." A top professional's eyes rely on what is technically termed "saccadic movements," where they shift at rates of between 700° and 1000° per second, repositioning their gaze from one viewing point to the next.^{1,2,3} During these movements, the information between each viewing point is interpolated by the brain. For example, the professional's eyes would shift from the ball's trajectory following the opponent's impact to the estimated position of the bounce, and then again to the estimated impact location, where the eyes are focused on the impact area.

The eyes control the positioning of the head and neck, which together represent approximately 7% of the body's weight, and therefore play an important role in providing a "stable" impact during a tennis stroke. Interestingly, high-ranked players on the men's Tour were more likely to be characterized by what is known as "total fixation," where the head is held in position with the eyes looking at the point of impact during the early follow-through, whereas high-ranked female players were characterized as "partial fixators," holding the head still at impact but looking up quickly afterward.

Very few professional players were characterized as using "no fixation," or looking forward and away at impact. Instead, holding the head "still" by watching the impact area during and after the hitting phase seems to help stabilize the shot.

► **Watching the ball** In recovering court position and then chasing down the ball hit wide to the advantage court, the gaze of the player will shift from the opponent's ball impact (A) to the ball bounce (B), and then to the impact zone (C).

Tracking the ball

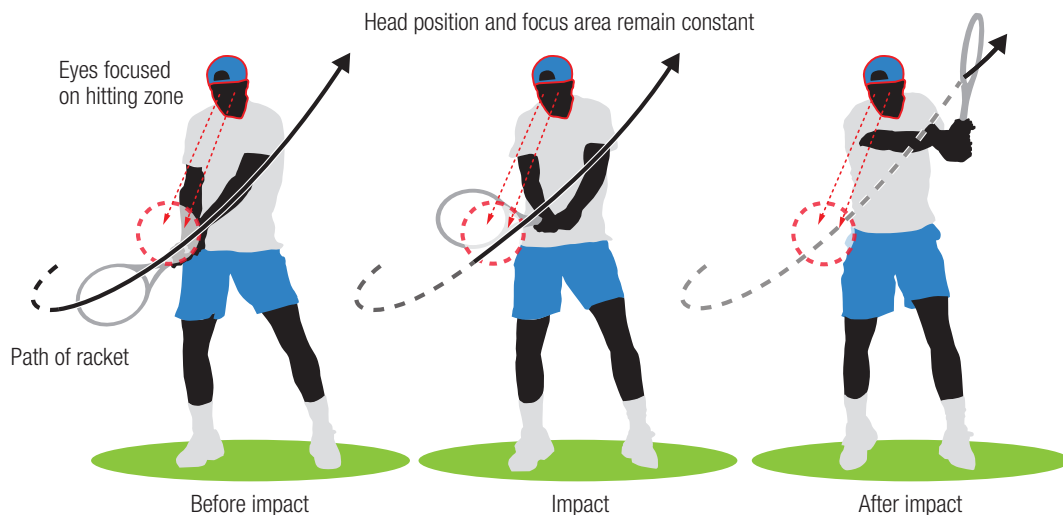


Eyes on the ball

► **Gaze behavior** Three categories of gaze behavior have been outlined, where head position almost serves as a proxy for gaze: *total fixation*, *partial fixation*, and *no fixation*.⁴

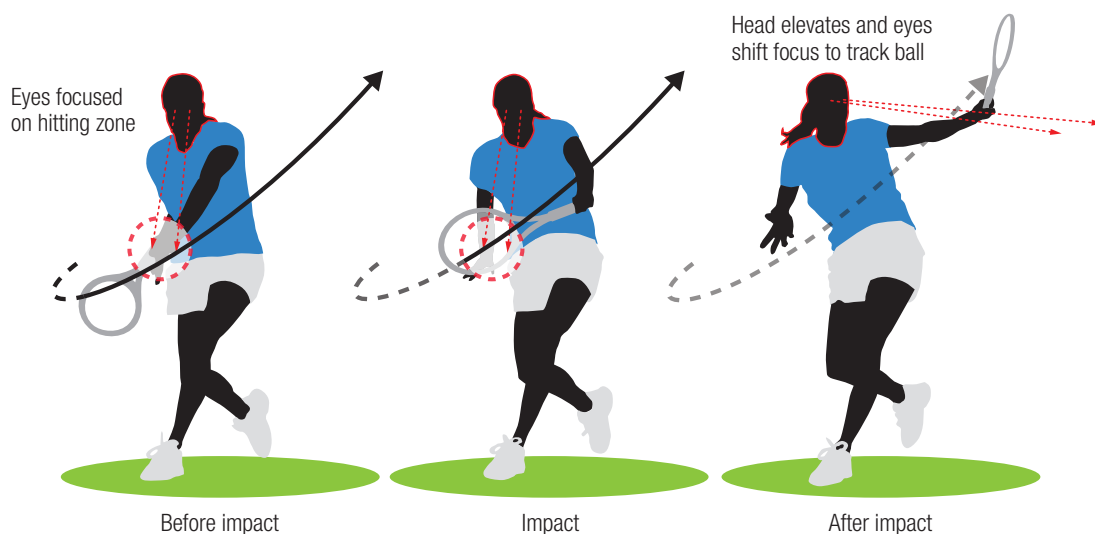
Total fixation

Here the head position is held constant through impact and well into the follow-through. Notice how the player's head is held stable with the eyes focused on the "hitting zone"



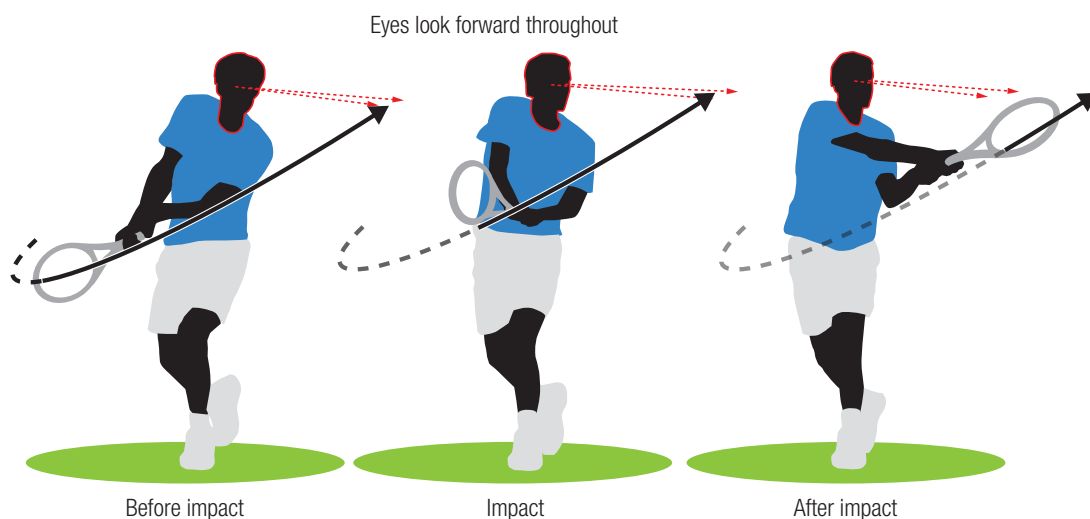
Partial fixation

The head is positioned correctly at the point of impact but is then elevated quickly afterward, as if to track the ball, even though the ball will move too quickly for this to happen



No fixation

The eyes are looking forward throughout the impact, and not at the zone in which the racket hits the ball. It is notable that very few professional tennis players seem to use this technique



Does spin affect ball movement?

How do I create topspin and backspin?

Spin plays two roles in tennis: influencing the flight of the ball in the air, and influencing the bounce of the ball from the court. A ball hit with spin has a boundary air layer that “clings” to the ball as it rotates. For topspin, the air particles on the top of the ball “crash” into the oncoming air and their velocity is reduced, whereas the opposite is true for the bottom of the ball. A downward force is therefore created (as interpreted by Bernoulli’s theorem), explaining the sudden change in the flight pattern. Players hitting with heavy topspin may hit the ball high over the net, yet it still drops into the court, whereas those balls hit with backspin must be kept closer to the net, otherwise they may fly long (see pages 170–171).

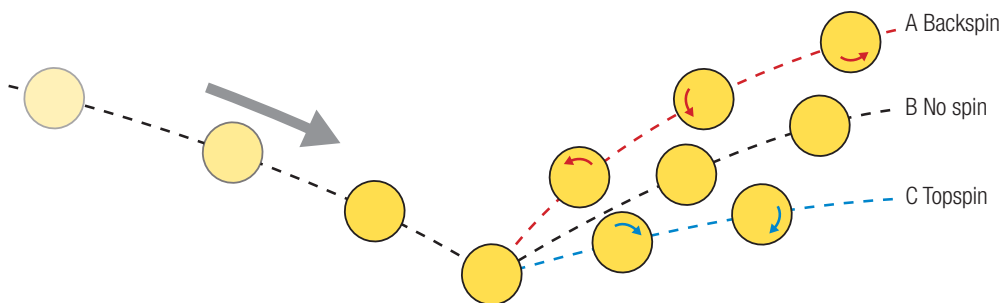
If a ball is projected at the court with the same angle, then science tells us that a ball with topspin will rebound lower and one with backspin will rebound higher. However, during play, balls hit with topspin “rear up” (with a higher angle of reflection with the court) and those with backspin stay low (with a lower angle of reflection with the court) as a result of the angle of approach of the ball (angle of incidence) in each type of stroke.

The swing path of the racket to create topspin in groundstrokes is from low to high, and for backspin it is from high to low, with the racket face near vertical to the court at impact in both cases. The racket face may be angled forward by up to 5° in the creation of topspin and back by up to 10° for backspin.^{1,2} The following forehand strokes use quite different vertical racket trajectories at impact to achieve their tactical goals: flat shot with some topspin at 20°; topspin at 40°; and topspin lob at 70°.³

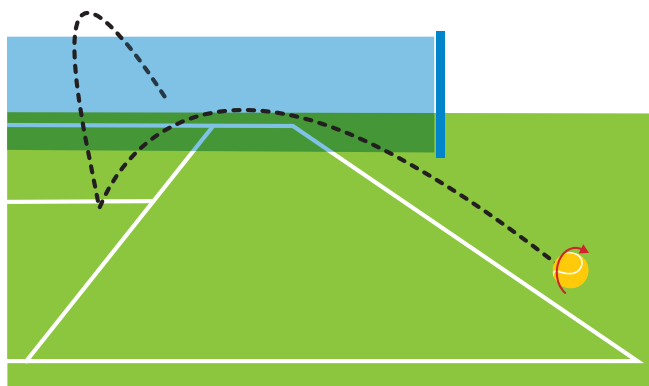
Playing a top professional is difficult because of the amount of topspin they apply to the ball. A “heavy” ball—hit with a combination of spin and velocity—carries almost as much energy in its spin as in its forward motion.⁴ Therefore, a player needs to swing approximately twice as hard to return a topspin stroke with topspin, as compared with slice. This may not be difficult when the ball is at hip height, but it is a different matter when the ball is at shoulder height.

► **On the bounce** Ball bounce trajectories as replicated in the lab for a ball hit with various types of spin. Note the angle of approach is the same for all spins: backspin (A), no spin (B), and topspin (C). These trajectories look different during matchplay though. On court, shots hit with topspin have a more arced trajectory meaning that they approach the court at a steeper angle, which then results in a higher bounce. The opposite applies to a shot hit with backspin.

Ball bounce trajectories



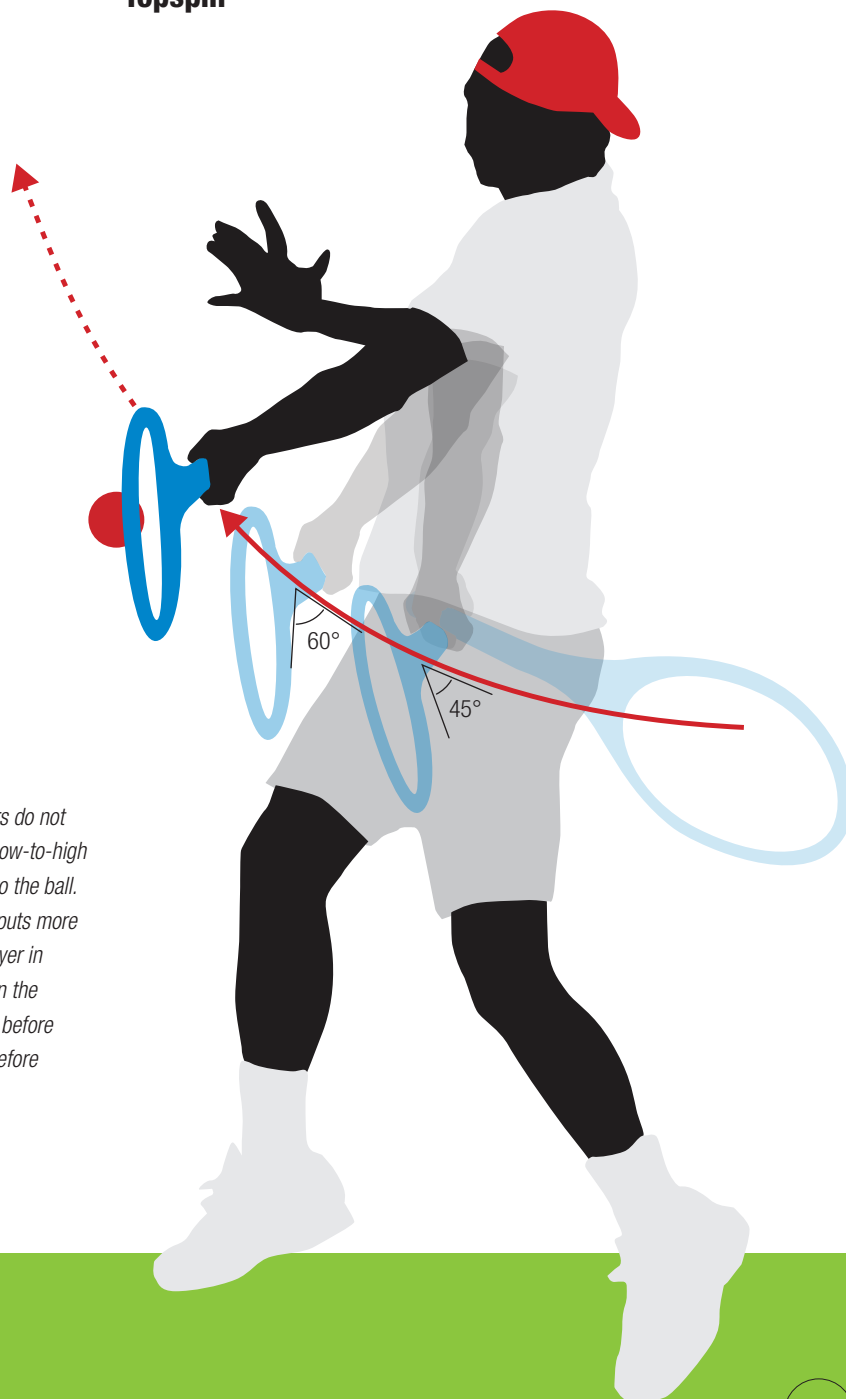
Sidespin



▲ **Slice and dice** Albeit less common than topspin or backspin, professional players often apply sidespin to their shots. In this instance, a player hits her backhand slice with sidespin—meaning that it not only stays low (effect of backspin) but also fades away from what is likely to be a scrambling opponent.

Topspin

► **Creating topspin** Top players do not follow a single racket path in this low-to-high racket trajectory to apply topspin to the ball. For instance, Rafael Nadal—who puts more spin on the ball than any other player in history (approximately 4000 rpm in the forehand)—initially swings at 45° before increasing this angle to 60° just before impact, as illustrated here.

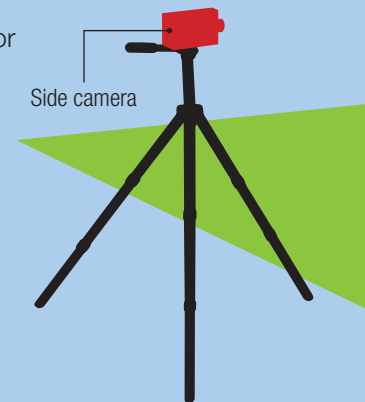


equipment: video analysis

As the dominant learning processes are both visual and kinesthetic (feeling and doing), on-court video is a great way to use both of these to help a player to develop controlled power in their game. Technical appraisal and adjustment based on a comparison of what is observed with a model of performance have been part of coaching for decades. Let's take the level of knee flexion in the serve as an example. Professional players flex the knees by about 70° to 80° during the preparatory phase of the serve. This angle can easily be measured using a video camera and readily available computer software. Coaches can then compare this level of knee flexion with that exhibited by their players, allowing for minor levels of individual variation. Remember, this level may not be necessary for young players, who are often concentrating on developing other aspects of the service action. While this level of flexion may occur before puberty, vigorous extension at the knees will only occur after puberty.

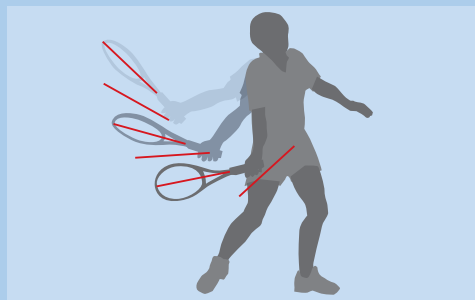
Video also offers the coach and player a different viewing perspective, with the advantage of frame-by-frame playback. Today, free apps and professional software packages, when linked with a camera, tablet, or cellphone, permit video to be viewed at speeds far higher than previously possible.

Using online sharing tools, such as *Dartfish.tv*¹ or the Tennis Australia Technique app, not only allows a player to review and reinforce concepts, but also enables easy access to all past analyses to track progress. You can also create a reference library of pro-level strokes, broken down into key positions for further comparative purposes.

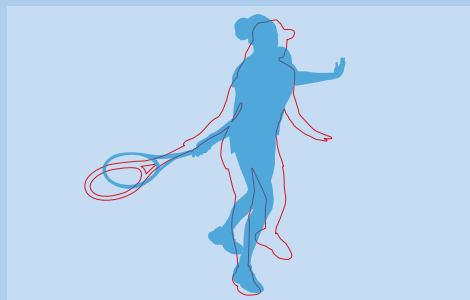


Video comparison

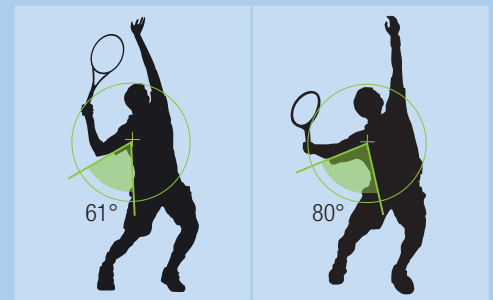
▼ **Racket paths** Forwardswing phase of a forehand showing racket path using a stroboscope software function. The racket paths can be compared with those of a player with sound stroke technique.



▼ **Video overlays** Digital video can be used to compare the backswing position of two players hitting a forehand drive by overlaying one video on the other.



▼ **Precise measurement** Here, the captured image of the player enables the shoulder angle during the serve to be measured.



Lights, cameras, action!

▼ **Video analysis** Careful planning and set-up of equipment are needed to be able to collect and analyze useful video images. Coaches can then view a player's stroke production and monitor their improvement by comparing their strokes over time.

Camera positions

Cameras must always be set perpendicular to the movement that you want to record

Framing

The subject should fill the picture, ensuring that all aspects of the stroke are recorded

Lighting

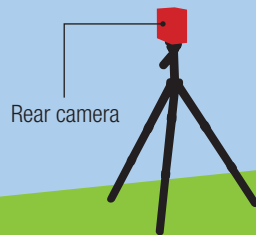
Make sure that the sun is behind your back to ensure good quality video

Filming angle

Position yourself at 90° to the plane of the movement you wish to record—while the side angle is frequently used by coaches, filming from behind also provides useful information

Sample number

Several strokes should be filmed to record a representative sample of a player's stroke



Computer display
for viewing video

How does body maturation affect tennis skill development?

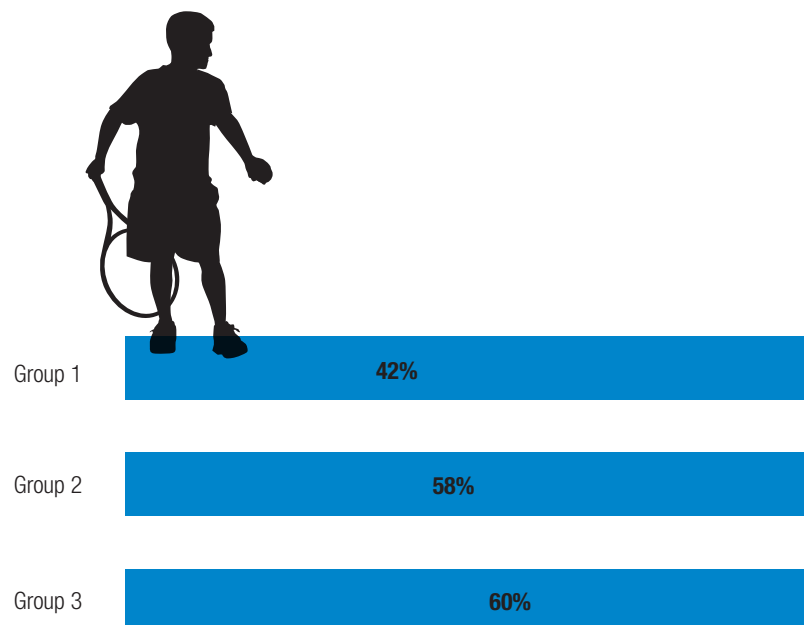
Will my tennis strokes change as I grow up?

The development of physical capacities and the performance of sporting skills have been related, at least in part, to puberty.^{1,2,3} Researchers and practitioners have tended to compartmentalize athlete development into three main stages: the pre-pubescent stage (about 12 years and under); the pubescent stage (from about 13 to 17 years); and the adult stage (18 or older).⁴ Regarding tennis stroke production, research has focused on the adult game and, in particular, the adult male game. This has led to a generalized approach to instruction, where adult performance models are applied to young players, and the mechanical characteristics of stroke production in men's tennis are thought to represent those that are also desirable in the women's game.

Of course, these assumptions appear to be sweeping and give rise to the following question: to what extent does an individual's physical development constrain stroke production? Evidence points to the need for coaches to better appreciate this dynamic. For example, research into the effect of age on lower limb strength^{5,6} supports the idea that the leg drive in young players is less pronounced than in adults. Jumping ability also differs between the sexes, particularly through the pubescent stage,^{7,8} which leads to probable differences in stroke coordination between female and male players. Differences in trunk strength between the sexes also emerge after the age of 9 to 10,^{9,10,11,12} meaning boys and girls may not rotate their trunks with the same efficacy after that age. Peak internal rotation of the upper arm is also more pronounced in the male adult serve (2520° per second for men against 1370° per second for women, in one study¹³), which appears to fit with the disparity between the shoulder joint internal rotation torques produced by elite adolescent and adult male tennis players as compared with female players of the same age.^{14,15}

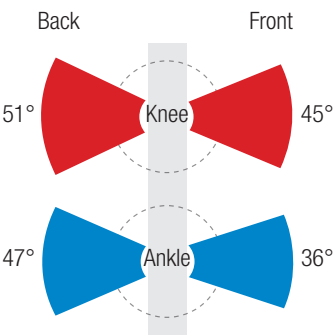
With this in mind, any expectation that junior players replicate adult stroke production or that the strokes of female and male players are interchangeable seems misplaced. Coaches require a more detailed appreciation of the differences between individuals than the simplified stages of development previously mentioned, and need to resist the convenience of defaulting to a “one-size-fits-all” approach to their instruction.

Phases of the serve by age

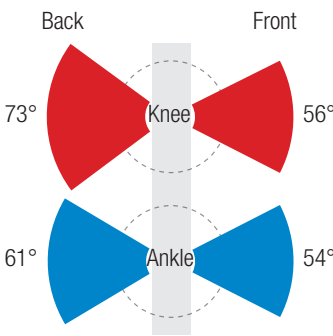


Range of knee and ankle motion by age

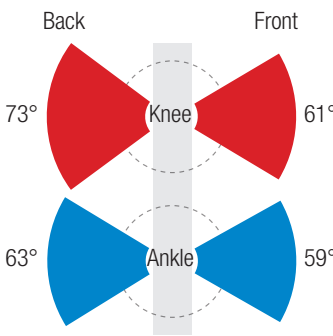
Group 1 (Elite pre-pubescent)



Group 2 (Elite pubescent)

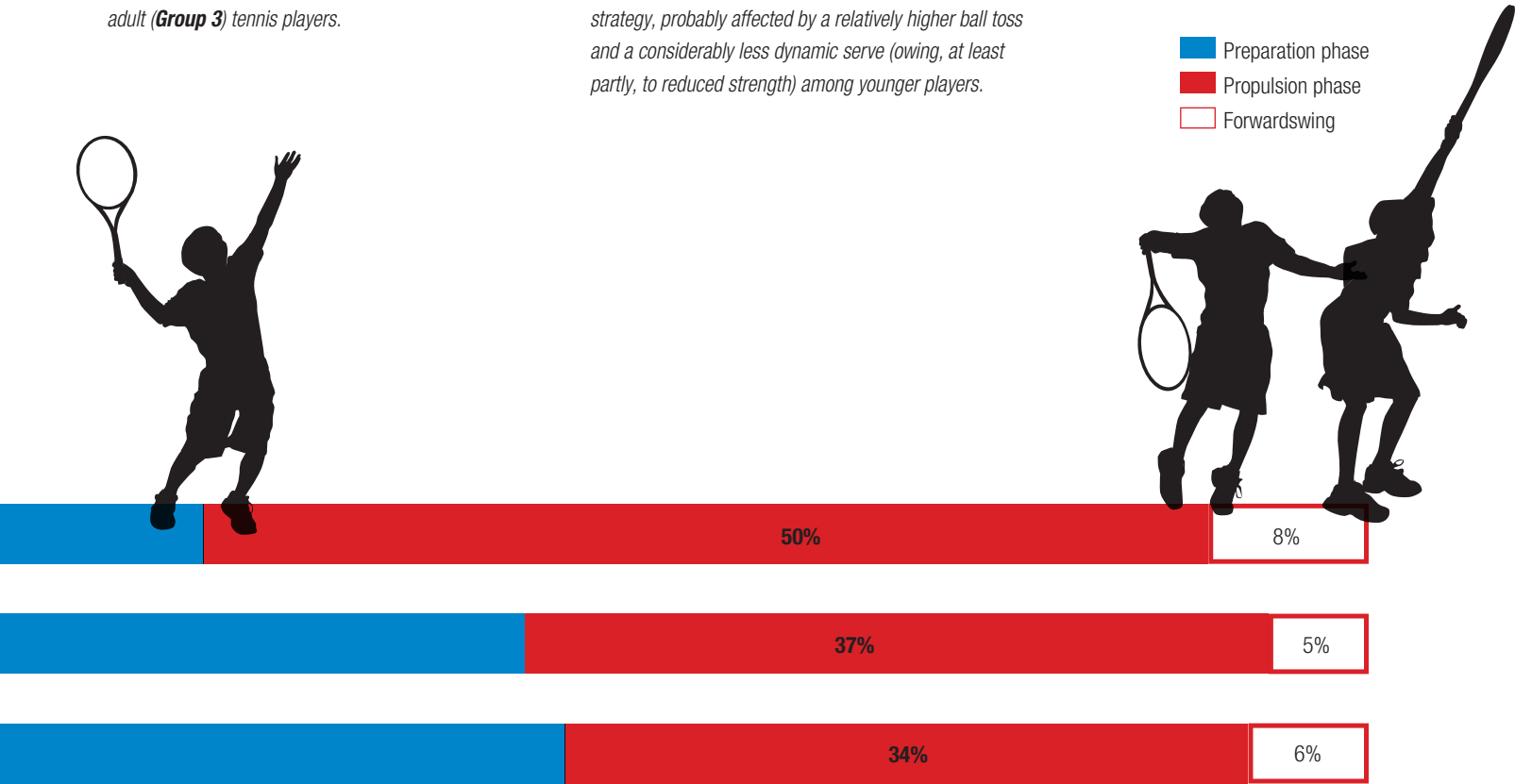


Group 3 (Elite adult)



▲ **Motion picture** The lower limb joints (knees and ankles) of pre-pubescent players extend through a considerably smaller range of motion (and in more time—50% of swing duration) than those of the older groups during the propulsion phase of the serve. The ranges of motion at the ankles and knees during the propulsion phase of the serve are grouped according to elite pre-pubescent (**Group 1**), pubescent (**Group 2**), and adult (**Group 3**) tennis players.

▼ **Phase changes** This shows the relative time (as a percentage) spent in the different phases of the tennis serve as performed by elite pre-pubescent (**Group 1**), pubescent (**Group 2**), and adult (**Group 3**) tennis players. Researchers have found that pre-pubescent players spent significantly less time in the preparation phase and considerably more time in the propulsion phase.¹⁶ In a practical sense, this is indicative of a different coordination strategy, probably affected by a relatively higher ball toss and a considerably less dynamic serve (owing, at least partly, to reduced strength) among younger players.



How does leg drive affect stroke effectiveness?

How do the legs affect my shot power?

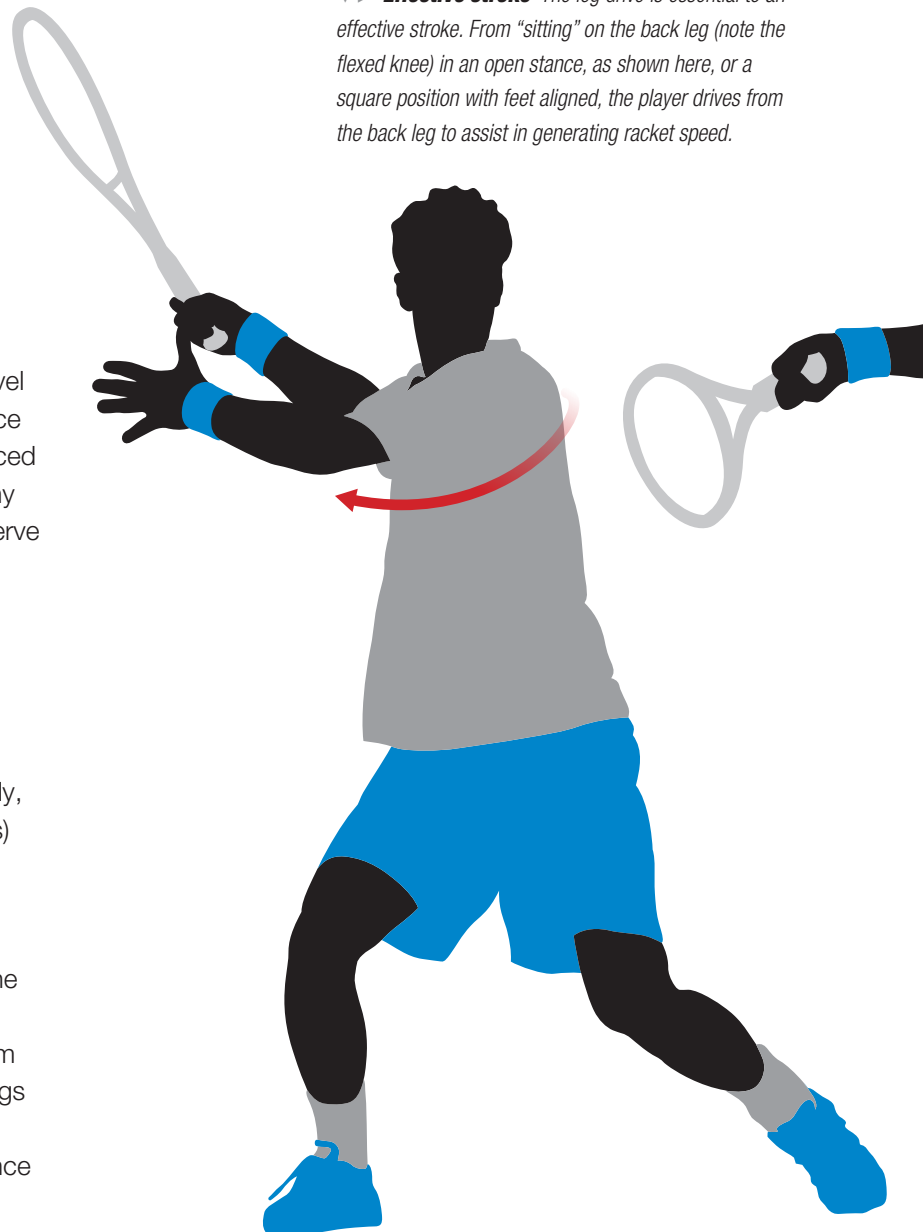
“Leg drive” initiates what coaches refer to as the “kinetic chain”—the flow of energy through the body from the feet to the racket. One of the most significant differences between professional and recreational players, irrespective of their sex, is how they use their legs to “push against the court.” Recreational players do not engage this aspect of the kinetic chain and generate racket velocity primarily with their arms. Professionals use leg drive to initiate trunk rotations to enhance power.^{1,2,3}

Leg drive is a common feature of an efficient service action with the lower limbs flexing and then extending at the knees and hips. Research has shown that, during the serve, the level of drive against the court increases with expertise, with novice players pushing with 1.7 times their body weight and advanced players pushing with 2.1 times their body weight.³ This is why advanced players elevate their bodies from the court, and serve at higher speeds than inexperienced players (105.6 against 68.4 mph, or 170 against 110 km/h).³ Importantly, the best serves are characterized by “drive” from both legs, which—when combined with appropriately aligned feet—elevate the back hip to create a tilted pelvis. This in turn primes the shoulder-over-shoulder trunk rotation that plays such a key role in high-speed serves. While both hips are driven vertically, the back hip has a higher vertical velocity (7.6 ft/s or 2.3 m/s) compared with the front hip (6.2 ft/s or 1.9 m/s).⁴

In groundstrokes, the back leg and hip, to a greater (square stance) or lesser (open stance) degree, are the first part of the kinetic chain. They begin trunk rotation and drive the trunk upward and forward. This enables the trunk and then the arm to build racket speed. Irrespective of the stance used, the legs still play a critical role.^{1,2} This is a consideration often lost on inexperienced coaches, who do not appreciate the importance of this aspect of stroke production.

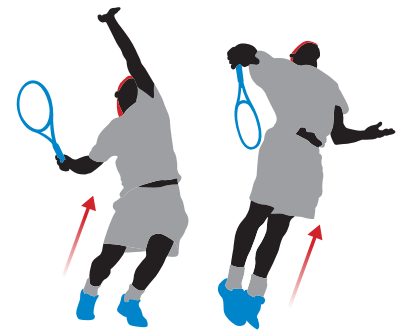
Groundstroke action

▼► **Effective stroke** The leg drive is essential to an effective stroke. From “sitting” on the back leg (note the flexed knee) in an open stance, as shown here, or a square position with feet aligned, the player drives from the back leg to assist in generating racket speed.



Serve

► **Vertical velocity** When a player serves efficiently, they use both of their legs for drive. This enables their hips to elevate, with the back hip achieving a higher vertical velocity than the front hip, so facilitating a shoulder-over-shoulder trunk rotation in order to strike the ball strongly.



Backhand



◀▲ **Back leg drive** Here, the player uses back leg drive (primarily from the hip) to “fire” the forward hip rotation and generate greater velocity in the stroke.

Tennis is a very demanding sport, both mentally and physically, requiring a great deal of technical skill. The body and mind need to be completely in tune to be able to cope with the range of shots needed throughout a match—volleys, groundstrokes, smashes—to accurately hit balls arriving at widely differing velocities and trajectories, while accounting for temperature and court conditions.

Given this, developing the full range of strokes needed to reach the highest level is extremely difficult, and even the very best players haven't been able to master all of them. This means that even top players can be vulnerable and so, during a match, two players will look for that chink in the opposition's armor which they can exploit. It is this strategic battle that makes watching tennis so enjoyable. At some point every player falters, and it is invariably the stroke that the player trusts the least—their weakest—that succumbs. Maintaining an advantage against an opponent crucially depends on being able to easily reproduce a range of shots consistently during the match, reducing exploitable weaknesses.

Scott Draper, a former Top 50 player and among a rare group of technically gifted athletes to have turned professional in two sports (tennis and golf), has a keen interest in developing playing technique that stands up under pressure. "The 'magic' lies in the link between trust and technique—knowing that you can play the shot you need just when you need it," he explains. "Players like Roger Federer are able to reproduce shots time and time again. Reaching this level of 'automaticity' requires countless hours of deliberate repetition—there is no substitute for hard work." Leading players and coaches know that "hard work" doesn't simply mean hitting the same shot thousands of times in practice. Instead, it has been shown that by rehearsing a greater variety of shots and skills during practice, and creating challenging drills which encourage greater concentration, the player is able to improve the rhythm and automaticity of their shots during matchplay.

► **At full stretch** *Learning to play accurate shots under pressure and at speed during a match is the result of many hours of varied and challenging practice.*



How does trunk movement maximize stroke power?

How should I rotate my body to improve my strokes?

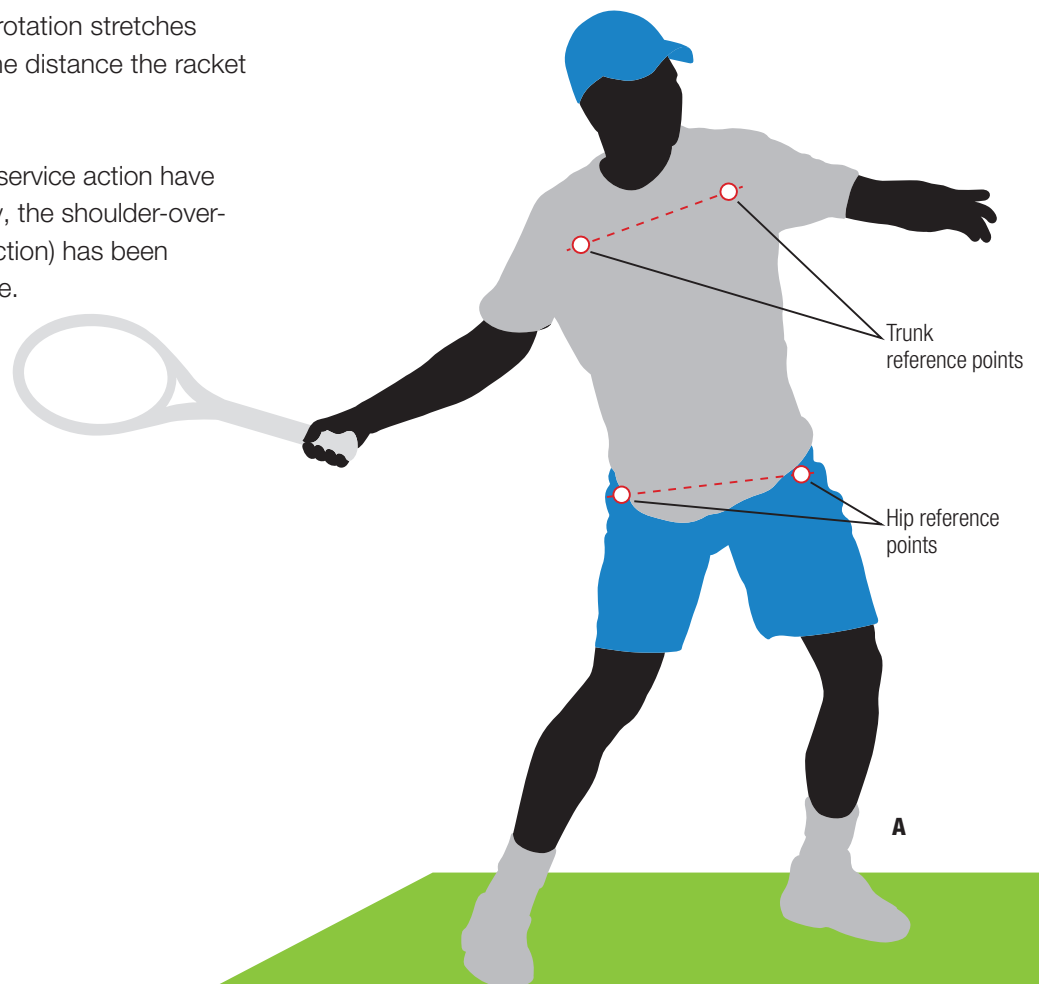
The trunk of the body links the legs and the racket arm, and has an important role to play in transferring energy from the slower-moving yet large legs to the faster-moving yet smaller upper limbs. Specific movements of the upper body, or trunk, have been linked with racket speed in groundstrokes¹ and the serve.²

Studies have shown that trunk rotation speed is directly related to ball speed¹—Association of Tour Professionals (ATP) players, who hit the ball harder than their junior counterparts, were also shown to use more trunk rotation in the forehand stroke.³ In groundstrokes, the shoulders typically rotate by more than the hips, twisting the trunk, to create what is called a separation angle (see page 35).^{4,5} This rotation stretches the muscles of the trunk and increases the distance the racket has to accelerate to impact.

In addition, specific trunk rotations in the service action have been linked with better serves.^{2,6} Certainly, the shoulder-over-shoulder trunk rotation (the “cartwheel” action) has been shown to differentiate service performance.

It is therefore critical that players use their trunk in all stroke production. The shoulders should be rotated 20–30° more than the hips in the preparatory phase of all strokes. This enables the trunk to rotate to impact, benefiting from the energy provided by the legs, while also transferring energy to the racket. The type of rotation is more complicated in the service action, but it is also essential to use trunk rotation to generate a high-power serve, particularly when applying spin to the ball.

Power generation



► **Forehand** The separation angle—the difference in rotation between the hips and the shoulders—and the forward rotation of the shoulders are key features of the forehand. These movements stretch the muscles in the trunk and shoulders (**A**), so allowing for greater acceleration of the racket before impact (from **A** to **B**), which in turn generates greater power in the stroke.

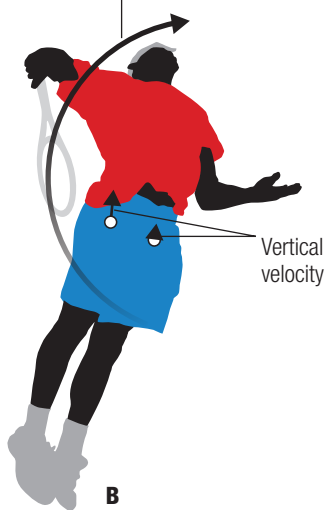
Trunk rotations in the serve

Shoulder-over-shoulder
"cartwheel" rotation

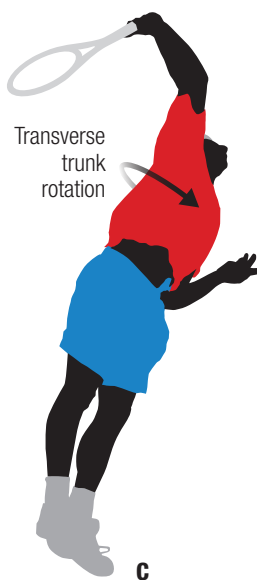


A

Shoulder-over-shoulder
"cartwheel" rotation



B

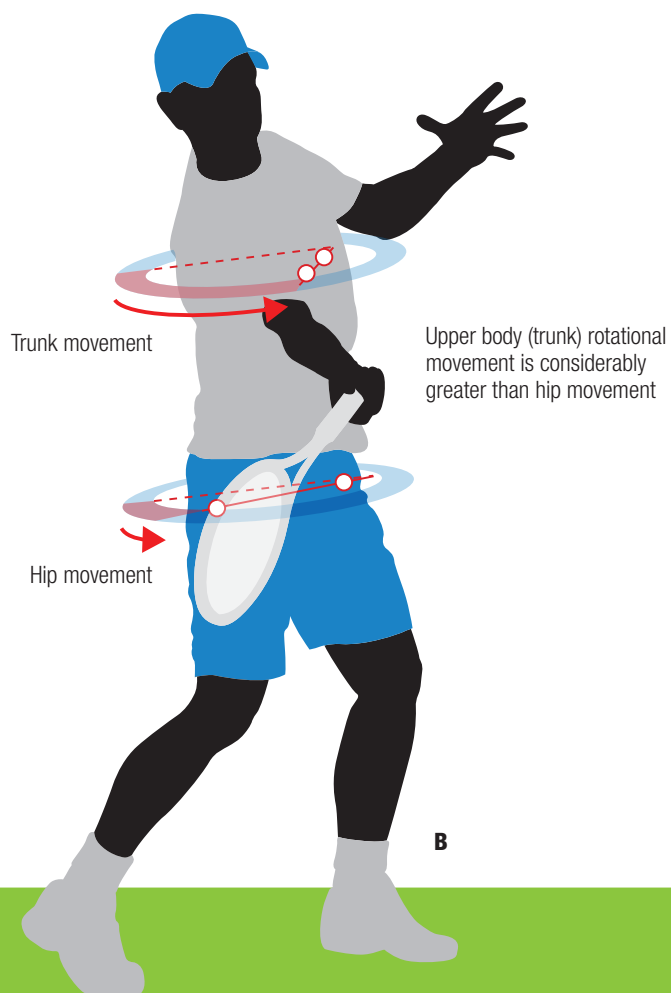


C



D

▲ **Trunk rotation** Various trunk rotations in the serve: shoulder-over-shoulder (A–B); transverse (B–C); forward trunk rotation (C–D). In this movement, an arabesque of the back leg is a good sign of a vigorous and effective transfer of weight, which will result in a more powerful serve.



B

What is internal rotation?

How does shoulder movement increase my shot power?

If one compares the highest service speeds of current Top 10 players (Milos Raonic at 155 mph or 250 km/h, Serena Williams at 129 mph or 207 km/h) or the fastest serves recorded on the ATP (Sam Groth at 163 mph or 263 km/h) or Women's Tennis Association (WTA) tours (Venus Williams at 130 mph or 209 km/h), the speed of the female serve is on average approximately 80% that of the male serve. Is this difference due purely to strength and physical size, or does technique also play a role?

There are obvious physical differences, but one movement clearly differentiates male from female players where service speed is concerned—shoulder internal rotation. This is the action that has been shown to be the largest contributor (approximately 40%) to the generation of racket velocity at impact in the male high-performance serve.¹ Furthermore, if you compare the magnitude of internal rotation velocity of the male professional players analyzed at the Sydney Olympics² with that of the Australian female professionals,³ the females record on average 83% of the males' values. While it is too simplistic to say that this is the cause of the serve velocity differential, it is a consideration for female players wanting to increase their service velocity.

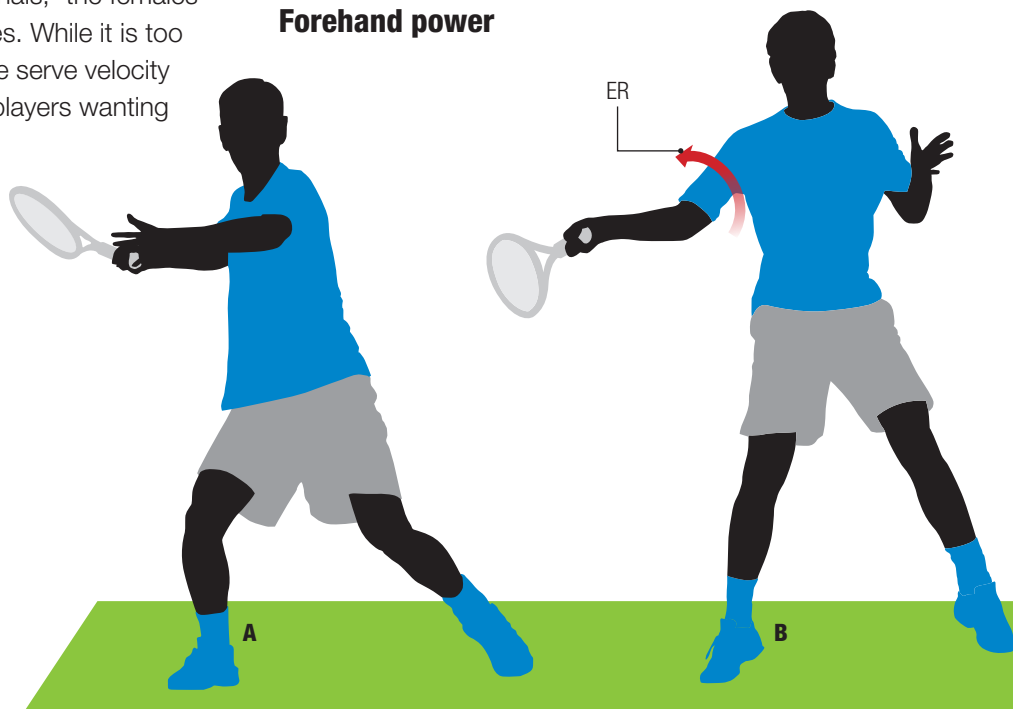
► Internal rotation and the forehand

The trunk and hips rotate and the arm externally rotates at the shoulder during the backswing (A). These movements enable the racket to be positioned so that power can be generated during the forwardswing. This external rotation (ER) is shown in B by the arrow. Just before impact, internal rotation (IR) may occur to assist in building racket power. This movement continues in the follow-through (C).

Coaches and young players alike must be careful to appropriately time when they emphasize the importance of internal rotation in the service action. For example, research has observed that increases in internal rotation velocity occur primarily after puberty.³ Therefore, young players should attend to other aspects of the service action and lay the foundations for appropriate internal rotation velocity development prior to puberty, so that they can most effectively use this aspect of the serve when they mature.

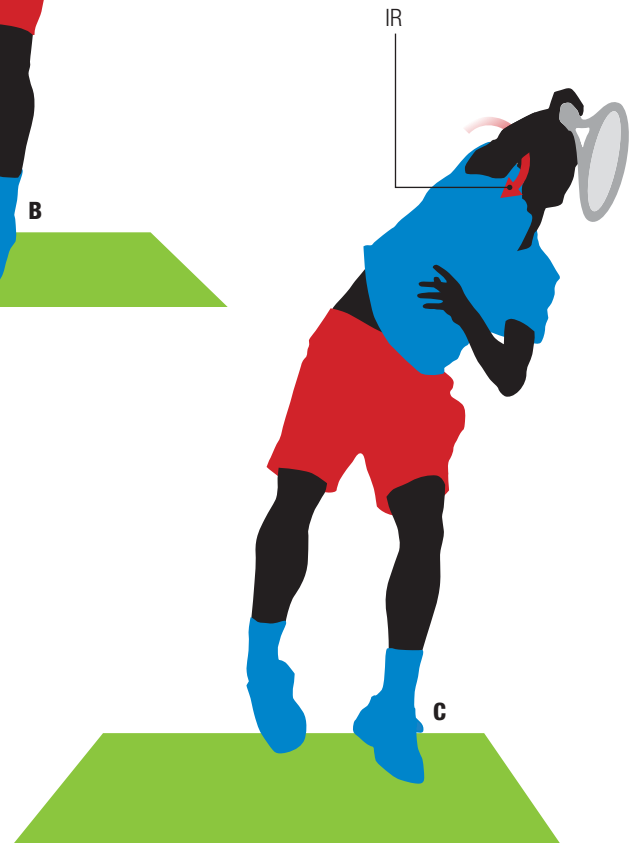
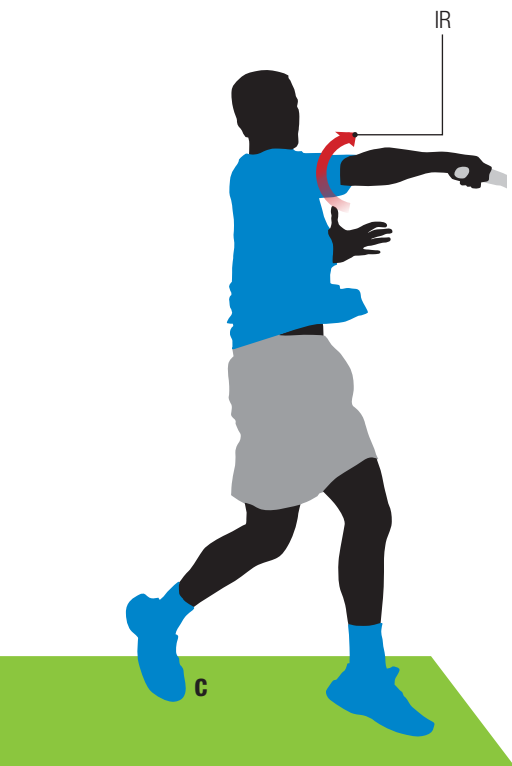
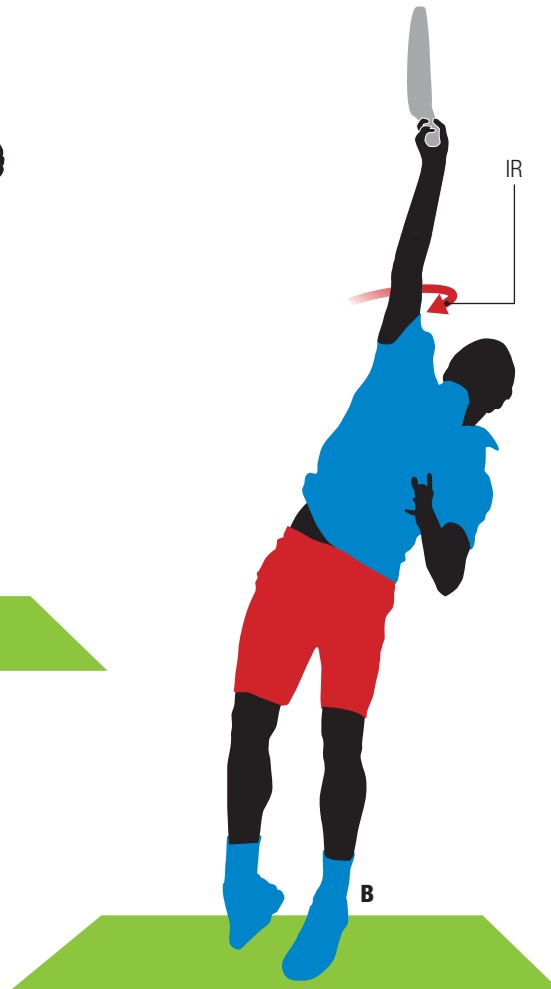
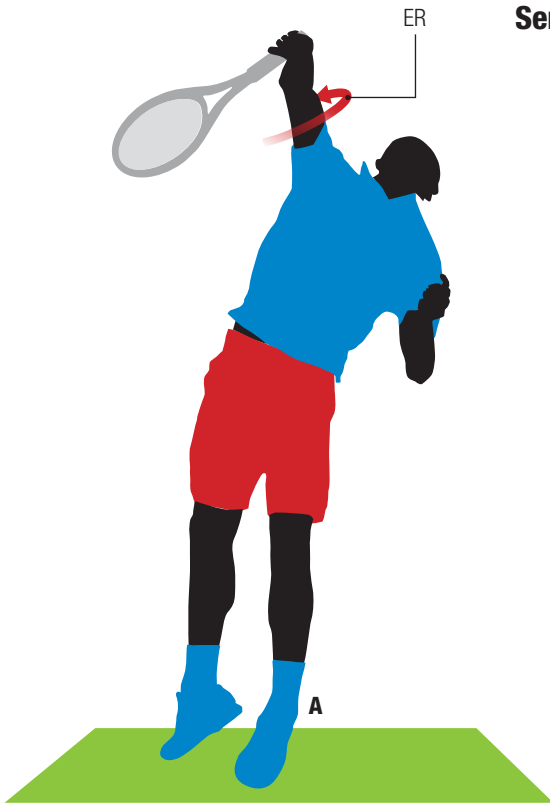
Internal rotation is also a contributor to racket velocity in selected forehands, particularly where a player is required to generate ball velocity (as is often the case on slower clay courts).⁴ It is worth noting that shoulder internal rotation may only occur after impact if the ball approaches at a higher speed or when a player directs the ball down the line.

Forehand power



Serving power

◀ **Internal rotation and the serve** The arm externally rotates (ER) during the backswing (A) to position the racket for acceleration to impact, and to put the muscles of the shoulder, the “internal rotators,” on stretch. Internal rotation (IR) then occurs during the forwardswing to impact (A to B), and into the follow-through (B to C). Remember, IR is the movement that most assists the generation of racket speed at impact in the serve.



How do body segments combine?

Do I need coordinated movement to optimize power?

A number of mechanical factors must be considered if a player is to build high racket velocity. One of the central components in coordination is the linking of linear or straight-line movements with angular or rotational motions through the entire body. While it is the velocity of the impact point (linear motion) that is ultimately critical for successful performance, this velocity will only be achieved by coordinating the rotations of a large number of body segments. This is particularly the case in linking the rotations of the trunk and hitting arm.

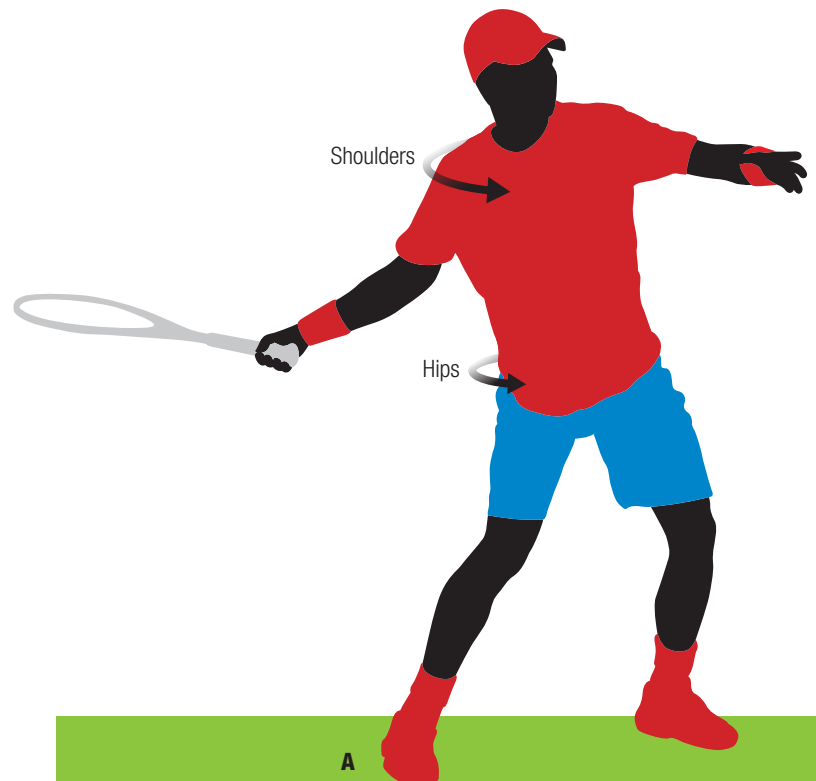
The angular rotation of each of the segments described in the preceding pages creates a linear velocity at the end point of that segment. For example, the angular velocity of the arm creates linear velocity at the wrist. This end-point velocity is equal to rotational velocity multiplied by the length of the segment. Or, at its simplest, the power of the shot is derived from the forward movement of the shoulder plus the rotation of the arm, multiplied by the combined length of the arm and racket (to the impact point).

So, if one assumes that players are equally adept at coordinating their body segments, they have a fundamental decision to make. If they choose to keep the arm relatively straight on impact, the linear velocity will be based more on arm length. If they choose to bend the arm, so reducing the length of the lever, linear impact velocity will be more heavily influenced by rotational speed. In both cases, coordination of body parts is essential if maximum power is to be achieved. Similarly, a player extends the hitting arm in the serve to increase both hitting height and velocity of the racket. The player may choose to flex at the elbow, thus increasing the ability to internally rotate, but this will come at the expense of the impact height, and potentially the effectiveness of the serve.

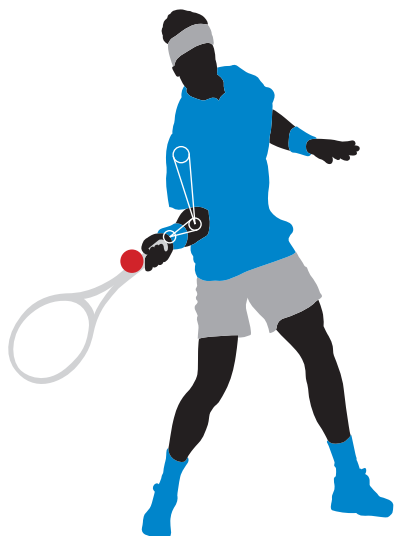
Need to know

In the forehand, the linear velocity of the center of the racket is calculated as:

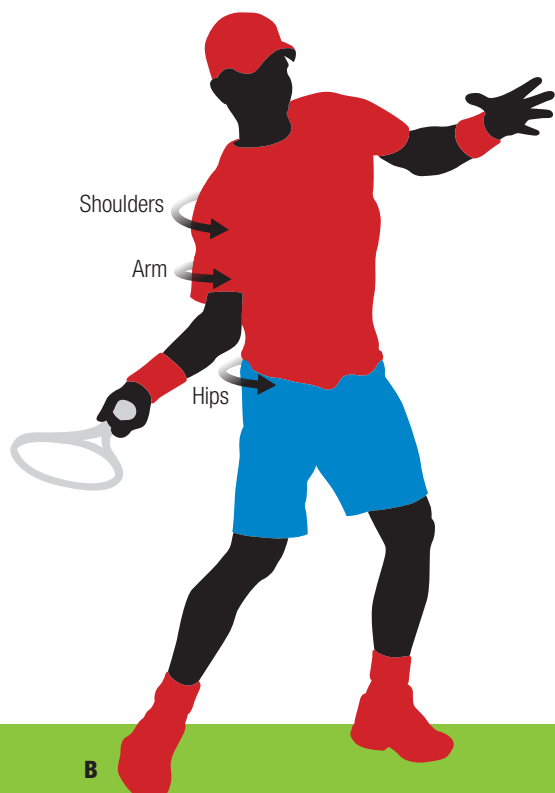
$$\text{the forward linear speed of the shoulder (linear velocity)} + \left(\text{angular rotational velocity of upper limb and racket} \times \text{the distance from the shoulder to the impact point on the racket (lever length)} \right)$$



Racket grip

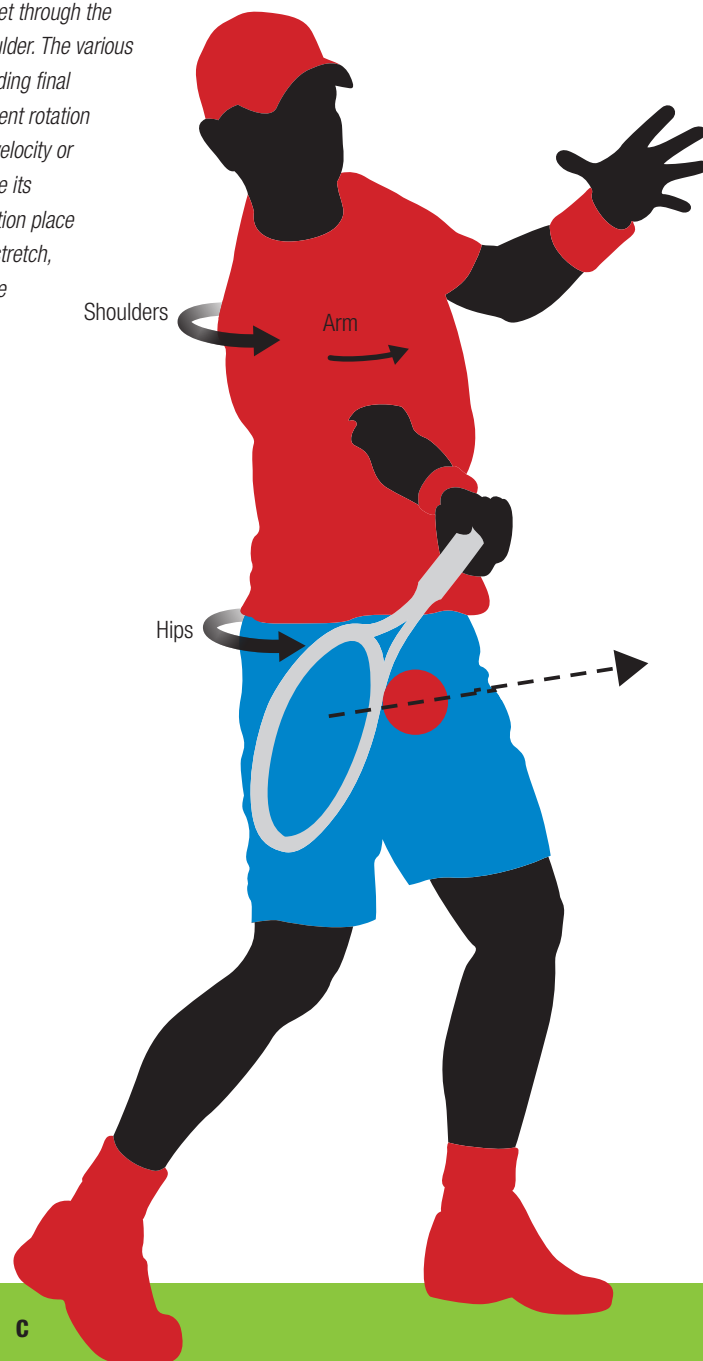


▲ **Western grip** Some players use a Western grip, as shown here. This grip inevitably reduces the effective length of the upper limb and racket. Players using this grip must therefore rotate their arm very rapidly to generate velocity.



Novak Djokovic forehand

▼► **Forehand** This sequence of the forehand of Novak Djokovic shows how a complex combination of linear and rotational movements can generate very high racket velocity. Novak Djokovic combines rotation of the arm and trunk (hips and shoulders) to add to the final velocity of the racket through the forward movement of the racket shoulder. The various segments of the arm all assist in building final racket velocity. Removal of any segment rotation will therefore either reduce the final velocity or require another movement to increase its contribution. High levels of trunk rotation place the muscles across the shoulder on stretch, allowing for subsequent release of the stored elastic energy.





For a game so rich in history, tennis is remarkably low in systematic and objective insight. It is a surprise to many industry outsiders that tennis trails other sports in the understanding of its own trends. It has been slow to embrace the virtues of performance analysis and this has hindered the extent to which the game's stakeholders (that is, players and coaches) can make informed decisions both on and off the court. The recent rule change by the International Tennis Federation (ITF) to allow technology to be used to collect data during play demonstrates that the game's governing body accepts that technology is part of tennis, and indeed the sport has now begun to benefit from the more strategic use of technology to grow its repository of game intelligence. The manner in which this information can be leveraged to inform the coaching process represents an increasingly important competitive advantage for the sport.

chapter three

performance analysis and game intelligence

Michael Bane, Bruce Elliott, and Machar Reid



Is there a relationship between junior and senior tennis success?

Will a good junior player become a world-class pro?

Imagine you've just won a Wimbledon Championship and reached number one in the world rankings, all before the age of 18. It sounds pretty unlikely but it happens more often than you would think—in the international junior game, that is. But what does this type of success mean in relation to the professional game? Do elite juniors become elite pros?

Many studies have investigated the relationship between junior and professional success in tennis, yet no universally accepted criteria exist for forecasting future success for junior talent. A recent study found that competitors (both male and female) in three tournaments that are regarded as being among the most important international under-14 events—Les Petits As (Tarbes), the French Open, and the European Championship—subsequently achieved significantly better professional rankings if they progressed to a final in one of the three events.¹ Indeed, approximately 18% of the male winners and 22% of the female winners reached the ATP and WTA Top 20, respectively.

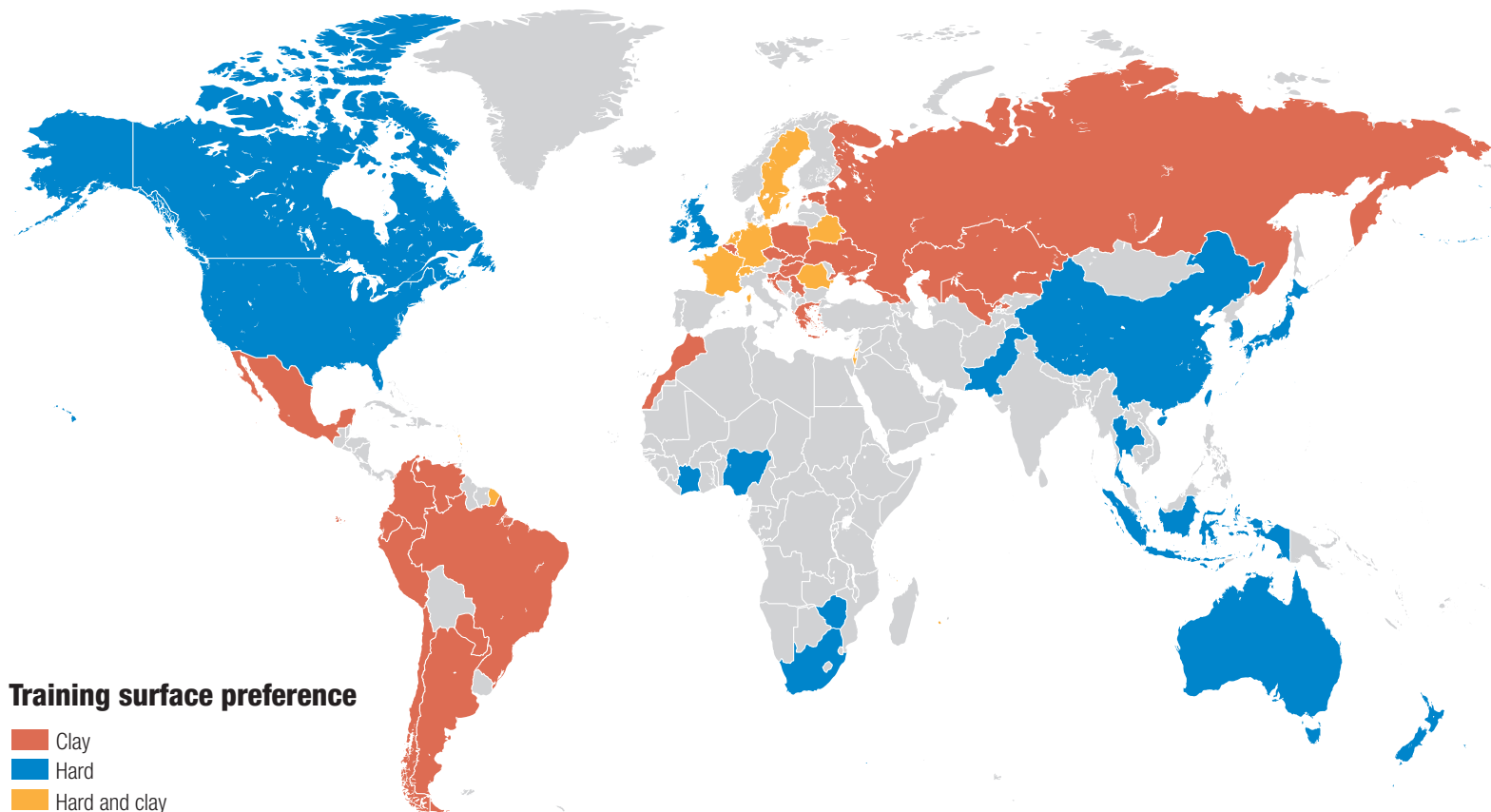
Similar findings are reported for results in the ITF junior (18 and under) competition. Separate studies of the ITF boys' and girls' circuits revealed significant associations between the junior and subsequent professional rankings of athletes who reached an ITF year-end junior Top 20 ranking.^{2,3} However, the vast majority of variance in professional rankings remained unexplained in these studies; and junior ranking should only be considered as an indicator of professional success, rather than a precursor. The raw numbers suggest that approximately 45% of boys and 61% of the girls who reach the ITF junior Top 20 later achieve a ranking in the ATP/WTA Top 100.¹ This compares favorably to the US college tennis circuit (for male players), which has been reported to have an 18% conversion rate from Top 10 college ranking to Top 100 ATP ranking.²

► **Junior success** Success at the junior Grand Slams can be an indicator of future ATP/WTA rankings. For example, every single winner of the French Open boys' title between 1980 and 2000 reached the ATP Top 100, and 81% reached the ATP Top 50. The US Open boys' champions (35%) were the most likely to later achieve an ATP Top 10 ranking. More generally, 82%, 62%, and 28% of boys' Grand Slam winners (1980–2000) achieved a ranking in the ATP Top 100, 50, and 10, respectively. The French Open girls' title is an even better predictor of success as a professional, with 100%, 90%, and 62% of winners achieving a position in the WTA Top 100, 50, and 10, respectively. Of all the girls' Grand Slam winners (1980–2000), 91%, 80%, and 35% achieved a ranking within the WTA Top 100, 50, and 10, respectively, indicating that success at this level translates to success on the professional circuit more readily in women's tennis.

French Open junior champions

Year won	Male player	Senior ranking
1980	Henri Leconte	5
1981	Mats Wilander	1 
1982	Tarik Benhabiles	22
1983	Stefan Edberg	1 
1984	Kent Carlsson	6
1985	Jaime Yzaga	18
1986	Guillermo Pérez Roldán	13
1987	Guillermo Pérez Roldán	13
1988	Nicholas Pereira	74
1989	Fabrice Santoro	17
1990	Andrea Gaudenzi	18
1991	Andriy Medvedev	4
1992	Andrei Pavel	13
1993	Roberto Carretero	58
1994	Jacobo Díaz	68
1995	Mariano Zabaleta	21
1996	Alberto Martín	34
1997	Daniel Elsner	92
1998	Fernando González	5
1999	Guillermo Coria	3
2000	Paul-Henri Mathieu	12

Year won	Female player	Senior ranking
1980	Kathy Horvath	10
1981	Bonnie Gadusek	8
1982	Manuela Maleeva	3
1983	Pascale Paradis	20
1984	Gabriela Sabatini	3
1985	Laura Garrone	32
1986	Patricia Tarabini	12
1987	Natasha Zvereva	5
1988	Julie Halard	7
1989	Jennifer Capriati	1 
1990	Magdalena Maleeva	4
1991	Anna Smashnova	15
1992	Rossana de los Ríos	51
1993	Martina Hingis	1 
1994	Martina Hingis	1 
1995	Amélie Cocheteux	55
1996	Amélie Mauresmo	1 
1997	Justine Henin	1 
1998	Nadia Petrova	3
1999	Lourdes Domínguez Lino	40
2000	Virginie Razzano	16



Developmental surfaces of junior Grand Slam winners

Boys' US open			
Year	Winner	Country	Surface
1990	Andrea Gaudenzi	Italy	Clay
1991	Leander Paes	India	Hard
1992	Brian Dunn	USA	Hard
1993	Marcelo Ríos	Chile	Clay
1994	Sjeng Schalken	Netherlands	Clay/Hard
1995	Nicolas Kiefer	Germany	Clay/Hard
1996	Daniel Elsner	Germany	Clay/Hard
1997	Arnaud di Pasquale	France	Clay/Hard
1998	David Nalbandian	Argentina	Clay
1999	Jarkko Nieminen	Finland	Hard
2000	Andy Roddick	USA	Hard

Boys' Wimbledon			
Year	Winner	Country	Surface
1990	Leander Paes	India	Hard
1991	Thomas Enqvist	Sweden	Clay/Hard
1992	David Škoch	Czechoslovakia	Clay
1993	Răzvan Sabău	Romania	Clay/Hard
1994	Scott Humphries	USA	Hard
1995	Olivier Mutis	France	Clay/Hard
1996	Vladimir Voltchkov	Russia	Clay
1997	Wesley Whitehouse	South Africa	Hard
1998	Roger Federer	Switzerland	Clay/Hard
1999	Jürgen Melzer	Austria	Clay
2000	Nicolas Mahut	France	Clay/Hard

Girls' US open			
Year	Winner	Country	Surface
1990	Magdalena Maleeva	Bulgaria	Hard
1991	Karina Habšudová	Czechoslovakia	Clay
1992	Lindsay Davenport	USA	Hard
1993	Maria Bentivoglio	Italy	Clay
1994	Meilen Tu	USA	Hard
1995	Tara Snyder	USA	Hard
1996	Mirjana Lučić	Croatia	Clay
1997	Cara Black	Zimbabwe	Hard
1998	Jelena Dokić	Australia	Hard
1999	Lina Krasnoroutskaya	Russia	Clay
2000	María Emilia Salerni	Argentina	Clay

Girls' Wimbledon			
Year	Winner	Country	Surface
1990	Andrea Strnadová	Czechoslovakia	Clay
1991	Barbara Rittner	Germany	Clay/Hard
1992	Chanda Rubin	USA	Hard
1993	Nancy Feber	Belgium	Clay
1994	Martina Hingis	Switzerland	Clay/Hard
1995	Aleksandra Olsza	Poland	Clay
1996	Amélie Mauresmo	France	Clay/Hard
1997	Cara Black	Zimbabwe	Hard
1998	Katarina Srebotnik	Slovenia	Clay
1999	Iroda Tulyaganova	Uzbekistan	Clay
2000	María Emilia Salerni	Argentina	Clay

▲ **Home ground** Success on the professional circuit has been linked to more than just the rankings and results achieved in junior competition—it has also been associated with the court surface on which players predominantly develop their game. Researchers^{2,3} have found that both male and female players who originate from countries in which the majority of junior competition is played on clay go on to achieve significantly higher professional tennis rankings.

◀ **Surface success** This table shows the winners in the Wimbledon and US Open girls' and boys' junior championships from 1990 to 2000, their nationalities, and the surfaces on which they learned to play tennis. Clay surfaces clearly predominate.

What is the “relative age effect” in tennis?

Does my birthday affect my chances of success?

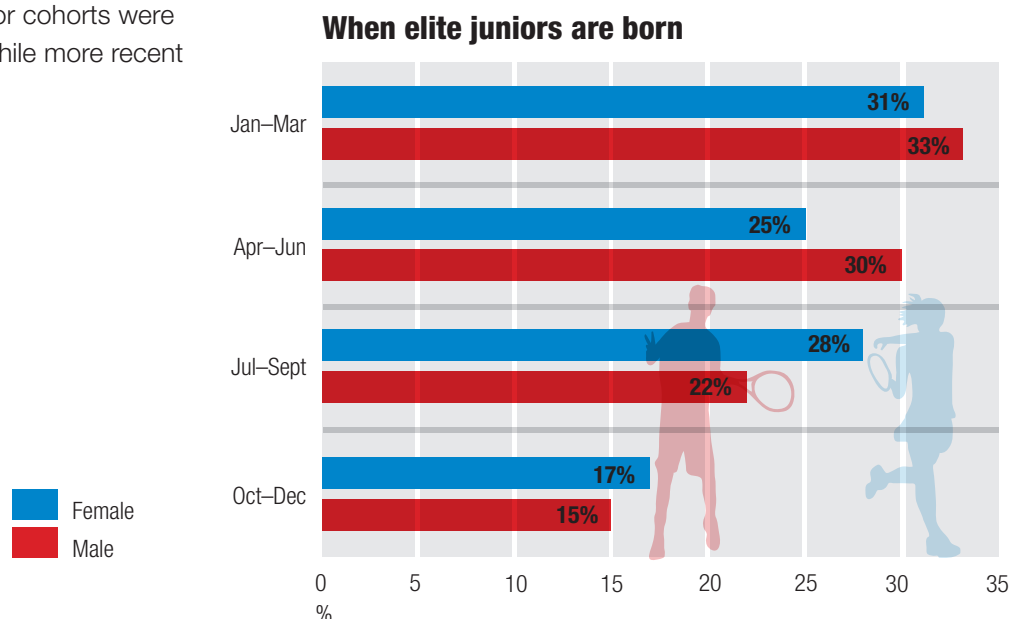
From early on in their careers, tennis players are organized into age groups to coordinate their involvement in competition and tournament play. The underpinning logic is relatively simple in that it's intuitive to use a player's age—as a proxy for physical and cognitive maturation—to encourage more equal, and therefore more enjoyable, competition. To this end, most junior sport—and certainly international tennis—runs through to 18-and-under, before transitioning into the professional and Open (that is, with no age constraints) competition arena. In junior tennis, players are grouped according to the year in which they were born.

It now appears that this method of grouping players in junior sports creates certain disadvantages. The “relative age effect,” which has been revealed by research across many sports, including tennis, serves as perhaps the most tangible example. This effect describes the skewed distribution of birth months observed in various sports, inferring that cut-off dates for junior competition discriminate against players born later in the calendar year.¹ In tennis, the seminal work of Dudink² has suggested that up to half of some elite junior cohorts were born in the first three months of the year, while more recent

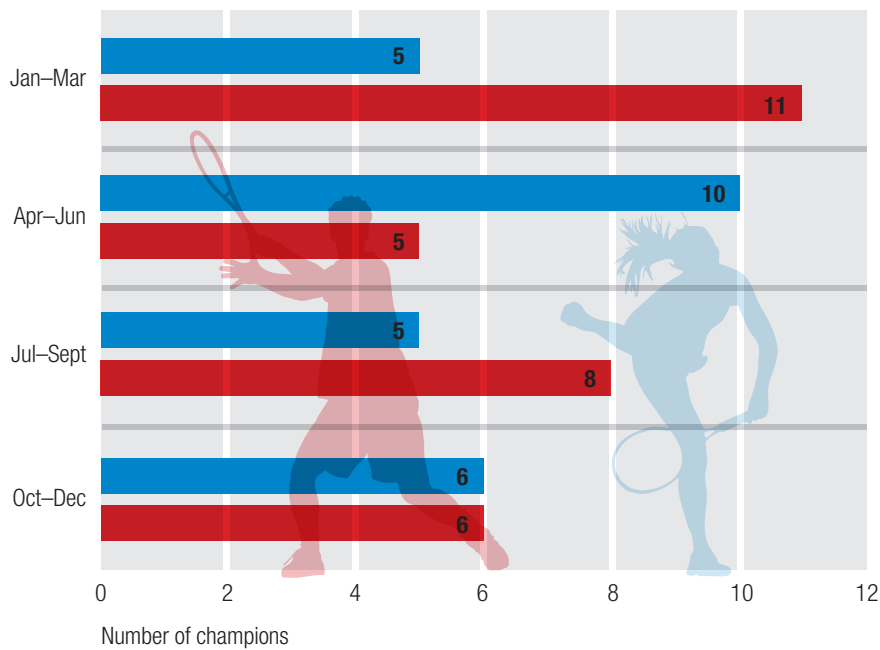
research has confirmed a significant season-of-birth bias for elite, top ranked junior male and female players.³ Interestingly, Edgar and O'Donoghue³ found a similar pattern among their sample of elite adult Grand Slam competitors, whereby the number of players born in successive quarters of the calendar year declined. Delorme, Boiché, and Respaud⁴ argue that these findings are symptomatic of an effect that might be observed from as young as seven, or as early as when age cut-offs are introduced.

From the work performed in tennis so far, there appear to be two groups of players that are less affected by relative age effect than others. First, it appears that birth month poses much less of an obstacle to the game's very best players, such as Grand Slam champions, than other players.³ Second, in what might otherwise seem a bit of an oddity, left-handers seem to be much less affected by their birth month than right-handed competitors.⁵

► **Relative age effect in juniors** This graph illustrates the “relative age effect” among a sample of the highest internationally ranked juniors in 2003. As depicted, players born in the last quarter, October–December, are under-represented, all but confirming the relative age effect in this group of elite juniors.



When Grand Slam champions are born

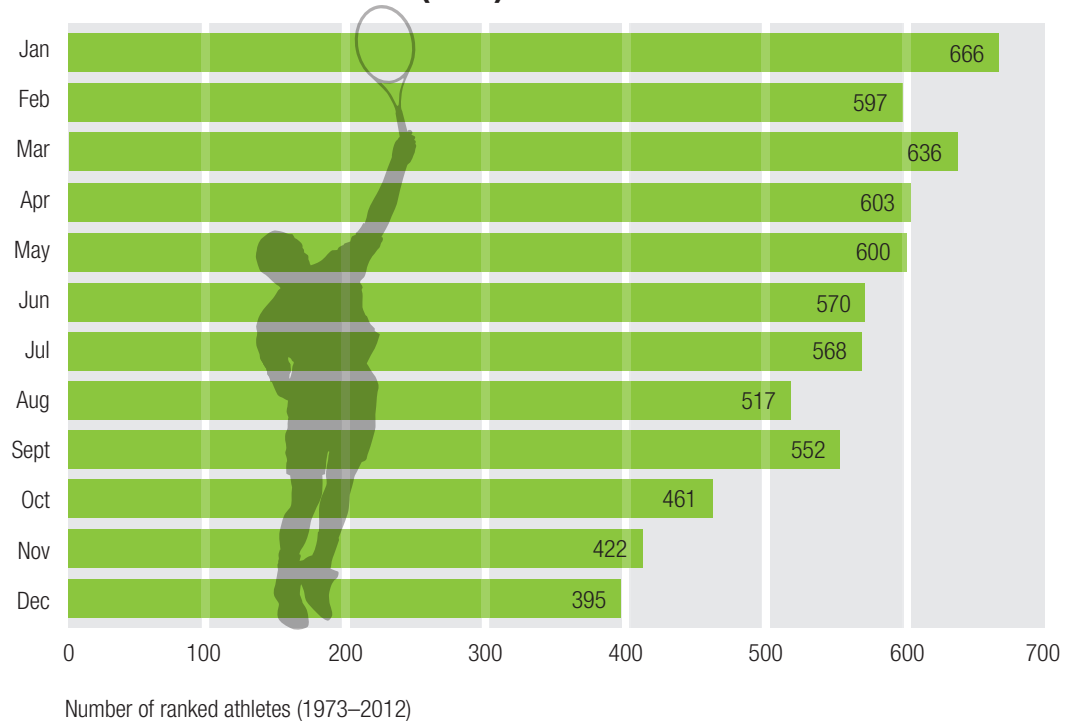


◀ **Relative age effect in pros** This graph illustrates the “relative age effect” in Grand Slam champions from 1990 to 2014. Evidence of the relative age effect among Grand Slam champions does not appear as pronounced as with elite juniors, with a more even distribution of Grand Slam champions born throughout the year.

Female
Male

Professional birth months (male)

► **Happy birthdays** This graph shows the distribution of professionally ranked male players between 1973 and 2012 according to the month of their birth. As can be seen, players with birthdays in the earlier months of the year outnumber those born toward the end of the year. This bias is less pronounced among Grand Slam winners and top left-handed players.



How long is the transition time for professionals?

How long will it take me to reach the Top 100?

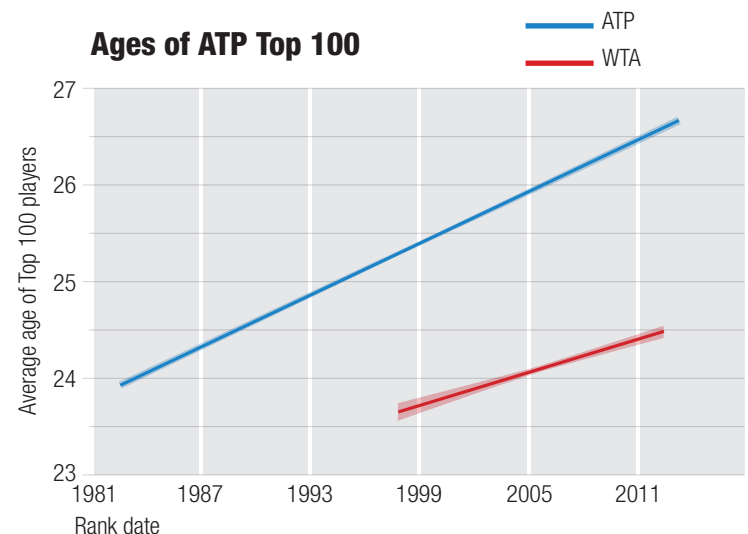
So, indications are that you're talented enough to turn "pro"... But what does that really mean, and how long will it take? Tennis has recorded professional rankings since the start of the Open era in 1973, yet it is only recently that these data have been analyzed to derive some answers to such questions.

For example, a study by Reid et al.¹ investigated the ranking trajectories of male players who achieved career-high rankings in the Top 250 between 1973 and 2011. They found that the professional rankings of players aged as young as 16 could indicate future career highs, yet the strength of this relationship was most clearly evidenced by their ranking after four years on the Tour. In other words, and bearing in mind there will always be exceptions, where players are ranked after their fourth year on Tour provides a relatively accurate guide to how far up the rankings ladder they will climb. At the same time, this climb has been noted to be taking progressively longer in the men's game, with Bane et al.² reporting that the transition time (the time between a professional player earning his first

point and his achieving a Top 100 ranking) has increased at a statistically significant rate of approximately one year per decade over the last 30 years.

The same data are not as readily available in the women's game, yet indications are that the age at which athletes enter the Top 100 has remained stable between 1998 and 2012.² Interestingly, in 1995, the WTA introduced an age-eligibility rule to restrict the number of tournaments that athletes could compete in prior to the age of 18. Two studies have investigated the effect that this rule has had on the careers of athletes. Rodenberg and Stone³ showed that its introduction did not significantly affect the duration of time that players spend within the Top 10 and/or Top 50, while Otis et al.⁴ suggested that the rule had indeed significantly increased the median career length of tennis players.

► **Top 100 ages** A useful metric for gauging the evolution of the ATP and WTA's Top 100 is the average age of players ranked in the Top 100. A near constant rate of increase is observed in the male game since the late 1980s, in contrast to the more subtle change in the WTA Top 100's average age. The average rate of increase in the age of the Top 100 is estimated at 0.90 and 0.58 years per decade in males and females, respectively. Note that only ranking data from 1998 onward are readily available from the WTA for analysis.



Grand Slam ranking points



▲ **Winning ways** A greater focus (in terms of prize money, exposure, and so on) is placed on Grand Slam competition in the modern day, which is reflected in the allocation of ranking points. For example, in 1995, a male player needed to win seven of the most competitive Challenger class tournaments (US\$125,000) to receive the same number of ranking points as a Grand Slam win. In 2014, the same player needed to win more than double that number of Challenger events. Needless to say, policy changes to the ranking system seem to have contributed to the increase in transition time over the past three decades.

▼ **Getting to the top** These tables show the times taken by leading male and female tennis players to move from their first ranking to the Top 100. For male players, the average transition time has been seen to increase by one year per decade over the last 30 years.

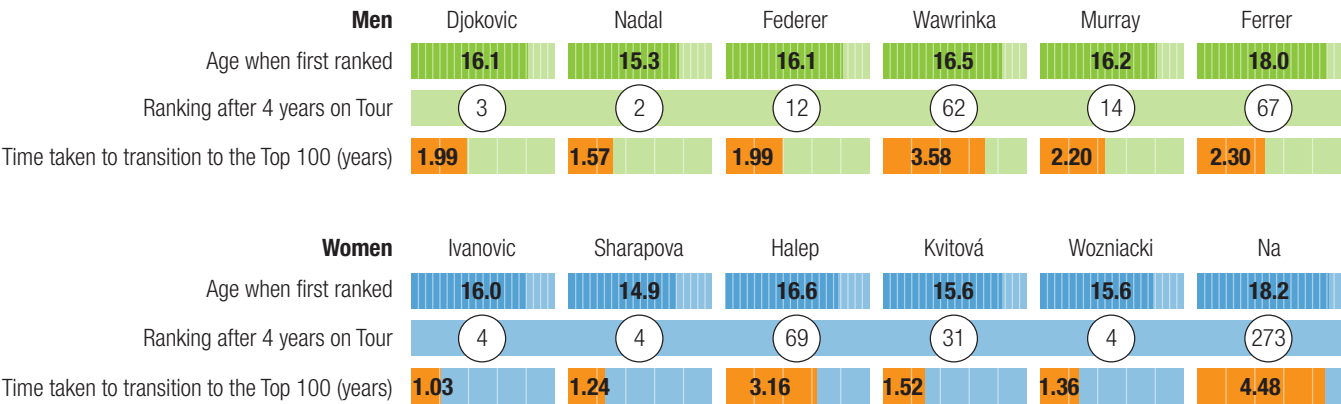
Each figure represents a \$125,000 tournament win



One Grand Slam win



Transition times



Before facing a new opponent, it's important to prepare your body for the physical contest ahead. Eating well, staying hydrated, and getting proper sleep all help to ensure you perform at your peak in the match. But smart players can also get an edge by preparing match tactics using a combination of subjective reports and objective data.

Every player is different, and the tactics that get you through the first round may be completely irrelevant in the second. It's instructive for players to compile an understanding of their opponent's preferences by watching them play, whether in person or on video. This process can help to uncover patterns of play—for example, it's not uncommon for players to tend to serve to a particular side of the court or to a particular wing (such as the backhand) on important points. Some top tennis academies and federations also annotate their video, labeling important events during play to enable coaches and players to analyze their opposition in even greater depth. The advantage of video analysis, which can pull together images across multiple matches, is that a lot of the tactical thinking can be completed before you walk on court, rather than in the heat of play when you are tired and under pressure.

In leaving no stone unturned, these same coaches and players will also consult statistics to garner further insight into the strengths and weaknesses of their opponents. The recent advent of Hawk-Eye (see pages 68–71) as an officiating tool has grown the number of statistics available to the game's elite exponentially. Players and coaches can now create a competitive advantage by making sense of these data.

Data are not the be all and end all, however—often, they confirm the subjective reports developed in consultation with other players and coaches when preparing for a match. With this in mind, some academies and federations require coaches and players to contribute to the profiles (outlining strengths and weaknesses) of opposition players, which may even include insights picked up during practice. When it comes to sizing up an opponent, however, sometimes there is just no substitute for matchplay.

► **Game of tactics** When young players, like Nick Kyrgios, first burst on to the professional scene, little is known about the way they win points. However, it doesn't take long for opponents to begin to unpick their tactical strengths and weaknesses and construct game plans accordingly.



Do a nation's tournaments affect its player rankings?

Which tournaments should an aspiring pro play?

A comprehensive review of tournament structure was recently undertaken by Filipcic et al.,¹ which investigated the relationships between the tournament structures of nations (including factors such as the number of tournaments and prize money offered) and their ability to produce players ranked in the Top 100. The study found that the strength of the association between the number of players from a geographical region and both the number of tournaments and prize money offered in that region were diminishing over time. These findings imply that a player's country of origin is less important in the modern game, presumably as access to global competition has improved. In turn, having more tournaments available to players introduces further complexity into their scheduling.

In the men's game, the ATP and ITF divide tournaments into classes. The ITF Futures tournaments are commonly contested by younger players, and represent the entry point into the

professional game. The next step is the ATP Challenger Tour, which requires players to be ranked approximately between 250 and 450. A series of higher-level ATP events (1000s, 500s, and 250s) caters for the most elite 250 players in the world, yet it's not uncommon for players ranked between 50 and 250 to compete in Challenger events as well. The Grand Slams are the bastions of the game's Top 100 players.

With such a hierarchical system of tournaments, it is logical that tournaments have an influence on everything from a player's competitiveness in matchplay to their rankings and earning capacities. Ultimately, though, the goal of most athletes is to climb the rankings and secure entry into Grand Slam competitions. A retrospective analysis of the tournament scheduling of the current Top 100 athletes can therefore provide a useful reference point in guiding players' decisions about which events to enter.

► **Top matches** This shows the percentage of matches that the ATP Top 100 (in 2014) played at various tournament levels as a function of the number of years that they had competed on the Tour. This provides a benchmark for new players. For example, if a player is still competing primarily at the Futures level in year four, they are unlikely to be performing at the level required of a typical Top 100 player. Also, the plot demonstrates the prominence of Challenger matches in the schedules of the Top 100 players.

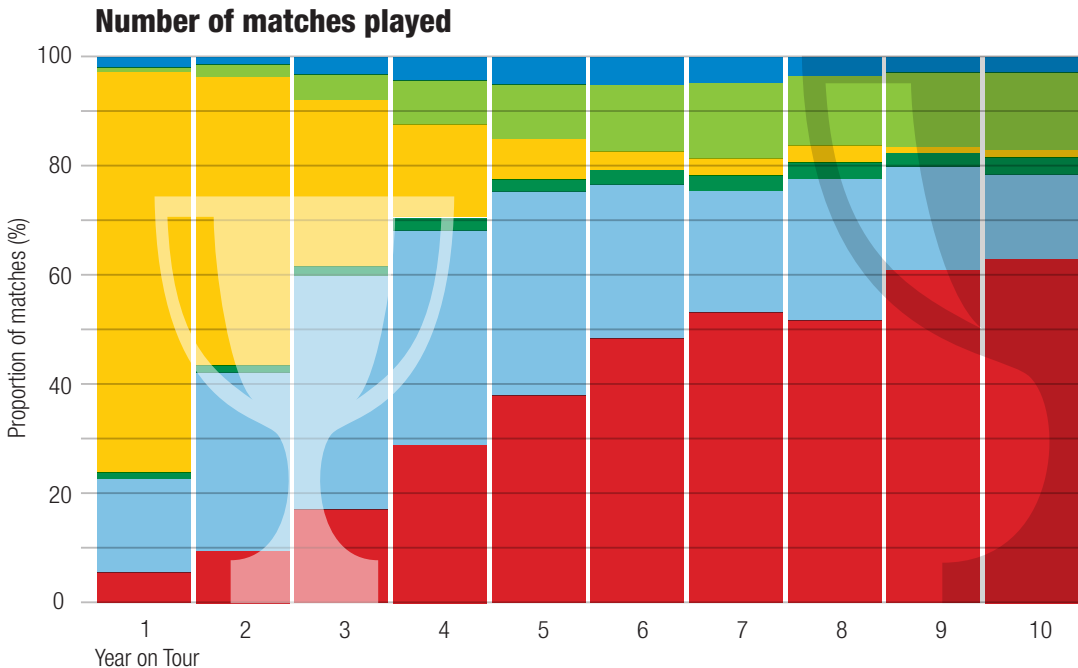
- ATP

Challenger

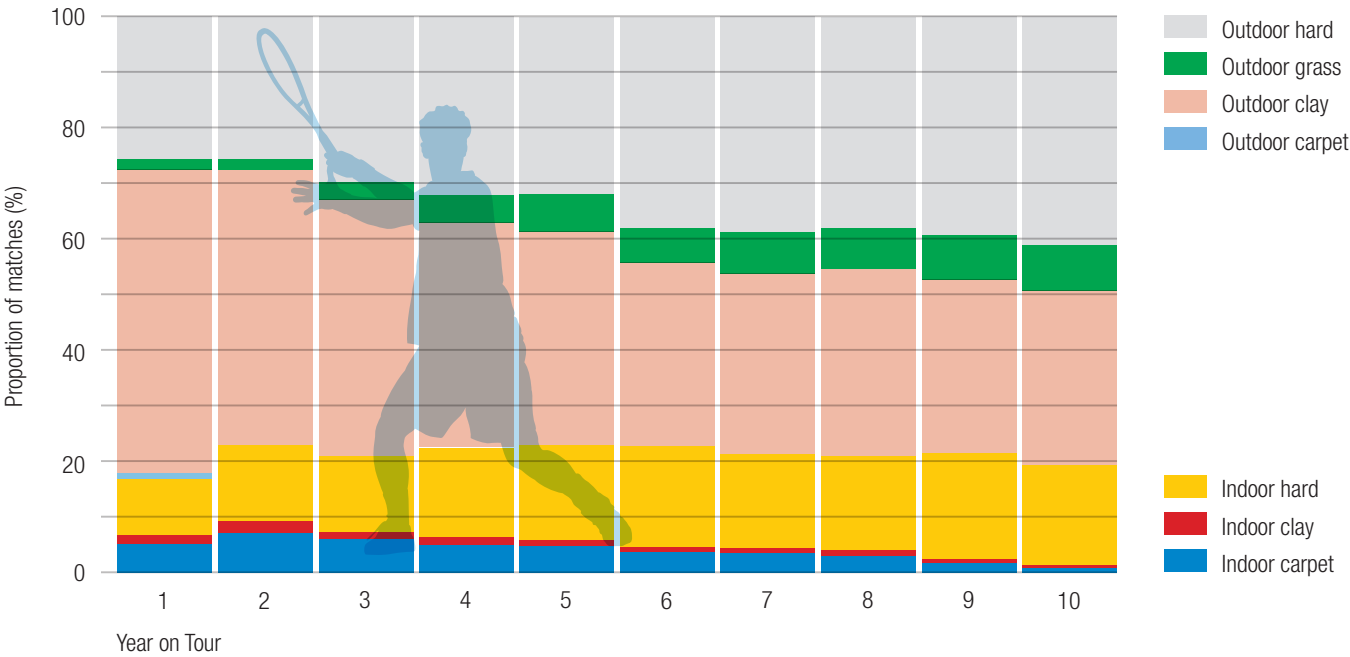
Davis Cup
- Futures

Grand Slam

Other



Surface statistics



▲ **On the surface** The graphic shows the percentage of matches played on different surfaces as a function of the number of years that the current ATP Top 100 players have competed on Tour. It's clear that tournament scheduling isn't just about what type of tournament you play. The surface upon which the tournament is held is

another major consideration. Developing your game on clay courts has been linked to better outcomes as a professional ^{2,3} (see also pages 56–57). The tournament history data support this observation. In the early years of their professional journeys, Top 100 players compete in the largest portion of professional tournament

matchplay on clay. In later years, a greater percentage of matches are played on surfaces such as outdoor grass and indoor or outdoor hard courts, presumably because of these surfaces' prominence in Grand Slam and high-level Tour competitions.

Number of tournaments played

MEN		
Tour category	Class	Average
World Tour 1000	ATP Pro Circuit	0
World Tour 250	ATP Pro Circuit	0.7
World Tour 500	ATP Pro Circuit	0.1
Challenger Tour	ATP Challenger	1.8
Davis Cup	Davis Cup	0.2
Futures	ITF Pro Circuit	8.5
Juniors Grade 1	ITF Junior Circuit	4.1
Juniors Grade 2	ITF Junior Circuit	1
Juniors Grade 5	ITF Junior Circuit	0
Juniors Grade A	ITF Junior Circuit	4.7
Juniors Grade B1	ITF Junior Circuit	0.4
Juniors Grade C	ITF Junior Circuit	0.1
Grand Slam	Grand Slam	0.2

WOMEN		
Tour category	Class	Average
\$10,000 Tournament	ITF Pro Circuit	2.1
\$100,000 Tournament	ITF Pro Circuit	0.2
\$15,000 Tournament	ITF Pro Circuit	0.2
\$25,000 Tournament	ITF Pro Circuit	2.9
\$50,000 Tournament	ITF Pro Circuit	1.2
\$75,000 Tournament	ITF Pro Circuit	0.4
Fed Cup	Fed Cup	0.3
Juniors Grade 1	ITF Junior Circuit	3.8
Juniors Grade 2	ITF Junior Circuit	0.7
Juniors Grade 4	ITF Junior Circuit	0.2
Juniors Grade A	ITF Junior Circuit	3.7
Juniors Grade B1	ITF Junior Circuit	0.5
Juniors Grade C	ITF Junior Circuit	0.1
International	WTA Pro Circuit	0.6
Premier Mandatory	WTA Pro Circuit	0.2
Premier	WTA Pro Circuit	0.3
Grand Slam	Grand Slam	0.1

◀ **Junior schedules** These tables show the average number of tournaments played in each category of Junior Tour tournament by the Top 10 ITF juniors in the years in which they made it into the Top 10. It can be seen that, for the male players, the Futures-level events clearly play a large role in their development. This is less true for female players, with Junior Grade A and Grade 1 tournaments together accounting for most events, followed by ITF professional events.

Which key variables affect outcomes at Grand Slam level?

What does Grand Slam tennis look like?

Many readers will be avid watchers and even players of tennis. However, if you were to be asked “How many shots are typically hit in rallies?”—would you be able to answer? Understanding what a typical match looks like helps players to tailor their training accordingly. For example, if the average rally lasted five shots, it would make little sense to spend most of your practice time hitting 20 or more balls in a row. Several studies have used notational analysis—the process of manually watching matchplay and recording key events—to provide an insight into the general trends of tennis matchplay at Grand Slam level.

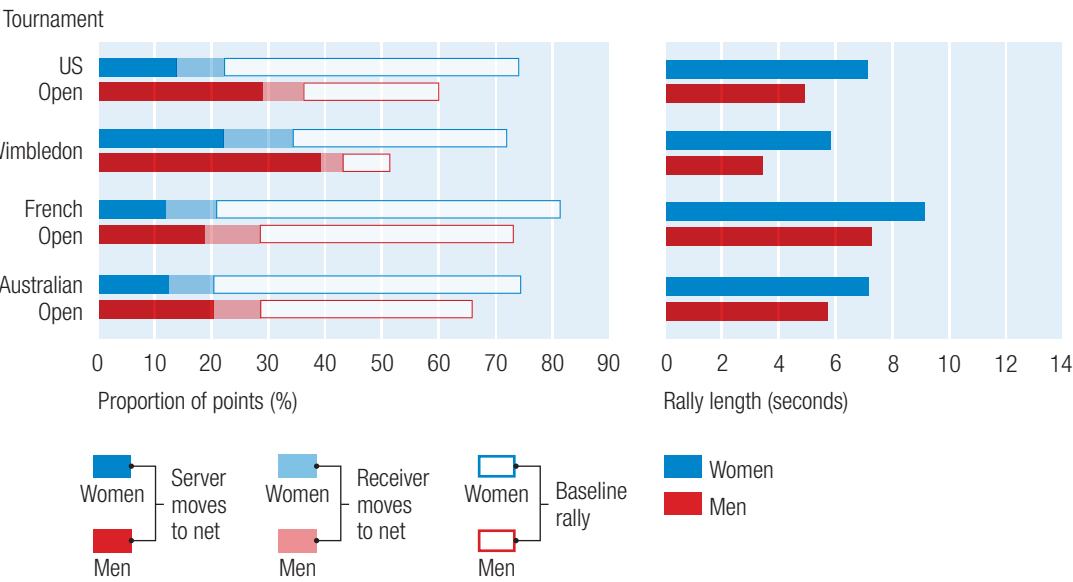
Perhaps the most comprehensive study into elite tennis strategy was performed by O’Donoghue and Ingram.¹ This study used notational analysis to derive statistics from matchplay in all Grand Slam matches between 1997 and 1999. The study found that rallies in men’s tennis were on average 5.2 shots in length, but significantly longer in women’s tennis

(7.1 shots). Logically, therefore, training should be tailored according to these gender differences. Rallies at the French Open were significantly longer (7.7 shots, on average) compared with the Australian Open (6.3 shots), US Open (5.8 shots), and Wimbledon—which itself had significantly shorter rallies than all other tournaments (4.3 shots on average).

The opposite trend was found for shots per second in rallies (a measure of tempo), with the French Open having the lowest shot rate and Wimbledon having the highest. These observations can be explained by the differing properties of the court surface in each Grand Slam tournament¹ (see Chapter 8, pages 164–165). Clay courts remove the greatest proportion of horizontal momentum from the ball through surface friction, resulting in a slower shot rate and greater difficulty in hitting winners—and thus more shots per rally. The opposite is true for Wimbledon, which is played on the fastest surface—grass.

► **Point to point** The O’Donoghue and Ingram study¹ provided an insight into the types of points played. In most Grand Slam tournaments, the majority of points are won during a rally, rather than directly from a serve. The Wimbledon men’s tournament is perhaps an exception, with close to 50% of points won as a direct result of the serve. Inter-serve time—the time between first and second serves—was not significantly different between sexes, and approximated 9.2–11 seconds across all tournaments. Inter-point time—time between subsequent points—is longer for men, and varied between 17 and 19 seconds over events. It is worth noting, however, that these data are from the late part of last century, and while it is likely that the game has moved on, research describing these relatively rudimentary game statistics has not.

Game statistics



▼ **Height/weight comparison** The average elite male tennis player (right) is not quite as tall as your typical NFL linebacker but the same approximate weight as an elite soccer player or 100 m sprinter. Interestingly, despite each sport's obvious physiological and mechanical differences, tennis players, soccer players and 100 m sprinters share remarkably similar body mass indexes of 23–24 (BMI = weight/height,² where weight is measured in kg and height is in m).

First among equals

Experience 7 ± 3 years



Basketball

Height 6 ft 6 in (198.4 cm)
Weight 208 lbs (94.4 kg)⁴



Soccer

Height 5 ft 11¼ in (182.3 cm)
Weight 172 lbs 10 oz (78.3 kg)⁵



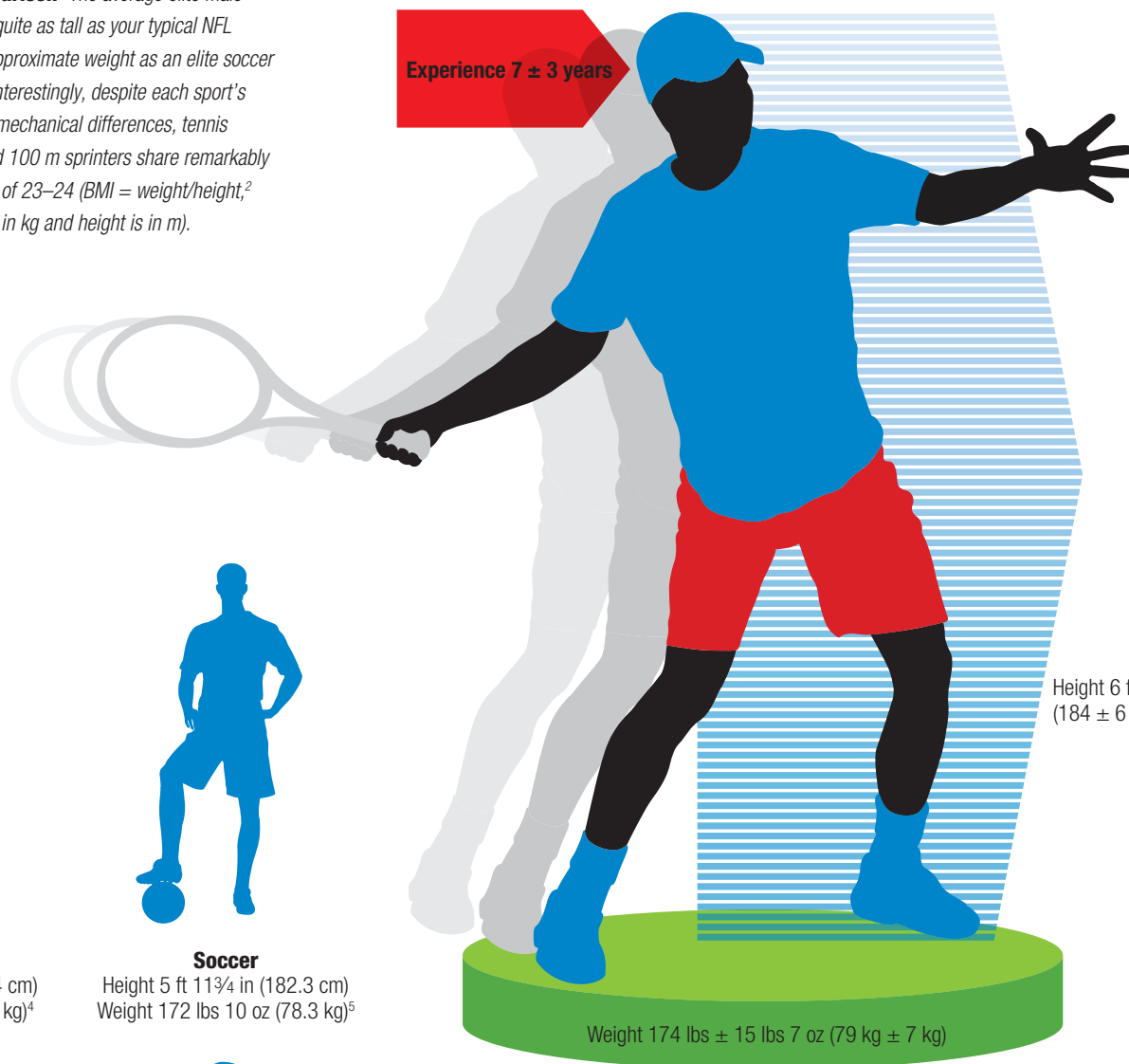
Sprinter

Height 5 ft 11¼ in (181 cm)
Weight 171 lbs 15 oz (78.0 kg)⁶



NFL linebacker

Height 6 ft 2 in (188.3 cm)
Weight 242 lbs 15 oz (110.2 kg)⁷



▲ **Beating the average** A recent study analyzed data from over 9000 men's Grand Slam matches played between 1991 and 2008 and determined the characteristics relating to the players who played in these matches.² It was found that the average competitor was 25 years old, with seven years of experience on Tour. Physically, on average, they were 6 ft (184 cm) tall and weighed 174 lbs (79 kg). Interestingly, the winner of a given match had two months' more experience on tour, and was quarter of an inch taller and almost two pounds heavier than his opponent, on average—all of these differences were statistically significant. This suggests that a taller athlete, who is likely to be able to serve faster,³ is at an advantage, and that experience certainly counts.

equipment: Hawk-Eye

You can't talk about modern performance analysis in tennis without mentioning Hawk-Eye. The technology first emerged during the television coverage of the 2001 Ashes cricket series, after which it won a BAFTA award for Sports Innovation.¹ It debuted in tennis as a broadcast tool during the BBC's 2002 coverage of the Davis Cup,¹ and—perhaps encouraged by the 2004 US Open women's semi-final, which was marred by a series of controversial line calls—it was embraced as a line-calling aid in October 2005, when Hawk-Eye was approved by the ITF for use.² In December of that year, it was implemented for the first time at a Tour event at the Nasdaq-100 Open in Miami.¹

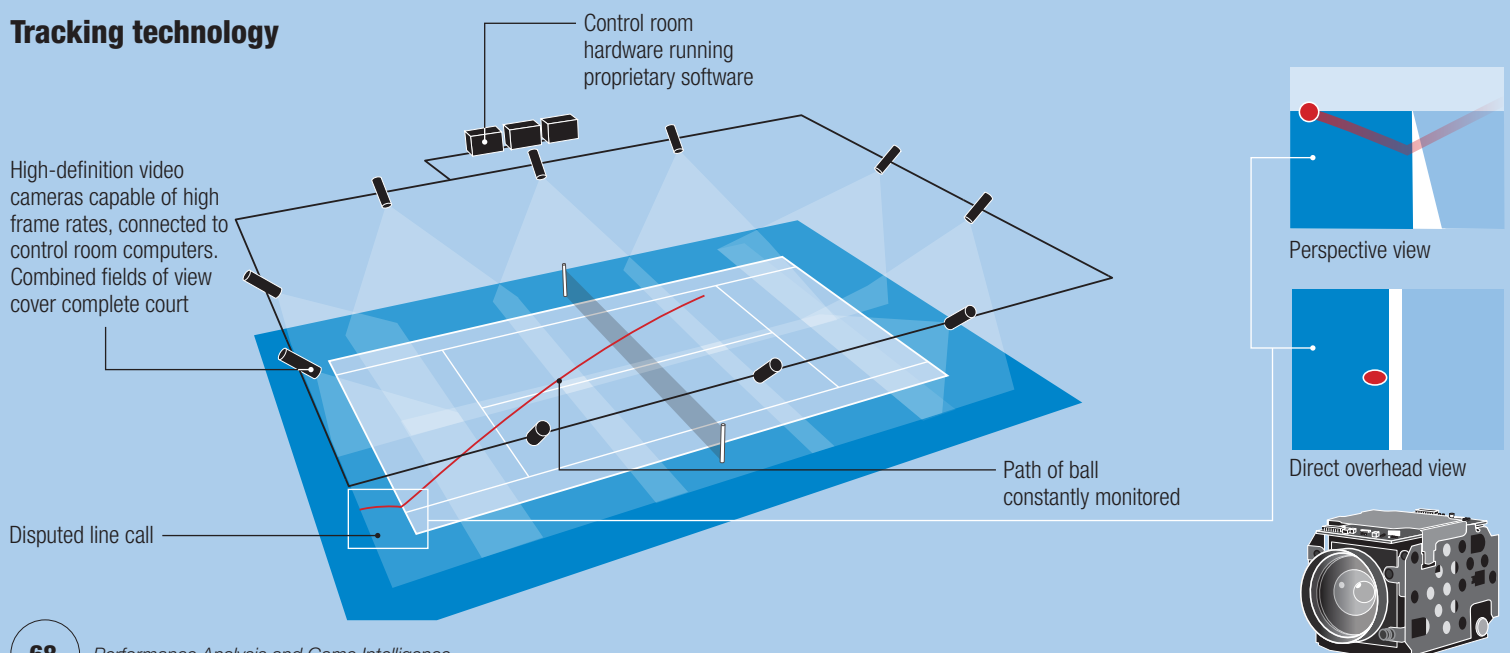
The technology, which tracks the motion of the ball in space and time, has led to an explosion in the quality and quantity of data available to tennis stakeholders. It has also greatly enhanced the fan experience, as matches are very rarely overshadowed by controversies surrounding line calls. While we now almost take

tracking technologies for granted, Hawk-Eye had to overcome significant technical hurdles to get to where it is today.

So, how does Hawk-Eye work? It's based on a sub-discipline of image-processing called "Computer vision."³ Fundamentally, videos are just large collections of numbers (three numbers—recording red, blue, and green—per pixel per frame). You can therefore subtract one frame from another, and this tells you where in the frame any specific moving objects might be. Of course, actually doing this in a practical, computationally efficient manner is very complex.

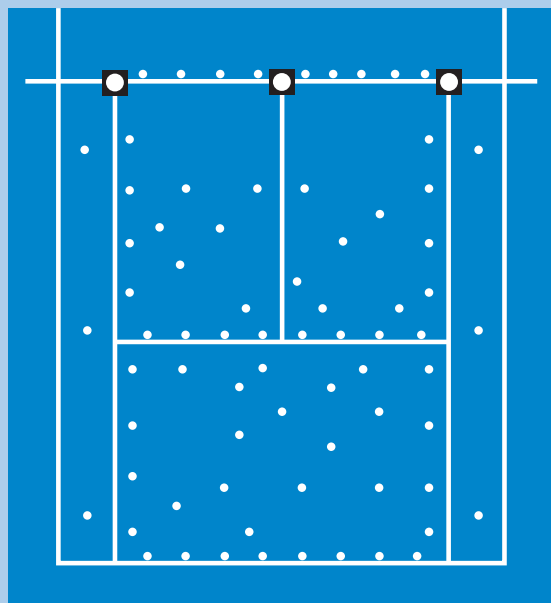
The technology has continued to evolve as adoption rates have increased. For example, in 2009, aspects of tennis play such as the type of shot being hit (backhand, forehand, or serve) were introduced as part of a typical Hawk-Eye output. Player tracking was then made available for the first time in 2012, and this has led to a better understanding of the typical work-rate of today's professional players.⁴

Tracking technology



► **Player tracking** Player tracking has enabled coaches to track players' movements around the court and help to provide guidance for stroke and fitness training. The trails in the image show the cumulative movements of two opponents during a set, amassing mainly around the baselines, with several moves toward the net for volleys. This detailed information can be used to analyze a player's own movements as well as their opponent's for future matches.

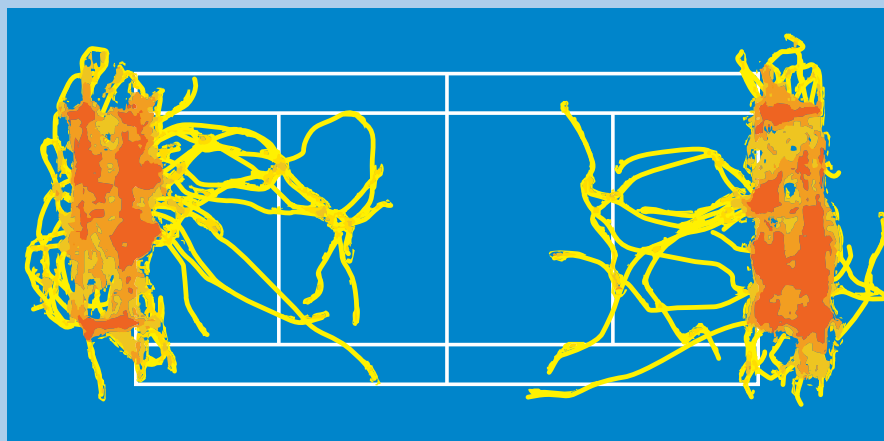
Hawk-Eye calibration



► **Service data** As well as helping with making line calls, Hawk-Eye's ball tracking can be used to analyze the precise placement of each shot, as with this picture of a player's first and second serves. Coaches and players are now able to access huge amounts of data to help guide shot-making and prepare for matches by analyzing the strengths and weaknesses of opponents.

◀ **Hawk-Eye system** Hawk-Eye uses high-frame-rate cameras (recording at 50–60 Hz²) to record the flight of the ball. Typically, you will find 8–10 of the cameras positioned around each court.² Each camera can only detect a ball's location in two dimensions. The three-dimensional location of a ball is then constructed from these 2D video feeds using triangulation. Finally, the 4D (3D plus time) trajectory of the ball is constructed by repeating the process of tracking and triangulation at each frame.¹

Match moves



◀ **Accuracy** The ITF has performed a rigorous validation of Hawk-Eye ball tracking, comparing it to a 2000 Hz video recording.² Ultimately, Hawk-Eye passed this validation, and became the first accredited tracking technology approved for use at official Tour events. The results showed a mean error for Hawk-Eye of 3.6 mm when compared to a high-speed camera. The testing was performed under variable light and on windy courts. Recent research, however, has called into question the accuracy of Hawk-Eye for line calling, specifically by investigating the deformation of the ball as it bounces.⁵ This deformation depends on multiple factors, such as spin and velocity, which complicate the task of reconstructing the shape of the bouncing ball. Ultimately, Hawk-Eye still gets line calls right more often than humans.⁶

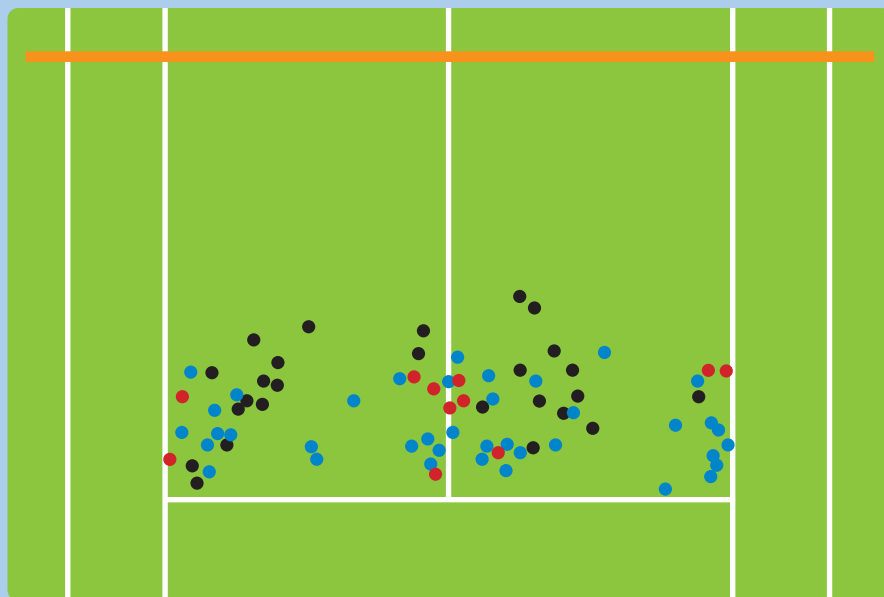
Service pattern

● ACE

● First serve

● Second serve

Serve analysis



What insights are gained from analyzing Hawk-Eye data?

The evolution of tennis has been closely linked to the development of a range of technologies designed to improve the performance of tennis players. When Hawk-Eye is mentioned, most people invariably think of its role in line calls. But Hawk-Eye records more than just the bounce of the ball (see pages 68–69), and has enabled far more detailed analysis of the way tennis is played than ever before.

Demaj and Kovacs¹ analyzed Hawk-Eye spatio-temporal ball trajectory data in order to gain insight into the Olympic gold medal play-off between Roger Federer and Andy Murray in 2012. They reported that Federer’s serve pattern was more variable than Murray’s during this match, with Murray more likely to target his opponent’s backhand. Players can take advantage of this sort of analysis to inform their training regimes. For instance, there are two ways to interpret this statistic: an opponent facing Andy Murray would be well advised to practice their backhand returns prior to playing

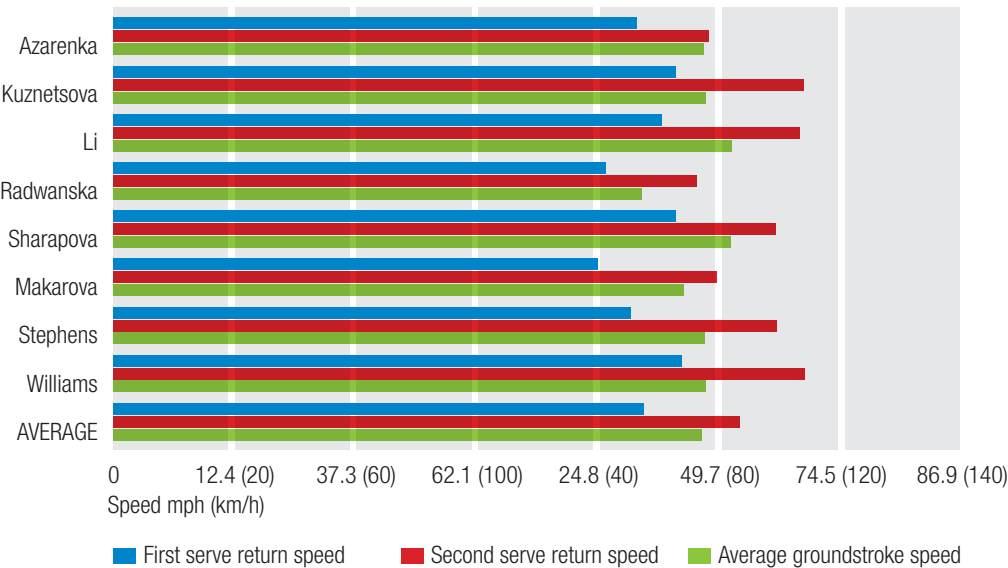
What can tracking technologies add to my game?

him; or, perhaps more likely, Roger Federer’s forehand return may be more effective than his backhand return.

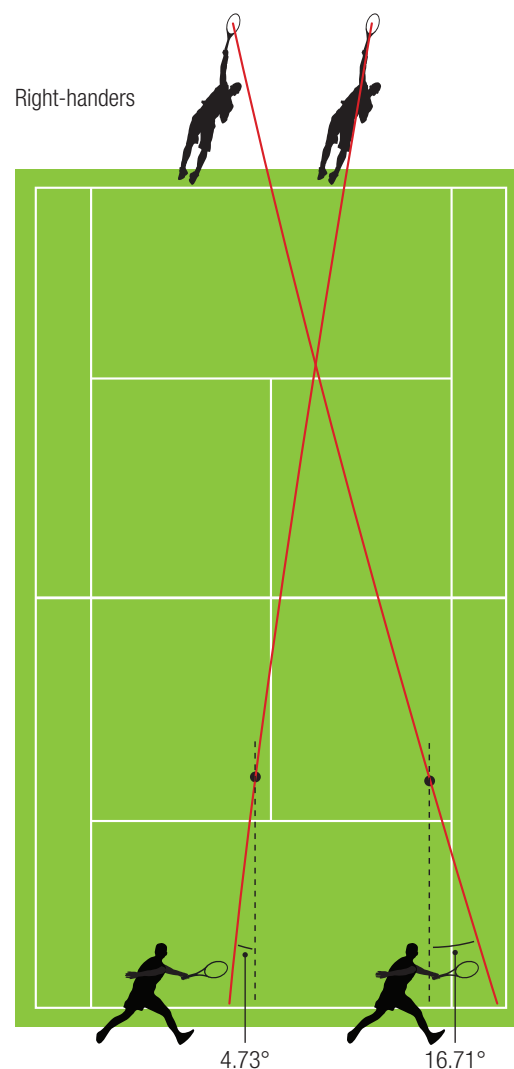
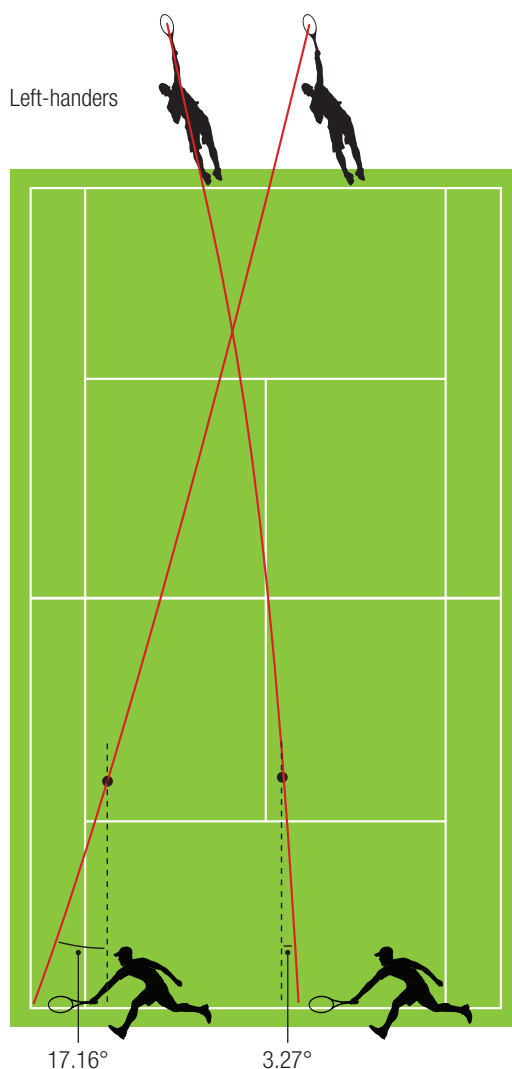
Several matches can be analyzed simultaneously to provide an insight into general patterns of play. Loffing et al.,² for example, analyzed over 4500 serves from male left- and right-handed players. What they found was that the mirrored angles of lateral ball flight were significantly different between left- and right-handed servers, for both T and wide serves. This means that, as the ball crosses the baseline, there would be approximately a 4 in (10 cm) difference in lateral position between the left- and right-handed serve were it to land in the same position—enough to ensure a return does not strike the racket’s center if a player doesn’t adjust accordingly. This can place left-handers at an advantage, given their low representation relative to right-handers on the Tour. The take-home message is that there really is no substitute for practicing against left-handers when you’re preparing to face a left-handed opponent.

► **Hawk-Eye data** Tennis federations around the world use Hawk-Eye data to analyze player techniques. This is an example of a Hawk-Eye report generated at Tennis Australia’s performance analysis unit. The first two graphics show that female and male players hit forehand and backhands at comparable speeds with the exception of the first serve return, which is hit at a lower pace by the men. In the graphic at far right, net clearance for the majority of male players is shown to be less on first-serve returns, intuitively brought about by a player’s need to keep their swings short, with less opportunity to impart spin on the ball. Such analyses can provide player-specific insight into the recovery time that servers can expect after their service, which can inform practice prior to matchplay.

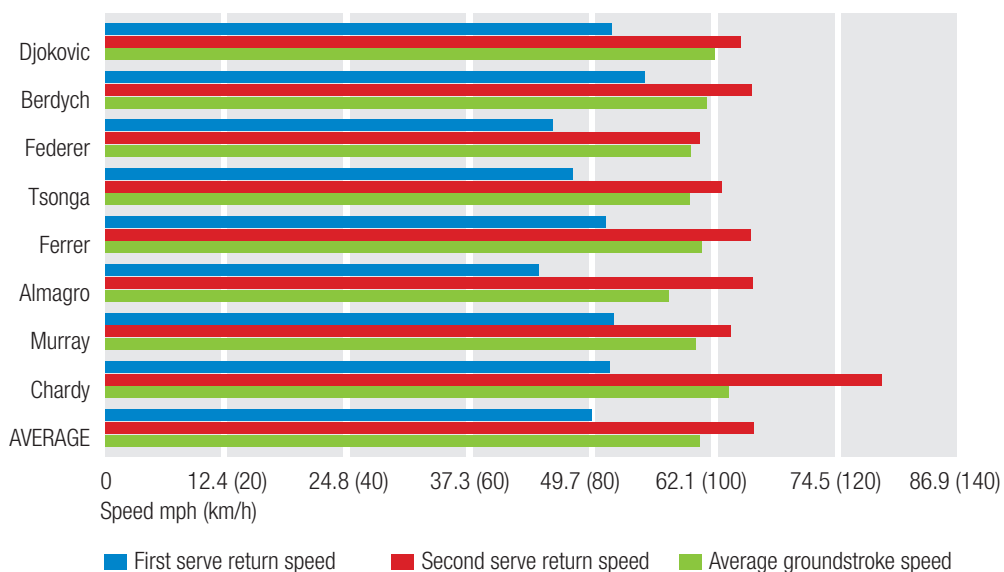
Female shot speed



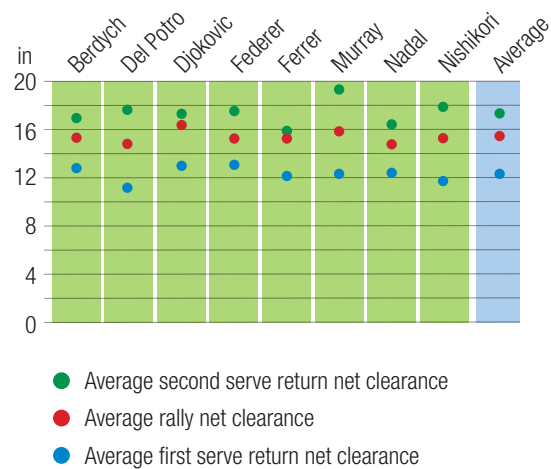
► **Angles** This shows the average, mirrored lateral angle of balls served by left- and right-handers, to both the T and wide parts of the court. Note that, in both cases, left-handers were able to direct the serve further away from their opponent.



Male shot speed



Male net clearance



Does scoreboard pressure affect winning points?

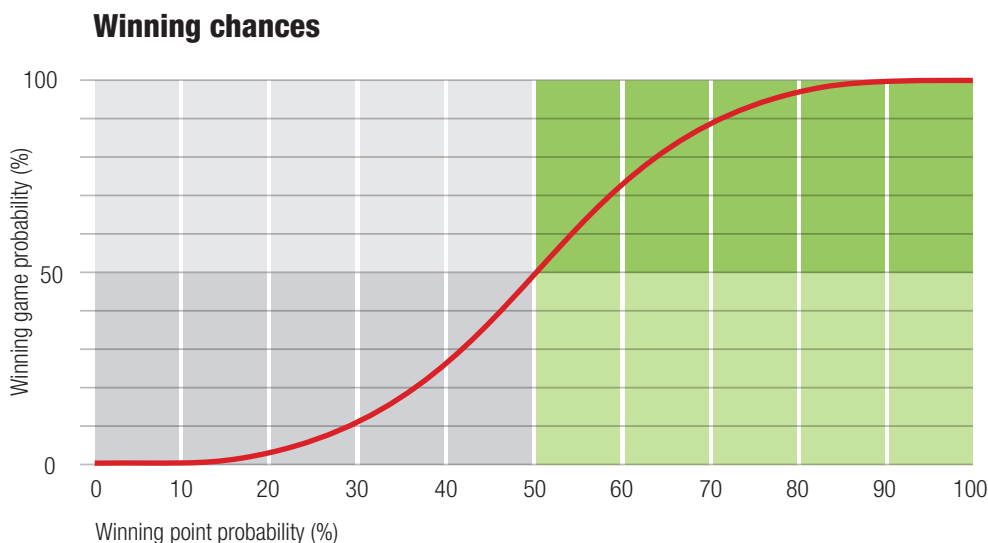
Are some points more important than others?

We instinctively feel a sense of importance on some points more than others. There are the obvious scenarios, such as at game point, when losing the game gives a clear advantage to one player, but what about the other points? Does it really matter if you lose the first point on serve, for instance?

Morris¹ investigated the concept of “point importance” and concluded that the “most important” points were “30–40” and “Advantage receiver.” This is logical, given that losing these points ensures a break of serve, and winning them evens up the game score, putting the server at an advantage. Points classed as “important” were “15–40,” “15–30,” “30 all,” and “Deuce.” All other points were deemed of “least importance.” Klaassen and Magnus² established that the chance of a server winning a point significantly decreases as point “importance” increases. That is, the increased pressure of these more important points presumably leads

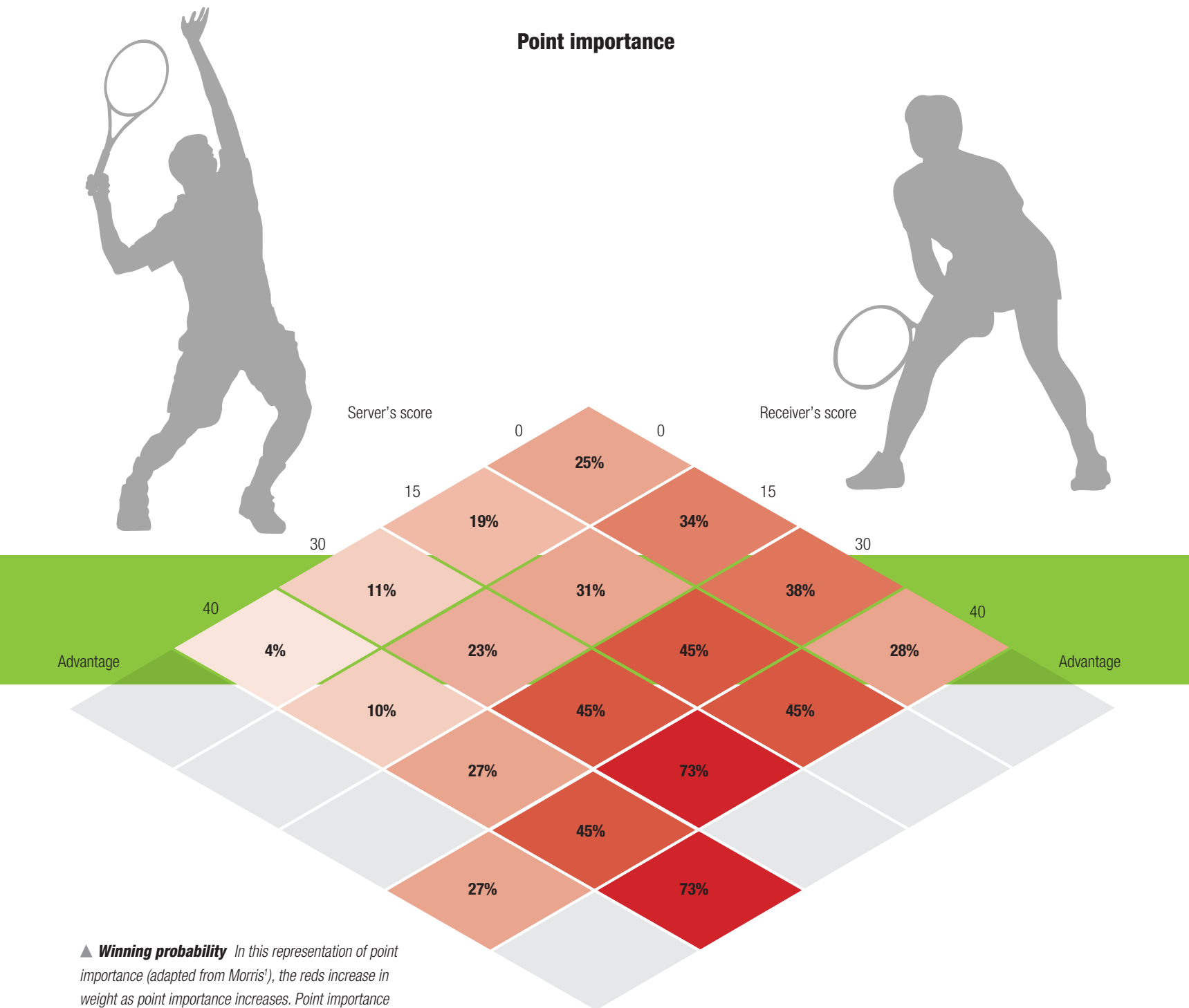
to mistakes from the server. Barnett³ has suggested that a higher-risk serving strategy (such as serving a far more aggressive second serve) could be employed on important points as a result.

Scoreboard pressure isn’t just about the absolute score, however. The effect of losing the previous point on an athlete’s chances of winning the next point was investigated in over 90,000 points at Wimbledon.² The researchers found that points were not identically and independently distributed. In fact, the chance of losing a point was significantly greater if you lost the previous point. Furthermore, the effect was smaller for players who were deemed to be of higher quality (taking into account a range of factors including ranking). In that sense, higher-quality players are presumably better able to “move on” from losing points, and actually significantly improve their chances of winning the next point.



◀ **Every point counts** One of the most unique aspects of tennis is its scoring system, which is complex compared to other sports, and ultimately leads to a non-linear relationship between winning points and winning games.⁴ For example, two players with a 60% and 70% chance of winning a point, might have a 74% and 90% chance of winning the game, respectively. The difference between winning and losing is smaller than final score lines may suggest, since small differences in the probability of winning points translate into large differences in the probability of winning games and tie-breaks. So, even though a focus on important points can be beneficial, small improvements in your chances of winning all points can pay big dividends.

Point importance



▲ **Winning probability** In this representation of point importance (adapted from Morris'), the reds increase in weight as point importance increases. Point importance (expressed by the percentage numbers) is defined as the probability that the server will win the game given that they win the next point, minus the probability that the server will win the game given that they lose the next point. It is assumed that the server has a 62% chance of winning a point of serve.



Coaches, players, officials, and fans all agree that the contribution of psychology to successful and healthy tennis play is significant. This consensus is borne out by game analysis, which highlights the psychological characteristics common to great players and the mental challenges inherent to the game, as well as the mental skills that players and coaches consider important for both winning and having fun when playing tennis. Research has shown that players and coaches are gradually becoming more aware of the importance of mental skills, as well as more interested in understanding and applying mental training techniques in their daily work. This chapter discusses the role that science plays in enabling a player to use mental skills for efficient performance and game satisfaction.

The first part introduces the psychological basis for tennis play, explaining the role of sports psychology in tennis development; the main psychological abilities and related strategies used to develop a healthy and competitive tennis mind; and the application of mental skills to tennis training. The second part focuses on how the different mental skills required for tennis all work together to maximize performance. Among the tennis-playing elite, the mind ranks as the strongest competitive weapon—the ability to learn, develop, and optimize the use of psychological skills in different game situations on court, and at different times off it, becomes vital to success.

chapter four

the mental edge

Miguel Crespo and Paul Lubbers



How does psychology affect tennis performance?

Do I need to be mentally tough to play tennis?

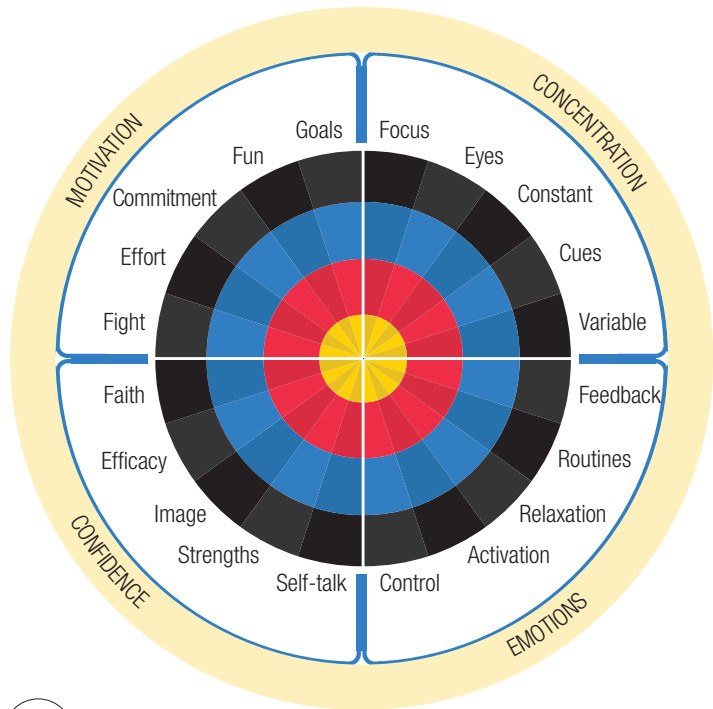
Competitive tennis involves two major mental challenges—one is concerned with the contest with the opponent, while the other is internal, as a player “wrestles with their own demons.” A player’s mental state during a match will often have an enormous impact on their physical state. Top players and coaches believe that the mental side of tennis is extremely important, especially when the physical abilities of two players are equal. After all, there is little that can be done to improve a player’s technical and physical play just before and during a match, but it is possible for mental skills to make a real difference to the outcome.

Given this, it is perhaps surprising that mental skills are not practiced as often as technical, tactical, or physical skills. The important thing for players and coaches to remember is that psychological skills can be learned and improved if

practiced regularly. These skills aren’t inherent in players, and coaches can help to develop them through exercises and techniques both on and off the court.¹

Many studies conducted with both recreational and competitive tennis players have shown a direct relationship between the use of one or more sports psychology strategies and an improvement in tennis performance. Studies using several psychological programs or techniques have demonstrated improvements in serve technique, anxiety control, self-confidence, and performance in adult players. Studies have also shown that for a sports psychology program to be successful, both athletes and coaches must take full part in its concept and implementation.²

Strategies for improvement



◀◀ **On target** This wheel outlines some of the key psychological components—motivation, concentration, emotions, and

confidence—that can help an athlete perform at their maximum, together with the main strategies that players can use to improve them.

Motivation	Concentration
This is the complex process that determines the direction (why tennis and not another sport?) and intensity (why work so hard?) of a player’s effort.	This is the ability to maintain attention on the relevant cues during an extended period.
Fight —the ability to be combative during matchplay	Focus —the center in which interest converges
Effort —the use of physical or mental energy	Eyes —one of the key body parts that affect concentration
Commitment —the attitude of being engaged or obliged to achieve something	Constant —the need for concentration to be continuous, recurrent, and regular
Fun —enjoyment, amusement, or pleasure in play	Cues —the signals or sources of information in the surrounding environment
Goals —the objectives and aims of a given action	Variable —the feature of concentration that needs to adapt to the environment

Training program

1. Analysis

The coach begins by gathering information on the player through observation, meetings, questionnaires, self-reports, or coach inventories. The information will include: personality, family background, interests in tennis, career expectations, and tennis characteristics, as well as their environment (roles of partner, parents, friends, and so on), and game (player development path, ranking).

2. Goal setting

The coach should next establish goals with the player that are specific, measurable, agreed, realistic, and timed (SMART). These are crucial for determining the training content in all periods of the season.

3. Training

On-court and off-court strategies should aim at meeting the established goals. Psychological training should consist of a combination of on- and off-court activities and drills that will assist players in improving their mental skills. Mental training drills should be included in the daily program by adapting the technical, tactical, and physical drills.

4. Competition

The player should follow individual psychological warm-up routines before a match, including relaxation or activation techniques, positive thinking, and specific match goals. The effective application of all of the mental skills strategies, including routines, is crucial during the match. Afterward, the coach and player should analyze and fine-tune the mental skills that have been used during the match.

5. Evaluation

Data obtained in the competition stage is used to optimize the effectiveness of the mental skills training program. Player feedback should be encouraged. The player should reassess their progress at the end of each year and plan new goals for future success.



◀ **Mind over matter** A set of steps need to be followed in order to implement a mental training program for the player.

▼ **Drills and exercises** The table lists some examples of recommended exercises for improving the key psychological skills that a tennis player needs to succeed in competition.

Exercises to improve mental skills

Mental skill	Exercises to improve skill
Motivation 	• Goal setting • Training diaries • Fun and optimal challenge drills • Drills that demand 100% effort from the player, creating the right motivational climate with varied and enjoyable practice, ensuring players win more matches than they lose • Competitive drills against other players or against themselves
Concentration 	• Focusing drills which use visual cues (targets or colored balls) or auditory distractions (music or noise) • Consistency and endurance drills • Routines before and after the point and during change-overs, goal setting, and visualization
Emotions 	• Activation or relaxation techniques (breathing control, bio-feedback, music, yoga, meditation, centering, progressive muscle relaxation, autogenic training, humor) • Visualization, behavior modification techniques (stress inoculation, systematic desensitization, cognitive restructuring), and routines
Confidence 	• Using self-talk, self-evaluation, and powerful verbal and non-verbal communication • Drills in which the strengths of the player are worked on, providing positive and realistic feedback • Competition drills against other players • Cognitive strategies (thought stopping, positive thinking, problem solving, cognitive restructuring, mistake management, assertive training, role modeling and playing, time management, rationalization)

Emotions

The ability to control feelings efficiently, maintaining an equilibrium, which is very important during play.

Control—the influence over feelings

Activation—a state of physiological and psychological arousal which runs along a continuum from deep sleep to intense excitement

Relaxation—a state free of stress or tension

Routines—rituals to help attain a particular mental state

Feedback—the information derived from a particular event

Confidence

The degree of certainty that players have in their ability to be successful in executing a skill or series of tasks, which is proven to be one of the best predictors of competition success.

Faith—the belief in one’s capabilities to achieve a goal

Efficacy—the opinion on how efficient you are when faced with a challenge

Image—the concept projected by someone

Strengths—the positive points of a player

Self-talk—the ability to effectively use verbal communication with oneself to affect performance

Can practicing mental skills improve performance?

How well can I train my mind?

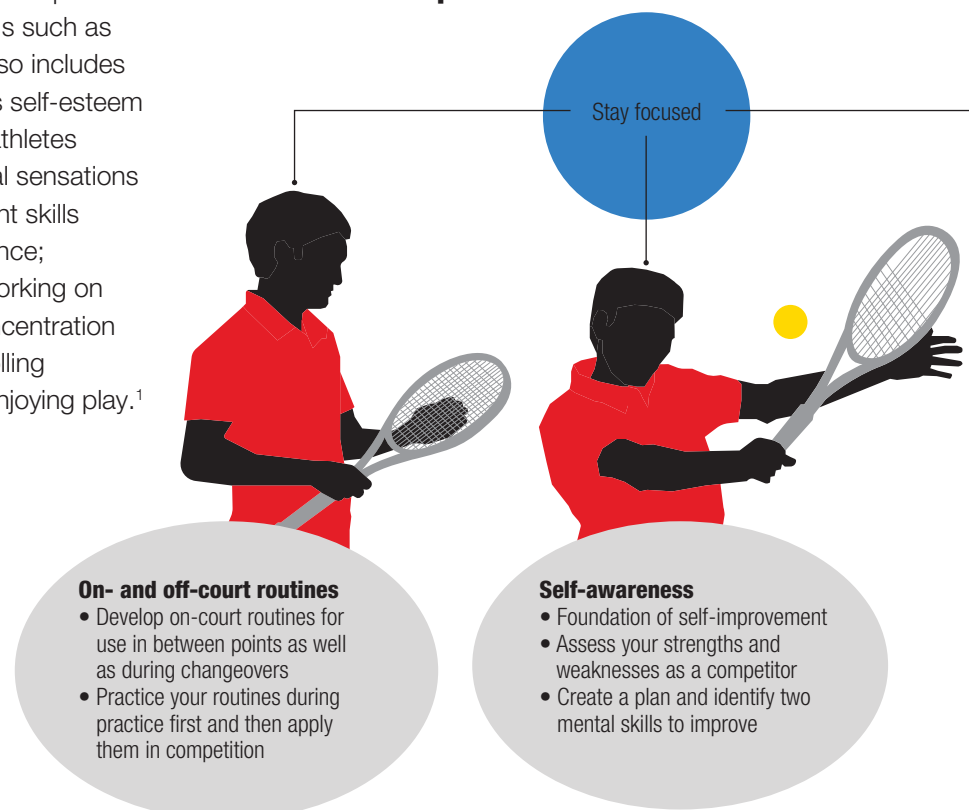
The field of sports psychology has contributed significantly to the improvement of tennis coaching and playing at all levels of the game. At higher levels of tennis competition, when physical skills and tactics are more comparable, psychological skills take on even greater importance. Most players and coaches agree that the mental game is essential to achieving peak performance. However, despite this widespread agreement on the importance of psychological factors such as motivation, confidence, and concentration, tennis coaches and players are often inconsistent in working on psychological skills as part of their daily training schedule. Mental skills cannot be treated casually or turned on and off at will—they need to be practiced regularly, just like the game's other skills.

Mental skills are procedures that help athletes to control their minds efficiently and consistently as they work toward sport-related goals. This not only involves developing skills such as concentration and positive body language, but it also includes efforts to influence personal characteristics such as self-esteem and sportsmanship. Mental skills techniques help athletes adjust their actions, thoughts, feelings, and physical sensations to improve their games. Some of the most important skills identified by research include: creating self-confidence; setting goals; using imagery and visualization for working on competitive skills; staying focused, maintaining concentration and attention; taking personal responsibility; controlling emotions; staying motivated and passionate; and enjoying play.¹

► **Stay focused** This is a brief summary of the most important mental skills to focus on in training. Mental skills such as match and practice preparedness, sportsmanship, on-court routines, error management, positive body language, and positive self-talk should be addressed during on- and off-court coaching sessions as part of the training program.

It is important to remember that these mental skills, like physical skills, must be introduced, rehearsed, refined, and developed both in practice and in competition. Research has shown that, when practiced in a systematic manner, they can become automatic.² Mental skills support physical conditioning, technical proficiency, and tactical understanding and can help improve the player's ability to deal with pressure and adversity; and, ultimately, improve overall competitive performance.

Mental skills to improve focus



Coaching mental skills

Mental skills development of players



Training program

Exercises, drills, and activities that can be performed both on and off court—they can be directed by the coach or a sports psychologist and can be specific or combined with other technical, tactical, or conditioning drills



Coach training knowledge

Content

Coach must possess adequate knowledge of mental skills techniques

Process

Coach must be able to understand how to implement and adapt a training program



Training climate

Player attributes

- Gender
- Skills
- Culture

Coach–player relationship

- Awareness/ability to read players
- Communication skills
- Trust

Outside factors or obstacles

- Parental or partner's views of mental skills
- Time constraints



Coach's approach to training

- Formal education in sports psychology
- Informal experience
- Reflection on importance of mental skills for tennis
- Desire to help players improve mental skills

Player's needs

- Session plan/goals/injuries
- Ability of the coach to recognize the player's needs
 - Increasing self-confidence
 - Arousal regulation
 - Improving sportsmanship

Translating training to play

- Understand the link between quality training and peak performance
- Train with intention and purpose

▲ **Mind coaching** This graphic outlines the factors that affect the coaching of mental skills, incorporating understanding, teaching, and studying mental skills to help athletes achieve their individual goals.²

How does self-confidence affect performance?

How much better will I play when I'm confident?

Tennis is an individual sport with an intermittent nature that causes a considerable amount of “dead time” during matchplay. This places high demands on the cognitive aspects of the player's performance. One of the key components in this area is the player's self-confidence, which can be defined as the belief or degree of certainty that the player has in their ability to be successful in executing a skill or series of tasks. This self-belief, which has been shown to be one of the best predictors of competition success, can also be improved with psychological training.¹

Building and maintaining appropriate thoughts before, during, and after a match is one of a player's main goals. To do so, players need to become aware of their thoughts and to regulate them, particularly during critical moments. This process, in turn, will help them to develop their self-confidence. In order to develop sound mental skills, coaches may assist players in the use of a variety of strategies such as: thought stoppage, positive body language, goal setting, imagery, focus on the process rather than the outcome, and the ability to increase and decrease intensity.

Self-talk—the use of positive and motivational key words—is one of the sports psychology strategies that can be used to improve confidence. Latinjak and colleagues² examined the effects of self-talk on thought content in tennis and showed that, as players' execution-related thoughts (for instance, “watch the ball until impact” or “follow through over the shoulder”) increased, outcome-related thoughts (for instance, “hit the ball in” or “win this point”) decreased significantly. This supported the idea that self-talk could help tennis players to focus on task-relevant information and thus improve their performance. Research by Van Raalte et al.³ has also found that negative self-talk is associated with losing, and those players who reported believing in the utility of self-talk

won more points than players who did not. Positive self-talk, such as “move the feet while the ball is coming” or “use a square stance to hit the ball,” does therefore influence competitive tennis outcomes.

Self-talk



**6 games all, 7-6 points up,
serving second serve**

▼ **Confidence trick** Self-talk can improve self-confidence. Research collectively suggests that self-confident players are characterized by or benefit from: being more positive; enhanced concentration; more fighting spirit, with positive flow-on effects to physical endurance; more challenging goal setting; being more successful during practice and matches; performing better under pressure and in adversity; having lower cognitive and somatic anxiety levels and lower total mood disturbance; and not being as affected by negative events, such as losing a match. ^{4, 5, 6, 7, 8}



Winning thoughts

◀ **Winning!** When comparing winners to losers, it has been found that winners do the following: attribute their performance more to internal or personal factors (effort) and stable factors (effort, difficulty of the match), and less to internal debilitating factors (lack of practice);⁹ associate the expenditure of high effort more with internal factors;¹⁰ and attribute convincing wins to skill and effort, but ambiguous wins to the difficulty of the match.¹¹ Some players will focus on their performance rather than the outcome of the match, and therefore be more or less satisfied (with their performance) irrespective of the result.¹²

"OK, here we go. This is it.
Will play my game. Will
use my strengths. Will fight
every single ball!"



One set all

"How have I dominated
the match so far? I need to
maintain the momentum!
Build my game around my
winning strategy!"



Changeover

"Need to keep this rhythm. Solid
with the return! Compact swing!
Show that I will close the match
as soon as possible!"



5-1 up in the third set,
return game

equipment: heart rate monitor

The heart rate monitor is a device that tennis players use during training and competition to improve their psychological performance by assessing heart rate. Despite the stop-start nature of the game, heart rates during matchplay are not decisively different from recovery periods between the points, and do not show distinct variations with the duration of the match.¹ However, during long and fast rallies the heart rate can increase to 190–200 beats per minute, which is very near to a fit player's maximum heart rate. These periods of high physical intensity are relatively short, and an athlete in good condition will recover quickly to the normal match level of heart rate. A player's concentration is much better at normal heart rates, and so being in good physical condition is critical to focus and being mentally prepared for the next rally.

The heart rate monitor provides crucial information in the form of biofeedback, which players can then use to control their body functions. Knowing their heart rate during a match or training session allows the player to compare it with that recorded in their Ideal Performance State (IPS). It is then

possible to make changes and adaptations—through breathing and relaxation techniques, for example—to control stress, improve focus, increase activation, and reduce worry. The IPS is the mental state that players experience when they bring their talents and skills together to sustain a high level of performance over time. Essentially, the player is able to mobilize their energy on demand to harness their physical, cognitive, emotional, and spiritual capacities to perform to their full potential.

It has been shown that psychological strategies that involve biofeedback are effective in arousal control. Arousal is a state of physiological and psychological activation, which runs along a continuum from deep sleep to intense excitement. Arousal needs to be optimized if maximum performance is desired. Finding and maintaining a state of optimal physical and mental arousal is highly individual and by no means easy, and, when confronted with high-stress environments, players skilled in doing so come to the fore. Anxiety is a negative emotional state—a form of arousal triggered by fear or the perception of danger. Players can use the biofeedback provided by the heart rate monitor as a means to effectively help them adapt their thoughts and behaviors to facilitate their best performance.

► **From the heart** Monitors come in a range of forms, from a chest strap to a watch or wrist strap. Most use sensors in contact with the skin to capture the heart rate signals of the player. The chest strap is made of a soft fabric, containing the sensor and transmitter unit, and uses a hook mechanism that makes it very easy to put on and take off. These straps are comfortable to wear during strenuous activity, and adapt to allow full freedom of movement in the upper body. The device then uses a wireless technology, such as Bluetooth, to transfer the data to a watch-based receiver or a compatible application running on a mobile device, such as a smartphone or tablet, or a computer.

Chest and watch strap



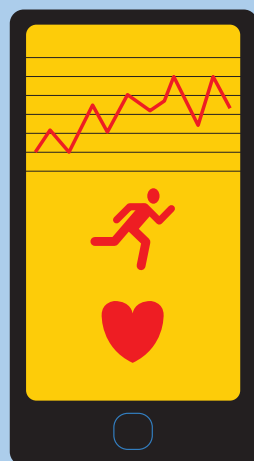
Fabric sensors



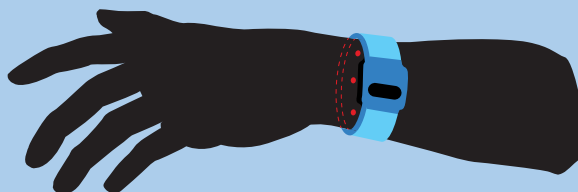
▲ **Wearable tech** With modern fabric technology, it is now possible to embed sensors, or any device which includes sensors and microprocessors, in the material of garments like this vest. It is expected that wearable biometric technology will develop over the coming years.

► **On the phone** The receiver of a heart rate monitor is generally a smartphone. When paired with the heart rate transmitter and using a specially designed app, this allows the athlete to view their heart rate, heart rate variability, breathing rate, calorie burn, and so on. The data can also be transferred to laptops to visualize the information in different ways. There are more sophisticated receiver devices that link heartbeat signals from heart rate sensors to other relevant data, such as breathing rate, to provide feedback to athletes that can help them to achieve optimal physical performance.

Receiving data



Wrist monitor



▲ **At your wrist** As your heart beats, your capillaries expand and contract due to changes in blood volume. A wrist-based heart monitor uses LED lights that shine on your skin and measure the rate of expansion and contraction. For example, Fitbit's band uses two bright-green LEDs (proven in scientific studies to be more effective at monitoring heart rate than other wavelengths) to shoot light into your flesh and detect these blood volume changes beneath the skin.

Server heart rate



◀ **Stress test** Research has recorded higher heart rates for the server than for the receiver.² The difference has been attributed to the more active and dominant role of the server in dictating the game, as well as to the higher psychological stress of the server. This stress in the server results in the increased release of epinephrine (adrenaline), which may contribute to the higher heart rate.

Do relaxation strategies enhance performance?

How important is it to relax during a match?

Tennis players want to win and play well, often competing for money, trophies, and rankings, either for their team or for personal achievement. This is part of the thrill of competition, but often this is also the root of stress and anxiety. Many of the world's best players have admitted to how, at times, they are overcome by nerves, but have dealt with the stress and anxiety. They have done this by learning to regain control, and using coping strategies and relaxation skills to enhance performance.

Stress begins when a player believes that they do not have the ability to meet the demands of competition—for instance, winning the match, or playing their best tennis in front of others. This perception triggers negative self-talk, doubt, anxiety, lack of confidence and feelings of fatigue, which in turn trigger a deep physiological response where the player's heart rate increases, blood pressure rises, and muscle tension increases. This is not a productive sequence if one is trying to compete at the highest level!

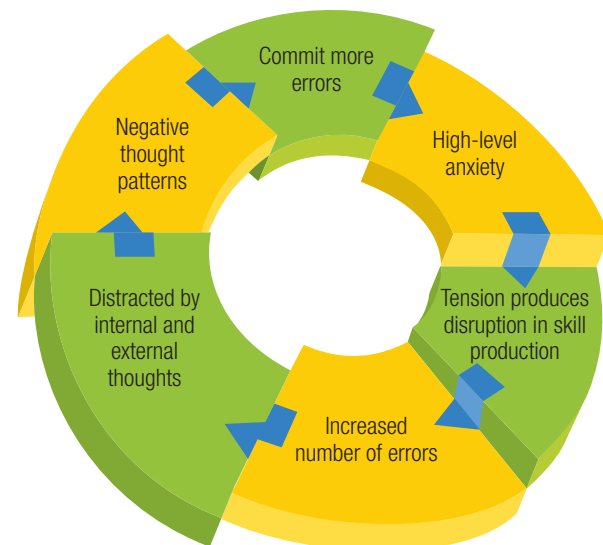
To combat this cycle, the first step to relaxing is for the player to become self-aware—monitoring both the causes and symptoms of the stress. Many players learn to view the symptoms of stress as positive and part of the routine for competition.¹ Another way to learn to relax during a match is to not only control negative thoughts, but also learn to control both breathing and muscle tension. Many players use the time

between points and games as an opportunity to employ centered breathing—this helps them to regain and maintain emotional control during high-pressured situations. In addition to breath control, many players use progressive relaxation, which involves the alternate tensing and relaxing of specific muscles. This helps the player to learn to feel the tension that is built up in the muscles and then let go of it.² With practice, players not only learn to recognize tension, but to release it and relax during competition.

Tennis players are relaxed when they are mentally and physically free of the tension and anxiety that produces thoughts such as: “I need to win this match” or “I cannot double fault.” Players in a relaxed state generally report feelings of tranquility, thoughtlessness, and calmness. Through the implementation of breath control, progressive relaxation, and the development of on-court routines, players can gain higher levels of concentration and focus, which in turn lead to more success and a more enjoyable competitive experience.

► **High anxiety** Most studies on anxiety and related thought management strategies in tennis have concluded that anxiety is detrimental to performance as it typically causes players to become more vulnerable.^{3,4} There are no gender differences seen in the effects of anxiety on tennis performance.⁵ Winners have significantly lower cognitive anxiety prior to competition than losers.⁶ Significant reductions in somatic anxiety (physical) and cognitive anxiety (mental), and significant increases in self-confidence, can be realized with proper training.⁷

Vicious circle of anxiety



Relaxation strategies



Heart

Heart rate and blood pressure rise—use deep/centered breathing efficiently



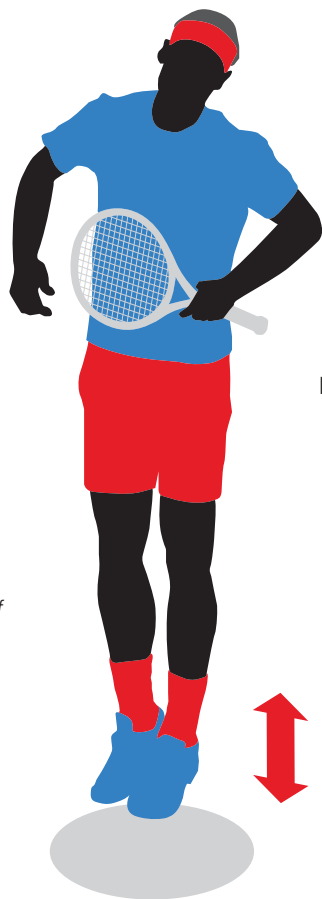
Face

Increase in perspiration—use towel-off and hydration strategies between points and during changeovers



Arms

Muscle tension increases—use relaxation strategies by tensing and relaxing specific muscles



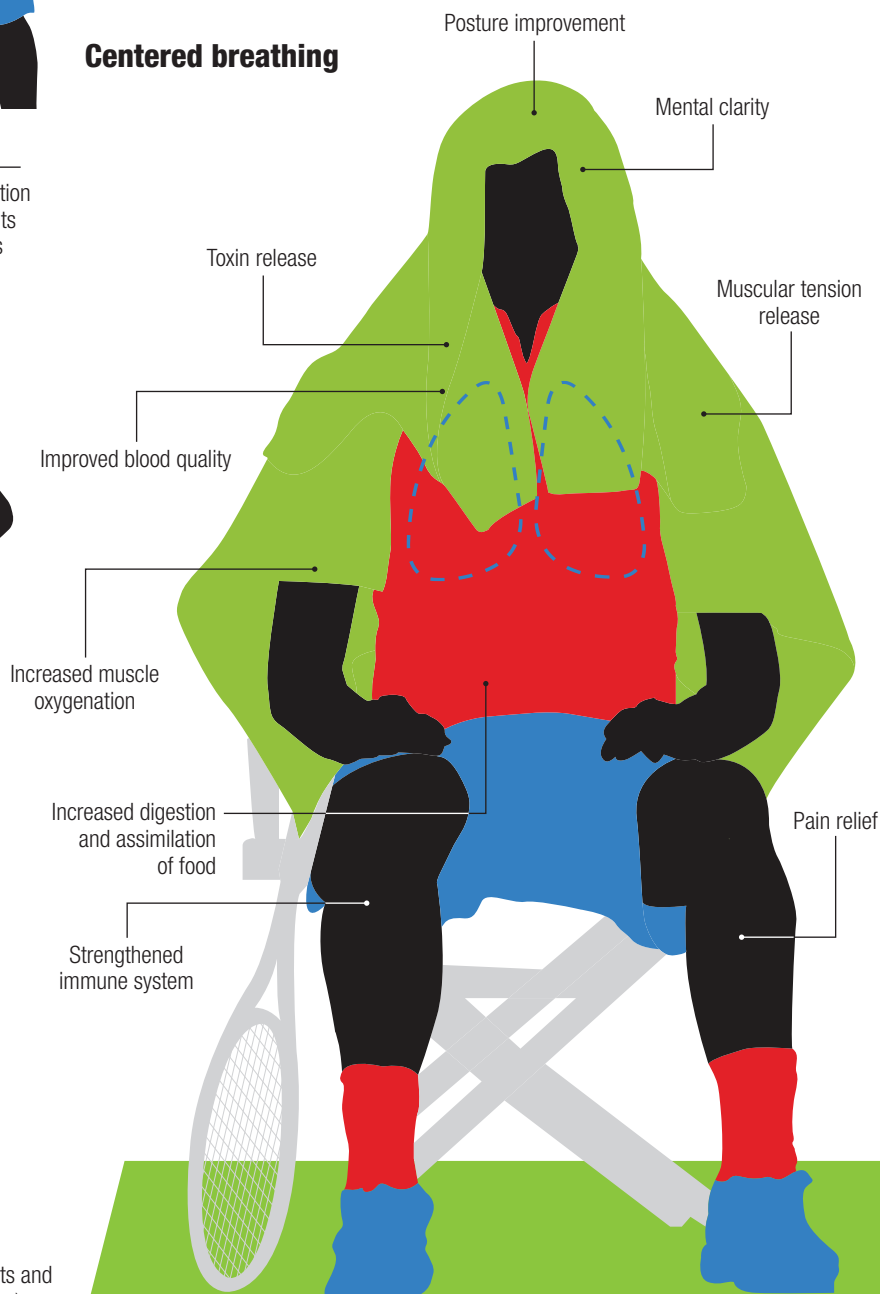
Legs

Body stiffness—use activation strategies (short, sharp movements and jumps before both serve and return)

▼ **Keep breathing** Centered breathing is a method of bringing your attention to your breathing. This has several beneficial physiological effects. Deep, or diaphragm, breathing decreases your heart rate and stress levels by maximizing oxygen levels in your blood (which causes the heart to beat slower, expending less energy);

increases oxygen saturation in the cells; and lowers your blood pressure. This in turn reduces the stress hormones in your system. All of these physical reactions are beneficial to your state of mind, calming you and enabling you to relax and make better playing decisions.

Centered breathing



▲► **Coping with stress** Here are some of the strategies that leading tennis players have learned to use to cope with anxiety and match pressure, improving their performance³:

- Focus on execution
- Follow the routine
- Follow the game plan
- Raise the level of play by expecting the opponent to improve their game
- Stay positive
- Exhibit positive body language
- Use deep breathing and relaxation techniques⁸

How does motivational climate affect performance?

Will motivation help my game?

Motivation underpins successful tennis performance, representing one of the game’s foremost psychological skills. Motivation, supported by related concepts (including drive, passion, persistence, competitiveness, effort, and the desire to participate and win), is important to all stages of player development.¹ Research has shown that a higher level of goal achievement motivation was found among top professional players when compared with junior players.² However, when coaches working with junior players were asked to list the most difficult mental skills to teach, motivation featured prominently.^{3,4}

What is known as the “motivational climate” is the goal structure of the training and competition program created by coaches, parents, peers, or others, and how it is perceived by the player. This climate is created by all those who have an influence on the player and it prevails in tennis lessons and at players’ homes. Children and adolescents develop their preferences for task- and ego-oriented goals through repeated interactions with these influences. When task-oriented, the individual player’s conceptions of ability are self-referenced and depend upon personal improvement and task mastery. When ego-oriented, conceptions of ability are referred to as norms or rules, and are based on comparisons with the performance of

others. Players also perceive a goal structure in tennis, which is largely created by the same influences mentioned above. As with individual motives, the terms task- and ego-oriented are also applied to describe motivational climates in tennis.⁵

Players who have a high level of task orientation, and who perceive a task-involving tennis environment, have been observed as less likely to report psychological withdrawal from tennis or suffer burn-out. Task-oriented environments are considered to reinforce effort, helping players to focus on the processes and intrinsic rewards of learning and improving, as well as group cooperation and cohesiveness. Task-oriented motivational climates foster strong work ethics and higher perceived competence, while also positively predicting self-confidence, improvement, satisfaction, enjoyment, persistence, and effort. Players have also been shown to display greater satisfaction with their coaches and fellow players, as well as reduced anxiety responses and “thoughts of escape.”⁶ Ego-oriented motivational climates tend to generate the view that sport involvement should enhance one’s self-esteem and social status. They also tend to produce pre-competitive cognitive anxiety, disrupted concentration, and maladaptive perfectionism.

Motivational climates

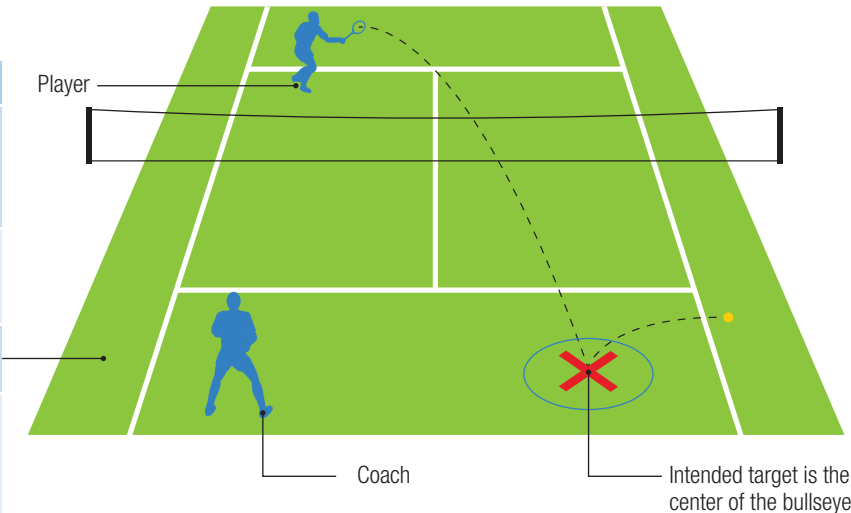
	Task-involving climate	Ego-involving climate
Main goal	 Reinforce progress	 Reinforce outcome
How to explain success	 Trying hard, improvement	 Outdoing others, achieving without effort
Mistakes	 Part of learning	 Punished
Recognition	 Everyone is part of the team	 For talented only
Valued	 Cooperation/cohesiveness	 Inter-team member rivalry

◀ **Climate balance** Motivational climate in tennis becomes more ego-involved as we move from beginner’s tennis to competition tennis. At the beginner level, task-oriented motivational climates are important to enhance the motivation and enjoyment of all players. At advanced levels, an ego-involving motivational climate may prevail, yet coaches should be task-involving in their interactions with players during training, as well as before and after competition.

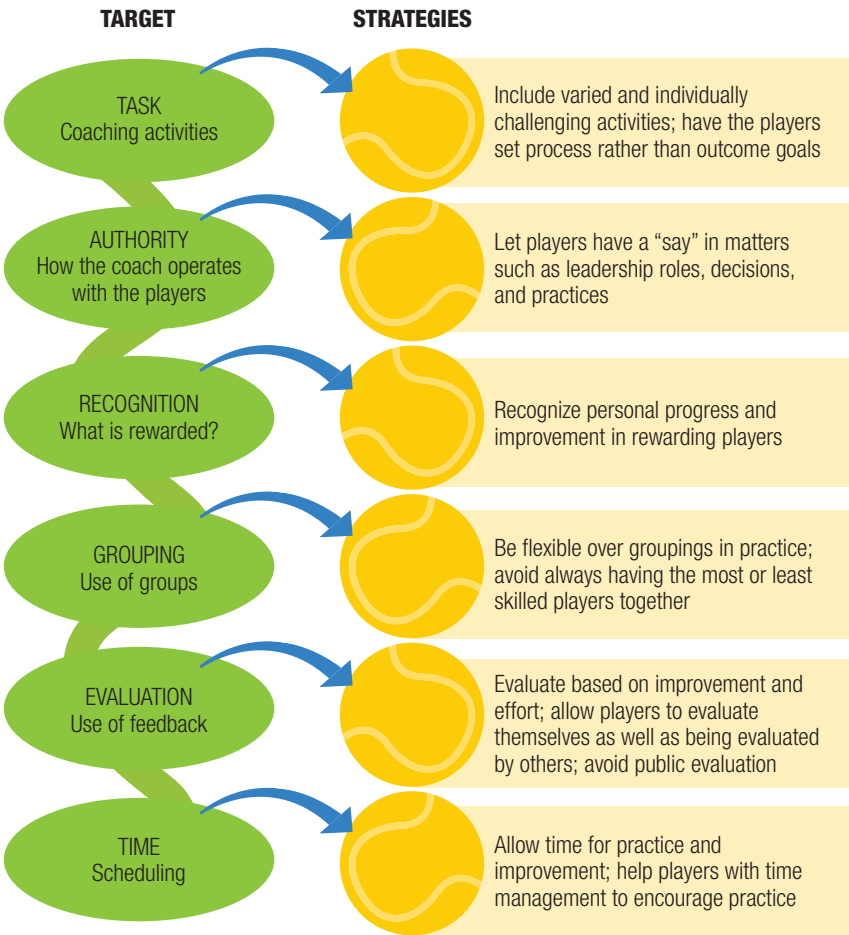
Task-oriented strategies for motivation

Strategy	Practical example
Focus on task-oriented goals	Ask the player to focus on moving their feet, watching the ball, and trying to accomplish 50 shots over the net in a row
Help players set realistic personal, short-term, and performance goals	Review the session, week, and season goals periodically
Recognize and encourage individual progress and learning	Ask the player to hit targets strategically placed on the court
Educate players on the importance of focusing on their own self-improvement and self-referenced behaviors	Ask the player to focus on their shot-production rather than on the calls from the umpire
Encourage maximum effort every day	Reinforce the “one-bounce” principle
Encourage personal development	Stress the concept of “learning something new every day”
Match the difficulty of the skills to the ability of the players	Challenge players individually by asking them to set their own goals
Keep practices stimulating by using a wide variety of drills	Ask players to suggest their preferred drills in certain phases of the training session
Keep everyone active	Set up drills that emphasize activity at all times
Emphasize the idea that success is not only winning, and congratulate good effort and not only ability	Reward “fighters” as well as winners
Involve players in decision-making and leadership roles	Ask players to decide some parts of the practice session and involve them in self-evaluation

▲ **Task in hand** The table summarizes the main strategies that coaches and parents can use to create a positive, task-oriented motivational climate that will help players develop their best tennis. Research has shown that there are two types of motivational climate—task-oriented and ego-oriented. In providing overwhelming support for task-oriented learning environments, findings suggest that these environments correlate well with positive perceptions of improvement, and player satisfaction with their performance and coach. While ego-oriented motivational climates become more prevalent as “stakes” increase, players’ perceptions of these climates produce more anxiety and pressure, and they are less conducive to learning, as well as being less enjoyable. With this in mind, it’s clear that coaches should, where possible, create high-level task-oriented environments.



TARGET strategies



▲ **On target** Different ways of creating a task-oriented motivational climate using the TARGET strategies.⁷

getting “in the zone”

At any level, playing good tennis is not just about playing effective strokes, understanding your opponent’s tactics, being capable of quickly recovering after an exhausting point, or being mentally tough—it is about aiming to play “in the zone.”

Players, coaches, and sports psychologists all refer to the need for a player to achieve an ideal mental state during play. In this state—which is often described by players as a heightened state of consciousness or a point when everything seems effortless—it is possible to perform at an exceptional level consistently and almost automatically. This state has been studied and given many names, including “peak experience,” “perfect moments,” “maximum performance,” “mindfulness,” the “ideal performance state,” being “in the flow,” or being “in the zone.” Players experience this at varying levels of intensity and complexity, but they share many of the same feelings. The player feels totally immersed in the game, as if playing on automatic pilot, with heightened mental acuity, when everything seems to “click.”

All of these mental states have been found to share these attributes: the player is physically relaxed, mentally calm, focused, energized, self-confident, optimistic, and has little anxiety. Players’ actions are automatic and they are able to enjoy play and feel they are in control. However, it has also been found that players reported they managed to get in the zone more frequently in training than in competition. Why is this, and what conditions need to exist to help a player get in and stay in the zone?

Players have reported playing in the zone for relatively short periods, during which they see themselves playing their best tennis and yet not necessarily winning. Studies have been able to identify the common factors that help to encourage this IPS. The player has clear goals and feedback, and there is a balance between the challenge and skills being tested. While the player is concentrating intently on the task in hand, they have a sense of control, but also experience a loss of self-consciousness, and even an altered sense of time. Ultimately, it is during these moments, when they are in the zone, that tennis players experience the game’s utopia.

► **In the zone** Learning to maintain an ideal performance state (IPS), or be “in the zone,” has been shown to help players perform at their maximum, and enjoy playing tennis, even if they ultimately lose the match.



What mental strategies enhance concentration?

How can I improve my concentration?

Concentration is the ability to direct and maintain focus on relevant cues. Several elements of which include the abilities to attend to relevant cues during play, tune out what is not, selectively direct attention from one cue to another, maintain attention over time, and process amounts of (internal and external) information at any one time.¹

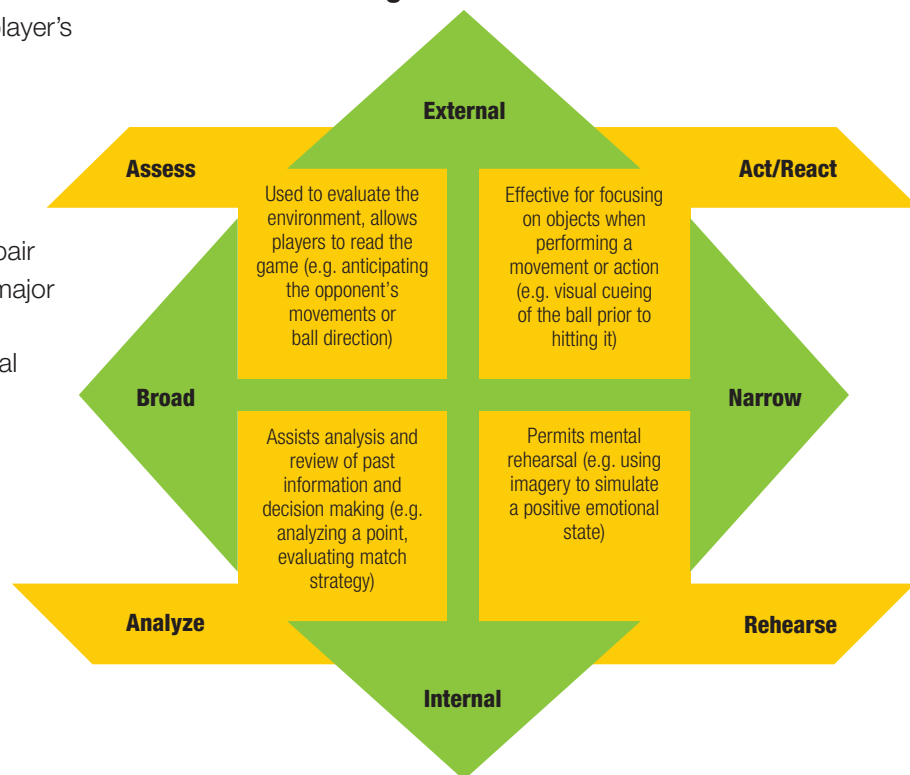
Concentration has been explained using the attentional focus model. This consists of two dimensions: direction (external, such as the environment; or internal, such as a player's emotions); and width (broad, or a high number of stimuli; or narrow, being fewer stimuli)—creating four different types of attentional focus.² A player may have preferred attentional styles, but they need to shift from one to another depending on the demands of the match. The activation level of the player influences their ability to shift attentional focus. Low activation states are associated with low motivation and poor focus on relevant cues, whereas high activation states impair the player's ability to maintain attention on the same cues.

Research has shown that players see concentration as a multi-dimensional process, consisting of a scanning and a focusing component. Studies have also found that attending to more than one source of information can impair the performance of some players; that “choking” (losing major points) is basically a concentration problem; and that encouraging players to direct their attention to the postural or body language cues of their opponents can facilitate early anticipation (the ability to discriminate task-relevant cues and predict shot direction).³

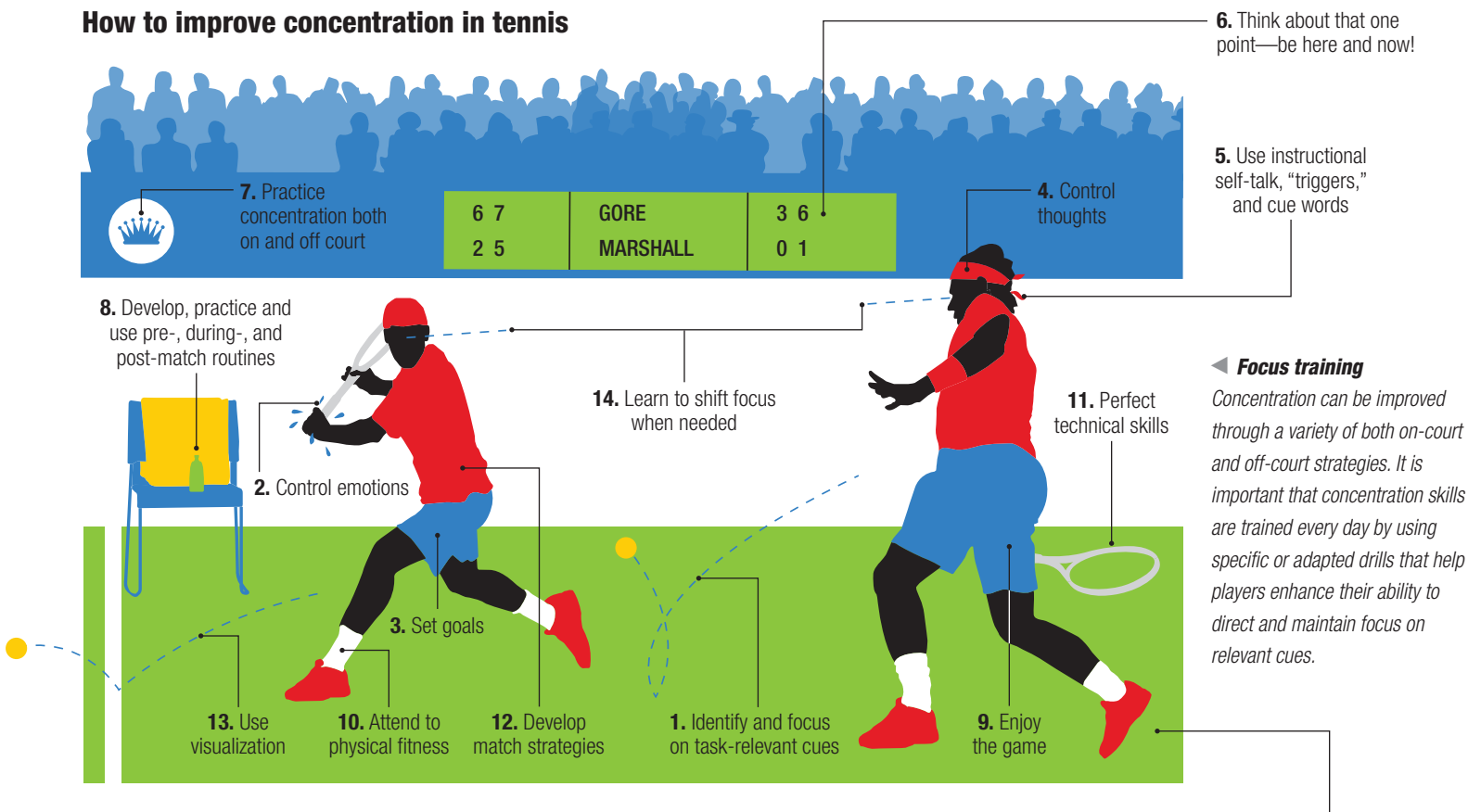
► **Pay attention!** These concentration strategies help the player to focus their attention during a match, depending on the situation.

Due to the individual and changing nature of the game, it is impossible to concentrate for 100% of the time during a tennis match. The ability to concentrate is commonly affected by external distractions (including boredom, anger, rush, noise, and spectator movement); internal distractions (such as mentally not being in the “here and now,” lacking in confidence, suffering from “paralysis by analysis,” excessive stress, or fear); and personal distractions (inadequate nutrition, hydration, physical fitness, sleep, or rest). Training to improve concentration should be designed to direct the player's attention to identify task-relevant cues (such as ball flight, trajectory of the racket of the opponent, and body position of the opponent); to adopt routines for before, during, and after the match; to effectively use self-talk and cue words; and to control thoughts to be in the “here and now.”

Concentration strategies



How to improve concentration in tennis



1. A coach can assist players to identify (or revise) key task-relevant cues and the times at which players should attend to those cues. Players should understand the game's attentional demands and potential attentional problems they may encounter.

2. Anxiety and tension can break player concentration by diverting attention to pounding heart, sweaty hands, and rapid breathing. To minimize this from occurring, a coach can work with players to identify their optimal arousal zone and the means of attaining and maintaining it under pressure.

3. Players will generally concentrate better if challenged to perform well. A coach can assist players to set specific

goals that are “parked” in their subconscious minds as they attend to the requirements inherent in achieving the goals.

4. Promote action driven by positive thought, and control thoughts irrelevant to the task.

5. A useful means of maintaining focus, or refocusing when concentration is broken, is for players to use “trigger” or cue words. Players should select some that are meaningful (for instance, “move in,” “attack,” or “hit the lines”).

6. Concentration can be vastly improved if a coach is successful in training players to think about playing one point, and only one point, at a time. Worrying about missed shots or thinking ahead to winning

or losing is the downfall of many players.

7. Hold practices in noisy places that may present additional distractions. Schedule simulated matchplay with distractions. Players can keep logs of factors that assist their concentration.

8. Most top players use a specific warm-up ritual to help them focus their minds on the pending match. This helps players concentrate only on what can be controlled. Similar to a pre-match routine, a routine during play can trigger players to focus on the task at hand, or refocus if concentration has been lost (serve and return of serve rituals are examples of this).

9. Having fun relates positively to concentrating well. In this sense, it is important for coaches to put competing—winning and losing—in perspective. The essence of competing is to perform to the best of one's ability in an ongoing process of self-improvement.

10. Since a loss of concentration can be due to a lack of conditioning, coaches need to address the level of physical fitness of their players. Coaches can work with players to ensure that their fitness exceeds the demands of successfully competing.

11. Player concentration can be adversely affected if concerns exist over technical proficiency.

12. Prior to competing, players need strategies that address how they (a) plan to play important points and the match, and (b) will effectively deal with potential distractions (such as bad calls, windy conditions, or spectator support for the opponent).

13. Visualization is a powerful concentration technique. By visualizing what to do next, often players will then do it.

14. Training to improve concentration should be designed to direct, or redirect, the player's attention to task-relevant cues. So, next time you are tempted to instruct players to “Concentrate!” remember it is far more helpful to say: “Concentrate on...”

Does visualization increase stroke success?

How can I use visualization to improve?

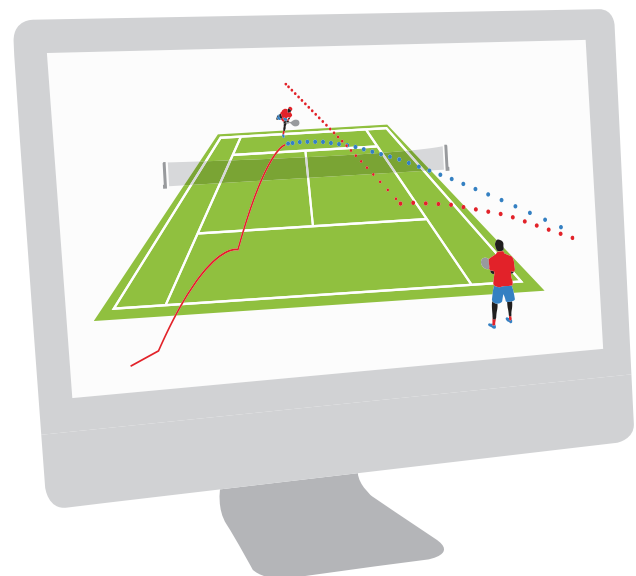
Visualization is the ability to consciously create images in your mind. It is a process which can involve the use of different senses such as visual (pictures and images), auditory (sound), taste, and kinesthesia (movement of the body and the muscles). It is also known as imagery or mental rehearsal. Visualization has been explained in different ways. It has been suggested that watching a tennis match can actually stimulate the muscles and areas of the brain that are activated during competition. It is also thought that visualization helps players to “understand” their movements, while helping to develop psychological skills such as concentration, stress management, and stress inoculation (preparing athletes to become resistant to the effects of stressors). Visualization can be performed internally (visualizing a movement as it is usually seen by a person, using a realistic visual perspective that simulates what the player experiences), or externally (visualizing a movement as if watching a video of oneself).¹

Experts recommend that players visualize internally most of the time, in blocks of five minutes, imagining difficult situations, errors, and solutions, and also visualize in real-time (so that the image lasts the same duration as the actual performance).² Using their mind, the player can recall the images or feelings of their best tennis over and over again. This process will enhance their skills through repetition, which is why visualization is thought to have similar effects as physical practice in performance improvement. Research on the benefits of the use of visualization to enhance tennis performance has been inconclusive. However, it is suggested that it can help players reduce anxiety, decrease errors, and heighten anticipation,

coordination, and concentration. It can also enhance self-confidence, accelerate learning, improve stroke precision and performance, and facilitate an injured player’s rehabilitation.³

Studies have shown that visualization practice alone is better than no practice at all, and that visualization when combined with physical practice is more effective in improving stroke performance than either on their own.⁴ Imagining positive outcomes may be more powerful in improving performance of closed skill movements, such as the serve, than of open skill movements, such as the forehand.⁵ For example, positive imagery and self-instruction just before serving lead to greater serving accuracy.⁶ Studies have also shown that expert tennis players used imagery more effectively than novices, but only for the activity in which they had expertise. This suggests that imagery focused on movements is helpful during the autonomous stage of motor learning.⁷

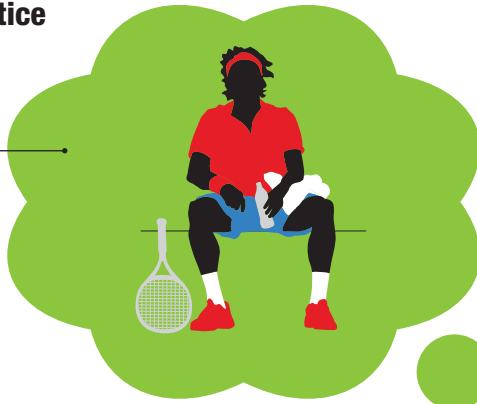
Video analysis



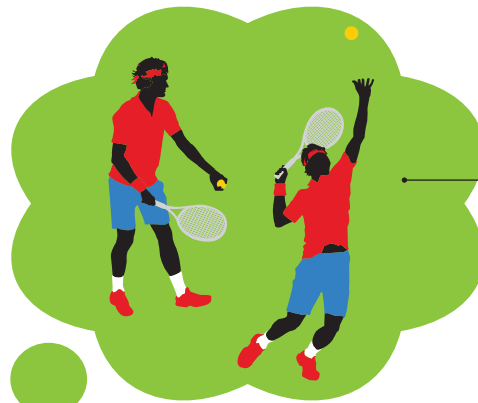
► **Screen time** *Watching and analyzing video sequences of points will help players to visualize their most efficient tactical patterns to be applied during matchplay.*

Visualization practice

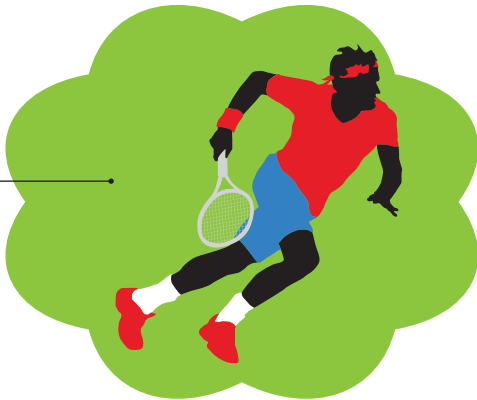
During the changeover,
visualize the successful
tactics used to put pressure
on the opponent



Visualize the ball
toss just before
serving



Before the match, visualize
yourself giving 100% and
chasing every ball



Just before the return of serve,
visualize the target you would
like to hit with your return



► **Seeing the point** *Players need to
visualize themselves playing the point before
they actually play it. They need to “watch
the movie of their point.”*





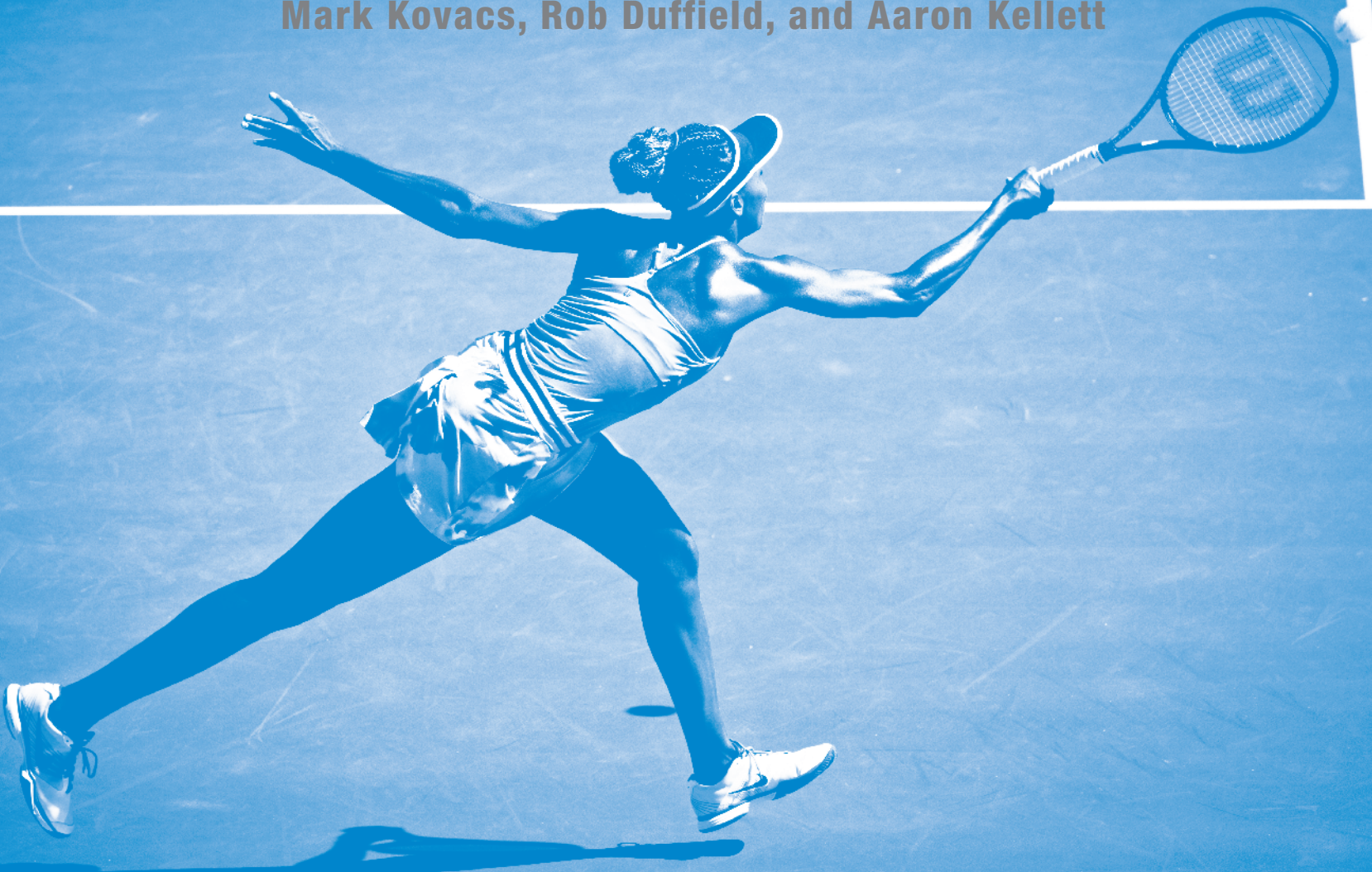
Today's game requires the professional player to be very fit, with matches often lasting well over two hours on the WTA Tour and four hours on the ATP circuit. Grand Slam tournaments are played on a variety of surfaces that each present different physical challenges. For instance, points take longer to play on clay, the ball bounces lower on grass, and hard courts are typically more physically demanding. The racket must also be swung with more speed on clay to produce the same outgoing ball speed as would occur on a hard court, due to the slower bounce. Therefore, all areas of physical development must be addressed in preparation for effective performance.

This chapter addresses questions concerning the type of fitness needed to permit repeated fast movements with the racket as well as around the court, while still being able to run after the ball hour after hour. How energy systems change as a player matures and the different training regimes required for junior and professional players are also explained. Issues relating to footwork are investigated, as reaching the ball is an essential part of being able to hit it. The physical capacities of strength and power across the developmental pathway are then thoroughly discussed, before the final section specifically deals with the health benefits derived from tennis, which are most relevant for veteran tennis players.

chapter five

physical development

Mark Kovacs, Rob Duffield, and Aaron Kellett



What are the aerobic and cardiovascular demands of tennis?

How taxing is tennis on my heart and lungs?

Tennis is physically demanding—prolonged periods of matchplay result in substantial external loads (speeds reached and distances covered) and internal loads (physiological and mental). Data suggest that competitive matches typically last 2–5 hours for professional tennis players,¹ and that players may cover up to 3–5 miles (5–8 km), performing a total of over 1000 strokes.² However, even these data do not wholly convey the potential demands of Grand Slam tennis, including marathon-length matches, late-night finishes, and competitive efforts over consecutive days. Recent examples of “worst-case” scenarios include the 2010 Wimbledon first-round match between Nicolas Mahut and John Isner, which lasted a record duration of 11 hours 5 minutes, and the 2012 Australian Open final between Rafael Nadal and Novak Djokovic, which lasted 5 hours 53 minutes, and finished at 1:37 am. These prolonged efforts place considerable demands on players’ physiological systems responsible for energy supply and skeletal muscle contraction, and on their cardiovascular systems in particular.

Even within the context of prolonged matchplay of moderate duration (about 3 hours), physical demands elevate physiological loads and reduce post-match skeletal muscle function. While tennis matchplay is often of intermittent, short-duration efforts, the prolonged duration of training and matchplay can result in excessive increases in physiological loads above tolerable ranges for performance maintenance. Consequently, the prolonged need for regular, high-intensity efforts (both locomotor and stroke production) places demands on aerobic and anaerobic energy supply that require sufficient training of cardiovascular and skeletal muscle systems to prepare the player for them.³

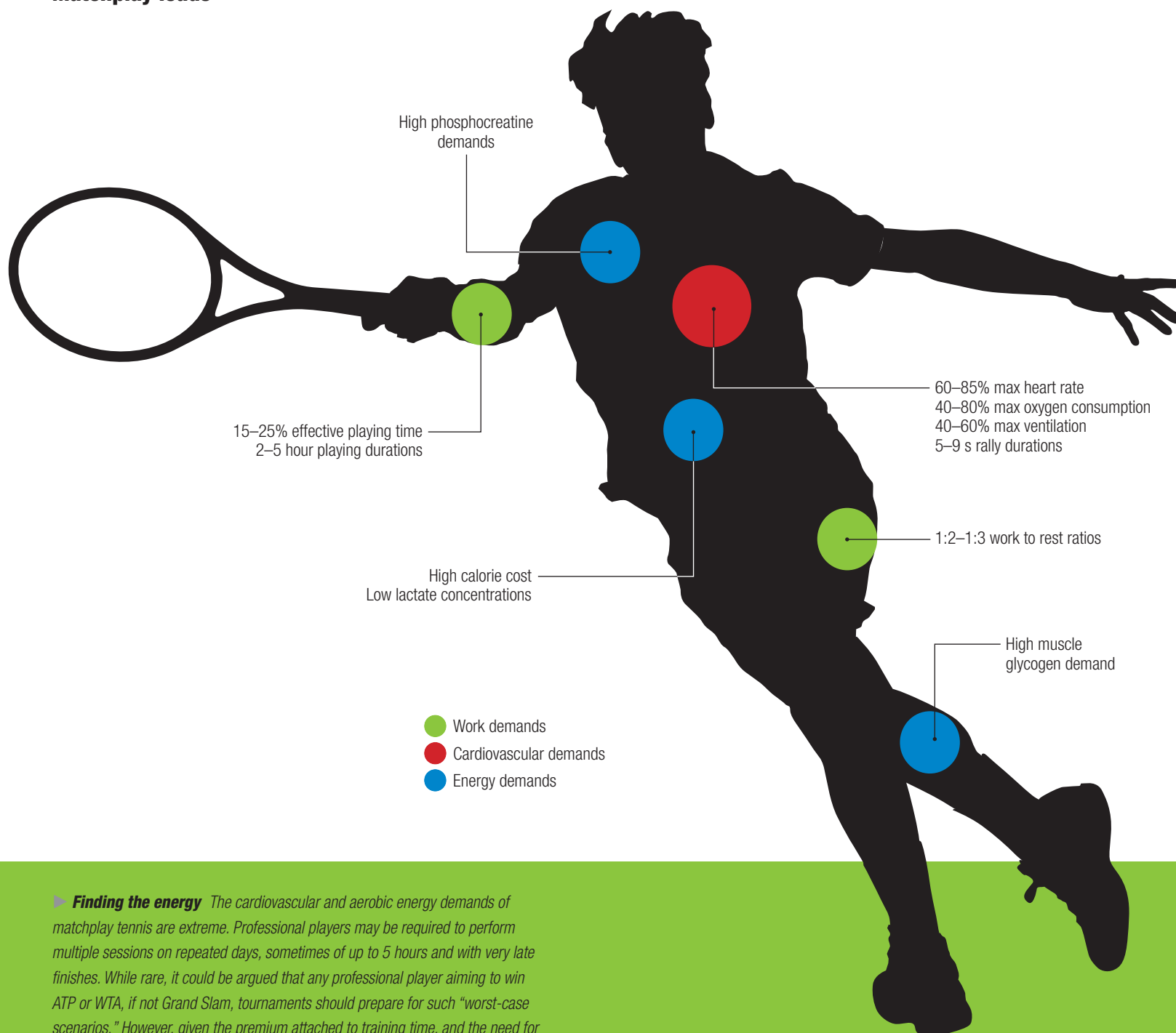
An athlete’s ability to repeatedly perform the short but high-intensity efforts needed in tennis is linked to their cardiovascular fitness; and, in particular, their phosphocreatine repletion—an important source of energy in high-power efforts, which requires effective oxygen delivery to the muscle. Consequently, performing large volumes of short-duration, high-power strokes and movements over a long period is directly related to aerobic capacity. Furthermore, recovery between matches and tournaments is fundamental for tournament success and the obtaining of ranking points. The greater the aerobic fitness of a player, the more they are able to tolerate the physical load during a match, and the faster they are able to recover after a match.

▼ **Physical loads** *Physiological load of singles matchplay tennis as compared to the normal range of physiological responses expected during prolonged exercise.³*

Physiological demands

Parameter	Matchplay tennis	Physiological range
Heart rate (bpm)	120–185	60–190
Oxygen consumption (ml kg ⁻¹ min ⁻¹)	15–45	10–75
Blood lactate (mmol l ⁻¹)	1–8	1–18
Core body temperature (°C)	37.9–39.0	36.5–40.0
Body mass change (kg)	1–2	1–3
Perceived exertion (RPE;au)	9–17	9–20

Matchplay loads



► **Finding the energy** The cardiovascular and aerobic energy demands of matchplay tennis are extreme. Professional players may be required to perform multiple sessions on repeated days, sometimes of up to 5 hours and with very late finishes. While rare, it could be argued that any professional player aiming to win ATP or WTA, if not Grand Slam, tournaments should prepare for such “worst-case scenarios.” However, given the premium attached to training time, and the need for technical and tactical skill development, such devotion to physical capacity development is difficult. HIIT (high intensity interval training) can help maximize aerobic capacity when confronted with limited training time, although care should be taken in the over-prescription of such sessions, as it is unlikely to help with resisting fatigue generated from extended durations of matchplay.

What velocities can tennis players reach?

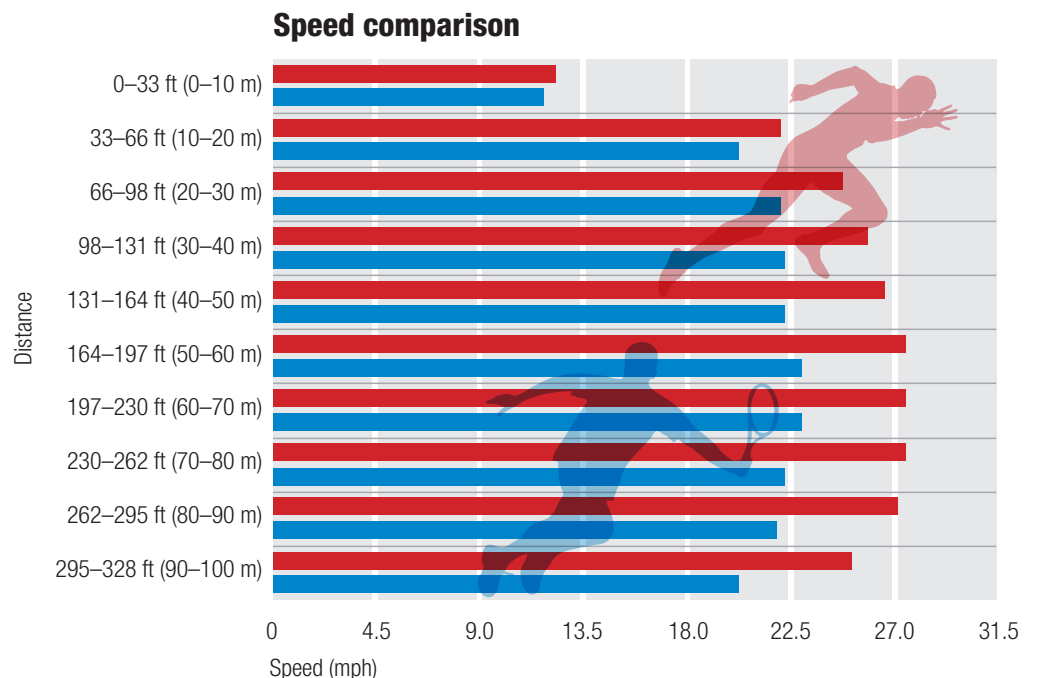
How fast can I move on court?

The movement velocities of tennis players vary substantially. During most points, a player will make a series of movements ranging in velocity from 0 mph, to a walking pace of 0.6–3.7 mph (1–6 km/h or 0.28–1.7 m/s), to a jogging pace of 3.7–6.2 mph (6–10 km/h or 1.7–2.8 m/s). However, during fast, explosive movements, over large distances (many times larger than in a normal tennis movement) a player may reach 12.4–18.6 mph (20–30 km/h or 5.5–8.3 m/s). The fastest athletes can reach velocities of approximately 27.3 mph (44 km/h or 12.2 m/s). However, this is achieved during “maximal velocity” running where the athlete is reaching a full running stride, which occurs between 164 and 263 ft (50 and 80 m) from a standing start. In tennis, all movements between strokes occur in distances of less than 66 ft (20 m), with the overwhelming majority of movements occurring in less than 33 ft (10 m), and so tennis players never reach these fast maximum velocities. However, during a tennis movement distance of 0–33 ft (0–10 m) players

can reach velocities of 6.8–9.9 mph (11–16 km/h or 3–4.5 m/s). This is slower than some of the fastest speed and power athletes in the world, who may reach a maximum velocity over the first 33 ft (10 m) of up to 11.8 mph (19 km/h or 5.5 m/s).¹

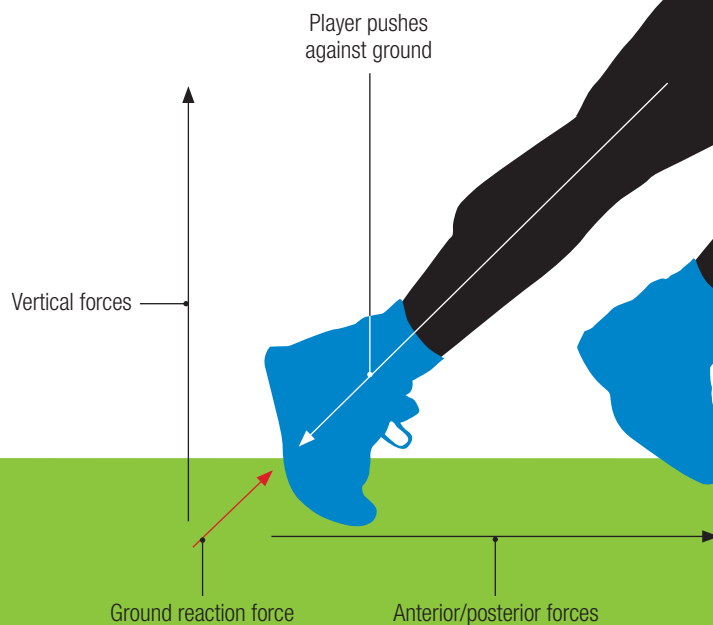
As tennis players train in short distances, they do not have maximum velocity numbers comparable to 100 m sprinters or other athletes that consistently train to improve speed over distances greater than 66 ft (20 m). At the time of writing, Usain Bolt holds the 100 m world record at 9.58 seconds,¹ whereas most professional male tennis players will record 100 m sprint times between 10.5 and 11.5 seconds. In addition, tennis athletes spend between 70% and 80% of their time moving on the tennis court, performing lateral and multi-directional movements.^{2,3,4} So, the needs of tennis athletes are rather different to those of track sprinters.

► **Velocity comparison** This graph shows a velocity comparison between a pro Tour tennis player and a top 100 m sprinter.¹ The two athletes demonstrate comparable speeds over short distances, of less than 33 ft (20 m), but the sprinter reaches a greater maximal velocity over 328 ft (100 m). Tennis players run for much shorter distances and spend between 70% and 80% of their time performing lateral or multi-direction movements.



Ground reaction force

► **Using force effectively** When a tennis player runs, their feet push against the ground. This same force is then exerted back against the player through their legs. This is known as the ground reaction force, and using it effectively—as a sprinter does—is crucial to covering the court quickly. A common misconception is that the fastest way to move on a tennis court is by taking many small steps, but this is incorrect. The most efficient movement is using the ground reaction force to spend more time in the air and less time on the ground, covering distance on the court more quickly.



Does lowering my center of mass increase my acceleration?

How can I improve my on-court speed?

A tennis player needs to cover the court as quickly as possible to provide the best chance of hitting a stroke effectively, allowing for optimum recovery for the next stroke. One of the most important ways an athlete can improve their movement is to optimize the position of their center of mass (also known as the center of gravity). An athlete's center of mass is the point where the relative position of the distributed mass is equal to zero.¹ The center of mass for the average person is located at a height of roughly 3.3 ft (1 m), usually slightly above the waist. The center of mass is different for all athletes and is determined by body shape, muscle, fat mass, and bone mass.

Nearly all movements on a tennis court (apart from the serve) are instigated with a “split step,” when the athlete performs a slight jump in the air. At the top of the jump, the athlete makes the decision to move in a certain direction—forward, backward, or laterally—known as the “decision step.” When the athlete lands from the split step, the first step is the slowest and shortest. If the athlete runs forward, force is applied downward and backward, and the leg movement involves a piston action that pushes the body forward. This results in a high horizontal impulse.² Impulse is when a force acts on an object with respect to time, changing the momentum of that object. As a result, a large force applied for a short period of time can produce the same momentum change as a small force applied for a long period of time. In tennis, like most speed and power sports, it is preferable to apply a large force into the ground over a very short period of time to produce a high horizontal impulse that results in the athlete moving quickly in a horizontal direction. In all acceleration movements in tennis, it is important to cover the longest possible distance in the shortest amount of time. Athletes that accelerate the fastest, over distances similar to those observed in tennis (i.e. 3 ft or 1 m or less), display less vertical impulse and have higher horizontal impulses than athletes who are slower accelerators. The faster accelerators also have shorter ground contact times.³

► **Fast footwork** Tennis coaches consider footwork to be one of the most important factors in improving a player's game. Some coaches advocate the “dig step” as a way of generating effective forward acceleration. In this movement, the athlete lowers their center of gravity by pushing off from one foot behind them, generating greater forward momentum than is possible with a normal step forward.

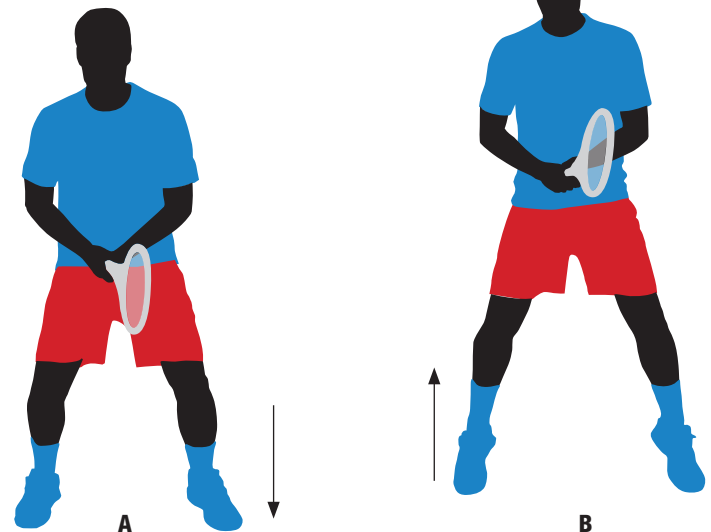
⊕ Center of mass

The “dig step” begins with the standard feet-apart stance

Dig step



Split step



► **Mass movement** With a standard amount of force, a shorter lever will rotate faster than a longer lever with the same mass. Therefore, the lower an athlete can position their center of mass, the shorter the lever effectively becomes, allowing for faster movement of the legs.³ When moving on court, the athlete should aim to lower their center of mass when landing from the “decision step,” while keeping the weight of the body leaning toward the direction in which they are moving. However, it is important to remember that all athletes have different optimum angles of acceleration, and having them adopt an excessively low position will not lead to greater efficiency.



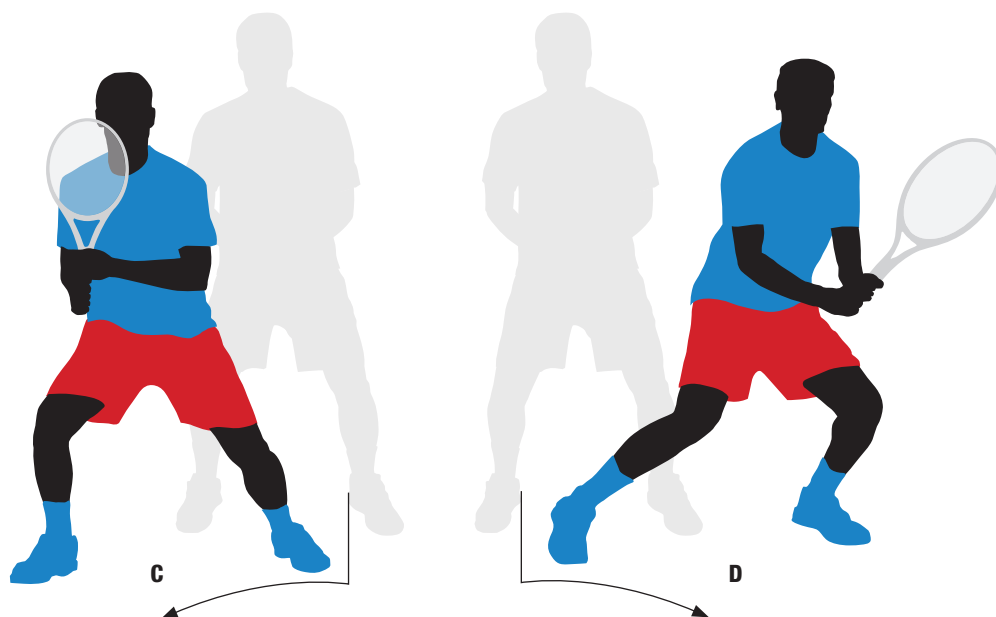
The player steps back to dig into the ground, pushing forward and lowering their center of mass

- ◆ Center of mass height while the athlete is standing
- ⊙ Center of mass height when athlete accelerating effectively

Center of mass



Center of mass during acceleration is below the center of mass when the athlete is standing



◀ **Power jump** In what is known as the “split step,” the player jumps (**A, B**) while watching the opponent strike the ball. This movement stores and releases elastic energy in the leg muscles (**A to C and D**), which the player uses to push in the direction of the ball at the right moment when they land (opaque **C and D**). In this case, the movement after the decision step is lateral—up to 80% of a player’s movement on a court is lateral, so the effective transfer of power to generate controllable lateral movement in the right direction is especially important. By placing their feet wider than their shoulders, the athlete’s center of mass is ready to be lowered when they begin movement in a sideways direction.

equipment: load monitoring

Many sports have tackled the problem of quantifying workload, but tennis presents some unique challenges to the coach—the tennis player encounters heavy competitive demands in different locations around the world, complicating the gathering and analysis of workload information. In addition, due to the size of the court, the space is too small for the use of movement-tracking technologies such as current Global Positioning Systems (GPS), the error rate rendering the data unreliable for use.

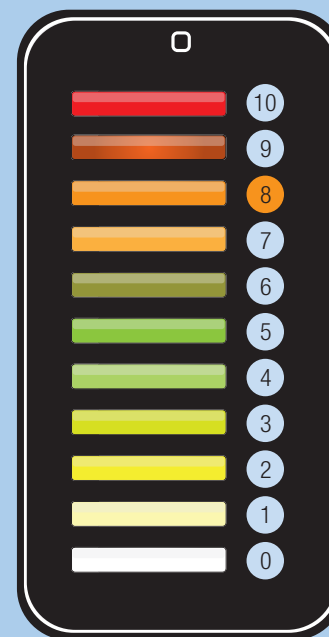
One of the most common methods for tracking a player's physical activity is the use of the Rating of Perceived Exertion (RPE) scale to assess session intensity—a numerical scale (0–10) accompanied by some verbal descriptors. Perceived intensity is combined with the training duration (in minutes) by multiplying the two values together to determine a “session workload.”^{1,2,3} Session workloads can then be interpreted by the coach for a better understanding of the magnitude of the training or match stimulus. In turn, this information helps to assess the effectiveness of the acute or accumulative training stimuli, and is used to adjust future training.

Mobile device applications allow athletes to enter their RPE and training durations from wherever they are in the world. These inputs can then be uploaded to a centralized athlete management system for reporting, analysis, and interpretation to assist the coach's decision-making process.

In addition to recording training information, athletes are asked to record various subjective measures of wellness. Large changes in variables such as feelings of mood, fatigue, muscle soreness, appetite, and anxiety, as well as sleep, have been associated with overtraining and overreaching in athletes. So, monitoring this information systematically allows coaches to

understand how their athletes are responding to the training that is being imposed on them.⁴ By combining the training workload information with the “response” from the athlete to those workloads, coaches can make even more informed decisions on whether their athletes are tracking as intended, or whether the training plan needs to be modified in order to avoid some of the possible negative consequences of overload, such as injury or illness.

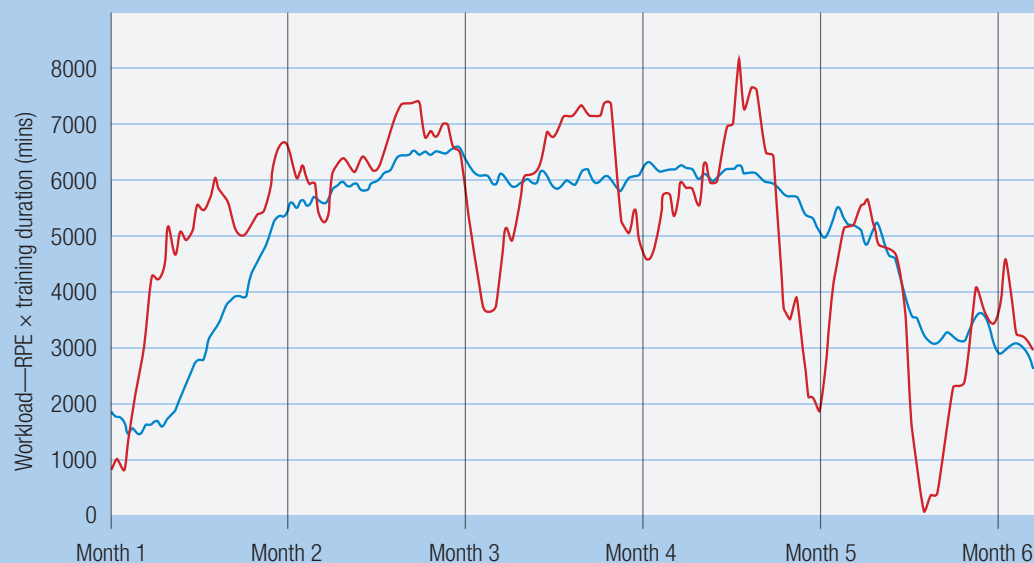
Exertion ratings



◀ **Self-assessment** This scale can be used by tennis players to record and share their subjective response to each match or training session electronically, wherever they are in the world. The coach is then able to assess the athlete's RPE, in combination with session length, to derive a “workload” and make decisions on how to adjust future training sessions.

- ⑩ Maximum
- ⑨ Extremely hard plus
- ⑧ Extremely hard
- ⑦ Very hard
- ⑥ Hard plus
- ⑤ Hard
- ④ Moderate plus
- ③ Moderate
- ② Easy
- ① Very easy
- ① Nothing

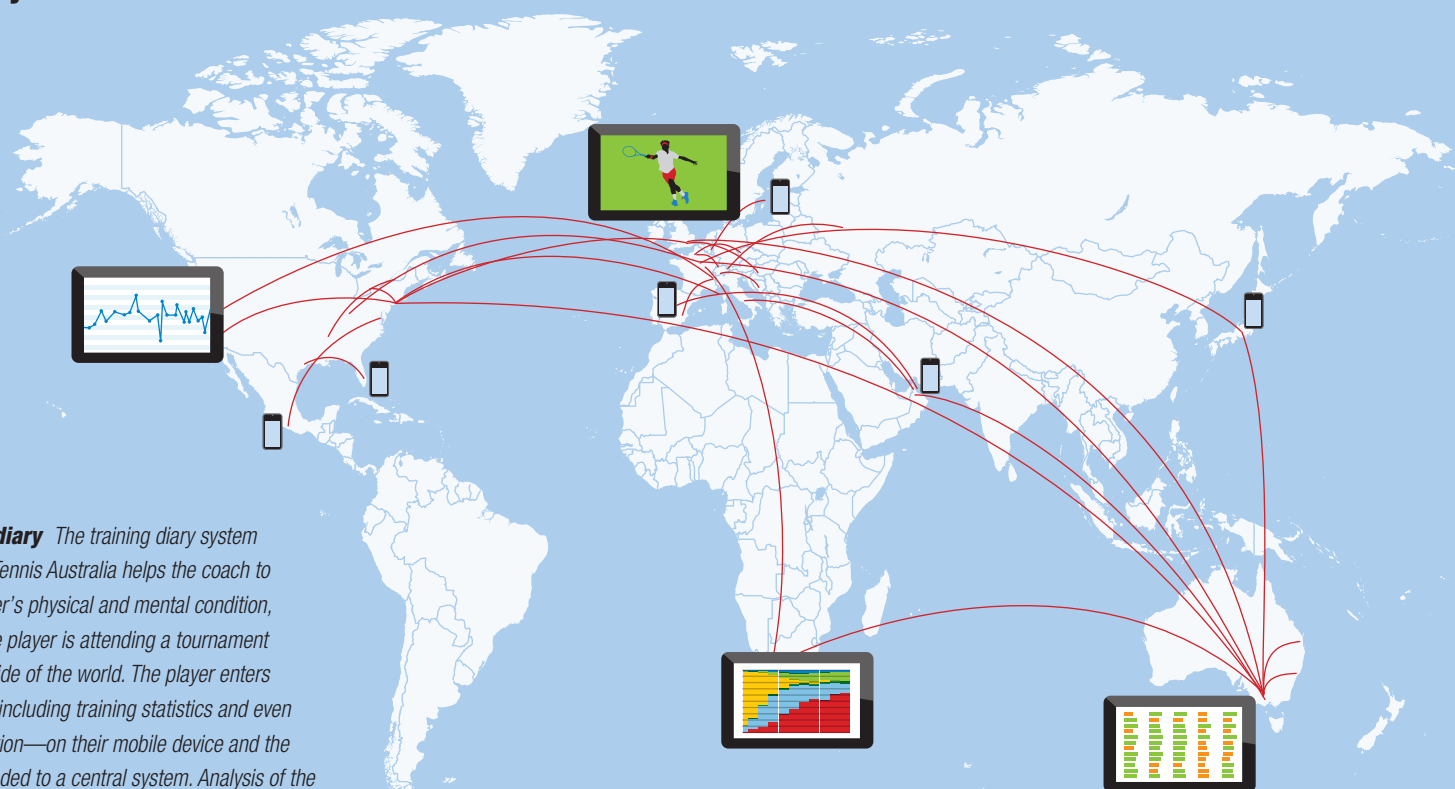
Training workloads



► **Calculating workload** By looking at the rolling averages of the workload measure, the coach can develop an understanding of whether the athlete is being exposed to a block of training (for instance, over 1 week) that is greater or less than a previous longer term exposure (4 weeks). This is done by calculating a rolling 7-day average (red line), and looking at this against a rolling 28-day average of load (blue line). This analysis allows the coach to assess whether the athlete is being exposed to an overloading stimulus—to improve a physical capacity in some way—or a period of lighter training to help with recovery, adaptation, or competition preparation.

Data analysis

► **Training diary** The training diary system employed by Tennis Australia helps the coach to assess a player's physical and mental condition, even when the player is attending a tournament on the other side of the world. The player enters information—including training statistics and even sleep information—on their mobile device and the data are uploaded to a central system. Analysis of the data enables the coach to track training loads over time, and to compare the planned training regime against the subjective responses of the athlete.



Does interval training improve aerobic capacity for tennis?

How can I improve my tennis-specific conditioning?

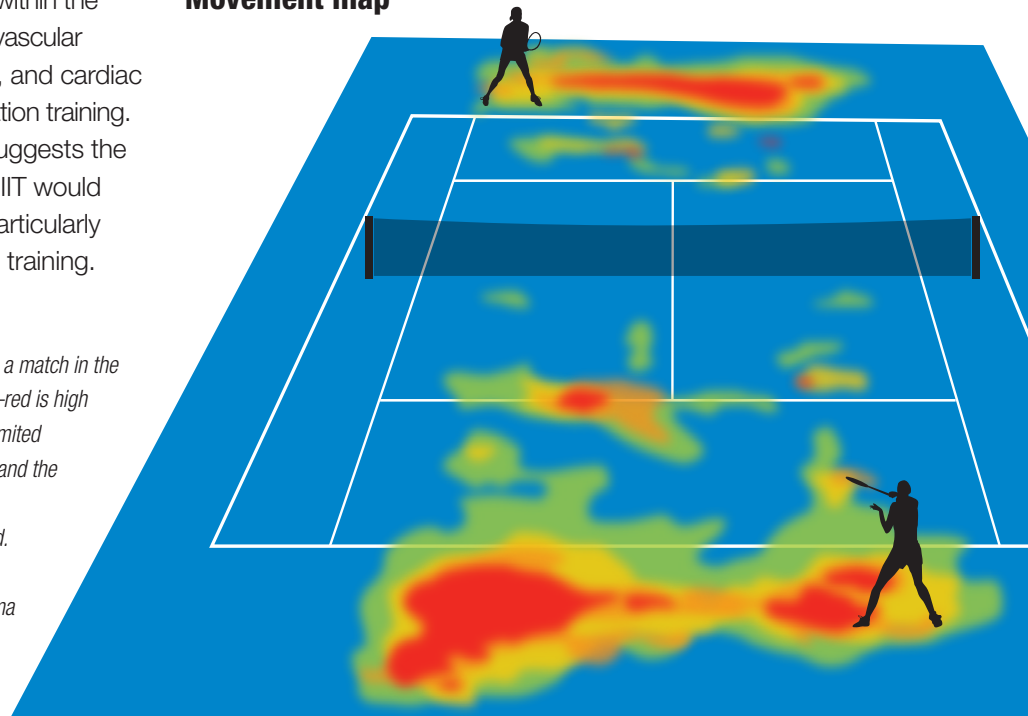
Interval training is a form of training intended to improve aerobic capacity. It is characterized by the use of repeated, discontinuous efforts of moderate-to-high intensities, separated by varying recovery durations, which are dependent on the intensity of the previous effort. Interval training is often proposed as an alternative to the continuous, prolonged duration methods of training to develop aerobic capacity. The form of interval training is malleable and, while fewer longer-duration efforts can be prescribed, recent practice has focused on high-intensity interval training (HIIT), which encompasses increased numbers of short-duration, high-intensity (maximal) efforts.^{1,2}

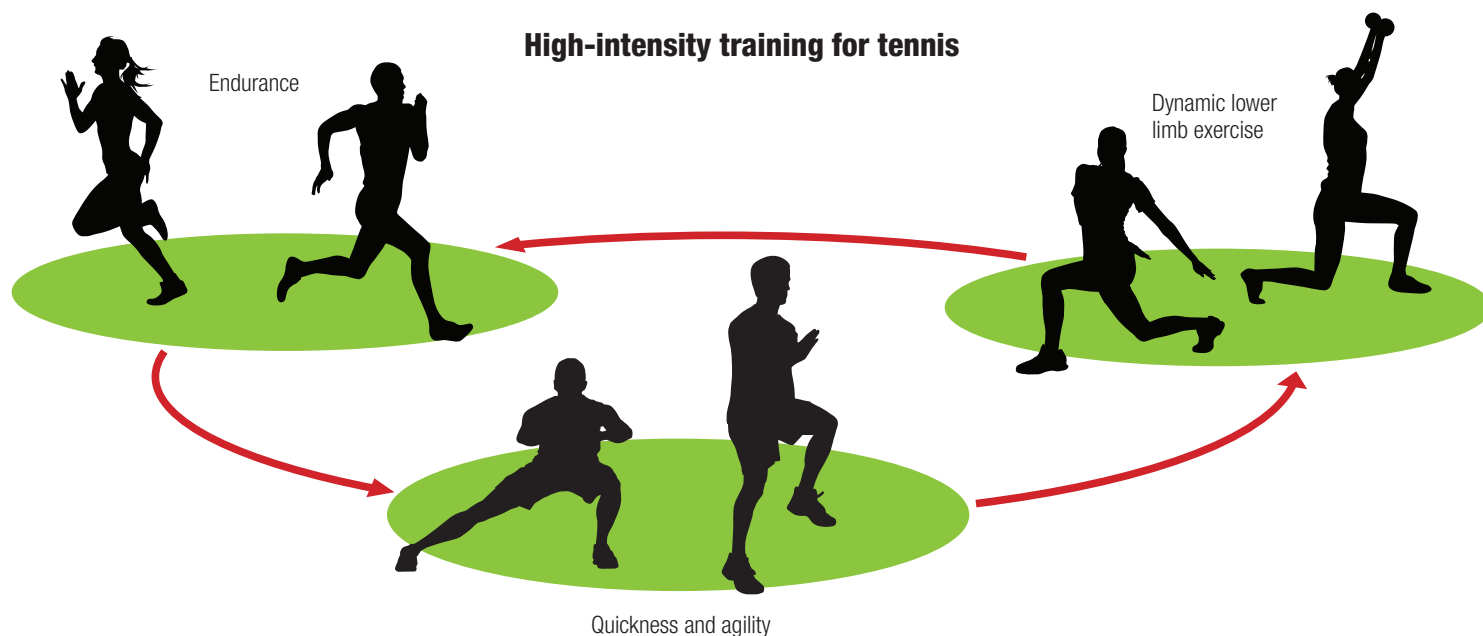
HIIT has been shown to be as effective at increasing the maximal aerobic capacity ($\text{VO}_2 \text{ max}$) of an athlete as continuous duration training when matched for work completed.¹ It is thought that HIIT is effective due to the very high-intensity work promoting adaptations to mitochondrial content and functioning within the athlete's skeletal muscle.² This contrasts to the cardiovascular adaptations—including blood volume, red cell mass, and cardiac output—often reported in response to prolonged duration training. Regardless of the mechanisms, training specificity suggests the work-to-recovery patterns and training duration of HIIT would seem more appropriate to the demands of tennis, particularly given the lack of time often available for conditioning training.

► **Movement patterns** An example of the movement patterns during a match in the French Open. The colors represent the extent of movement in that area—red is high movement volume, yellow is moderate movement volume, and green is limited movement volume.^{1,2} The duration of competitive matchplay (2–5 hours) and the estimated distance traveled (3–5 miles or 5–8 km) suggest high aerobic demands, and thus high levels of cardiovascular conditioning are required. However, the movement patterns highlight very high volumes of short-duration efforts within a 8–13 ft (2.5–4 m) radius. This presents a dilemma to the conditioning coach as they contemplate training for the physical capacity needed to endure such prolonged efforts against the specific work-recovery patterns for the movement demands of the sport.

Recent research suggests tennis-specific HIIT—involving the repeated hitting of balls and moving—is better at improving tennis-specific endurance than repeated sprint training.³ The effectiveness of HIIT in improving aerobic capacity is also linked to the exposure to the training stimulus—moderate-to-longer duration HIIT efforts (of 30–60 seconds) seem more effective in promoting improved aerobic capacity. However, increasing the duration of efforts to promote fitness adaptations defeats the purpose of HIIT, as these durations no longer replicate tennis movement durations. Hence, it is necessary to balance training between the appropriate duration and number of efforts to both maximize physiological capacity development and also meet tennis-specific demands.

Movement map





▲ **HIIT session** To appropriately train for the demands of tennis, HIIT-based sessions may form an integral component of the training program. Such sessions may be either conditioning-focused (on- or off-court) or a blend of technical/tactical and conditioning exercises (on-court). To optimize aerobic capacity development, longer-duration

repetitions (of between 30 seconds and 3 minutes) may be more appropriate, but these lack match-specificity. Consequently, such training may be more focused on off-court conditioning, such as gym-based bike and treadmill sessions. Conversely, repeated efforts (of less

than 10 seconds) are unlikely to be as effective for developing maximal aerobic capacity, despite being of direct relevance to the patterns of matchplay, and may be more appropriate for on-court conditioning and technical training.

► **Fitness gains** A comparison of the changes in tennis-related fitness capacities following six weeks of three days per week of either high-intensity interval training (HIIT) or repeated sprint ability (RSA) training compared to a control group.³

Training comparison

HIIT TRAINING	3 x 10 shuttle sprints (72 ft or 22 m) with 20 s rest + on-court 2 v 1 point play, 3 min recovery		
RSA TRAINING	3 x 90 s of hit and turn test + on-court 2 v 1 player, 3 min recovery		
CONTROL	Normal tennis training with no additional fitness training		
FITNESS PARAMETER	HIIT TRAINING	RSA TRAINING	CONTROL
Maximal aerobic capacity	▲▲	▲	—
Lactate threshold	—	—	—
Repeat sprint ability	—	▲	—
Hit and turn tennis test	▲▲	▲	—
Counter movement jump	—	—	—
72 ft (22 m) speed	—	—	—

▲▲ Substantially improved
 ▲ Improved
 — Unchanged

Does tennis-specific agility training increase speed?

How can I move faster?

Tennis is all about an athlete's ability to reach a tennis ball, make clean and efficient contact with it, and then move as fast as possible to the next position on court. Being able to change direction quickly (agility) is one of the major factors that separate some of the top tennis players from the rest. Acceleration is one half of the agility equation—the other is effective deceleration. Being able to slow down quickly needs to be considered a vital component of a competitive tennis player's training routine to achieve top-level tennis performance.

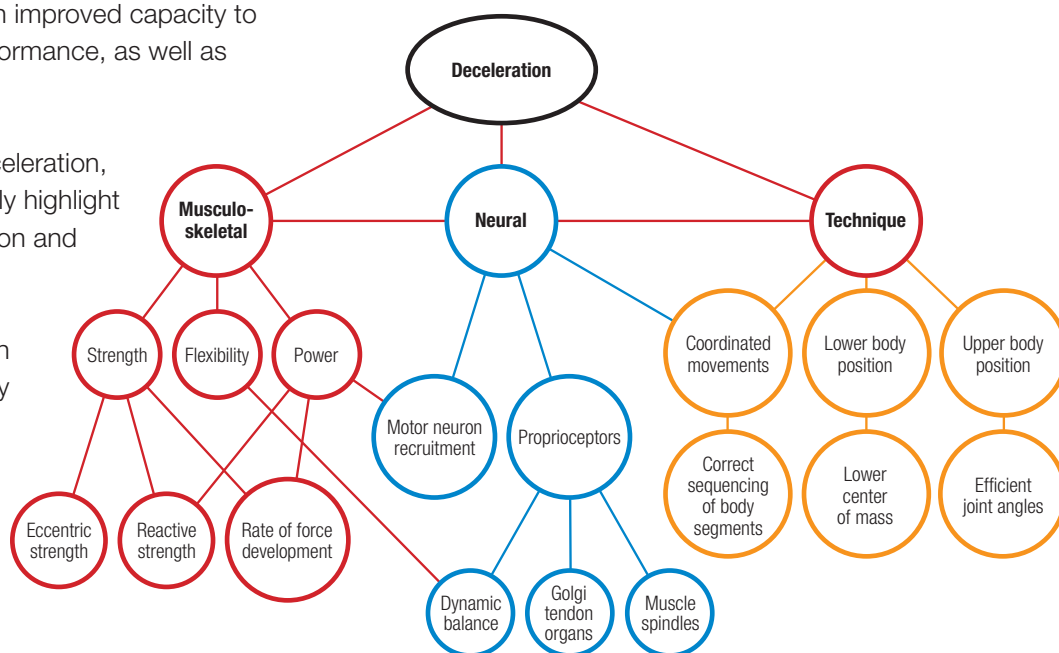
Improved deceleration results in an athlete being able to slow down quicker and therefore move faster to a ball.¹ A major influence on a tennis player's ability to decelerate is momentum. Momentum is the product of the mass of a moving athlete and their velocity. As an athlete's velocity increases, momentum is amplified, requiring greater forces to decelerate. Apart from the performance aspects of improved deceleration, many athletic injuries are the result of poor deceleration abilities.^{2,3} Developing an improved capacity to decelerate can lead to improved performance, as well as reduce the chance of injury.

To explore the complex nature of deceleration, a deterministic model can successfully highlight the multi-faceted nature of deceleration and the many components involved in successfully executing the correct movements. This analysis provides an approach that is based on a hierarchy of factors depending on the result or outcome of the performance.⁴ At the basic level, athletes with

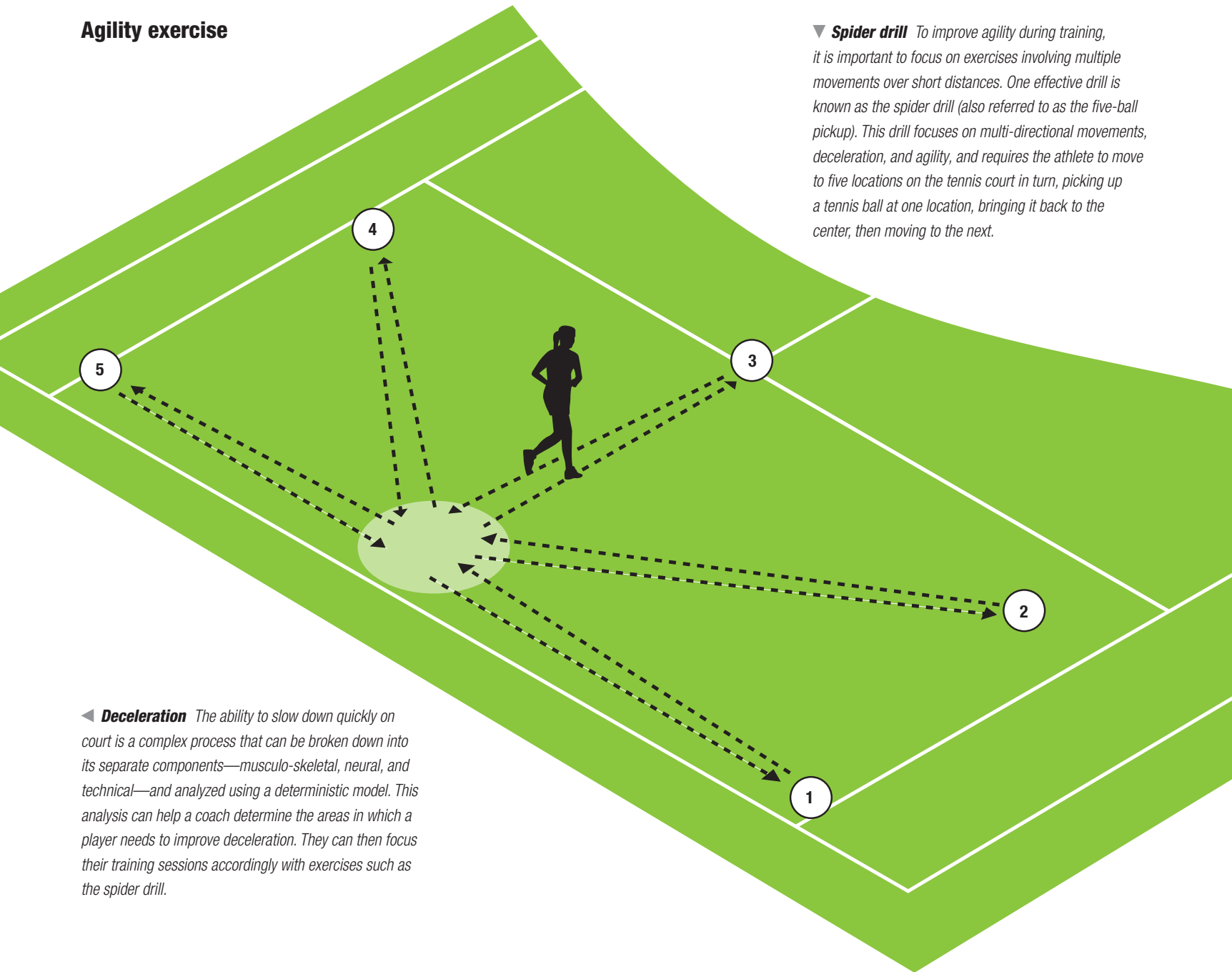
good deceleration abilities are able to effectively control and execute the musculo-skeletal, neural, and technical components of efficient movement mechanics.

It is well understood that agility and change of direction movements require separate training and involve different biomotor qualities to those involved in linear acceleration and linear maximum velocity movements. It has also been shown in data published in the *Journal of Strength and Conditioning Research* that straight-ahead sprinting does not transfer to the majority of multi-directional movements seen on a tennis court.⁵ Therefore, to improve tennis-specific agility it is important to train regularly with court-specific exercises.

Deceleration deconstructed



Agility exercise



▼ **Spider drill** To improve agility during training, it is important to focus on exercises involving multiple movements over short distances. One effective drill is known as the spider drill (also referred to as the five-ball pickup). This drill focuses on multi-directional movements, deceleration, and agility, and requires the athlete to move to five locations on the tennis court in turn, picking up a tennis ball at one location, bringing it back to the center, then moving to the next.

◀ **Deceleration** The ability to slow down quickly on court is a complex process that can be broken down into its separate components—musculo-skeletal, neural, and technical—and analyzed using a deterministic model. This analysis can help a coach determine the areas in which a player needs to improve deceleration. They can then focus their training sessions accordingly with exercises such as the spider drill.

Does muscle strength affect stroke production?

How strong do I need to be to play tennis?

Unlike many other field and court sports, tennis does not require a player to overcome an external force such as an opponent's body or a particularly heavy weight or implement. The major forces at play are those required to swing the racket to generate a tennis stroke, and those involved with movement around the court.

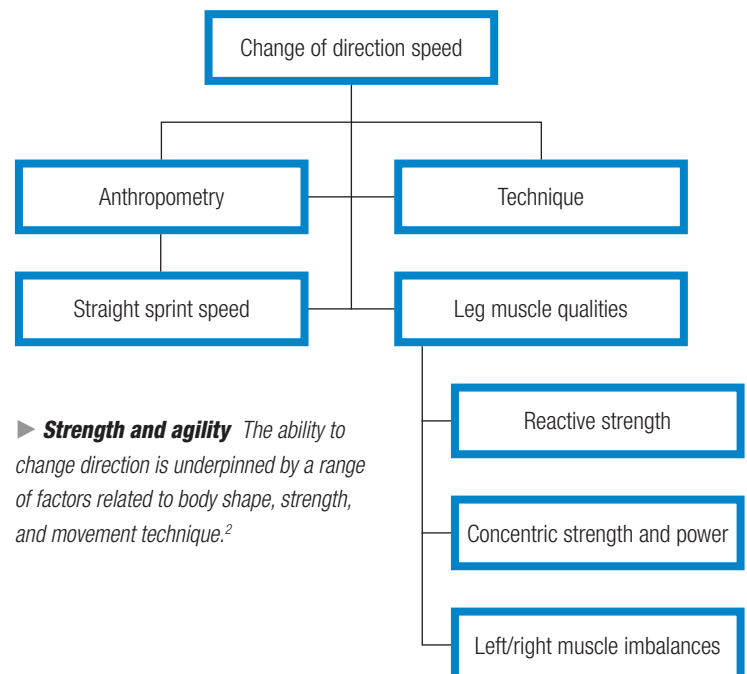
Some of the movement demands on tennis players include changing direction up to as many as 15 times per point, with average distances covered between strokes approximating 8–13 ft (2.5–4 m).¹ These changes of direction—in response to the stimulus provided by the opposing player's shot—form the modern definition of agility. When analyzing the actual acceleration or sprint component of locomotion, research has shown strong correlations between an athlete's strength levels and these performance qualities.²

At its most basic level, groundstroke production in tennis involves the sequential use of the kinetic chain, with the muscles of the lower body and trunk producing force that is then transferred to the arm and hand to generate racket head speed.³ While research has variously revealed some positive associations between trunk and upper limb strength measures and racket head speed, the biomechanical complexity of stroke production—as well as the isolated and non-specific methods used to investigate these relationships—tends to preclude any definitive conclusions being drawn.⁴ However, it is commonly accepted that hitting from a “stable base” is a precursor to producing powerful tennis strokes. Stable bases require players

to decelerate effectively, get balanced, and assume appropriate stances to unfurl the cascade of kinetic chain contributions that ultimately result in a high-speed shot. As effective deceleration is, in large part, driven by an athlete's strength levels,⁵ improving the lower limb strength of tennis players will enhance their deceleration ability, allowing them to develop more stable hitting bases and therefore higher ball speeds.

Stronger tennis players (particularly in relation to lower limb strength per unit of mass), relative to their weaker counterparts, will be quicker off the mark; accelerate more quickly to the ball; slow down and get balanced more effectively; execute more powerful tennis strokes; change direction more quickly and then recover; and repeat the next movement cycle in a more effective way.

Strength and agility factors



Power training

► **Building power** While it can be suggested that developing the strength of tennis players will result in an increase in performance potential, it is critical that training interventions follow one of the basic principles of resistance training design—the concept of specificity. Ensuring “functional” specificity—which considers contractile movement as well as muscle group specificity—will optimize the transfer of increased strength capacity from training to tennis performance. The serve in tennis, similar to other throwing activities, follows a proximal to distal sequence of force generation. The forces from the leg drive are transferred up through the body to ultimately accelerate the racket in a throwing motion. The squat is an example of a bilateral lower body exercise used to promote strength and power in a vertical plane.

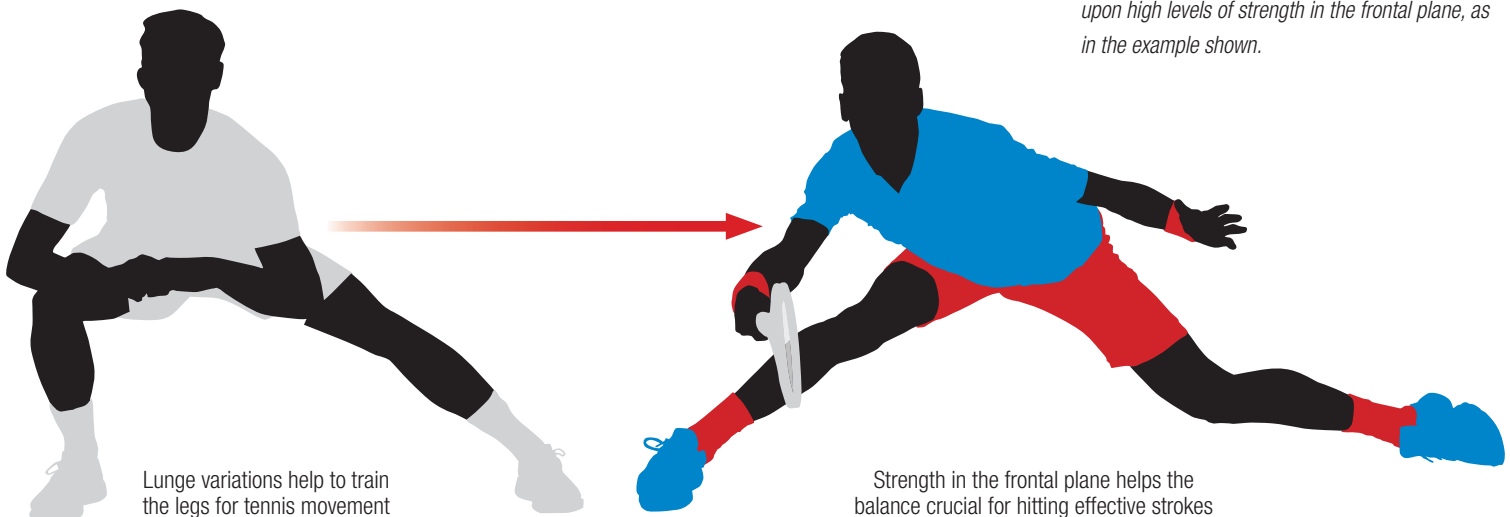


The squat builds strength in the back, legs, and core

The same muscular groups are needed in the serve

Balance training

▼ **Stable base** When decelerating, a stable base is required to hit and prepare for a likely change in direction. The ability to decelerate and balance to execute strokes at end range is in turn heavily reliant upon high levels of strength in the frontal plane, as in the example shown.



Lunge variations help to train the legs for tennis movement

Strength in the frontal plane helps the balance crucial for hitting effective strokes

be prepared

Among the many uncontrollable factors in the sport of tennis, there is one thing that a tennis player can control—taking steps to ensure that their body is prepared to withstand the many physical rigors of the game.

However, seeing a tangible return on this investment of effort often takes some time, and this can present a challenge to the developing athlete. Indeed, it is something that Roger Federer reflected on in an interview in 2013: “I came in at a time when others were unbelievably successful at a young age... They were just a bit ahead of me. I didn’t understand why it wasn’t happening for me... I didn’t know why I was lifting weights, or when it was going to help me later in a tennis match. Then I understood more and more how important fitness was. The physical strength and the mental strength were the last things to fall into place.”

In essence, taking the time to establish a robust physical foundation can start as early as an athlete’s introduction to structured sport. Arguably, this is even more important in sports like tennis that can be unilateral and involve a large amount of skill repetition. Engaging professionals—who are already familiar with all of the concepts discussed in this chapter—with the appropriate expertise is a necessary step in structuring an effective program of strength and fitness training.

Ultimately, physical prowess underpins tennis success—among both recreational participants and professionals—and, as Federer eventually realized, the result is that the ball is well and truly in your court.

► **Training benefits** *Being prepared for the physical stresses and strains of matchplay is certainly an essential part of performing at peak level for all professional tennis players, but appropriate training can also help recreational players enjoy the game.*





How does periodization help with physical development?

How should I organize my physical training?

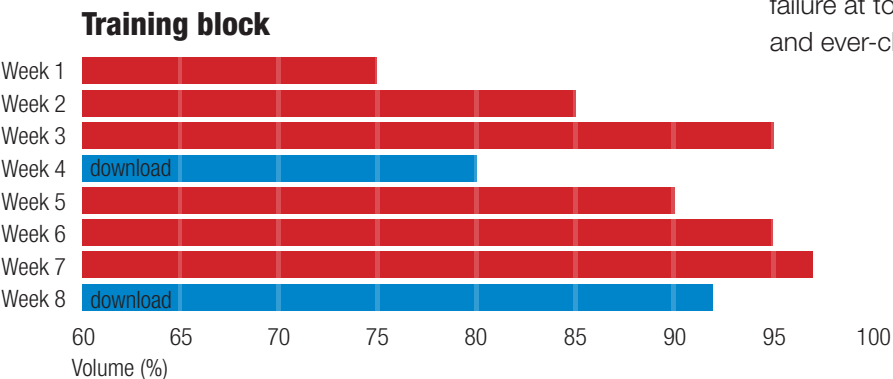
Periodization is the manipulation of training variables over specific periods of time to promote maximal performance when needed—during matches in a tournament, for example—while decreasing the risk of overtraining and injury.^{1,2} Well-planned programs which have been periodized have been shown to lead to greater performance improvements than non-periodized programs.^{3,4} To design an effective training program, the following areas need to be measured and assessed for each athlete: speed, agility, power, strength, flexibility, tennis technique, tactical proficiency, anticipation or reaction time, recovery capabilities, and time constraints that may affect the training schedule.

Linear (or staired) periodization—sometimes referred to as traditional periodization or block periodization—is a method of systematically increasing exercise intensity while manipulating its volume over a predetermined time period. When a tennis player receives a training stimulus at the beginning of a training block (or cycle) that is higher than the previous load, fatigue will occur. If the same load is maintained over the period of this training block, during subsequent training sessions, the body will begin to adapt to the new training intensity. This new level is the new ceiling of adaptation.⁵ During the “download” period, the intensity levels are those reached at the midpoint of the

stair progression phase, allowing for tissue regeneration and protein synthesis as well as the replenishment of energy stores. This is known as “supercompensation,” and it should leave the athlete in a heightened state of training preparedness for another successive series of increasing training intensities.⁶

The linear model of periodization is characterized by initial training volume with low levels of intensity. As training progresses toward major competitions, volume decreases and intensity increases in order to maximize strength, power, and endurance. Linear models of periodization are more appropriate when large periods of time are allocated for training with very limited competition periods. This is rare in the competitive annual tennis cycle, but does occur during different periods of a tennis player’s career—for example, when an athlete may have a 4–6 week period (or more) of focused training time. This is most common during the off-season/pre-season periods or when an athlete may be coming back from an injury.

The non-linear (undulating) periodization approach allows for more variation in intensity and volume within each training cycle by alternating different training protocols to prioritize various components of the neuromuscular and metabolic systems (strength, power, speed, endurance, and so on). This is the preferred approach for professionals given that success or failure at tournaments leads to uncertain annual match counts and ever-changing annual schedules.^{1,2}



◀ **Training program** This example of an eight-week block of training involves two “download” weeks. The horizontal axis highlights the maximum volume the athlete can handle per week. It is important to include download weeks every three to four weeks to allow for increased improvement and also to reduce the risk of overtraining, psychological burnout, or musculo-skeletal injury.

Five-day off-season training program

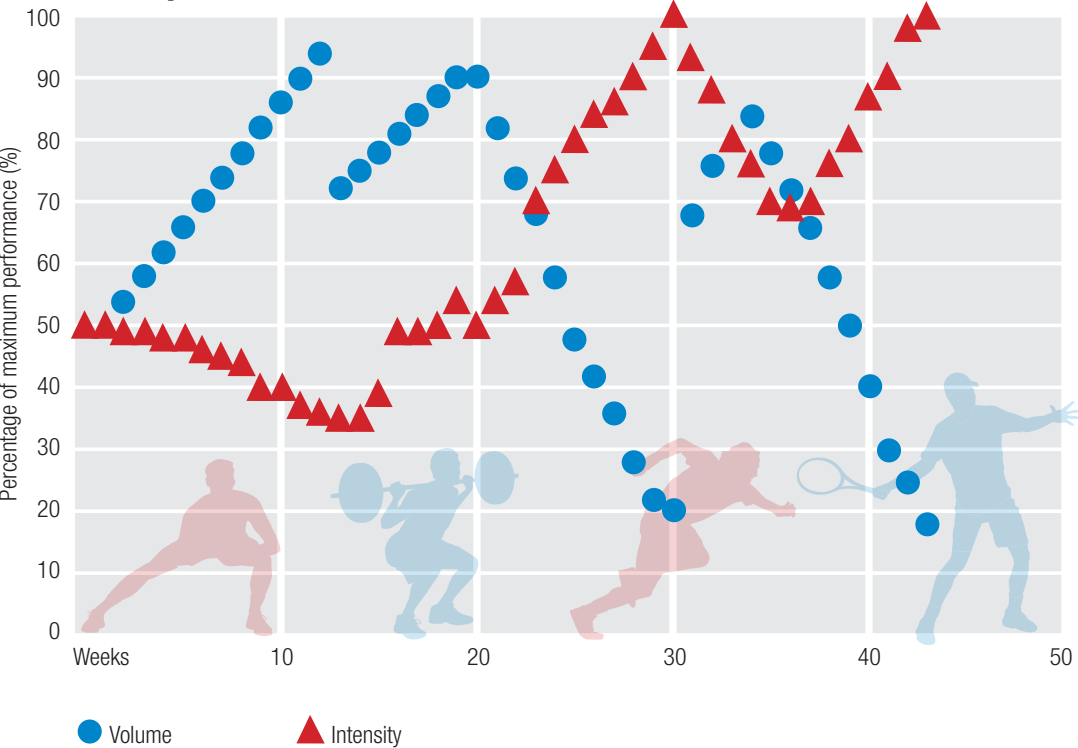
► **Week plan** This is a weekly outline for a five-day cycle of off-season tennis-specific training. It is a simple plan for a training week that involves all the major aspects involved in physically training a tennis athlete. The example shows a heavy training week with the objective of developing strength, while still hitting a relatively high volume of tennis balls (as is seen by the two-per-day practices).¹

Monday	Dynamic stretching	SAP	Morning practice	TSE	L	SAP	Dynamic stretching	Afternoon practice	UL	Static stretching
Tuesday	Dynamic stretching	SAP	Morning practice	R	U	SAP	Dynamic stretching	Afternoon practice	LH	Static stretching
Wednesday	Dynamic stretching	SAP	Morning practice	TSE	N	SAP	Dynamic stretching	Afternoon practice	R	Static stretching
Thursday	Dynamic stretching	SAP	Morning practice	R	C	SAP	Dynamic stretching	Afternoon practice	UH	Static stretching
Friday	Dynamic stretching	SAP	Morning practice	TSE	H	SAP	Dynamic stretching	Afternoon practice	LL	Static stretching

SAP On-Court Speed Agility and Power (10–15 min)
TSE Tennis Specific Endurance (30–45 min)
R Recovery

UL Upper Body Light (strength training)
LH Lower Body Heavy (strength training)
UH Upper Body Heavy (strength training)
LL Lower Body Light (strength training)

Linear periodization



◄ **Training chart** This chart shows a traditional linear periodization training schedule for an athlete, outlining the stepped adjustments in intensity and volume.^{1,2} Note how the volume of exercise decreases as its intensity increases. This improves the athlete's strength, power, and endurance as they approach a major event, while minimizing the risk of injury and overtraining.

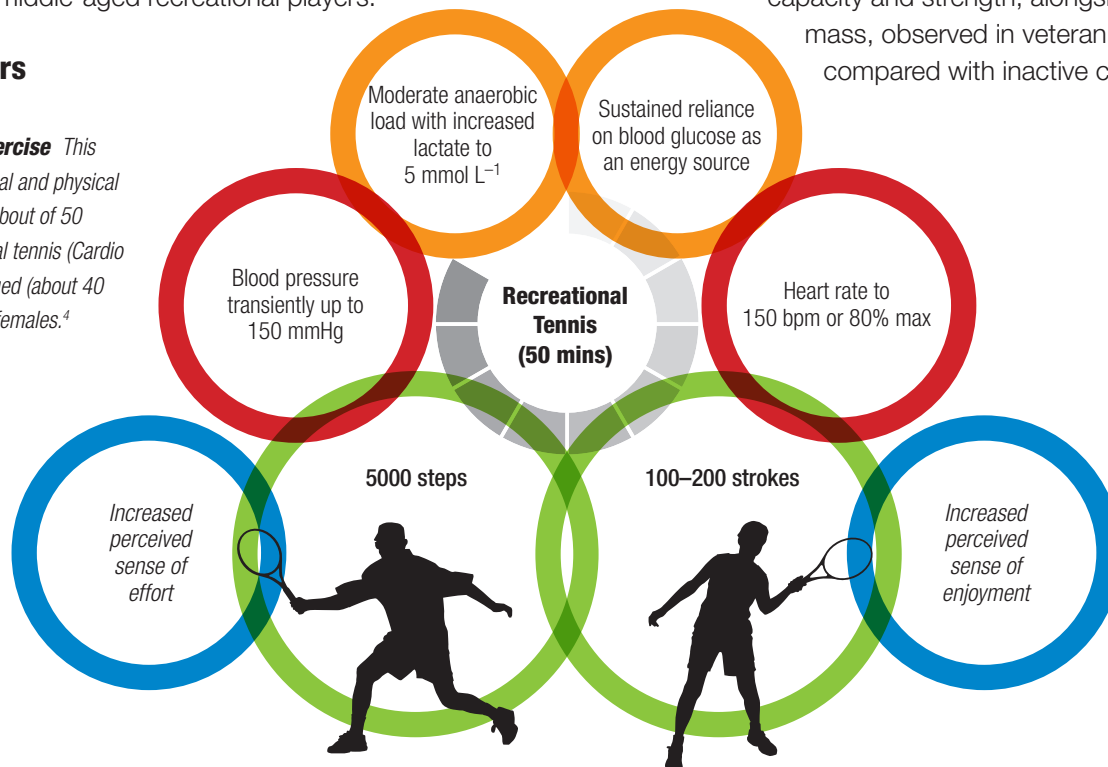
What health markers can tennis improve?

Can playing tennis improve my overall health?

There is a growing concern regarding public health as a result of increased inactivity and sedentary lifestyles, which are potentially complicit in the increase in chronic, lifestyle-based diseases. Specifically, the loss of cardiovascular fitness, glucose regulation, and lean body mass that results from sedentary lifestyles may lead to the development of cardiovascular disease, diabetes, and sarcopenia or muscle atrophy. In contrast, regular exercise can maintain, if not improve, such factors, and act as a defense against disease development. The physical demands of competitive tennis result in substantial physiological stress and potential improvement in aerobic fitness and body composition, exemplified by the high fitness capacities of professional players. In relation to tennis, research has shown that six weeks of tennis training improved cardiovascular fitness and body composition in middle-aged recreational players.¹

Health markers

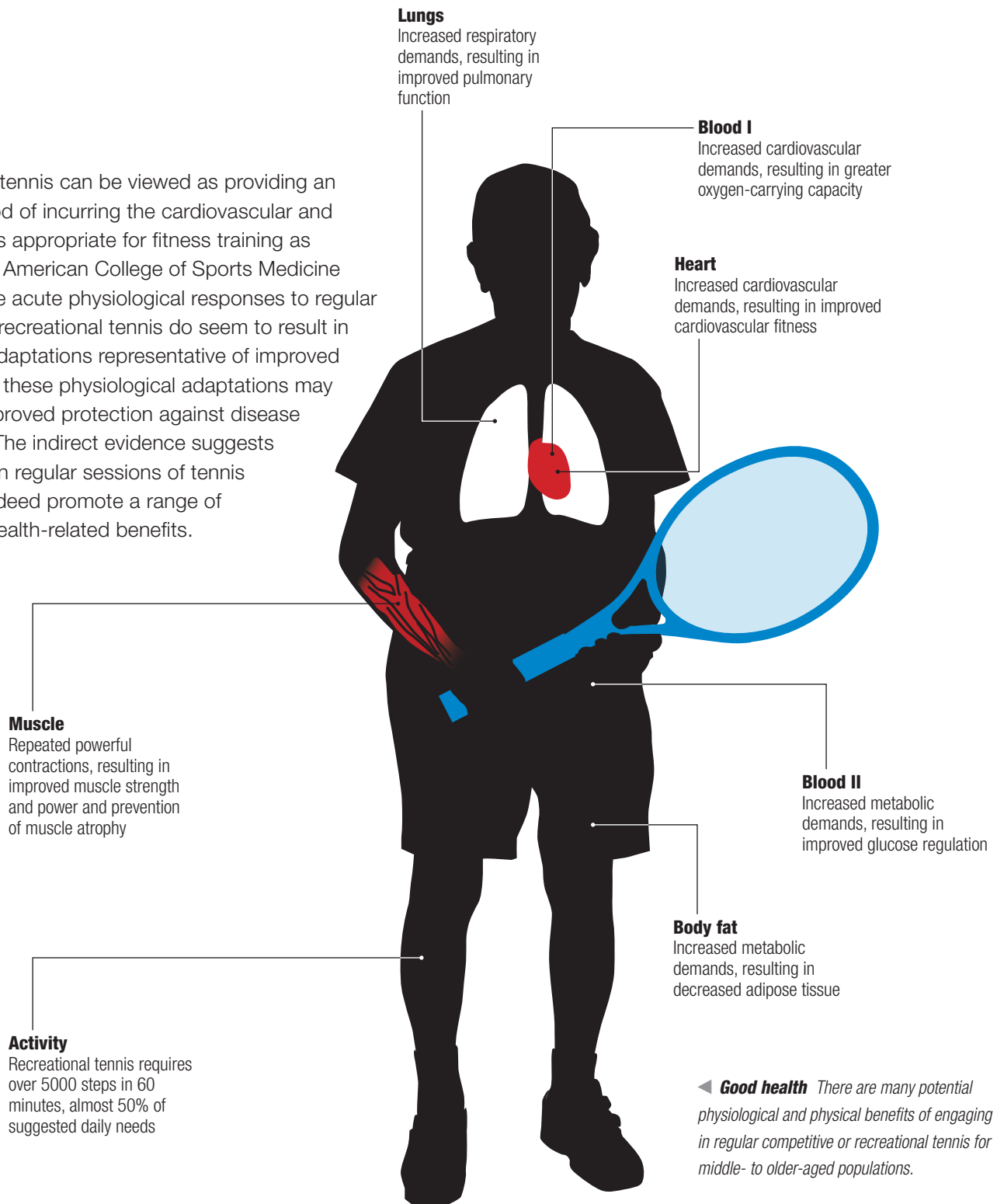
► **Response to exercise** This shows the physiological and physical responses to a single bout of 50 minutes of recreational tennis (Cardio tennis®) in middle-aged (about 40 years old) males and females.⁴



Competitive tennis is known to induce sustained and substantial physiological responses, including increased oxygen consumption, cardio-respiratory demands, and glucose and free fatty acid utilization.² The intermittent efforts of prolonged duration matchplay are likely to result in sufficient cardiovascular demands to improve aerobic fitness. In addition, the moderate-to high-intensity exercise of prolonged duration involved in playing tennis also induces substantial metabolic demands, requiring increased metabolism of glucose and triglycerides, which in turn is likely to assist long-term glucose regulation. The movement demands of competitive tennis, including regular explosive upper- and lower-body skeletal muscle contractions, can also result in the development and maintenance of skeletal muscle mass and reduction in fat mass. Such acute responses to competitive tennis may explain the noted higher aerobic capacity and strength, alongside lower fat mass, observed in veteran tennis players compared with inactive control groups.²

Health benefits

Consequently, tennis can be viewed as providing an effective method of incurring the cardiovascular and metabolic loads appropriate for fitness training as outlined by the American College of Sports Medicine standards.³ The acute physiological responses to regular competitive or recreational tennis do seem to result in physiological adaptations representative of improved fitness. In turn, these physiological adaptations may bring some improved protection against disease development. The indirect evidence suggests that engaging in regular sessions of tennis training may indeed promote a range of physiological health-related benefits.



◀ **Good health** There are many potential physiological and physical benefits of engaging in regular competitive or recreational tennis for middle- to older-aged populations.



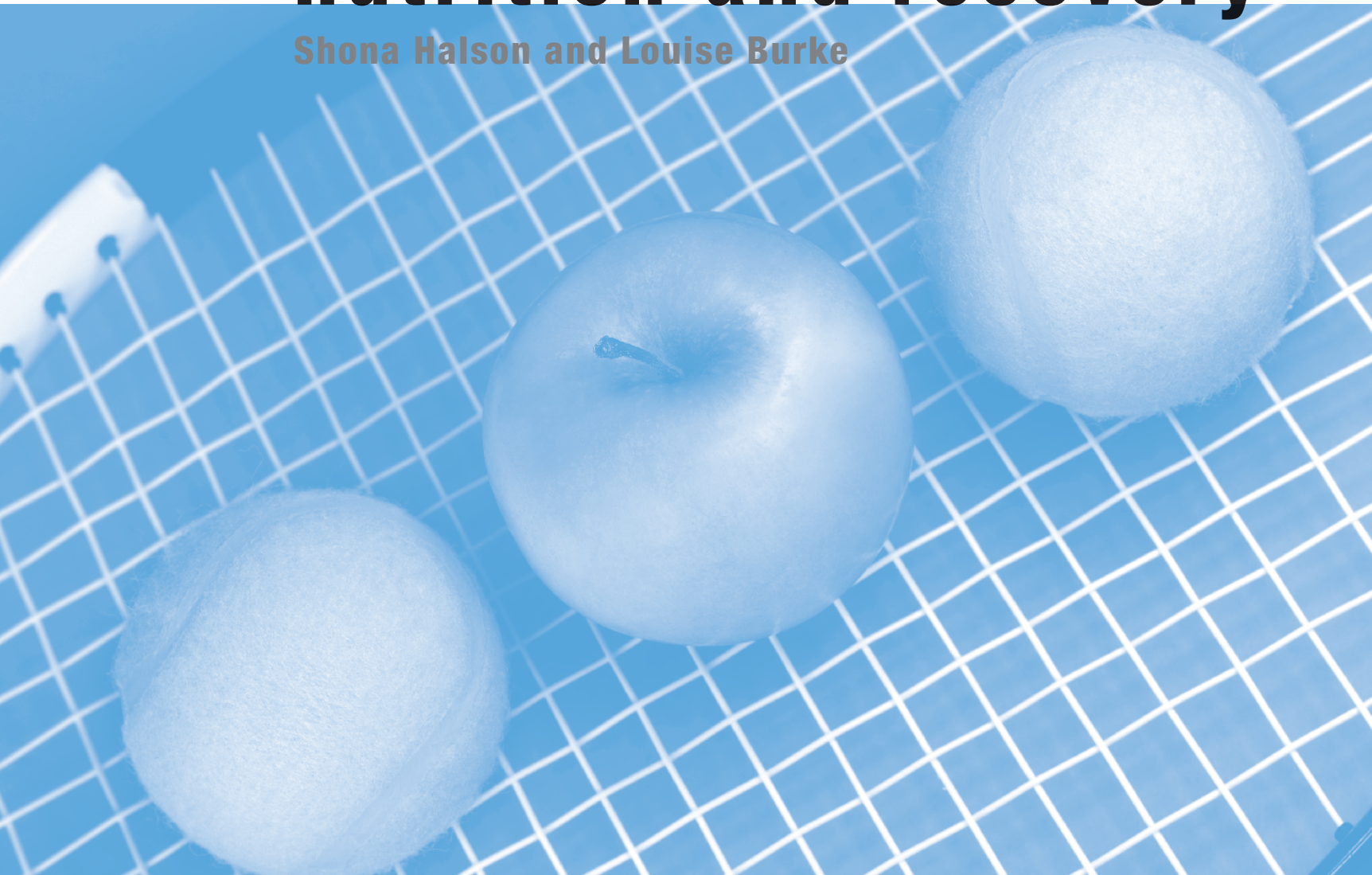
Performance nutrition and appropriate recovery are important components of success for the tennis professional. While there is limited tennis-specific scientific information, there is an increasing amount of research that is relevant. Although it is difficult to investigate the effects of nutrition during a match, nutritional strategies are gleaned from direct investigations of dietary components and simulations of play.

The development of a nutrition plan, including fluid balance, and consideration of how this may differ across the development pathway are obviously integral to successful performance. The roles of sleeping, eating, and other techniques in recovery are also taken into consideration as part of the broad training plan for all tennis players.

chapter six

nutrition and recovery

Shona Halson and Louise Burke



How can nutrition contribute to tennis success?

What should I eat to improve my tennis?

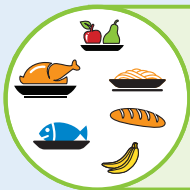
Creating a winning diet for a tennis player involves designing an individualized eating plan that can meet a range of different and changing goals. Just as the goals and demands of the player's exercise load can be periodized over the weeks and months of the tennis calendar—and throughout their career—so should the nutrition plan change to reflect different priorities, requirements, and challenges.

Energy intake in the form of carbohydrates should match the demands of training and match volume, as well as the needs of growth or manipulation of physique. Eating patterns should also be timed to ensure key nutrients are provided to support performance and recovery, as well as to benefit from a regular intake of protein over the day. Focusing on nutrient-rich foods and drinks ensures that micronutrient (for instance, iron and calcium) needs are met and phytochemicals (found in selected fruit and vegetables) provide full health benefits. Matchplay demands an understanding of the factors that will interfere with the player's ability to maintain coverage over the court—including speed, agility, and endurance, as well as the power,

concentration, and skills needed to read and execute play. The focus will be on strategies before, during, and between matches to maintain optimal fuel for the muscle and brain and to prevent levels of dehydration that impair performance.

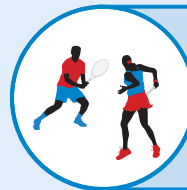
While many of these principles may apply equally to other sports, both the specific needs and the practicality of achieving them for a tennis player are unique. The tennis calendar is lengthy and the match load is unpredictable as players rarely determine when they qualify for, and exit from, tournaments. The ability to organize a stable nutrition environment is challenged by constant travel and the added unpredictability of training and match schedules. Matches are played over an indeterminate duration, in a variety of environments, and may finish late at night. Players must develop an understanding of the nutrition scenarios they might face, and need to remain flexible. Sound nutrition knowledge and practical skills must often be developed at an early age to allow young players to become sufficiently independent to join the competition circuit or to move away from home to train in specialized academies.^{1,2}

Building the winning diet



The most important nutrition strategy for the junior player is to develop sound eating plans based around nutrient-rich foods and drinks, which suit the player's lifestyle, food enjoyment, and energy needs. Carefully chosen meals or snacks can manipulate energy and carbohydrate intake.

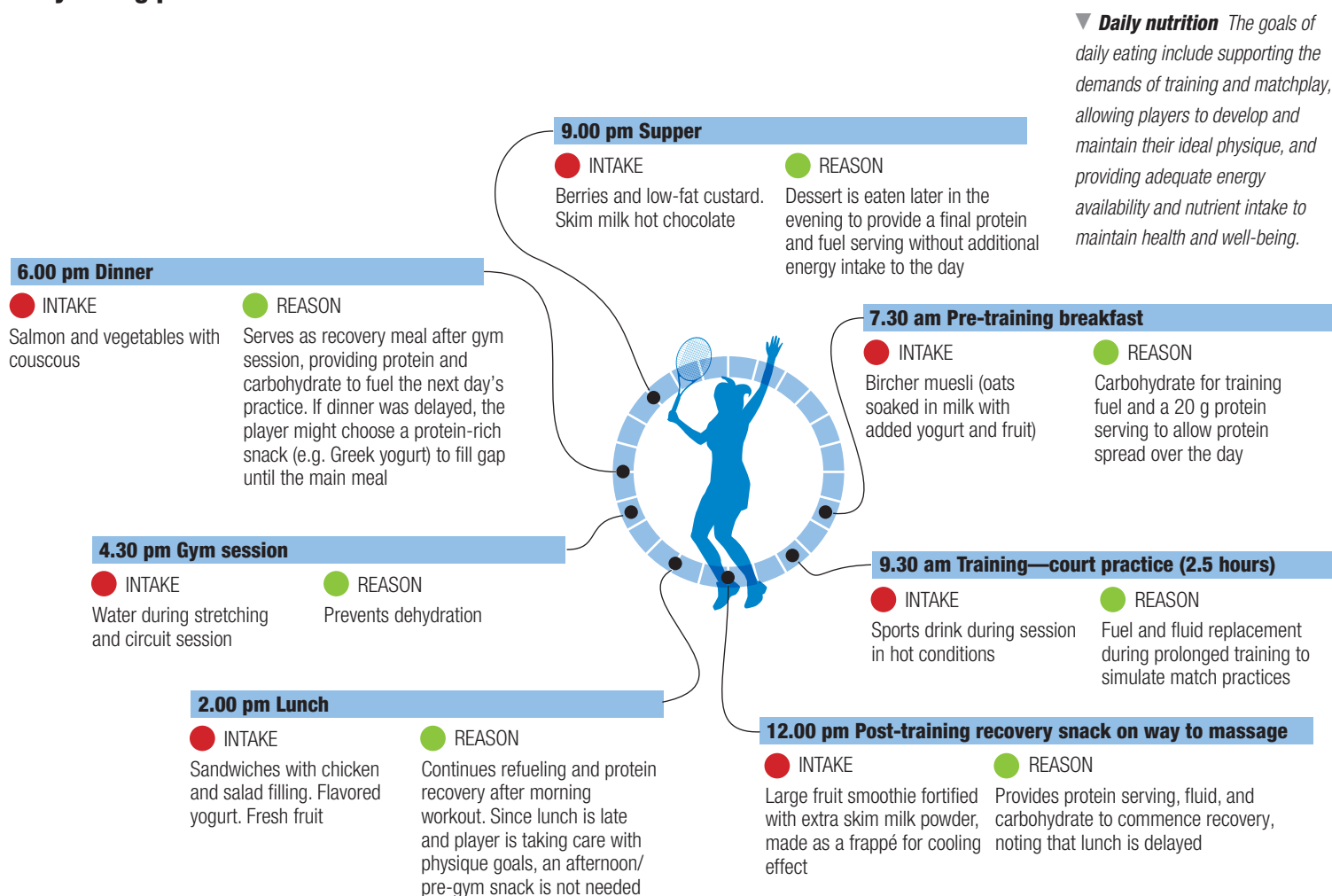
▲ **Eating for the basics: staying healthy, injury-free, and in shape** Daily eating plans should provide energy and carbohydrate for workouts and matchplay, increasing intake during high-volume training and tournament play and decreasing intake during periods of reduced activity. Intake should be manipulated carefully during periods of growth or to change lean mass or body fat. Regular meals and snacks should provide moderate servings of high-quality protein, vitamins, minerals, and phytonutrients.



Even junior players can start to develop successful plans for pre-match eating, hydrating, and fueling during matches, and recovery post-match. As the level of play increases, plans should evolve to address the greater fluid and fuel requirements of a match or tournament.

▲ **Match nutrition: nutritional strategies to delay fatigue** A number of nutrition-related factors (for example, dehydration, fuel depletion) cause a loss of performance during a tennis match. Nutrition strategies before, during, and between matches which reduce or delay these factors will allow the player to sustain optimal movement patterns, skill, and concentration, which increase their chances of winning.

Daily eating plan



From junior levels, it is useful to develop good post-match recovery eating for tournament play. As the level of play increases, eating plans should target recovery nutrition after key workouts. High-performance players may benefit from working with a sports nutrition expert.

▲ Periodizing adaptation and recovery around workouts and matches

Studies of the interaction of training and nutrition have identified strategies that promote recovery (for example, rapid intake of key nutrients such as high-quality protein, fluid, and electrolytes for rehydration, carbohydrate for refueling and immune system, micronutrients and phytochemicals for repair and restoration). Sports nutrition requires periodizing strategies around training and matches to balance short-term and long-term goals.



Ergogenic (or performance-enhancing) supplements may be suitable for the high-performance player after all other layers of the nutrition plan are in place. Even so, the use of supplements should be undertaken under the supervision of a sports nutrition expert.

▲ **Evidence-based ergogenic supplements** Among the many supplements promoted to players, there are a few that have documented or probable benefits for matchplay (e.g. small to moderate doses of caffeine) and/or to support player conditioning (e.g. creatine, beta-alanine).

What body fuels best enhance tennis performance?

What should I eat before, during, and after a match?

Exercise is powered by an integrated set of energy-producing metabolic pathways. Carbohydrates provide an important fuel source for the brain and muscle, releasing its energy via both oxygen-dependent (aerobic) and oxygen-independent (anaerobic) pathways. Twenty years ago, sports nutrition guidelines promoted a universal message that all athletes should eat carbohydrate-rich diets at all times in training and competition. New messages have evolved in the light of new evidence, but not all coaches and athletes have caught up with these changes. Also, some best-selling diets add to the confusion by appearing to be “anti-carb.” This creates the need for clear messages about carbohydrates for sports performance.¹

Although it can sometimes be difficult to effectively measure sports performance, many studies, including some involving tennis, show that performance during prolonged activity using high-intensity efforts, skill, and concentration is enhanced when the body’s carbohydrate supplies keep pace with fuel needs

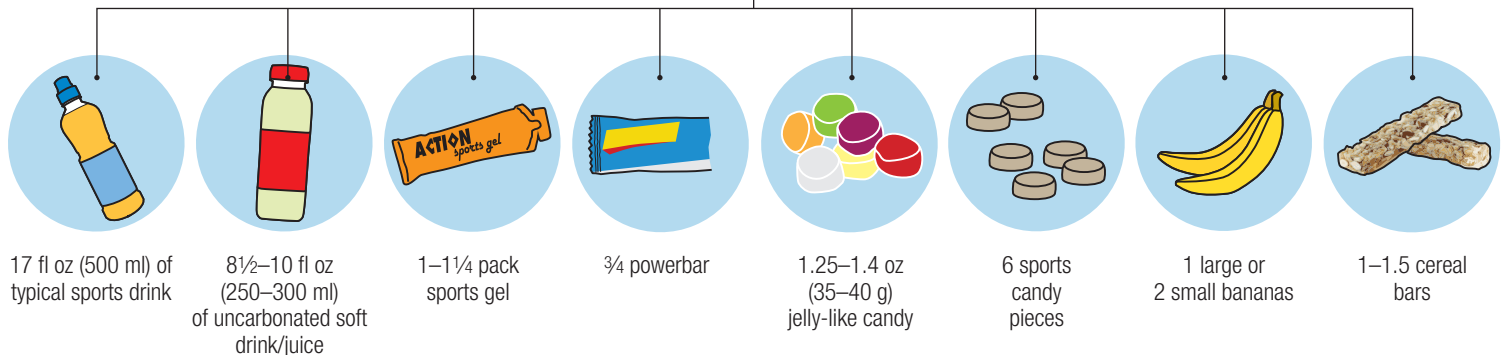
(termed “high carbohydrate availability”). These supplies, which can be depleted by a single exercise session of sufficient intensity and duration, include glycogen stored inside the muscle and blood glucose, which is topped up by liver glycogen and carbohydrates consumed just before and during exercise. Although guidelines continue to promote high carbohydrate availability for optimal sports performance, current advice is that athletes should consume carbohydrates according to the demands of their sport.

Tennis is a challenging sport due to the variation and unpredictability of match fuel needs—the duration and intensity of most matchplay is highly variable and hard to anticipate. While some general principles can be suggested, these must be continually changed according to personal experience and, often, guesswork. The disadvantages of being under-fueled for a demanding match include fatigue and performance impairment. Conversely, over-consuming carbohydrates for a match that is won quickly, forfeited, or postponed can lead to the intake of excess energy.

This may not be problematic on a single occasion, but can lead to problems with weight management if it becomes a frequent experience over the lengthy tournament calendar.^{2,3}

▼ **Refueling during a match** Carbohydrate-containing fluids (sports drinks) and other easily tolerated carbohydrate forms (such as sports gels and candy) can be consumed at each change of ends for additional fuel for the muscles. It has been suggested that 1–2 oz (30–60 g) of carbohydrate per hour of matchplay can help maintain performance.

What does 1 oz (30 g) of carbohydrates look like?



Fueling for matchplay



1. Restoring muscle glycogen

Well-trained players can restore muscle glycogen levels to those suited to a single tennis match by 24 hours of rest and carbohydrate-eating. Carbohydrate intake targets of 2.3–3.2 g/lb or 5–7 g/kg body mass (BM)—for example, 350 g of carbohydrates for a 154 lb or 70 kg player—are suitable for shorter-duration matches (three sets) and many longer matches.



2. Carbohydrate loading

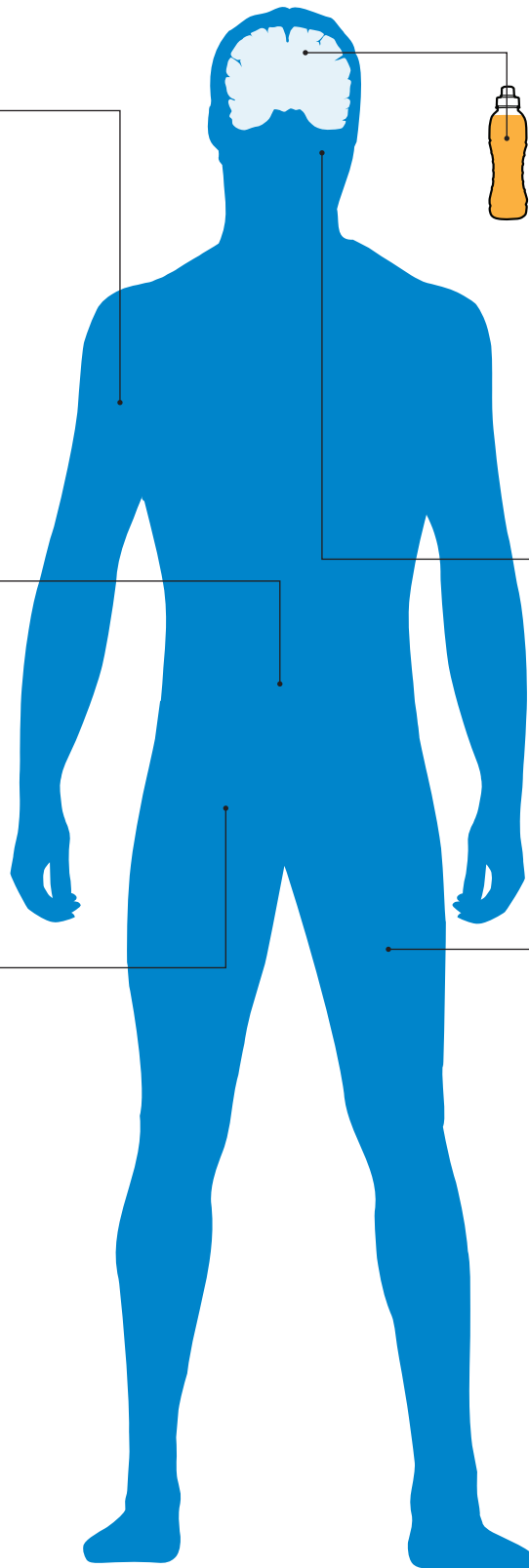
Full restoration and even super-compensation of muscle glycogen stores in anticipation of a “marathon” match can be achieved by 24–36 hours of rest and higher carbohydrate intakes (about 4.5 g/lb or 10 g/kg BM). Players should experiment with such strategies to identify any disadvantages such as weight gain, gut discomfort, and muscle heaviness.



3. Pre-match meal

Carbohydrate stores can be further topped up by a meal providing 0.45–1.8 g carbohydrates/lb BM (1–4 g carbohydrates/kg BM) from foods that are familiar and well tolerated. The size of the meal will depend on individual preference and the period until matchplay. When the time of commencement of the match is unknown, many players will have a moderate size meal or snack two hours before the possible start of play, then top up with smaller snacks or liquid meals as commencement time is extended.

► **Brain and muscle fuel** Opportunities to increase carbohydrate availability for matchplay include diet intake during the 24 hours prior to a match, the pre-match meal, intake during the match, and refueling between matches.



4. Intake during matches: the “happy” brain

Recent research shows that the brain responds to the sensation of having carbohydrate in the mouth and throat, feeling energized, and able to work at a higher output.⁴ This is best achieved by swilling or holding carbohydrate sources in the mouth for about 10 seconds at each changeover. Even if muscle fuel demands are low (because of shorter matches or good fueling practices), there may still be a benefit to following this practice with small amounts of carbohydrate drink, gel, or candy.



5. Post-match refueling

Speedy intake of easily consumed carbohydrate-rich drinks and foods (0.45 g/lb or 1 g/kg BM per hour for the next 4 hours) can promote aggressive refueling for matches played within the next 24 hours. When games finish late at night, the player must be organized and have access to suitable supplies, but they may have to balance refueling goals against sleep needs. A source of high-quality protein should also be consumed to address a range of recovery goals.



6. Intake during matches: muscle needs

Carbohydrate-containing fluids (e.g. sports drinks) and other easily tolerated carbohydrate forms (e.g. sports gels and candy) can be consumed at each change of end to provide an additional fuel source for the muscle. Extra fuel supplies become important as the match duration or demands increase, or in tournament scenarios in which there is inadequate opportunity for refueling between matches. The player should experiment with targets of 1–2 oz/h (30–60 g/h) of carbohydrate, steering toward the higher end of the range when demand is high. Practice will help to identify successful strategies as well as train the gut to improve carbohydrate absorption.

How does dehydration affect tennis performance?

What should I drink during a match?

Evaporation of sweat provides the major opportunity to dissipate the body heat either generated as a byproduct of exercise or absorbed from a hot environment. Sweat rates during tennis vary according to factors such as the duration and intensity of play (length of rallies), environmental conditions (heat, humidity, airflow), and the player's size, clothing, and state of fitness and acclimatization. Typical sweat rates vary from 15–70 fl oz/hour (0.5–2.0 liters/hour)—although rates in excess of this have been recorded under extreme conditions at major tournaments (for instance, the Australian Open), and these can cause substantial losses of fluid and electrolytes. This is compounded if the player starts a match already dehydrated because of failure to rehydrate from a previous match in the tournament.^{1,2,3}

As the body fluid deficit increases, there are physiological, psychological, and performance adjustments. Although this is often presented as a graph—which shows a consistent decrement in running speed and endurance or measures of skill and concentration at different levels of dehydration—this oversimplification has allowed some controversy to occur regarding hydration guidelines for sport. However, it is likely that rising levels of dehydration increase the perception of effort of play, and therefore decrease both the physical and mental levels of performance. Indeed, complex activities carried out in hot environments are the very worst scenario for performance impairment. Furthermore, at the elite level of the sport, even small decrements in speed and skill cost points and matches.

► **Sweat loss** A rough estimate of sweat losses can be gained by measuring the change in body mass over a match/training session, adjusting for (adding) the weight of fluid and food consumed. This helps to set fluid intake goals or to assess the success of current drinking practices.

Although some argue that fluid guidelines should encourage athletes to drink only when thirsty, competitive sports rarely provide opportunities to drink enough to compensate for the levels of fluid loss. Therefore, sports nutrition practitioners prefer to assist athletes by developing a competition plan that paces fluid intake across the opportunities for drinking. Such a plan can integrate a series of goals that includes keeping the overall fluid deficit to a moderate level (typically less than 2% = or BM). This approach maintains gut comfort and uses fluids to achieve other ergogenic effects (for instance, consuming carbohydrate or caffeine, or to achieve cooling).⁴ Such a plan should never allow a player to overdrink (in excess of sweat losses) so that water intoxication occurs with the dangerous risk of hyponatremia or low blood sodium concentrations.

Example calculations

Your fluid intake = mass of drink bottle before – mass of drink bottle after (g)
= 900 g – 100 g = 800 g
= 800 ml (since 1 ml water has a mass of 1g)
(contained 6% carbohydrate sports drink)

Your fluid deficit = body mass pre-session – body mass post-session (kg)
= 60.50 – 59.05 = 1.45 kg = 1450 g
= 1450 ml

Your fluid deficit (% body mass) = (fluid deficit in kg/body mass in kg) × 100%
= (1.45/60.50) × 100% = 2.4%

Total sweat losses over the session = fluid deficit + fluid intake + food intake
= 1450 g + 800 g + 40 g (sports gel) = 2290 g
= 2290 ml

Sweat rate over the 90-min session = sweat losses per hour
= 2290 ml/1.5 hours = 1530 ml/hour = 1.53 liters/hour

Note also the total carbohydrate content from sports drinks, gels, popsicles, or other foods:

Total carbohydrate intake = sports gel (25 g) + sports drink (800 ml of 6% carbohydrate drink, gives 48 g)
= 73 g

To convert to imperial measurements: 1 liter ≈ 34 fl oz ≈ 2.2 lb body mass

Hydration for performance

Electrolytes

There is some controversy about the need for sodium (salt) replacement in a player's fluid plan. Some case histories report that players who are heavy or salty sweaters have reduced or even reversed their risk of cramping by replacing their large sodium losses during the match via the use of higher-sodium sports drinks. Most cramps, however, are caused by the fatigue associated with exercise of unaccustomed duration or intensity.

What to drink?

Drinks should be kept courtside for easy access. They should be kept cool and refreshing to encourage intake and to contribute to body temperature management in hot conditions (e.g. icy slushies). Sports drinks can contribute to fueling goals as well as hydration needs.

How much to drink?

Fluids should be consumed during warm-up, and at changeovers at a rate that is comfortable and tracks with sweat rates (i.e. drink more with greater sweat rates and less with lower rates). Target volumes will differ from player to player, and should be practiced so the athlete develops tolerance, and adjusted accordingly. In most cases, a fluid deficit will occur across high-intensity matches in the heat, but the goal is to keep this deficit to acceptable levels. It is not necessary or helpful to overdrink.



◀ **Staying hydrated** Even a small amount of dehydration reduces performance. Although it might be imperceptible, a rising fluid deficit is likely to reduce running endurance, impair skills, and reduce concentration and comfort. In most cases, players should aim to keep the total fluid deficit to less than 2% body mass (BM), particularly in hot weather. This may not always be possible but provides a reasonable target.

Post-match rehydration

When large sweat losses occur during play, the pre-match to post-match weight change provides a guide to rehydration needs. Since urine and sweat losses continue during the recovery period, the player should aim to drink a volume of fluid equal to 125–150% of their match deficit over the following few hours to restore fluid levels. Electrolytes should be replaced simultaneously, with sodium-containing drinks or salt-containing foods in recovery meals and snacks.

Assessing hydration levels



Weigh yourself before the session, using reliable digital scales—this should be done wearing minimal clothing (underwear only, if possible) and after going to the bathroom. Also, weigh your drink bottle(s) before your workout



Weigh in again after training in the same clothing, and after towel-drying

Weigh your drink bottle(s) after your workout to find out how much fluid you consumed—or just estimate the amount of fluid consumed and convert ml of fluid into grams

Note the weight of any foods or sports products consumed during the session (e.g. gels, popsicles, bars)

equipment: compression garments

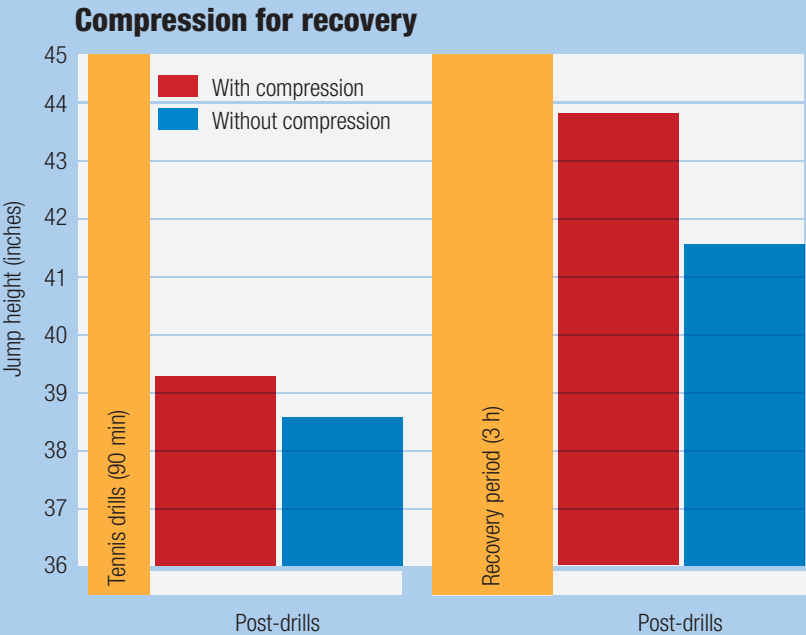
Graduated compression has been used in the medical industry for many years to prevent lymphedema—the accumulation of fluid—and to manage wounds and scars. Compression garments are believed to assist in relieving these ailments by enhancing blood circulation. Like many other recovery tools, the use of compression in the medical realm has led to its use in the sporting industry. Many of the benefits associated with the use of compression garments are attributed to an increase in blood flow. It is believed that the optimal method of applying the compression to increase blood flow is to do so by using materials that exert greater pressure on the body at the ankle than further up the leg.

The external pressure is thought to reduce swelling, inflammation, and muscle soreness, and so enhance recovery. Research has been done investigating a multi-faceted approach to recovery, including the use of full body compression garments, cold water immersion, and sleep—which was shown to assist subsequent tennis performance, as well as resulting in favorable physiological outcomes such as reduced blood lactate, heart rate, and perceived muscle and joint soreness.¹

► **Jump heights** This graph demonstrates the effects of a program of recovery—including the use of compression clothing, cold water immersion, and sleep—on the heights of jumps performed by athletes after a 90-minute and 180-minute period of tennis drills.

The continuing improvements in fabric technology and compression design have resulted in various forms of compression garments that are used by different athletes, as well as improvements in comfort, performance, and the degree of compression. For example, calf sleeves have been developed that can be worn during certain tennis tournaments as well as during training. Other types of compression garment available include socks, arm sleeves, shirts, tank tops, shorts, leggings, and tights.

Improvements in fabric technology have also resulted in specialized fabrics and designs for compression garments. The mechanical properties of these clothes include thermal resistance, extension, recovery behavior, and elasticity, which are important factors in maintaining compression over time.



Fabric technology and compression design

► **Full leg compression tights** Improved circulation for athletes allows faster delivery of nutrients to fatigued muscles, removes waste products built up during exercise, and delivers oxygen to the muscles more efficiently. Limb swelling may also be limited by compression garments, as the external pressure gradient they provide reduces the space available for edema to form.

Fabric has antibacterial properties and UPF50+ sun protection—important for athletes competing outdoors

High-filament yarns for dryness—the material is designed to wick sweat away from the skin to the fabric exterior. This minimizes increases in skin, muscle, and core temperatures

Flatlock seams to reduce chafing—ensuring greater comfort vital to the player when training, playing, or wearing compression for recovery

Constructed from spandex (Lycra) to optimize fit, support, and recovery, the precise pressure of the garment on the muscle is an important factor—so the size and fit of the clothing, as well as its fabric properties, all need to be carefully assessed

Structured fabric creates graduated compression—this is thought to constrict superficial veins, thereby improving circulation to increase recovery



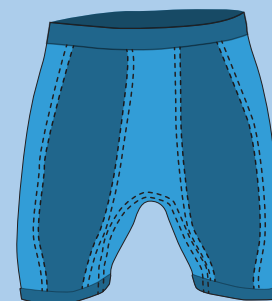
▲ **Calf sleeves** Calf sleeves worn during training have the effect of improving muscle performance and muscle recovery.



▲ **Arm sleeves** Tennis players use compression arm sleeves to keep their arms warm on colder days, protecting muscles from injury and improving recovery times.



▲ **Tank tops** Wearing a compression top helps to keep the body warm and provides support for the core, improving upper body stability and reducing fatigue during practice sessions.



▲ **Shorts** Modern fabrics combine comfort, breathability, and support, helping athletes to endure longer sessions. Many pro tennis players wear compression undergarments after training to help them recover more quickly.

What are the most effective post-match recovery strategies?

How do I recover after a match?

Recovery aims to restore physiological and psychological processes so that the player can compete or train again at an appropriate level. The rate and quality of recovery are extremely important for the high-performance player, and optimal recovery provides numerous benefits during repetitive high-level training and tennis competition. There are a number of popular methods used by players to enhance recovery. Of the various recovery techniques available, some of the more popular include hydrotherapy, active recovery, compression garments, and massage.

Various forms of water immersion are becoming increasingly popular with elite athletes. The most common are cold water immersion (CWI), hot water immersion (HWI), and contrast water therapy (CWT), where the athlete alternates between hot and cold water immersion. The human body responds to water immersion with changes in the heart, peripheral resistance, and blood flow, as well as changes in the skin, core, and muscle temperature.¹ These changes in blood flow and temperature responses are thought to have an effect on inflammation, immune function, muscle soreness, and perception of fatigue. When performed correctly, hydrotherapy can have significant positive effects on athletic performance. Numerous tennis

players report using hydrotherapy after matches, in particular cold water immersion or ice baths (see pages 128–129).

While the research on the benefits of active recovery—beyond simply removing lactate—is minimal, the role of active recovery in reducing muscle soreness and increasing the range of motion after training and matches may be an important factor for tennis players. Similarly, while there is currently limited research into compression garments and recovery for tennis players, early data suggest that they may be beneficial and do not appear to be harmful in any way.² Finally, research into the effects of massage has concluded that, while massage is effective in improving psychological aspects of recovery, most evidence does not support massage as a means to improve functional performance. However, as it may have potential benefits in injury prevention and management, massage should still be incorporated in the elite tennis player’s training program.

Recovery plan

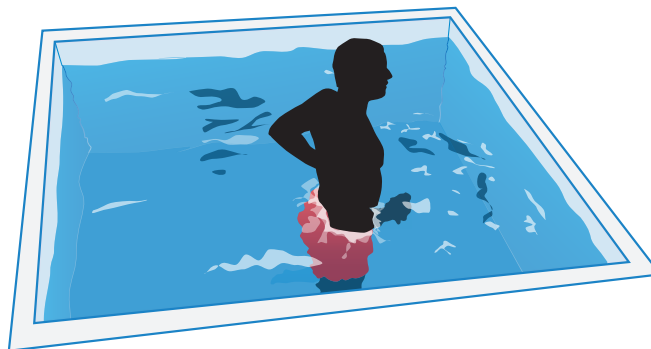
1. Active recovery	5 minutes of low intensity activity (stationary bicycle is ideal)
2. Nutrition	Commence replenishment of your energy stores and fluid levels
3. Water immersion	Cold water immersion or contrast water therapy as soon as practical post-match, accumulate 10–15 minutes in 50–59°F (10–15°C) water to shoulder level
4. Compression garments	Wear compression garments for more than 60 minutes following water immersion
5. Nutrition	Consolidate replenishment of your energy stores and fluid levels with a meal
6. Sleep during day	Brief periods of sleep during the day may be appropriate after morning matches so long as it does not impair the next night’s sleep
7. Massage	The type of massage will depend on what training or matches are planned in the next few days
8. Overnight sleep	Give yourself the opportunity to get plenty of quality sleep that night

► **Recovery strategies** *The type and sequence of recovery is important to ensure optimal repeat performance. This recovery plan outlines an example of both potential strategies and a sequence that may be incorporated post-match by tennis players.*

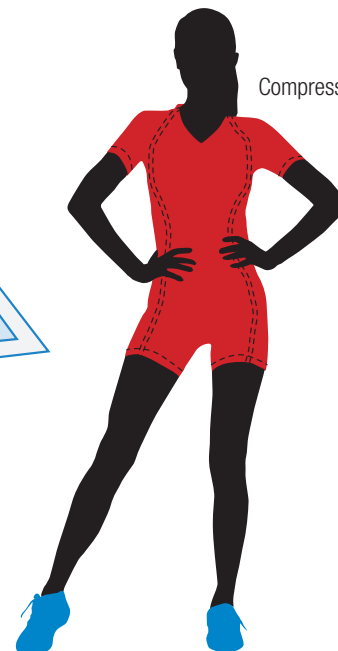
▼ **Variety** Incorporating a variety of recovery strategies into training and competition can be an effective way for tennis players to enhance performance and reduce the risk of injury and overtraining. There are a number of popular methods used by athletes to enhance recovery—depending on the type of activity performed, time until the next training session or event, and equipment or support personnel available.³

Recovery strategies

Hydrotherapy



Compression



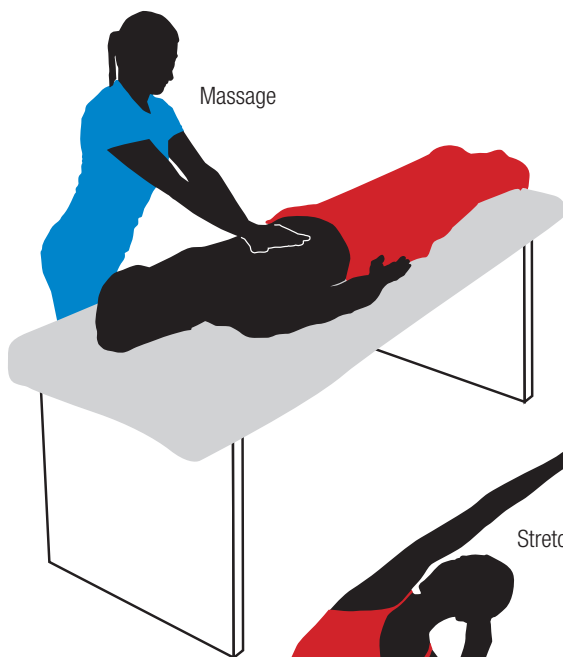
Sleep



Active recovery



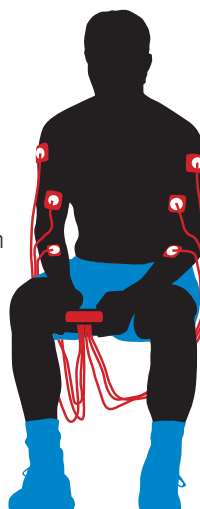
Massage



Stretching



Electrical stimulation



Whole-body cryotherapy

How does cold water immersion enhance physical recovery?

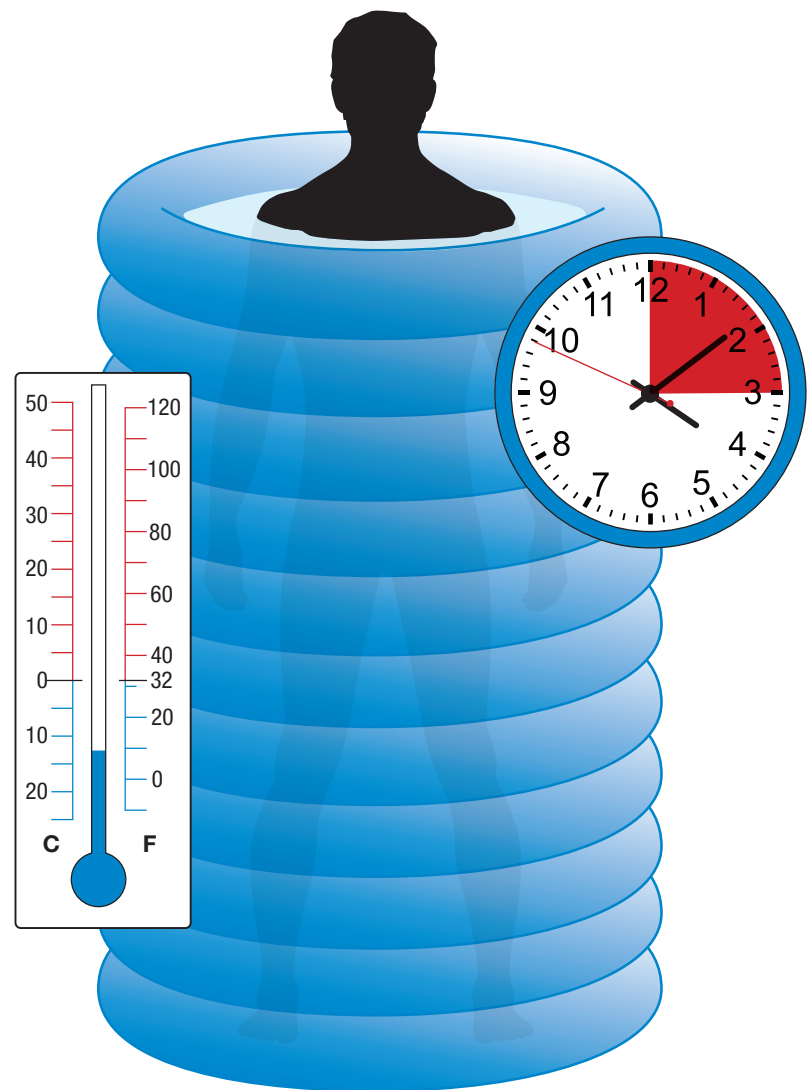
Will an ice bath help me to recover?

Cryotherapy, meaning “cold treatment” (normally in the form of an ice pack), is the most commonly used method for treating acute soft tissue sports injuries, due to its ability to reduce the inflammatory response and to alleviate spasm and pain. Cold water immersion (CWI) or ice baths are one of the most common forms of cryotherapy used by elite athletes, including tennis players, to enhance recovery. Multiple physiological responses to various cooling methods have been observed, including a reduction in heart rate and cardiac output, and an increase in arterial blood pressure and peripheral resistance. Other responses include decreases in core and tissue temperature, acute inflammation, and pain, and a better maintenance of performance. Cryotherapy is an effective method for decreasing skin, muscle, and core temperatures, inflammation, blood flow, muscle spasm, and pain.

The majority of research supports the notion that when performed correctly, CWI is an effective treatment intervention for the reduction of symptoms associated with delayed onset muscle soreness. It is also thought to enhance repetitive high-intensity exercise performance. This is particularly important during tournament play, where players must compete on consecutive days. Recent research demonstrated that combining CWI and compression garments after tennis sessions increased the shots per minute of highly trained tennis players, increased their lower-body power, and reduced the amount of perceived muscle soreness.¹

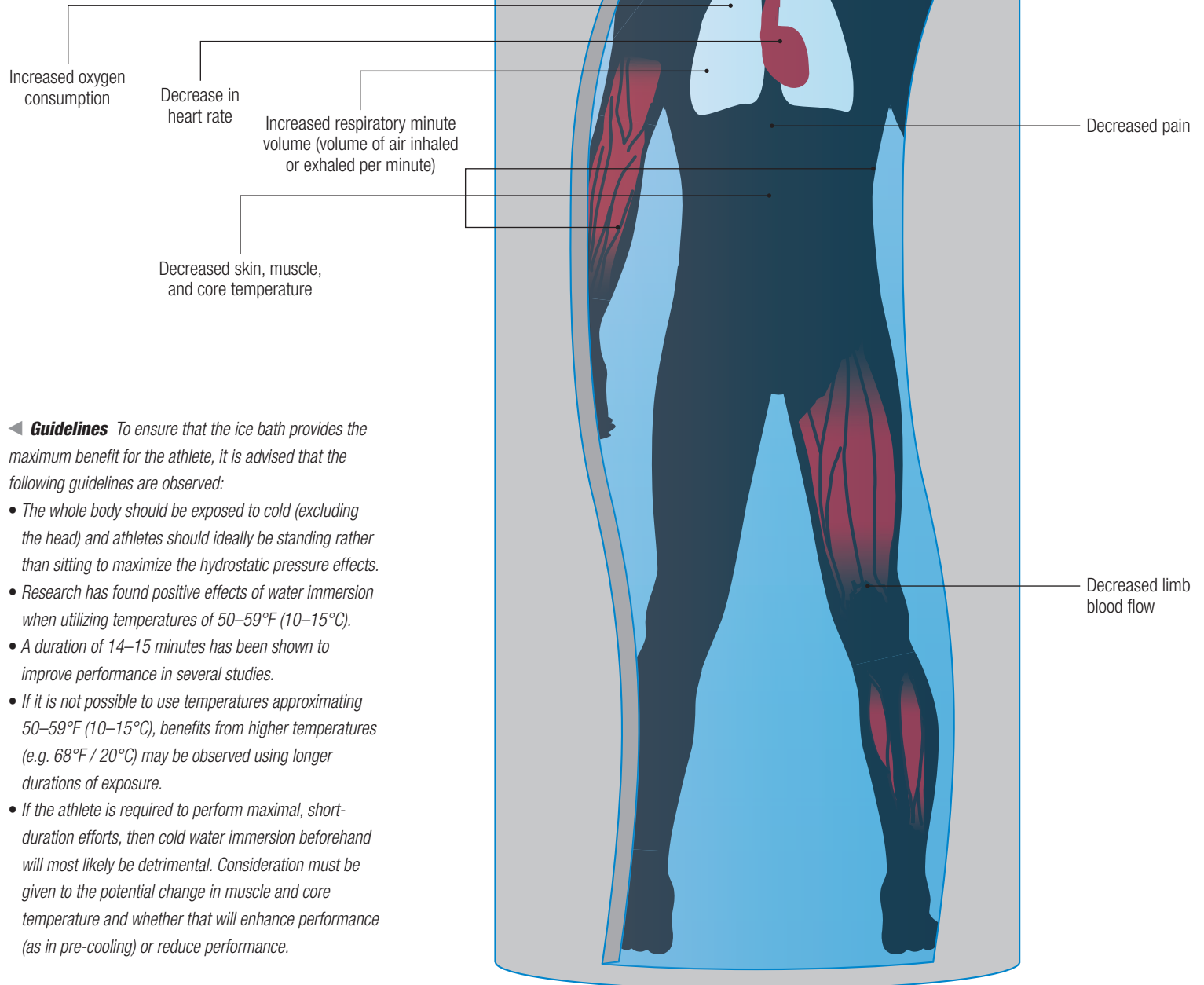
To ensure positive performance outcomes occur as a result of CWI, it is important that optimal durations of exposure, and levels of immersion, as well as appropriate water temperatures are utilized. Consideration should also be given to the time needed until the next training session or match, to ensure that the athlete's performance is optimized.

Ice bath recommendations



Physiological effects of cold water immersion

► **Ice bath effects** When immersed in water, the human body responds with a number of physiological changes as a result of both water temperature and hydrostatic pressure. Cardiac and blood flow changes are two of the most significant effects, resulting in a redistribution of blood flow and alterations in body temperature that may speed up the recovery process.^{2,3}



◀ **Guidelines** To ensure that the ice bath provides the maximum benefit for the athlete, it is advised that the following guidelines are observed:

- The whole body should be exposed to cold (excluding the head) and athletes should ideally be standing rather than sitting to maximize the hydrostatic pressure effects.
- Research has found positive effects of water immersion when utilizing temperatures of 50–59°F (10–15°C).
- A duration of 14–15 minutes has been shown to improve performance in several studies.
- If it is not possible to use temperatures approximating 50–59°F (10–15°C), benefits from higher temperatures (e.g. 68°F / 20°C) may be observed using longer durations of exposure.
- If the athlete is required to perform maximal, short-duration efforts, then cold water immersion beforehand will most likely be detrimental. Consideration must be given to the potential change in muscle and core temperature and whether that will enhance performance (as in pre-cooling) or reduce performance.

the one percenters

It's not uncommon to hear those that work in professional sport refer to the need for players to take care of the "one percenters"—looking for every little edge wherever they can. However, whether you think nutrition and recovery belong in the 1% basket (representing potential points of difference for players to exploit) or form part of the other 99% likely depends on your sport and your perspective, among any number of other variables.

Ultimately, in tennis, professional players need fuel to perform. They are exposed to intensive playing, training, and travel schedules that are among the rarest in professional sport. All this means that it is in their best interests to accelerate their recovery, which includes refueling. To draw a parallel with the FIA Formula One World Championship®, what the gasoline and the mechanic are to the car, the right nutrition and recovery are to the tennis player. Astute, ethical nutritional practices are known to provide competitors with a performance benefit. Similarly, the emerging evidence of the efficacy of specific recovery techniques—carefully adapted to each individual to ensure their effectiveness—has seen the integration of such practices into the tennis mainstream.

Two strategies that are important to the success of nutrition and recovery goals are planning ahead and undertaking regular debriefs. According to the characteristics of the tournament or the country of play, planning ahead may include organizing hotel menus, bringing a supply of important foods from home, or instigating a special hygiene regimen to account for differences in the safety standards of local food and water. Having a supply of portable fluids and foods at the court may help a player cope with the unpredictable match timetable, or a match that finishes late in the night after catering facilities have closed. Professional players know the advantages of keeping good records of their tactics in each tournament. An objective account of strategies that were undertaken, metrics of each match (duration, performance outcomes, fluid and fuel intake tactics, net fluid loss) and lessons learned can build into a valuable resource that will help the player continue to fine-tune their practices into the perfect plan.

► **Drinking to success** All leading tennis players on the professional Tour, including Novak Djokovic, look to every possible part of their game to improve their performance. Understanding the need for appropriate nutrition before, during, and after matches and tournaments is one such part.



What are the benefits of enhancing sleep quality and quantity?

Why is sleep important for my matchplay?

An individual's recent sleep history has a marked impact on their daytime functioning. Restricting sleep to less than six hours per night for four or more consecutive nights has been shown to impair cognitive performance and mood, and disturb glucose metabolism, appetite regulation, and immune function. From the available research on athletes, it appears that sub-maximal prolonged tasks, such as tennis play, may be more affected by sleep deprivation than maximal efforts, particularly after the first two nights of partial sleep deprivation.¹ The mechanism behind the reduced performance following prolonged sustained sleep deprivation is not clear, but it has been suggested that an increased perception of effort is one potential cause. As tennis players often experience some mild sleep deprivation, especially with matches played late into the evening or early morning, it is important that players who are involved in late matches get into their usual routine as quickly as possible on the following night. They may also need to sleep strategically during the day to recover.

While the scientific evidence in elite athletes is minimal, it appears that on average athletes go to bed at 10:59 pm plus or minus 1.3 hours; wake at 07:15 am $\pm$ 1.2 hours; and obtain 6.8 ± 1.1 hours of sleep per night.² These data, based on a sample of elite Australian athletes, also demonstrated that athletes from individual as opposed to team sports went to bed earlier, woke up earlier, and obtained less sleep than athletes from team sports (6.5 hours' sleep as opposed to 7 hours' sleep). This suggests that athletes often get less sleep per night than the recommended 8 hours.

Elite professional athletes who compete at night anecdotally report that sleep onset time (the time taken to fall asleep) can be very high. These athletes often report that it may take 3–5 hours to fall asleep after major competition occurring in the evening. As some tennis matches will begin at unknown times (upon completion of the previous match), strategies for sleeping during the day of the match, if possible, as well as recovery the following day, become particularly important.

Strategies for quality sleep

Routine

Create a good sleep routine by going to bed at the same time and waking up at the same time. Before-bed routines can help the body prepare for sleep. The routine should start about 30 min before bedtime (e.g. clean teeth, read a book)

Bedroom

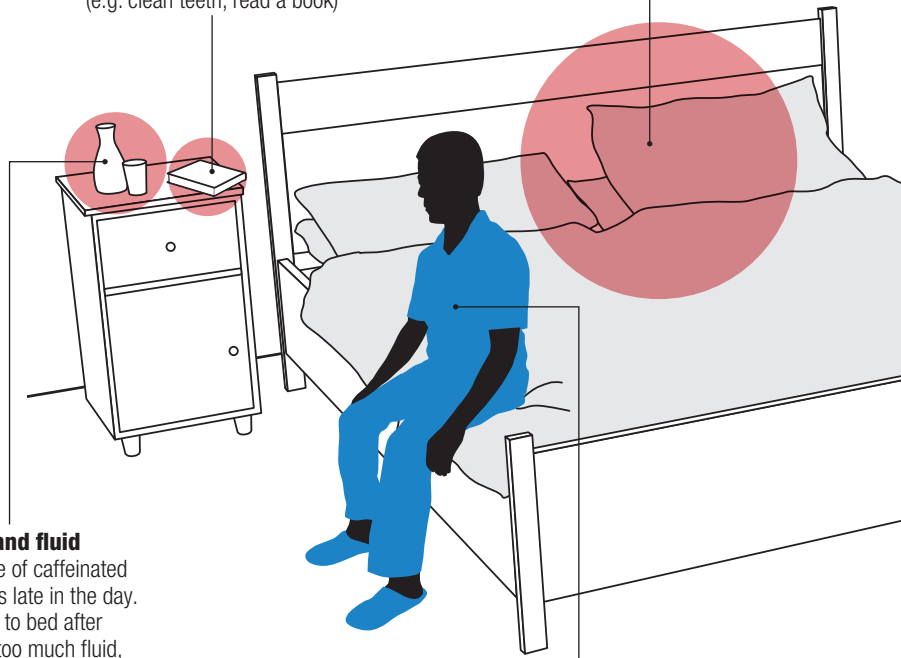
The bedroom should be cool (70°F/21°C is best), dark and quiet. A comfortable bed and pillows are important

Food and fluid

Avoid the use of caffeinated food and fluids late in the day. Do not go to bed after consuming too much fluid, as this may result in waking up to use the bathroom

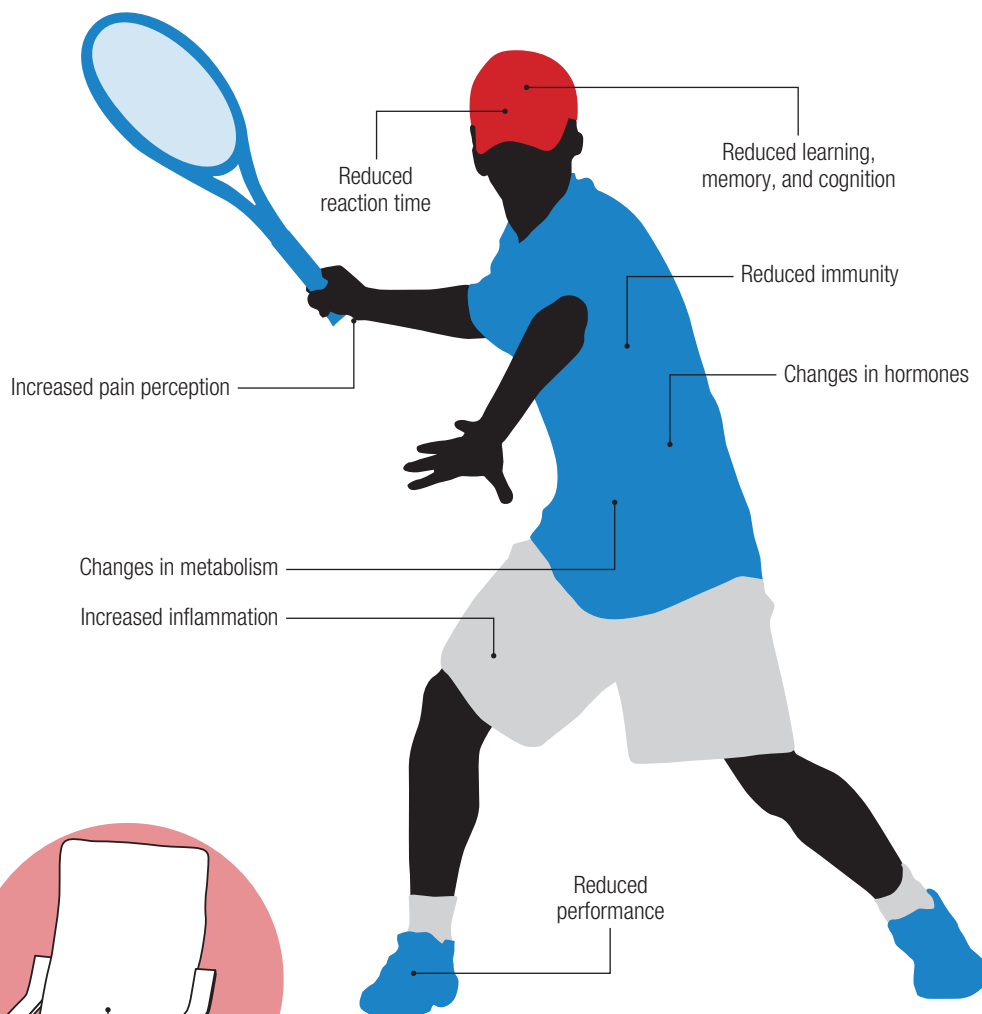
Relax

Investigate relaxation and breathing techniques



▼ **Getting a good night's sleep** Sleep is an important component in the preparation for, and recovery from, strenuous exercise. Sleep is one of the most efficacious recovery strategies available due to its physiological and restorative effects.³ Obtaining sufficient sleep can aid reaction time, coordination, concentration, memory, motivation, mood, and performance. Sleep also aids the repair and regeneration of muscles and tissues. The graphic illustrates useful strategies used by elite athletes to aid in getting a good night's sleep.⁴

Physiological effects of lack of sleep



Electronics

Avoid watching television in bed and using the computer in bed. These can steal sleep time and form bad habits

Be organized

Use a "to-do" list or diary to ensure organization and restrict unnecessary over-thinking while trying to sleep

Avoid watching the clock

Many people who struggle with sleep tend to watch the clock too much. Frequently checking the clock during the night can wake you up (especially if you turn on the light to read the time) and may reinforce negative thoughts

Get up and try again

If you haven't been able to get to sleep after about 20 min or more, get up and do something calming or boring until you feel sleepy, then return to bed and try again. Sit quietly on the couch with the lights off (bright light will tell your brain that it is time to wake up)

▲ **Morning after** Not getting enough sleep, or not enough restful sleep, can have severe consequences for an athlete's body and brain.

How does travel affect performance?

How can I best cope with jetlag?

Travel is an inherent part of competing in professional sport. Tennis players are arguably the most traveled athletes, with players reported to have covered 48,237 miles (77,600 km) in a two-month period.¹ Travel may be in the form of long-haul international flights, shorter domestic flights, or even hours spent on buses and trains, or in cars. Given the symptoms of jetlag, it is not surprising that research has identified performance decrements associated with such frequent long-haul travel. The effects that jetlag may have on performance will depend on a number of factors, such as crossing several time zones, the direction of travel, the type of activity performed, and the time of day for optimal performance of that type of exercise. Individual responses will likely also determine the severity of the adverse impacts on performance, as well as the level of concentration and complex coordination required for optimal performance in the sport. In order to transition effectively into the time zone, an athlete needs to address several considerations, specifically regarding light exposure and sleep hygiene.

Light is one of the most powerful means of altering circadian rhythms and strategic exposure to, or avoidance of, light at specific times can help speed resynchronization of the body clock.² A number of web sites as well as smartphone applications are available to assist with calculating the specific timing of light exposure or light avoidance.

► **Desynchronization** Jetlag refers to the desynchronization of circadian rhythms that occurs when traveling across multiple time zones. Jetlag can result in feelings of disorientation, light-headedness, impatience, lack of energy, and general discomfort. The feelings associated with jetlag may persist for several days after arrival and can be accompanied by loss of appetite, constipation, difficulty in sleeping, and reduced motivation. Performance may be affected due to lapses in mental attention and unusual errors in mental performance such as distorted estimation of time, space, and distance.^{3,4}

Sleep is an extremely important part of performance and recovery. It is essential that good sleep habits are maintained while traveling. Setting up an optimal sleep environment can ensure good sleep and assist in overcoming jetlag:

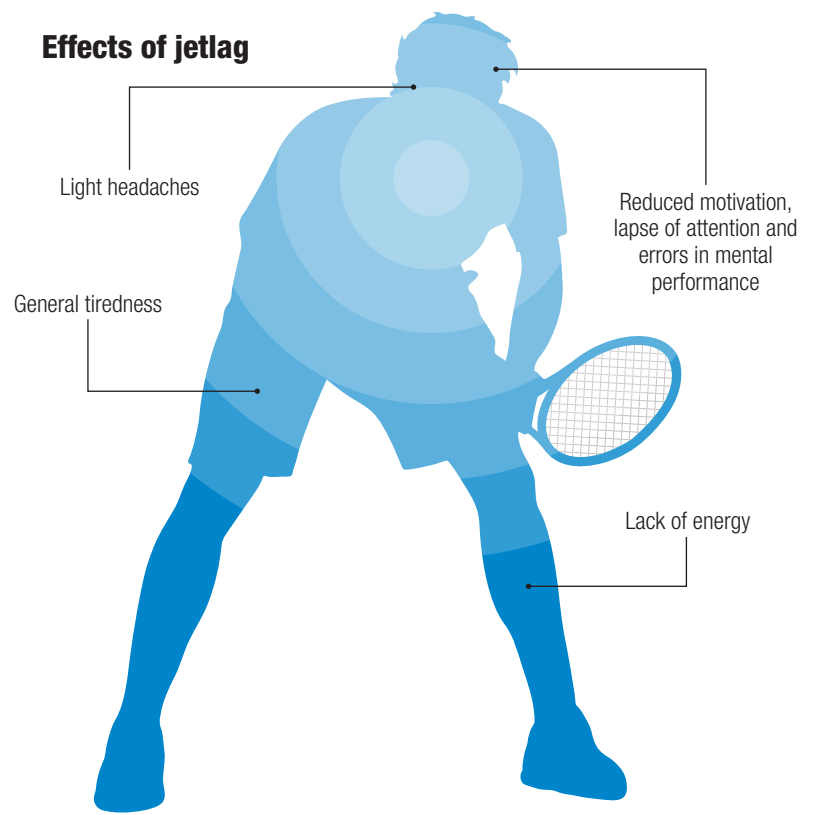
Darkness—Ensure the windows are covered with black-out blinds. Eye masks are an alternative option.

Noise—Arrange for a room where there is minimal outside noise (away from street traffic). Earplugs are also useful.

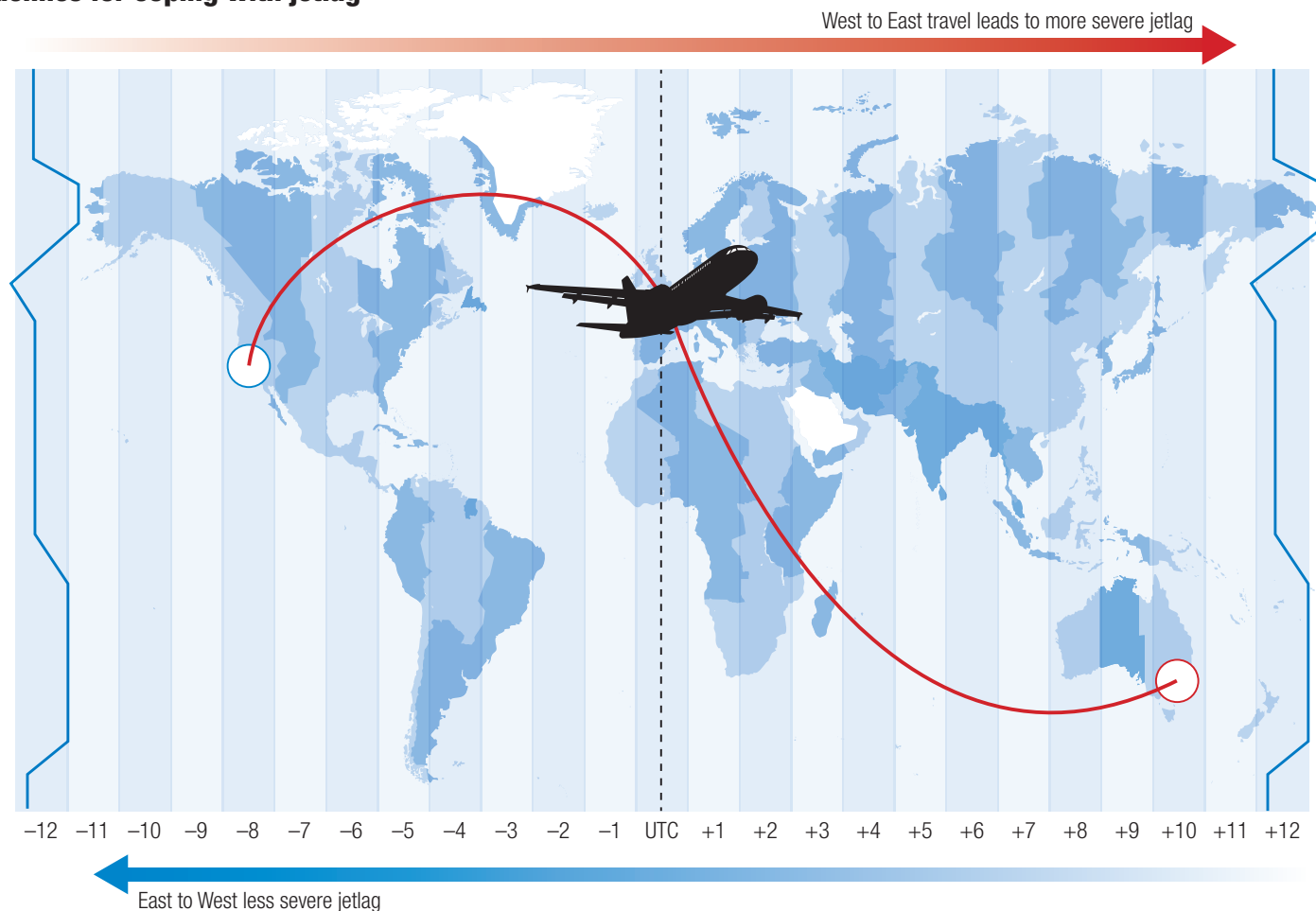
Stimulants—Avoid stimulants such as caffeine in the hours prior to sleep as well as excessive ingestion of fluid.

Routine—Perform a pre-sleep ritual to prepare your body for sleep. This may be as simple as reading a book for 10 minutes and avoiding the use of computers and smartphones in the 30 minutes prior to sleep.

Effects of jetlag



Guidelines for coping with jetlag



• Before travel

- Ensure you are well rested before traveling. Get plenty of sleep and avoid intense training the day before—traveling already fatigued will increase symptoms of jetlag
- Pack in advance so you aren't late to bed the night before travel
- Consider whether travel food meets your nutritional needs
- If possible, schedule flights that arrive late afternoon—this minimizes the time before the first night's sleep
- Tall players should book exit row seats for more space
- Organize arrival date several days before competition to allow for jetlag
- Speak to your doctor prior to using any sleep medication

✈ During travel

- Adjust your watch to your destination's time. Sleep quality will probably be poor, so get more sleep than normal
- Try to sleep during your destination's nighttime—avoid watching movies or playing games during this time
- Recline the seat; use the headrest, an eye mask, and earplugs. Ask others not to disturb you during sleep. When awake, walk around the plane and stretch every hour to promote blood flow and loosen muscles
- Wear compression socks to reduce swelling and promote blood flow, helping you feel better on arrival and reducing risk of deep vein thrombosis
- Try to eat at your destination's meal times
- Stay well hydrated

• After travel

- As soon as possible, establish a regular routine for sleeping during nighttime. Allow yourself a short sleep-in but set an alarm
- If tired, try to sleep for up to 90 minutes during the morning or early afternoon to catch up, and use an alarm to wake you up. Don't doze close to bedtime or it might compromise your night's sleep
- Nighttime sleep is your priority. Use natural light exposure, exercise, and a shower to stimulate the body and stay awake during the day
- Ideally, avoid scheduling hard training sessions in the two days after travel
- Avoid caffeine in the afternoon and evening

◀ ▲ Beating travel fatigue

The degree of jetlag is not associated with the length of flight, but rather the number of time zones crossed. The body copes with East-to-West travel better than West-to-East travel. The duration of jetlag can differ substantially between individuals. It is normal for jetlag to occur, but it can be minimized by following these guidelines.

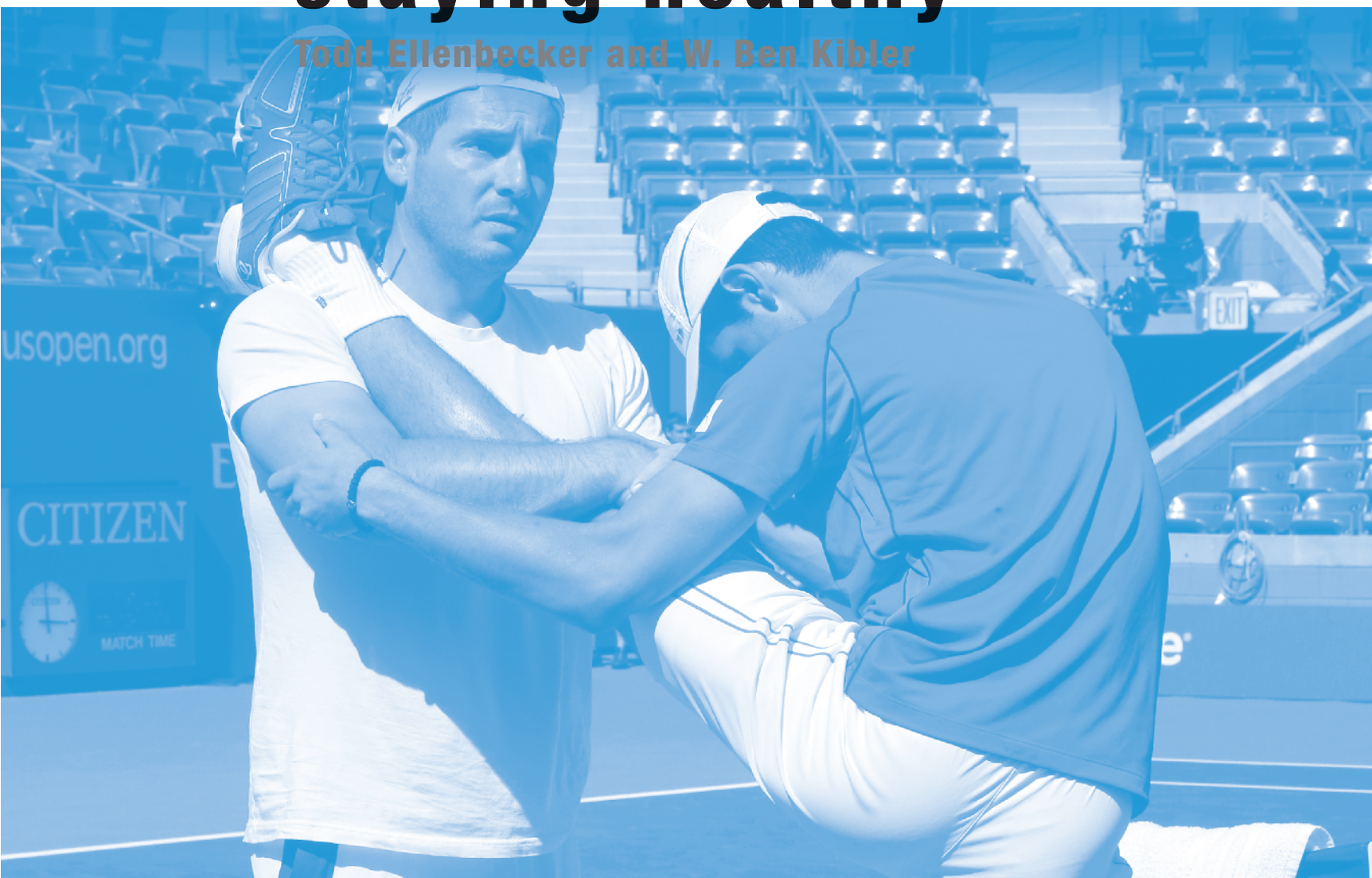


Injuries in tennis players commonly occur because of the repetitive overload of tennis strokes and tennis-specific movement patterns. Successful skill development in tennis requires many hours of practice and competition, resulting in the use of repetitive body movements that lead to characteristic muscular imbalances and the risk of injury in both elite and recreational tennis players. Knowledge of these specific injury risks, coupled with sport-specific injury prevention exercises, can help provide a successful strategy for staying healthy as well as optimizing performance. This chapter reviews the common risk factors associated with tennis performance and offers strategies for minimizing injury.

chapter seven

staying healthy

Todd Ellenbecker and W. Ben Kibler



What is kinetic chain breakdown? → Which movements lead to injury?

The kinetic chain is the coordinated activation of all the body segments. It starts at the court surface, continues through the trunk (the core) to the shoulder (which acts like a funnel for energy), and onto the arm and hand to achieve the required positions and motions. It is the system by which players efficiently pass energy from the court surface to the racket, and is particularly important in the serve, where large forces are required to produce a high racket speed at ball impact. To accomplish this, joints must move through large ranges of motion at high speed, which places high loads on them and the surrounding muscles. Injuries to muscles and joint structure therefore occur most frequently from overuse and overload, particularly when the flow does not occur from the lower limbs to the racket in a coordinated manner. There must be a generation and transfer of forces to produce an optimal result, while still protecting the joints. Studies have shown that a properly functioning kinetic chain produces the best performance—maximum ball velocity and spin—with the minimal risk of injury.^{1,2,3}

Biomechanical analysis has demonstrated that the optimum kinetic chain involves the body progressing through a specific set of positions and motions in a certain order. These positions are called “nodes,” and have been correlated with maximal force development for performance, minimal joint load, and

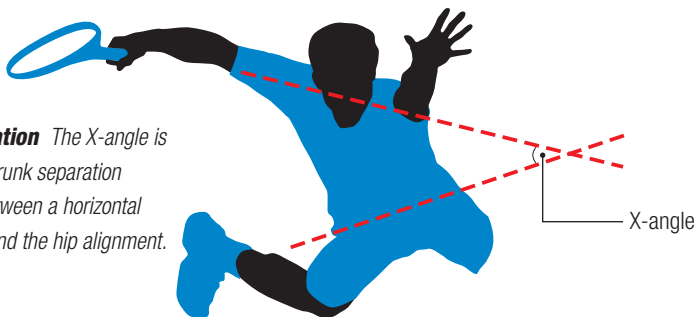
low injury risk.^{4,5,6,7} Every node contributes to maximal serve function when it is present, and decreases the maximal serve performance when it is not. When a player serves, these nodes can be visually observed and analyzed by a coach to determine whether they achieve the correct position or motion and create a smooth energy flow for optimal performance. Any break in the chain—from bad mechanics, muscle weakness, injury, or imbalance—will create problems all along the kinetic chain, reducing the effectiveness of the stroke and increasing the chance of injury over time. Frequently, the muscle base has to be improved before the technical corrections can be made. This is especially true in younger athletes, who have weak muscles and suboptimal technique, but also in high-level players, who fatigue and develop muscle tightness with continual play. The analysis can then be used to guide the player's periodized training and playing program.

► **Chain reaction** In a properly functioning kinetic chain, the player uses the flow of one movement into the next to carry the energy into the ball impact. The contribution each movement makes to the final ball velocity is noted as a percentage. However, if any of the movements are less than optimal, their repetition in practice and matchplay may lead to below-peak performance and muscle injury.

Kinetic chain of the serve

X-angle

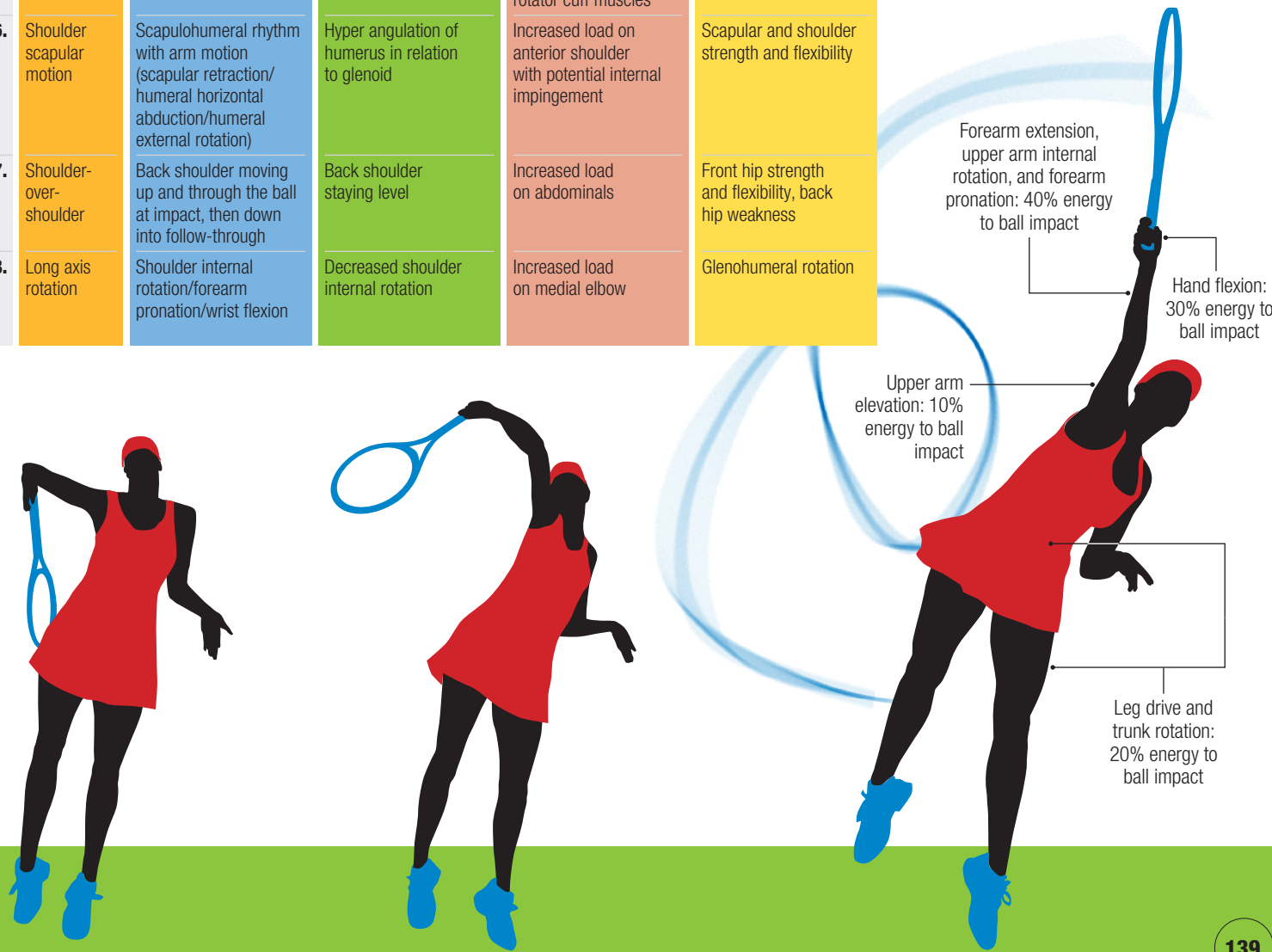
► **Angle of separation** The X-angle is also termed the hip-trunk separation angle—the angle between a horizontal shoulder alignment and the hip alignment.



Nodes in the kinetic chain

	Node	Normal mechanics	Pathomechanics	Result	To be evaluated
1.	Foot position	In line, foot back	Foot forward	Increased load on trunk or shoulder	Hip and/or trunk flexibility and strength
2.	Knee motion	Knee flexion approximately 70°	Decreased knee flexion less than 15°	Increased load on anterior shoulder and medial elbow	Hip and knee strength
3.	Hip motion	Counter rotation with posterior hip tilt	No hip rotation or tilt	Increased load on shoulder and trunk; inability to push through, increasing load on abdominals	Hip and trunk flexion flexibility and strength
4.	Trunk motion	Controlled lordosis; X-angle of about 30°	Hyperlordosis and back extension; X-angle of less than 30° (hypo), X-angle >30° (hyper)	Increased load on abdominals and “slow arm”; increased load on anterior shoulder	Hip, trunk, and shoulder flexibility
5.	Scapular position	Retraction (scapulae pinching together)	Scapular dyskinesis	Increased internal and external impingement with increased load on rotator cuff muscles	Scapular strength and mobility
6.	Shoulder scapular motion	Scapulohumeral rhythm with arm motion (scapular retraction/humeral horizontal abduction/humeral external rotation)	Hyper angulation of humerus in relation to glenoid	Increased load on anterior shoulder with potential internal impingement	Scapular and shoulder strength and flexibility
7.	Shoulder-over-shoulder	Back shoulder moving up and through the ball at impact, then down into follow-through	Back shoulder staying level	Increased load on abdominals	Front hip strength and flexibility, back hip weakness
8.	Long axis rotation	Shoulder internal rotation/forearm pronation/wrist flexion	Decreased shoulder internal rotation	Increased load on medial elbow	Glenohumeral rotation

◀ **Order of position and motion** The table lists each “node” in the kinetic chain of the serve action. A coach can use the table to analyze a player’s serve by noting if the correct position or motion has been achieved (“yes”) or not (“no”). If a node is not achieved, the coach should check to see if there is a problem with the mechanics (for instance, a bad ball toss, or no hip or shoulder rotation) that can be corrected by technical modification. Evaluation of physical deficits (hip or shoulder rotation tightness, muscle weakness) can be performed, and corrective measures can be instituted.



How can I prevent labral and rotator cuff injuries?

Can I avoid shoulder injuries in tennis?

Shoulder injuries are very common in tennis players of all skill and age levels.^{1,2,3} Frequently caused by overuse, they develop over a long period of time and can result in fairly long recovery times. Preventative measures are often helpful in decreasing their incidence. Typical shoulder injuries experienced by professional and recreational players are shoulder tendinitis, labral injury (known as SLAP), and the rotator cuff tear.

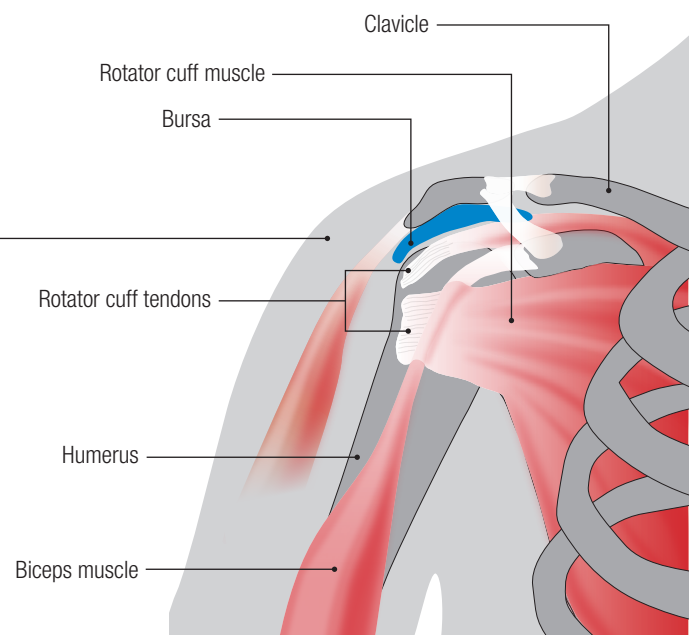
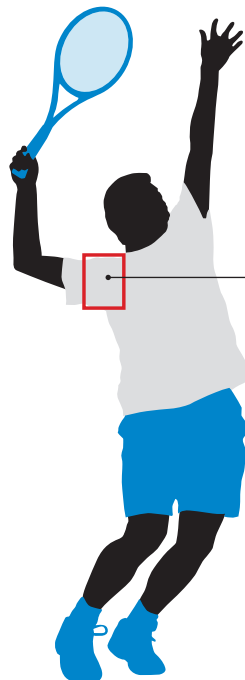
Shoulder tendinitis is the inflammation or irritation of the rotator cuff muscles, causing pain when the arm is at or above shoulder level and rotated, as in the serve movement. Typical symptoms are pain along the outer edge of the bone with motion, muscle weakness, fatigue, and pain at night. This injury is generally caused by too much serving, rotator cuff weakness or imbalance, decreased shoulder motion, weak scapular muscles, or problems with the kinetic chain (see pages 138–139).

The labrum is a cartilage structure inside the joint that stabilizes the joint during motion. Symptoms of labral injury include posterior shoulder pain on rotation in cocking and ball impact, clicking or catching during rotation, and general stiffness. Causative factors are a fall on the arm, kinetic chain weakness, or poor scapular position (scapular dyskinesis).

Rotator cuff tear is an acute or chronic progression of tendinitis to a tendon tear from the bone, and mainly occurs in older players. Symptoms include increased pain, especially at night, decreased ability to move the arm overhead, weakness with rotation, and fatigue with continued use. Causative factors include a fall on the arm with acute loss of ability to raise the arm, chronic overuse, and the development of bone spurs.

Shoulder muscles

► **Shouldering the burden** *Constant serving can lead to injury in the shoulder muscles, particularly if there is a problem with the player's kinetic chain.*



Typical shoulder injuries

►▼ **Treatment and prevention** Here are some of the most common rotator cuff and labral injuries in tennis with advice on treatment and prevention. Prevention is always better than cure, so players of all levels should pay particular attention to reducing the risk of injury.

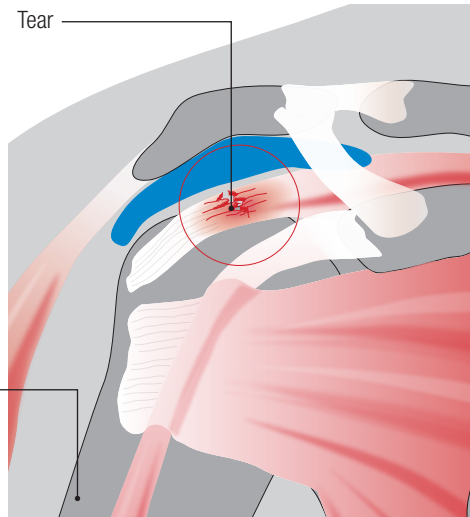
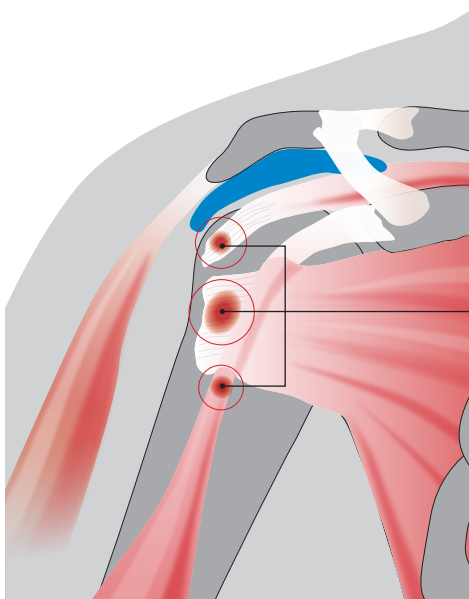
Rotator cuff tendinitis

Treatment

Relative rest; decreased serving or overhead motion; medical evaluation for muscle weakness; kinetic chain analysis for deficits; coach analysis for technical deficits; rehabilitation for muscle deficits; gradual return to serving with rising "serve count"

Prevention

Periodization of tennis conditioning, practice, and matchplay to minimize overload; conditioning emphasis on core strength and stability, scapular control, and shoulder rotation; emphasis on optimal serve technique



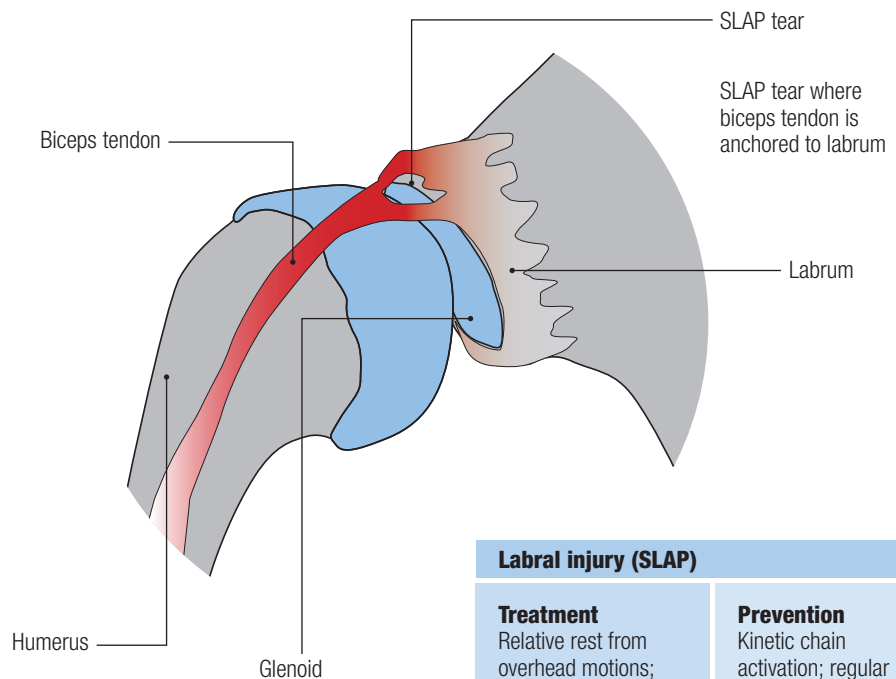
Rotator cuff tear

Treatment

Relative rest from overhead motions; medical evaluation for extent of injury; rehabilitation for motion and strength; alteration of serve mechanics to compensate for decreased strength—this frequently requires surgical repair

Prevention

Maintain full range of motion; emphasize balanced rotator cuff and scapular muscle exercises



Labral injury (SLAP)

Treatment

Relative rest from overhead motions; medical evaluation to determine anatomic injury; rehabilitation of muscle deficits; improvement in serve mechanics—this may require surgical treatment

Prevention

Kinetic chain activation; regular conditioning for scapular muscle strength and shoulder rotation flexibility; minimal practice or play when excessively tired; optimal serve technique with emphasis on core control; use of ground to push; hip and trunk rotations

What are medial and lateral epicondylitis?

What common elbow injuries do I need to avoid?

Elbow injuries common to recreational and advanced players can occur on either side of the elbow from overuse, and are frequently associated with poor technique.^{1,2,3} The most common elbow injuries experienced, particularly by the recreational player, are lateral epicondylitis (popularly known as “tennis elbow”), medial epicondylitis (popularly known as “golfer’s elbow”), and elbow ligament injury.

Lateral epicondylitis is an injury to the muscle attachment on the outer (lateral) edge of the arm (epicondyle) above the elbow. It is rarely an inflammation (even though “-itis” means inflammation) but is usually due to chronic overload with scar tissue, which weakens the tendon. It can vary from irritation to a complete tear, and occurs mainly in older recreational players. The symptoms are localized pain to the epicondyle; mild swelling; decreased strength in the elbow or wrist extension; pain on gripping or turning the wrist; occasional pain into the forearm; and pain during a one-handed backhand. Causative factors include chronic wear and tear and poor backhand mechanics—in other words, too much wrist pronation during the early acceleration phase of the backhand, hitting the ball behind the body, weak shoulder muscles, and tight or weak forearm muscles.

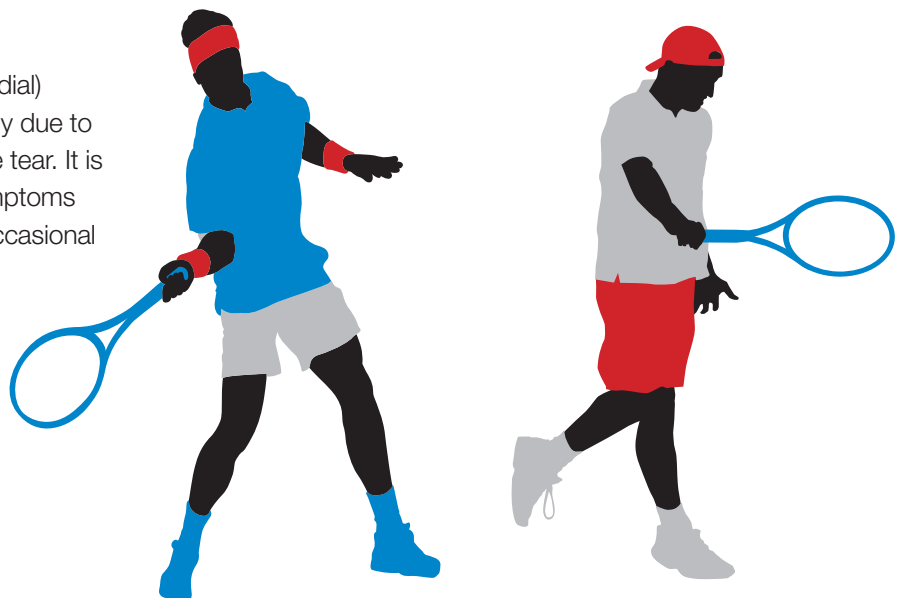
An injury to the muscle attachment along the inside (medial) epicondyle at the elbow—medial epicondylitis—is usually due to chronic overload, can range from irritation to a complete tear. It is more common in younger and competitive players. Symptoms are pain and/or swelling along the medial epicondyle; occasional

tingling along the forearm to the little finger (the “funny bone” nerve); decreased forearm or grip strength; and pain in the forehand or serve. Causative factors include overload in play, weak shoulder and core muscles, and poor stroke mechanics; such as an excessive western grip, placing the hand/forearm in too much supination, too much wrist rotation trying to hit topspin, and hitting the ball behind the body in the forehand.

The elbow ligament injury is an injury to the ulnar collateral ligament (UCL) on the inside of the elbow that stabilizes the bones. The injury can vary from a strain to a complete tear. Symptoms may include a “pop” when the ligament tears; pain and/or swelling on the medial elbow below the epicondyle; pain before and at impact on the serve and forehand; and occasionally tingling into the forearm and little finger. Causative factors include poor mechanics—excessive western grip, leading with the elbow, or hitting the ball behind the body on the forehand—and kinetic chain deficits with weak hip strength and weak shoulder muscles.

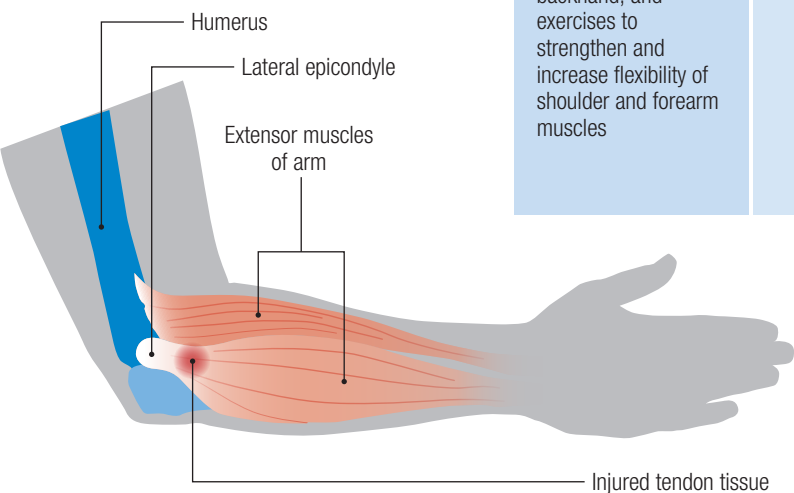
Different strokes cause different injuries

► **Strokes that cause injury** While shoulder injuries may be the more common among professional players, elbow injuries are certainly more common in recreational players, almost certainly as a result of a combination of overuse and poor technique. Elbow injuries are associated with both forehand and backhand strokes.



Common elbow injuries

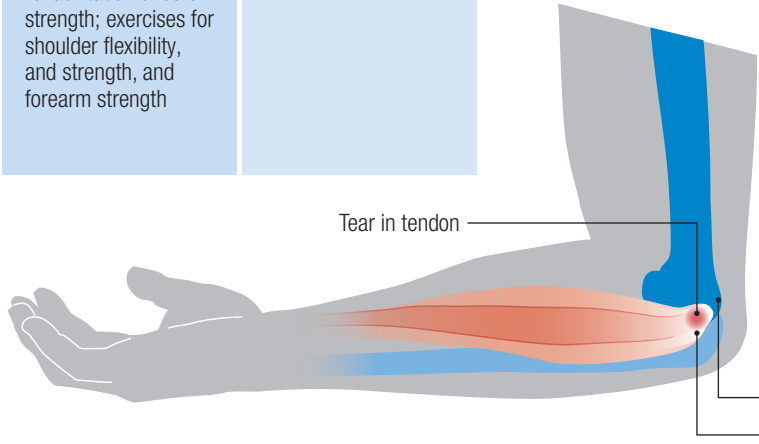
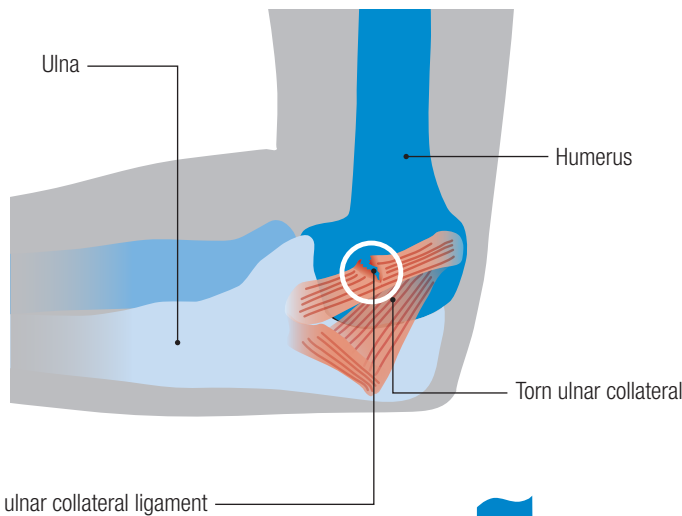
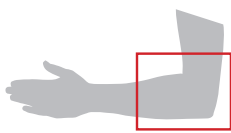
▼ **Treatment and prevention** Here are some of the most common elbow injuries in tennis, with advice on treatment options and preventative measures.



Lateral epicondylitis	
Treatment	Prevention
Medical evaluation to determine the extent of injury, with possible injections or bracing; review of poor stroke mechanics; development of a two-handed backhand; and exercises to strengthen and increase flexibility of shoulder and forearm muscles	Appropriate stroke mechanics; preventative stretching; strengthening of shoulder and forearm muscles

Elbow ligament injury	
Treatment	Prevention
Medical evaluation to determine extent of injury; correction of kinetic chain deficits and shoulder and forearm muscle weakness—this may require surgical treatment	Proper mechanics, especially in younger competitive players; proper core and shoulder strengthening

Medial epicondylitis	
Treatment	Prevention
Relative rest from high-intensity stroke production; medical evaluation to determine extent of injury and possible treatment; attention to grip and stroke mechanics; rehabilitation of core strength; exercises for shoulder flexibility, and strength, and forearm strength	Periodization of conditioning, practice and matchplay; appropriate stroke mechanics; preventative strengthening of core, shoulder and forearm muscles



Western grip

► **Get a grip** The western grip for the forehand stroke—used to generate lots of topspin—has been linked to more arm injuries in recreational players than other grips. This is because the western is a relatively “extreme” grip and requires a strong wrist and perfect timing to avoid injury.



equipment: measurement tools

Several measurement tools are used during the routine assessment or testing of the strength of muscles about a joint and the range of joint motion in tennis players. Tennis associations routinely record data on players as they progress through the different age groups with the ultimate goal of becoming a professional. These devices, which include goniometers and dynamometers, give scientists and medical professionals important information about players' physical development, which is then used to drive training programs geared to improve their performance and reduce the risk of injury.

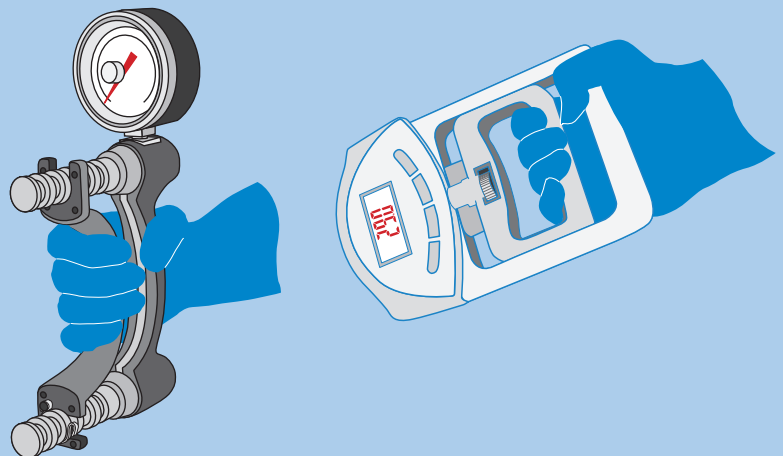
At first glance the goniometer used by physiotherapists and doctors looks very similar to a standard protractor used in school by students to measure angles. That, indeed, is what a goniometer is used for. This important device is used to measure joint angles throughout the body, and accurately provides the clinician and scientist with valuable information about the flexibility of muscles and joint structures—for example, in the shoulder joint. This information is very important and allows recommendations to be made about training protocols. Elite-level tennis players often have a loss of internal rotation range of motion in the dominant shoulder, and to address this a specific stretching program may be devised.

► **Measuring grip strength** This type of dynamometer is used to measure grip strength. Research has shown that elite-level tennis players have a minimum of 10% greater grip strength in the dominant arm than in the non-dominant arm.

A second tool that can be used to measure muscular strength around a joint is called an isokinetic dynamometer. This machine allows for very precise measurements of muscular strength and endurance using a computer. It provides comparisons between the left and right sides of the body, and can be used to test many different areas—particularly the shoulder and knee joints. Special programs are developed for tennis players to target the weaker muscles and provide a proper balance of strength and optimal function around the specific joint.

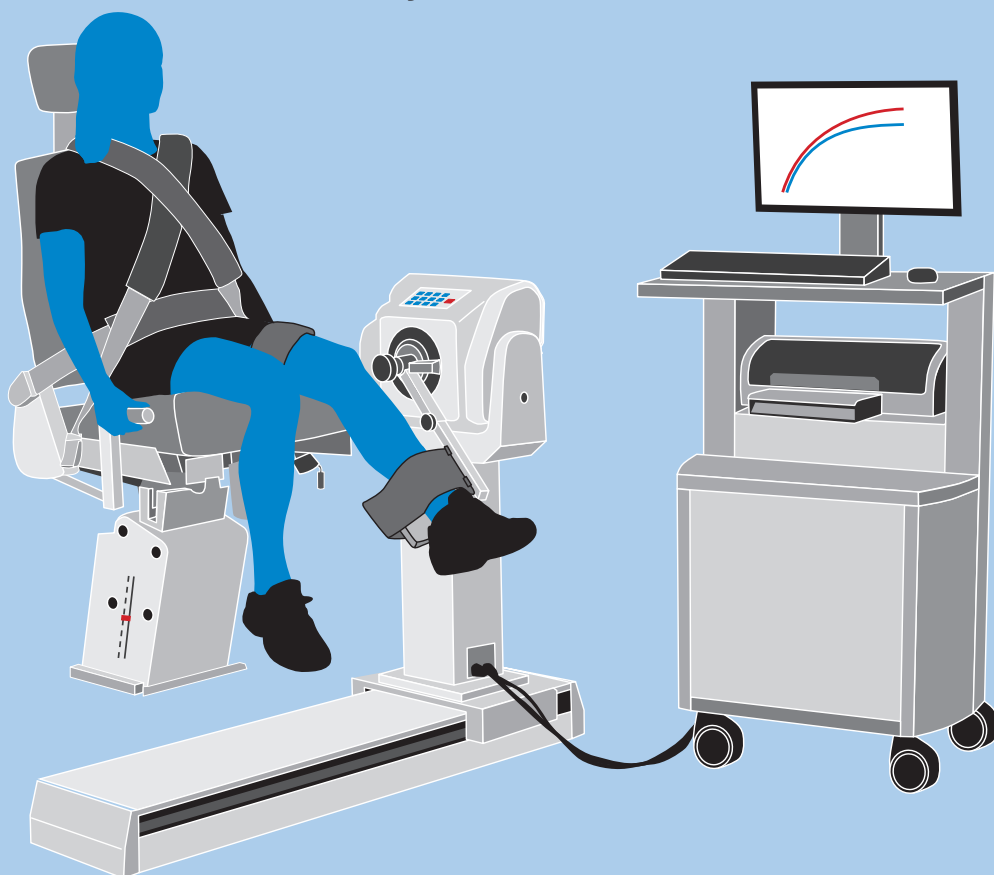
Another tool used by sports medicine and strength and conditioning professionals is the hand-grip dynamometer, which is used to measure grip strength. Players who have less grip strength on the dominant arm are encouraged to perform specific exercises to improve their grip strength. Finally, a sit-and-reach box is used by sports medicine professionals and sport scientists to measure lower back and hamstring flexibility. The player takes a seated position with knees straight and leans forward.

Hand-grip dynamometer

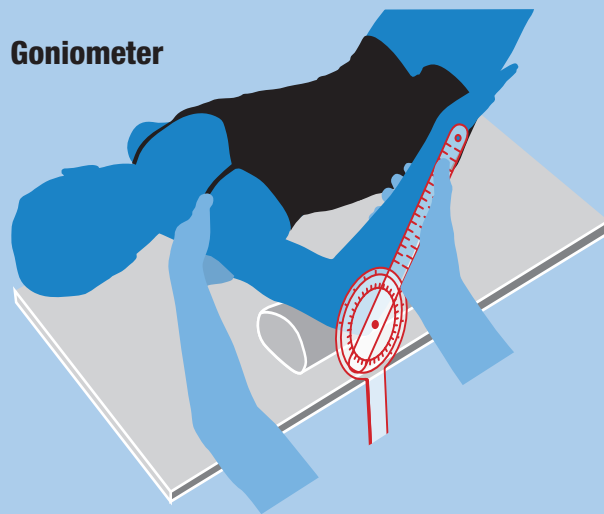


▼ **Testing muscle strength** This shows a player seated on an isokinetic dynamometer being tested for the strength of their quadriceps (front of the thigh) and hamstring (back of the thigh). During this test, the player rapidly straightens (extends) and bends (flexes) their knee. The measurement data are stored in the computer for comparison between muscle groups and between sides of the body.

Isokinetic dynamometer



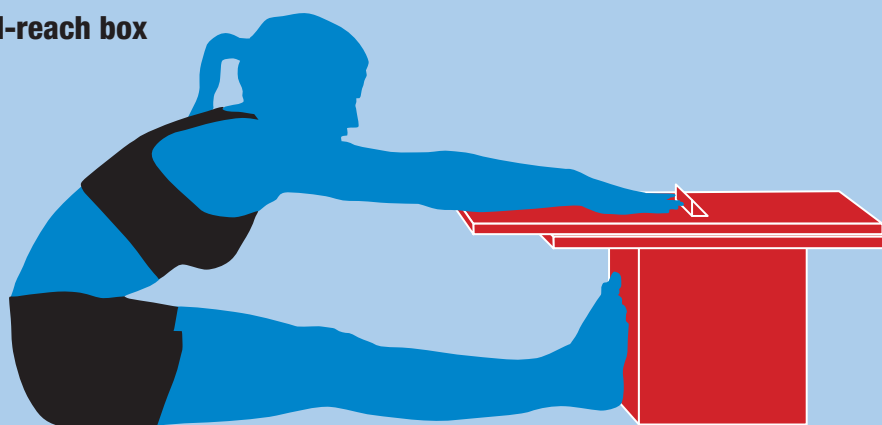
Goniometer



▲ **Shoulder joint assessment** The goniometer is used to measure the range of motion in the shoulder joint. The player is positioned with their arm elevated to the side, simulating the position they would adopt in the serve (shoulder and elbow at 90°). In this position, the therapist positions the player's arm at the end range of the motion and records the specific angle. This informs them about the flexibility, or lack of it, in the shoulder.

Sit-and-reach box

► **Flexibility test** The player reaches forward as far as they can without moving their body to compensate. A positive number is recorded if the player can reach past their toes—this indicates very good flexibility—while a negative number indicates the need for the player to work on hamstring stretching.



How can I address muscle imbalance in the kinetic chain?

What exercises will help me strengthen muscles equally?

Tennis requires a balance of muscle strength between opposing muscles surrounding the joints actively involved in the kinetic chain (see pages 138–139). Similar amounts of opposing force are necessary to permit the joint to function correctly—this would be considered “muscle balance.” Muscular imbalances occur in tennis due to repeated use of certain muscles, while other opposing muscles (often on the opposite side of the joint) are not used at the same rate. This creates a muscular imbalance, which both hinders performance and, more importantly, may lead to injury. There are two main areas in which tennis players have significant muscle imbalances that can lead to injury: the shoulder (see proprioception, pages 152–153) and the core (see core stability, pages 154–155).¹

During the serve and forehand, large forces are generated by the muscles in the front of the shoulder (internal rotators), such as the pectoralis major, latissimus dorsi, and subscapularis. This is due to their use during the acceleration phase of these strokes to develop racket velocity. These muscles that internally rotate the shoulder become very strong on the dominant arm in elite tennis players.² The muscles in the back of the shoulder, however (the external rotators), or the posterior rotator cuff, do not develop as much strength and may break down, due to the type of muscle contractions (eccentric or lengthening contractions) used by tennis players during the follow-through phases of the tennis serve and forehand (see pages 140–141). Therefore, the shoulder becomes imbalanced. Players must perform specific

exercises to improve the strength of the muscles in the back of the shoulder and shoulder blade (scapula) region to keep this imbalance in check and prevent shoulder injury.

The second area in which tennis players have muscular imbalances is the core (or central portion) of the body. Training and tennis play often overdevelop the muscles at the front of the core (abdominals), while the muscles in the lower back do not receive the same attention. During the serve, a stretch to the abdominal muscles followed by a strong shortening (concentric) contraction provides a great training stimulus to increase abdominal muscle strength in the core. However, players need to improve strength in the lower back with specific exercises to maintain muscle balance in the core.

Serving muscles

During the cocking phase of the tennis serve, the abdominals are in a stretch position—optimally preparing for the strong forceful contraction required as the body accelerates forward to ball contact

The muscles in the front of the shoulder internally rotate the arm from this lengthened position during cocking. The repetitive, forceful internal rotation contractions lead to increased development of the anterior (front) shoulder musculature—and can lead to muscular imbalances if left unchecked

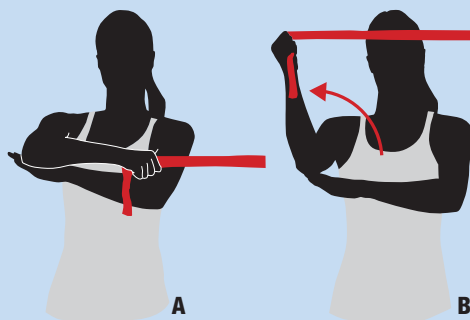
► **Strength for service** Several muscles are dominant during the serve, in the core and shoulder, and strengthening these muscles so that they are balanced through the stroke is the key to an effective serve and reduction in the risk of injury.



Recommended exercises

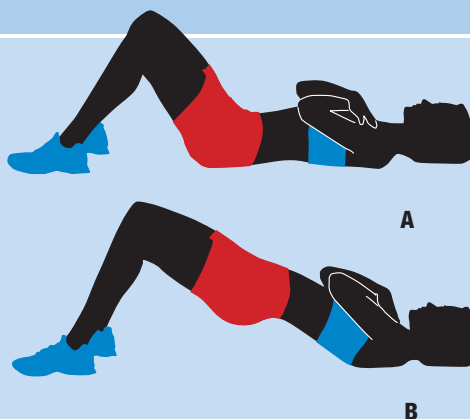
Shoulder external rotation at 90°

This exercise provides a key stimulus for training the rotator cuff. Attach a piece of elastic tubing to a door at about chest height. Hold it and raise the arm to 90° as pictured. Start with the forearm horizontal (A) and rotate the shoulder externally until the forearm is in a vertical position (B). Then, return the arm under control to the start position and perform 2–3 sets of 15 repetitions using slow, controlled motions. You should feel the fatigue of the muscles behind your shoulder, in the shoulder blade region.



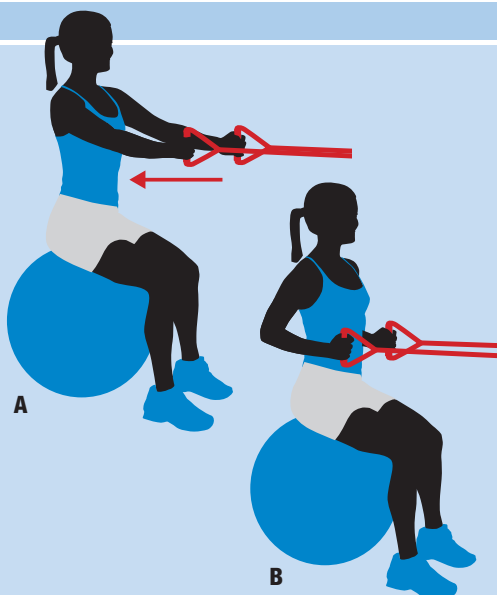
Bridging extension exercise

Begin by crossing your arms over your chest (A), then raise your bottom up off the table or mat (B). Hold this position for several seconds, then slowly return to the starting position. This exercise works the back extensors, which are often underdeveloped in tennis players—strengthening them is very important for minimizing the risk of lower back injury. To make this exercise more difficult when you advance—extend one leg at a time, while keeping the pelvis and torso level and stable. Perform multiple sets of leg extensions with each leg before returning to the start position to recover.



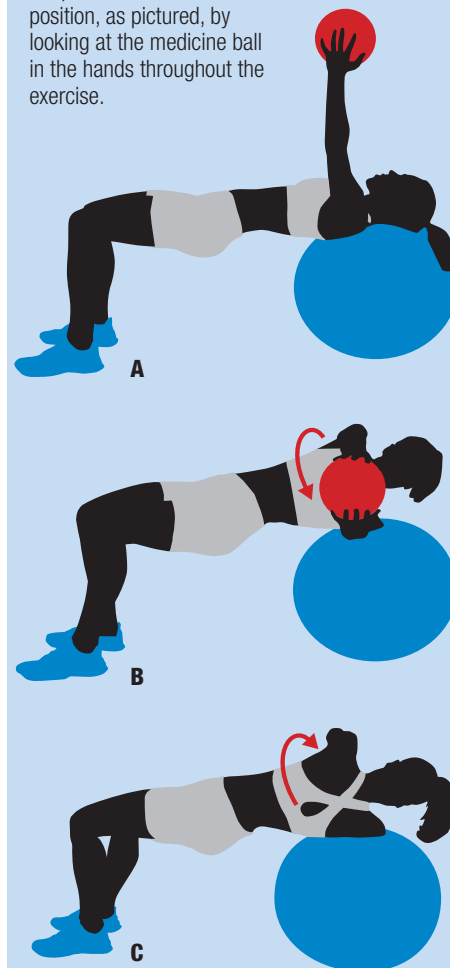
Seated row on physio ball

This exercise targets the scapular stabilizer muscles in the upper back and should be part of a tennis player's injury prevention training program. From a seated position on a ball, with the arms out directly in front of you holding the handles of the tubing (A), the arms are brought back toward the body and the shoulder blades are "pinched" together (B). The pinching movement requires the chest to be thrust forward slightly and results in a very good upright posture. Hold the shoulder blades in the pinched position for 1 second, then slowly return the hands and arms to the start position. Repeat multiple sets of 15 repetitions. Be careful not to "shrug" your shoulders upward during this exercise—pinch the shoulder blades straight back, not up.



Russian twist on physio ball

Begin by lying over a physio ball with arms extended and the pelvis and back in straight alignment (A). Before movement, draw in the stomach toward the spine to tense the abdominal muscles and squeeze the muscles in the buttocks together to enhance the activity of these important muscles. With a small medicine ball (of 4–6 lb or 2–3 kg) rotate left (B) and right (C) with control, making sure to keep the pelvis up (don't let it sag). Repeat 10–15 rotations for each side. Keep the neck in a neutral position, as pictured, by looking at the medicine ball in the hands throughout the exercise.



◀▲ **Addressing muscle imbalance** These important exercises can be used to address the muscle imbalances that can cause shoulder and back injuries in tennis players.

How does stretching help muscle performance?

How can I reduce the risk of muscle tear?

Stretching may help athletes to improve flexibility and the range of motion in their joints. It may therefore improve their tennis performance and decrease the risk of injury, by helping their joints to move through their full range, and thus enabling their muscles to work most effectively when hitting high-velocity strokes. There are two types of stretching commonly used in sports performance—dynamic and static. In dynamic stretching, the joint is rapidly moved through its range of motion; while in static stretching, a joint posture near the end of range is typically held for a short period. Research has identified dynamic stretching as the method of choice, as it prepares the muscles for the movements you will encounter in tennis.^{1,2} Tennis players should include this type of stretching as an integral part of all on- and off-court training. The reason static stretching is not advocated as widely is because it has been shown to induce a short-term strength loss for up to one hour following the static stretching.² Surprisingly, studies do not identify a direct relationship between stretching and reduced injury risk or improved performance in sports generally.² However, most sports medicine professionals recommend dynamic stretching

to help prevent injury and improve joint range of motion both in preparation for, and recovery from, play or training.

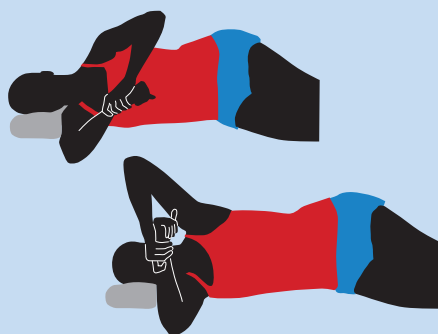
Research has demonstrated that on-court dynamic stretching and repetitive efforts at “end of range” consistently increase range of motion adaptations.³ Demands of tennis play on both the upper and lower extremities induce subsequent muscular adaptations that influence joint range of motion. Lower limb flexibility and the ability to rotate the trunk are both needed to compete, and both are clearly visible when stretching as part of a groundstroke. Similarly, external shoulder rotation (the upper arm rotated backward at the shoulder—forearm almost parallel with the court) is required during the backswing of the serve to increase the distance over which internal velocity may be developed. As a basic tenet of muscle physiology, it is known that muscles working in chronically shortened positions (contracted) cannot produce optimal force. In addition to the enhanced joint range of motion and articular flexibility gained through regular flexibility training, players can also benefit from improved muscular force production.^{1,2}

Static stretching

► **Stretching for recovery** While dynamic stretching is preferred before tennis play, static stretching may still be used—particularly during recovery, following play or high-intensity workouts. Static stretching involves isolating a particular muscle or muscle group through strategic positioning; moving to a point where a deep stretching sensation is felt in the muscle; being sure to stop at a position short of pain; and only using very slow, controlled movements. This static stretch position is held for 20 to 30 seconds and is repeated multiple times. Static stretching is particularly recommended for stretching areas like the posterior shoulder musculature (back of the shoulder), which are difficult to stretch dynamically.

Sleeper stretch

Lie on one side with the shoulder flexed to 90°. Use the opposite arm to rotate the shoulder toward the thighs, feeling a stretch in the back of the shoulder.



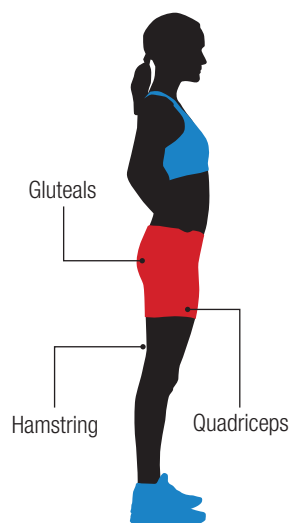
Cross-arm stretch

Stand next to a wall or supportive surface to stabilize your shoulder blade. Use the non-dominant arm to guide the dominant shoulder across the body just below shoulder level, feeling a stretch in the back of the shoulder.



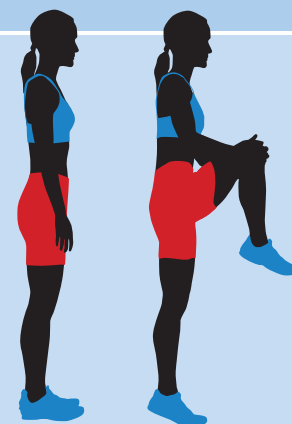
Dynamic stretching

▼► **Preparing for play** Performing multiple repetitions of tennis-specific movement patterns helps to prepare the body for the upcoming demands of play. Additionally, such movements elevate the heart rate and produce a light sweat in the player, increasing tissue temperature and further preparing the body for strenuous activity. Roetert and Ellenbecker¹ list a full set of examples of dynamic flexibility exercises for tennis players.



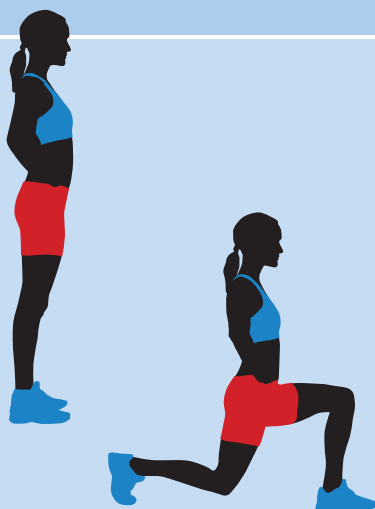
Standing single knee to chest

Raise one knee toward your chest and grab your leg with both hands just below the knee. Pull the knee as close to your chest as possible, flex your feet, and stand on your toes. Hold, lower your leg, then repeat for the other leg.



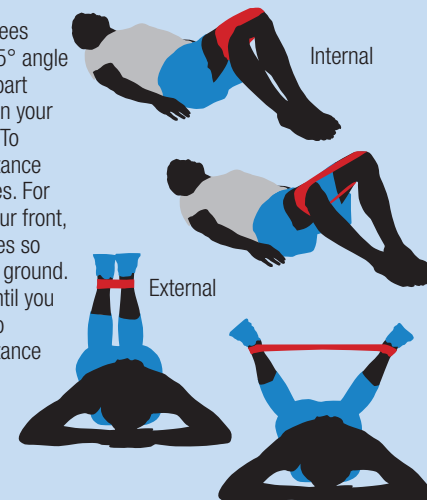
Front lunge

Start in a standing position. Step forward with a large step, with the feet in line, and slowly lower your hips so that you stretch your glutes, hamstrings, and quadriceps.



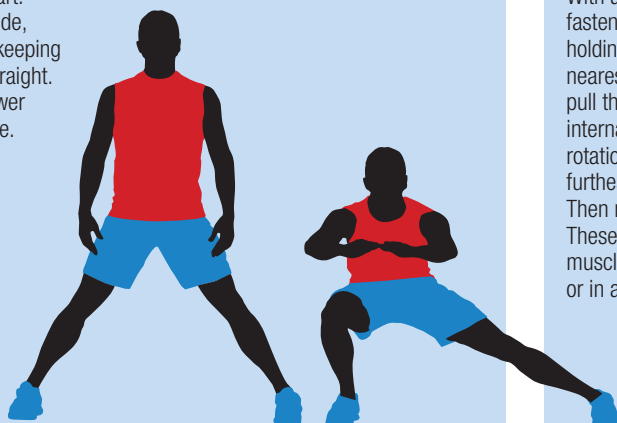
Hip rotation

Lie on your back, with your knees together and bent to form a 45° angle in the leg. Move your knees apart slowly until you feel a stretch in your hip, then bring them together. To increase intensity, use a resistance band looped around your knees. For internal hip rotations, lie on your front, bending your legs at your knees so your lower leg is at 90° to the ground. Move your feet apart slowly until you feel the stretch in your hips. To increase intensity, use a resistance band looped around your ankles. Increase levels of intensity prior to play or training.



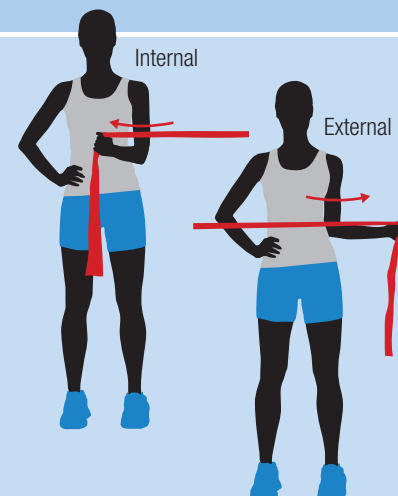
Side lunge

Stand with your feet apart. Lower yourself to one side, bending your knee but keeping your outstretched leg straight. Hold, then raise, and lower yourself to the other side.



Shoulder rotations

With a resistance band held or fastened at hip level, stand holding the band with the hand nearest the fastened end. Gently pull the arm in—this is the internal rotation. For external rotation, repeat with the hand furthest from the fastened end. Then reverse the exercises. These exercises replicate the muscle movements in a serve or in a groundstroke.



preventing injury

Todd Ellenbecker is a physical therapist and vice president of medical services for the ATP, and Dr. Ben Kibler is an orthopedic surgeon and also a sports science advisor to the WTA and USTA. In their roles, both frequently assist players of all levels at national training camps and at tournaments such as the US Open. They often provide advice on modifying technique to improve performance and reduce the risk of injury.

Both Todd and Ben recommend including dynamic and static flexibility exercises as part of tennis training, to improve muscular balance and strength. For instance, they advise players to perform rotator cuff and scapular muscle exercises as part of their training programs. Research has shown that without these exercises, elite tennis players and athletes in sports that require overhead movements suffer from imbalances in muscular strength—which lead to increased shoulder injury risk. Just performing the simple exercises outlined in this chapter will go some way to protecting against injury.

Recent research has also provided clarity on the inherent benefits and limitations of both dynamic and static stretching routines for elite athletes. This has led to the current recommendations of using dynamic stretching prior to workouts, and static stretching—particularly in problem areas or areas of need particular to each athlete—after workouts.

The advice of Todd and Ben has benefited many professional players from the US and other countries. It has been proven that players who stay healthy enjoy the game more, and are generally more successful.

► **Stretch for success** *Flexibility exercises are an integral part of on-court and off-court training for elite players, helping them to prepare for demanding matchplay and reducing the risk of injury.*



How does proprioception affect joint control?

How do I control my joint movements?

Proprioception is the ability to sense stimuli arising within the body regarding position, motion, and balance. It is the means by which a player uses information from receptors in the muscle and joints to vary muscle activity; and thus permit sequential joints in the kinetic chain to integrate, and create strokes that are suitable for varying tactical situations.¹ Proprioception is most simply defined as the ability to subconsciously control joint movement using various forms of input regarding where each joint segment is in space. Without thinking, it allows joint and thus movement control. Obviously, high levels of proprioceptive ability are needed in tennis to protect the body from injury, and permits each joint to play its role in building racket velocity and constantly adapt to the tactics used in a match.

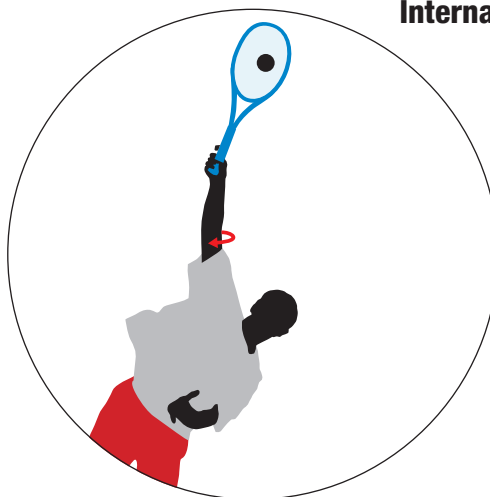
Which joints must a player control to produce optimal stroke efficiency? The simple answer to this question is almost all of them. Joints require this proprioceptive function to provide feedback to the brain, about position and speed of rotation, to enable high velocity control. However, the shoulder joint is

special, as it acts as the funnel for energy flow from the legs and trunk to the racket arm. For this reason, this joint needs to be controlled more than any other, if injury is to be avoided and performance optimized.² In order to regulate and control shoulder motion, the rotator cuff muscles and scapular stabilizers have to function at very high levels to maintain joint stability and allow the rapidly accelerating arm to hit the ball. They must also then decelerate the arm to protect the shoulder structures from injury, during the highly skilled and repetitive function inherent to the serve. Therefore, high levels of proprioceptive control and eccentric muscle action are required.

The shoulder muscles have to be trained with an emphasis on both concentric (shortening) muscle contraction and eccentric (lengthening) muscle contraction. Several important exercises are recommended to help tennis players build strength and flexibility. These exercises increase both the concentric and eccentric strength of musculature, such as the rotator cuff and scapular stabilizers, and enhance proprioceptive control—to improve performance and reduce the risk of injury.

► **Serve stroke efficiency** During the male adult serve, the shoulder internally rotates through the acceleration phase at velocities of over 2000° per second to produce a ball velocity of approximately 112 mph (180 km/h).

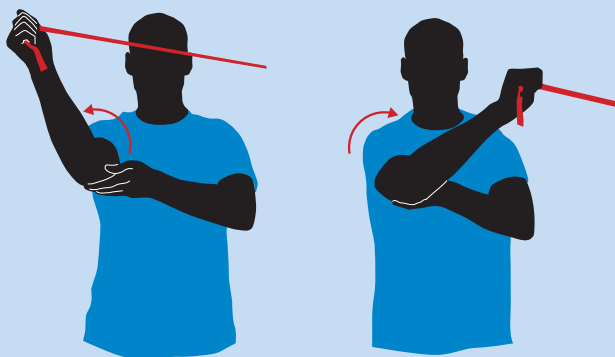
Internal rotation



Shoulder muscle training

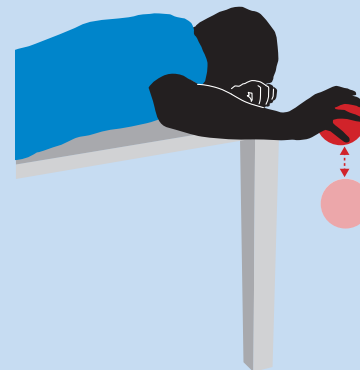
Resistance band exercises

This exercise uses a slow, controlled movement to train the rotator cuff and scapular stabilizers. Attach a piece of elastic tubing to a door at about chest height. Hold it and raise the arm to 90° as pictured. Start with the forearm horizontal and rotate the shoulder externally until the forearm is in a vertical position. Then, return the arm to the start position and perform 2–3 sets of 15 repetitions using slow, controlled motions. The shoulder remains elevated at a consistent 90° angle, while the joint is internally and externally rotated.



Plyometric exercises

Used to improve shoulder stabilization, this type of exercise uses an eccentric contraction immediately followed by a concentric contraction, to improve the strength and power of the musculature being trained. The exercise can be performed with a 1 lb (0.5 kg) ball. Lie on a bench or low table with the shoulder and elbow bent at 90°. Using repeated movements, drop and catch the ball in rapid succession. Repeat multiple sets of 30 seconds to increase strength and endurance of the rotator cuff and the scapular muscles.



Reverse catch

Another exercise to promote strength and endurance of the rotator cuff and scapular musculature is the reverse catch. This also uses a position of 90° of elevation of the shoulder and 90° of elbow bend. Position yourself as shown below with a partner standing behind you. Hold the shoulder at a 90° angle and the elbow bent at 90°. The partner throws a 1–2 lb (0.5–1 kg) ball underhand. Catch the ball, then very rapidly throw it back as shown below. Perform multiple sets of 15–20 repetitions.

In this exercise, the player catches and decelerates the ball as the shoulder internally rotates. Following the deceleration, the player immediately uses a very strong contraction of the rotator cuff to rapidly throw the ball back with external rotation. The shoulder remains at right angles to the body (90° of abduction) and the elbow also remains bent at 90° throughout the exercise.



What role do the core muscles play? — How can I improve my trunk stability?

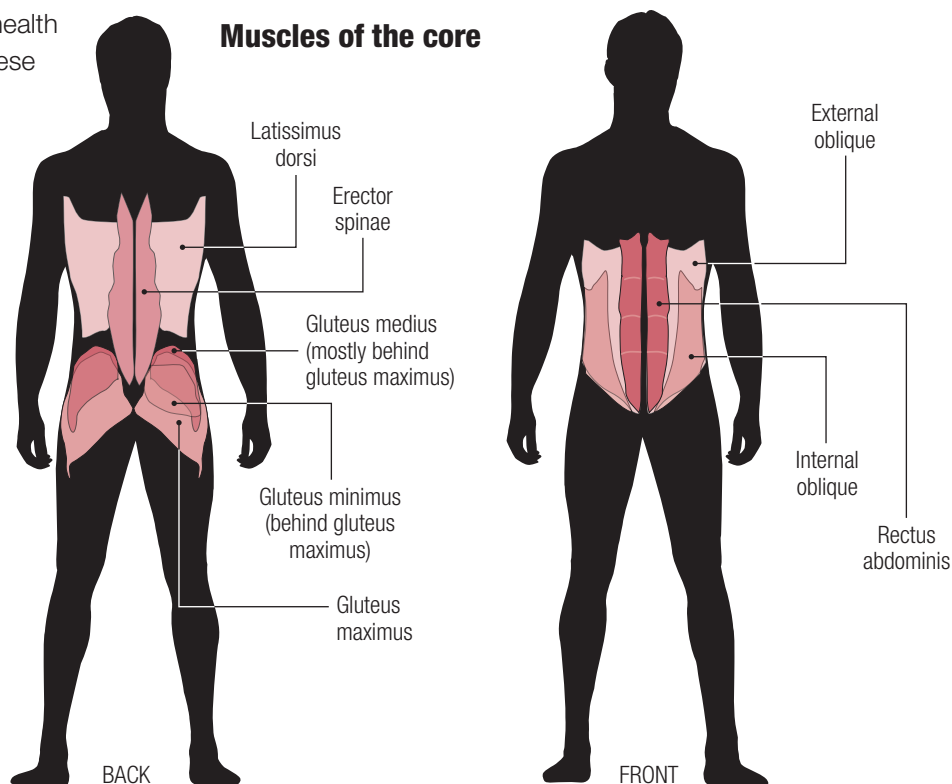
The “core” is the region in the center of the body, between the chest and the hips, that forms a cylinder-like area. This encompasses many muscular structures that provide power for stroke production, as well as control, and stability to protect the spine and internal organs. It is recommended for athletes and tennis players of all levels to have a strong core, to protect the lumbar spine from injury. A strong core where the muscles are balanced (front to back) will provide valuable stabilization to the lumbar spine during play. This assists in stroke production, in which the trunk plays such a critical role.

There are several key muscular structures that comprise the core. Perhaps the most well known of these muscle groups are the abdominal muscles—not only the rectus abdominis but also the obliques and transversus abdominis (located underneath the obliques). Unfortunately, many health professionals and athletes initially considered these to be the most important core muscles. While these muscles are certainly important, it is critical to note that they are only one part of the core, and can be overtrained and overused, leading to a muscular imbalance in the body that can jeopardize optimal core control and consequently kinetic chain development. This in turn affects a player’s performance and can lead to injury.

► **Power core** Several muscles in the body comprise what is known as the core: the abdominals including the obliques and transversus abdominis, the erector spinae muscles, the gluteals and latissimus dorsi, and the hip flexors. Together, these muscles provide stabilization of the spine and hips.

The erector spinae muscles—which are the large columns of muscle that descend along the spinal column from our neck to our lower back—have been found to be relatively weak and underdeveloped in elite tennis players. This is because frequent and intense tennis sessions develop the abdominals but not the erector spinae, leading to imbalance and injury. The only way to correct this is to undertake specific exercises to strengthen these muscles.

The gluteals, or “glutes” as they are often called, and the latissimus dorsi—a massive muscle that covers the lower back and thoracic region of the body—may also be considered part of the core, as may the very strong and often overly tight ilio-psoas group, known as the hip flexors.

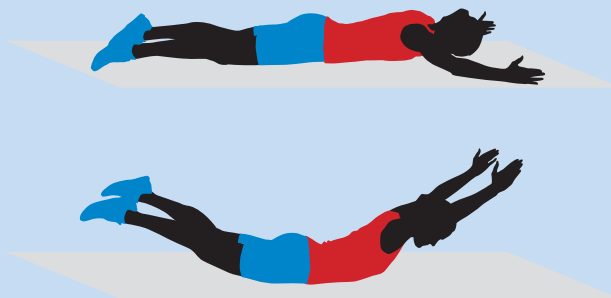


Core stability exercises

► **Improving core stability** One of the greatest advantages of working to improve core stability is that little if any equipment is needed in order to strengthen these important muscles. Targeting the lower back (erector spinae) muscles in tennis players is very important and can be accomplished through a progression of exercises such as those shown here. These emphasize the erector spinae and the gluteals, which are often underdeveloped in tennis players.

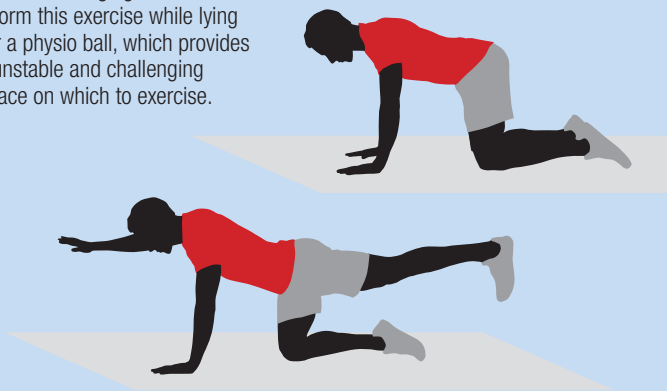
Superman exercise

Lie on your stomach with your arms and legs extended. Tense your gluteal muscles by squeezing them together. Then, simultaneously raise the arms and legs 4–6 in (10–15 cm) off the ground, holding for a count of 1–2 seconds before returning to the starting position. Repeat multiple sets of 10–15 repetitions. Try raising alternate pairs of arm and leg combinations (for instance, left arm and right leg).



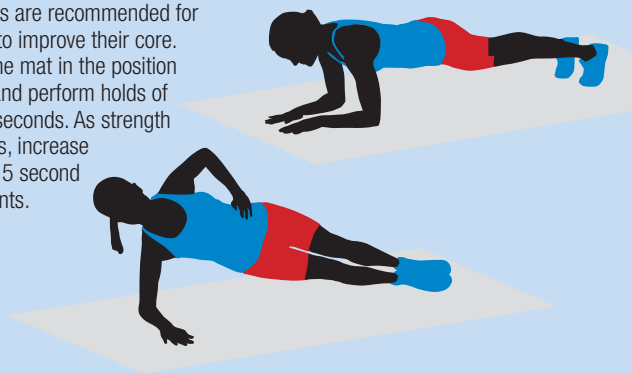
Bird dog exercise

Start on your hands and knees and squeeze the gluteal muscles together. Also tense the abdominals by drawing the stomach toward the spine—this increases the co-activation of the core muscles. Then, alternately extend crossed pairs of arm and leg combinations (left arm, right leg), keeping the back straight. Lower back motion may be monitored by placing a tennis racket across the lower back. Another challenging alternative is to perform this exercise while lying over a physio ball, which provides an unstable and challenging surface on which to exercise.



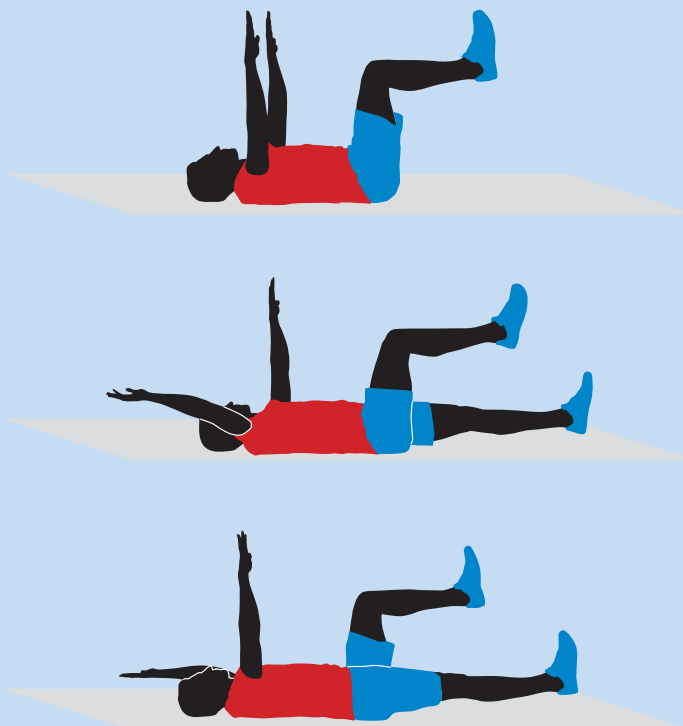
Plank

The “plank” (front and side) exercises are recommended for players to improve their core. Lie on the mat in the position shown and perform holds of 30–45 seconds. As strength improves, increase by 10–15 second increments.



Dead bug exercise

Although the abdominals should not dominate exercise programs, they are still very important for tennis players. One widely used exercise that focuses on the abdominal muscles and the front of the core is the so-called “dead bug.” Lie on your back with your arms pointing up, and your hips and knees bent 90°. Tighten your abdominal muscles and lift your knees, all the while keeping your lower back pushed into the floor. As you get stronger, you can try raising and lowering alternate pairs of opposite arm and leg. Careful performance of this exercise ensures that the abdominal muscles and obliques are all engaged. Working up to multiple sets of 15–20 arm and leg pairs is an excellent long-term goal.





This chapter explores how sports sciences have contributed to the monitoring and improvement of tennis equipment. Research that has influenced tennis equipment has been conducted by sports governing bodies, sports scientists, sports organizations, and equipment manufacturers. All have contributed to improving performance, as well as to the enjoyment and safety of the sport.

The scientific disciplines most closely related to studying tennis equipment are biomechanics, ergonomics, kinesiology, physics, and sports engineering. All provide important knowledge to help tennis coaches and players alike select the most appropriate equipment.

chapter eight

equipment and technology

Duane Knudson



What scientific measurement techniques are used to study tennis?

How can science help me select better equipment?

Advances in materials, design, and construction of tennis equipment have increased the enjoyment of tennis for players at all levels, but like all developments in technology they can have unintended consequences—for example, improvements in racket design and materials can increase ball speed, changing the nature of the game. The International Tennis Federation (ITF) oversees the rules of the sport and has established a Technical Department to assist with regulations to protect the nature of the game, but also to perform research to help with innovation and improvement. This scientific research goes beyond the traditional data collected about tennis matches, such as match scores, serving percentages, errors, time of play, or injury events.

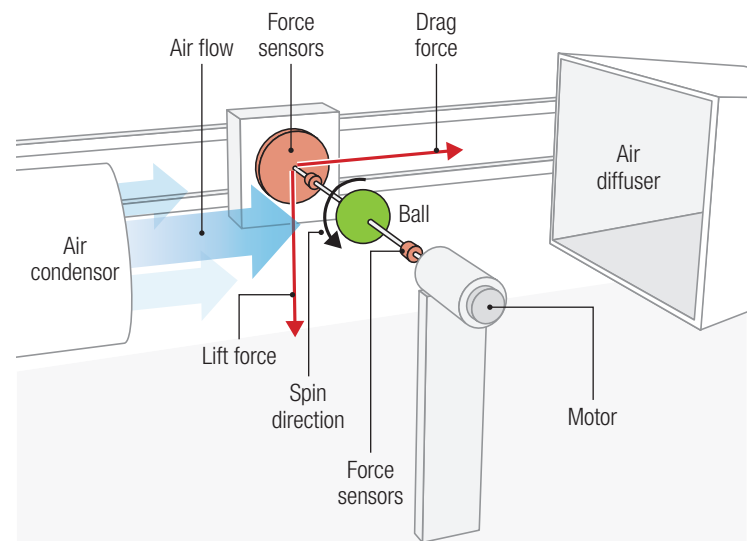
Physical instruments, as well as theoretical and computer models, are used to collect data on the interaction of the equipment, player, and environment during play. The sciences of engineering and biomechanics use all three of these approaches, and are perhaps most influential in measuring the key performance parameters of the sport.

Examples of physical instruments include motion and force sensors. The player and racket movements in tennis are often measured using special high-speed cameras, while the forces on the racket or body during strokes and at impact are measured with sensors that record acceleration or force. Forces are complex parameters that have specified size, direction, and location, and represent the push between two objects. Force sensors are used in wind tunnels to measure air resistance. Small force sensors are also used on the racket to assess grip pressure during stroke production and to analyze the link between the hand and the racket during strokes. Such sensors can also record impact loading for different rackets and impact situations.

Mathematical models of tennis equipment or ball flight help us to understand the interaction of the key physical variables in the sport. The motion of the ball and racket can be modeled using simple mathematical relations or complex, structure-specific equations. Finite element modeling is a complex technique that breaks up objects into smaller elements to examine the forces and deformations of a structure. The forces and motions measured by scientific instruments are also very important in validating theoretical models of tennis equipment.

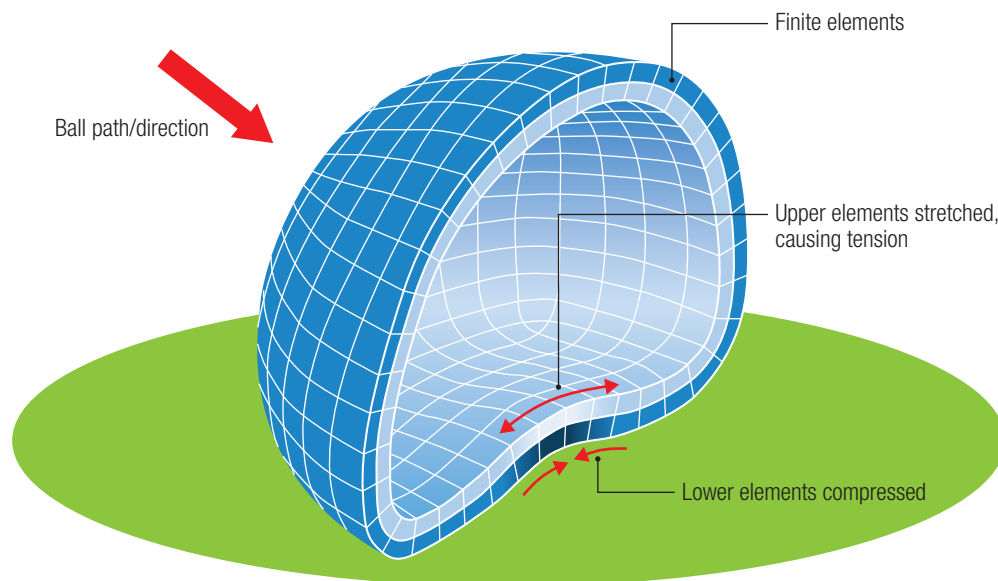
▼ **Ball testing** Precise multi-direction force sensors built into a wind tunnel are used to measure the forces of air resistance—lift and drag—that strongly influence ball trajectory.

Measuring air resistance



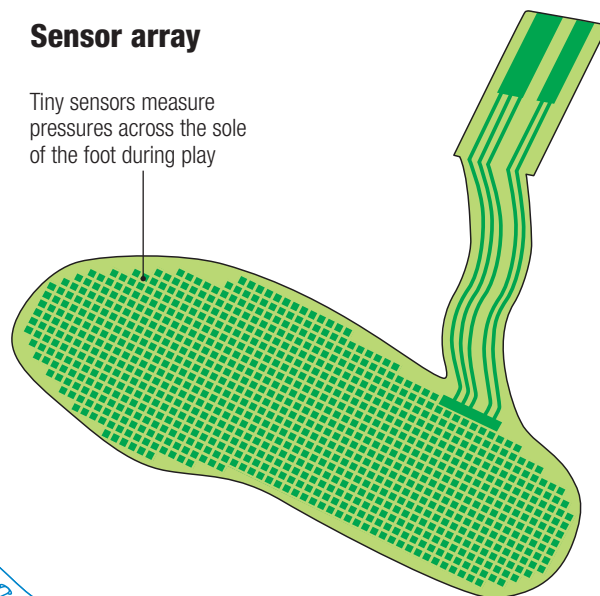
► **Ball modeling** A finite element model is a computer simulation of a structure that can be used to study the forces and deformations within a tennis ball. Notice the concave area under the bouncing tennis ball. If you have ever been unfortunate enough to be hit by a fast-moving tennis ball, this dynamic behavior of the ball is why you may have had an uneven bruise on your body. This bruise is more common among racketball players who use a softer ball and play in a very small space.

Impact assessment



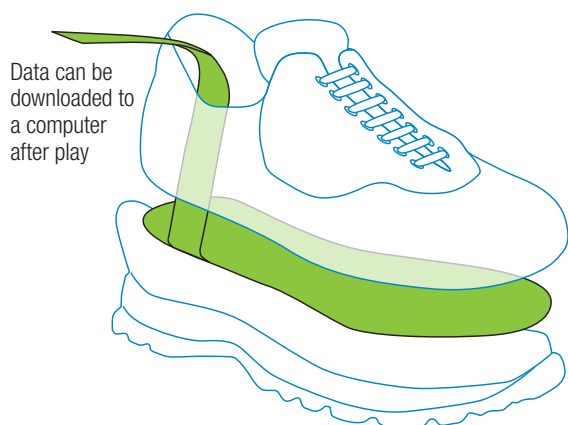
Sensor array

Tiny sensors measure pressures across the sole of the foot during play



◄ **Under pressure** A specially made device—similar to an insole—for measuring the right-angled force between the foot and the shoe is placed inside the shoe underneath the foot. The “insole” contains many tiny force sensors in the form of conductive elastomers to enable the study of pressure (force per unit area) at various locations on the foot.

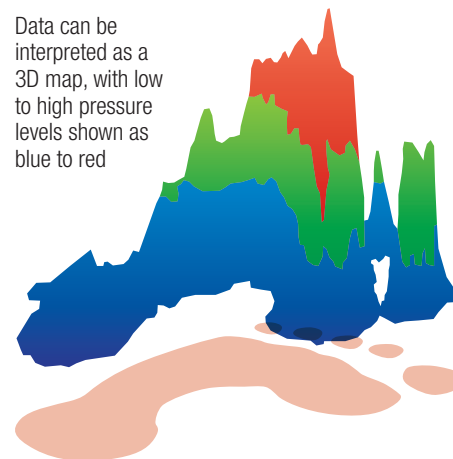
High-tech insole



3D pressure map

Data can be interpreted as a 3D map, with low to high pressure levels shown as blue to red

■ High pressure
■ Moderate pressure
■ Low pressure



Which racket characteristics power the ball?

Can racket design improve my tennis?

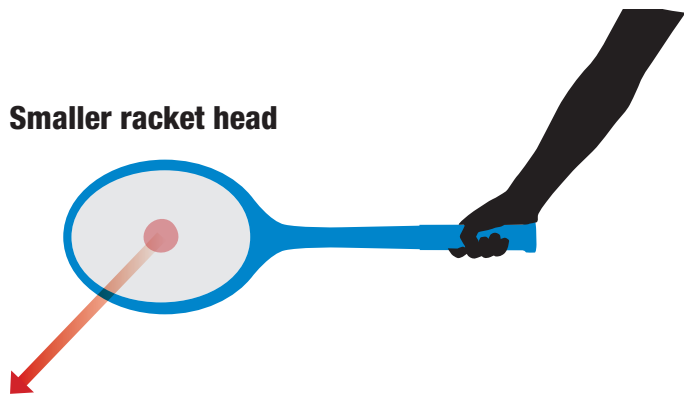
Tennis rackets are often marketed to players with design features described as improving shot velocity and accuracy. The experience of striking the ball perfectly—near the “sweet spot”—hitting a fast “winner” past an opponent is highly valued by most players. So, scientific research has explored how changes in racket design can affect the accuracy of shots as well as the speed of ball rebound.

The most influential change in the design of rackets may have been the increase in size of the racket’s head. Howard Head’s 1975 patent was based on data that a larger head increased the high-power sweet spot by four to five times that of a regular-sized racket. The more recent increases in racket length of 1–2 in (2.5–5 cm) to 29 in (73.5 cm) have been found to increase ball speed in groundstrokes by a smaller amount (2 to 6%).¹ Overall, the increased head size and frame diameter have increased stiffness and, along with stronger and lighter racket materials, have also increased the speed of the game.

One can look at how much this increase in speed from larger-headed rackets affects the sport by using computer simulations. The ITF has worked with scientists at the University of Sheffield to create a three-dimensional model (called the Grand Unified Theory or GUT) to simulate the effect of equipment, strokes, and environmental factors on the sport. Researchers used the GUT simulations to show that the average speed of the serve of advanced male players has increased by 18%—from 112 mph (180 km/h) to 130 mph (210 km/h)—as a result of changes to the racket and ball from 1870 to 2007.²

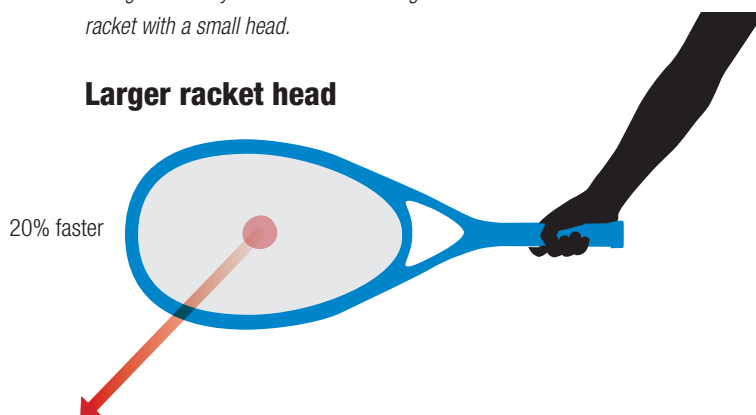
The increased power zone and stiffness of oversize graphite rackets, combined with a longer frame, mean that modern rackets can create about 20% greater ball speed than a perfect impact with an older wooden racket. Small-headed, wooden rackets performed even worse when the ball did not impact the center of the racket face. Modern, large rackets are much less susceptible to the off-center impacts that tend to create lower ball velocity and reduced accuracy with older, smaller rackets.

Smaller racket head



◀◀ **Power zone** Two rackets with the same string tension, stroke speed, and central impact in the power zone can create different ball velocities. A racket with a large head has a big power zone or “sweet spot,” so a player is more likely to consistently hit higher-velocity shots than when using a similar racket with a small head.

Larger racket head

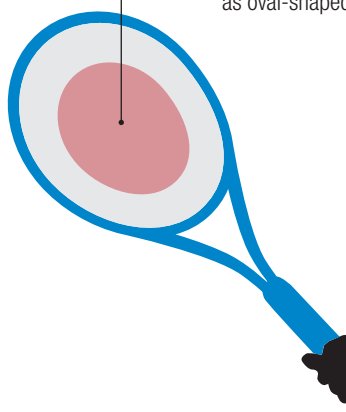


Racket head comparison

►▼ **Head to head** A racket with a large head has clear advantages in accuracy and speed of ball rebound compared to a racket with a smaller head. A reflex volley, for example, may be impacted off-center on the racket face. A larger head frame has greater resistance to rotation in the player's hand, resulting in a faster and more accurate ball rebound than would be possible with a smaller racket head.

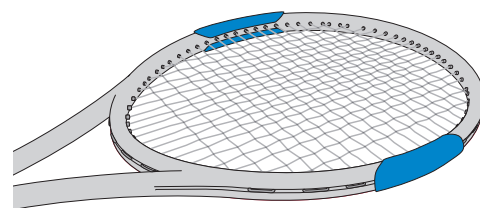
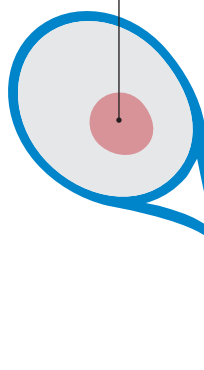
Larger racket head

Power zone is larger for larger racket heads and is more centered as well as oval-shaped



Smaller racket head

Power zone is small and round, and an off-center impact is also likely to rotate the racket in the hand, causing a mishit



▲ **Added weight** Pro tennis players often customize the swing-weight of their rackets by adding lead tape to the frame. Placing extra mass laterally on the frame increases ball speed and greatly increases the racket's resistance to adverse rotations for balls impacted off-center on the racket face. The tape can be added on the outside and the inside of the hoop.

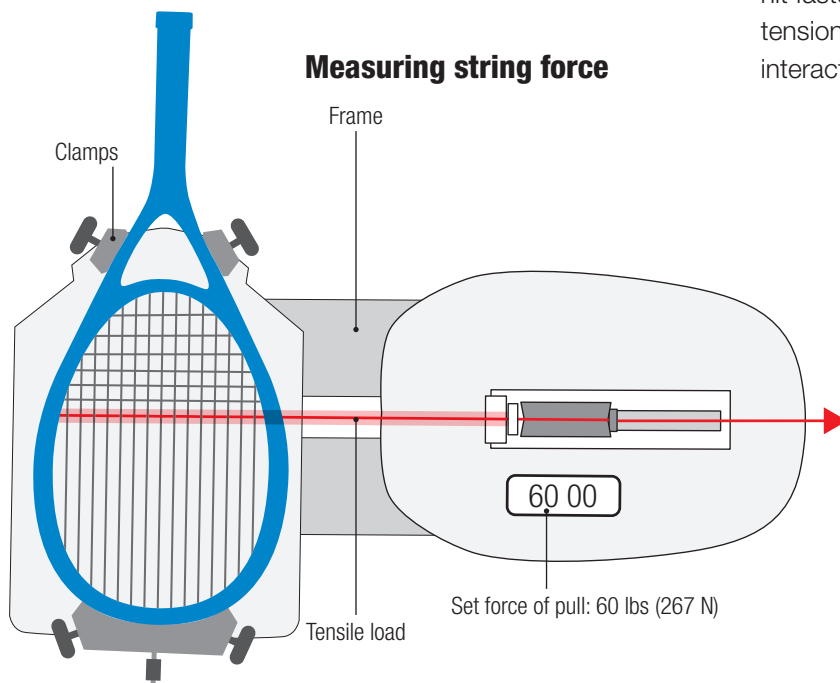
How does racket string tension affect ball movement?

How do racket strings affect my tennis strokes?

One of the most influential factors in performance and injury risk in tennis is the science of the strings. The material in tennis racket strings, and their tension, have a large effect on both the shot and the forces transmitted to the player's body.

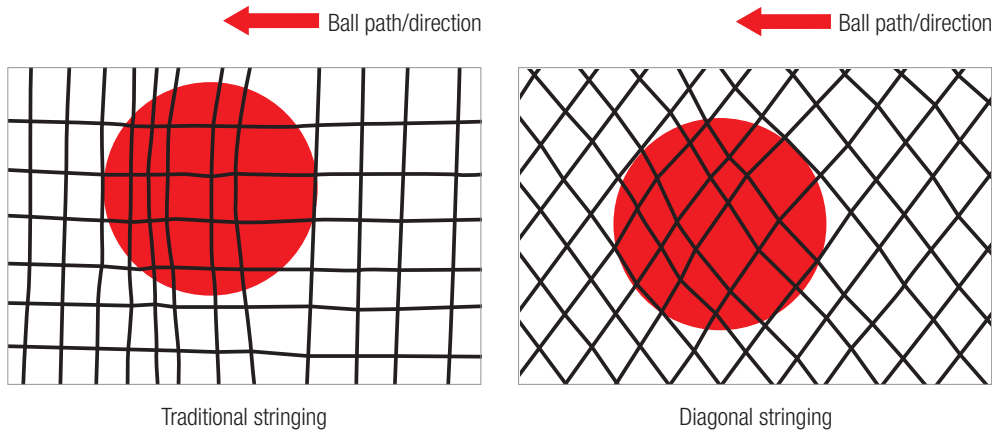
While the racket provides the structure and mass to resist the forces of impact in each stroke, it's the elasticity of the strings that captures the kinetic (motion) energy from the ball and racket, returns between 90% and 95% of this energy to the ball speed, and creates spin after impact. More compliant strings (like natural gut or softer nylons) waste less energy in ball and frame deformation, resulting in less shock being transmitted to the body and greater ball speeds. Interestingly, the trade-off with more compliant strings is that they tend to create less ball spin because of greater inter-string friction than stiffer strings (made from polyester, for example).

Modern tennis rackets can be strung at a variety of tensions (from 50 to 70 lb, or 222 to 311 N), and that tension has a large influence on the speed and spin of the ball. Increasing string tension will decrease speed of ball rebound, but will improve stroke accuracy. The higher tension stiffens the string bed, creating greater ball deformation and energy losses in the stroke. This greater ball deformation interacts with lateral string motion to create more ball spin in the stroke. The combination of these two effects is the origin of the common and accurate player perception that higher string tensions tend to benefit shot accuracy. Any string material at a lower tension will create greater ball rebound speed than the same string at a higher tension. A reduction of 20 lb (89 N) in tension can increase ball speed by 5–10%. Interestingly, many players incorrectly perceive that the softness of “feel” with lower string tensions means the ball is hit with lower speeds, when in fact the ball is hit faster than with the harder feel of the same string at a higher tension. How strings affect ball rebound results from an interaction of the properties of the strings, ball, and frame.



◀ **String tension** Racket stringers use machines that measure the force applied to a string as it is stretched and clamped into position in a frame. Over time, with play, the residual tension in the strings declines. More sophisticated force sensors are needed to understand the dynamic forces and length changes of strings during impacts.

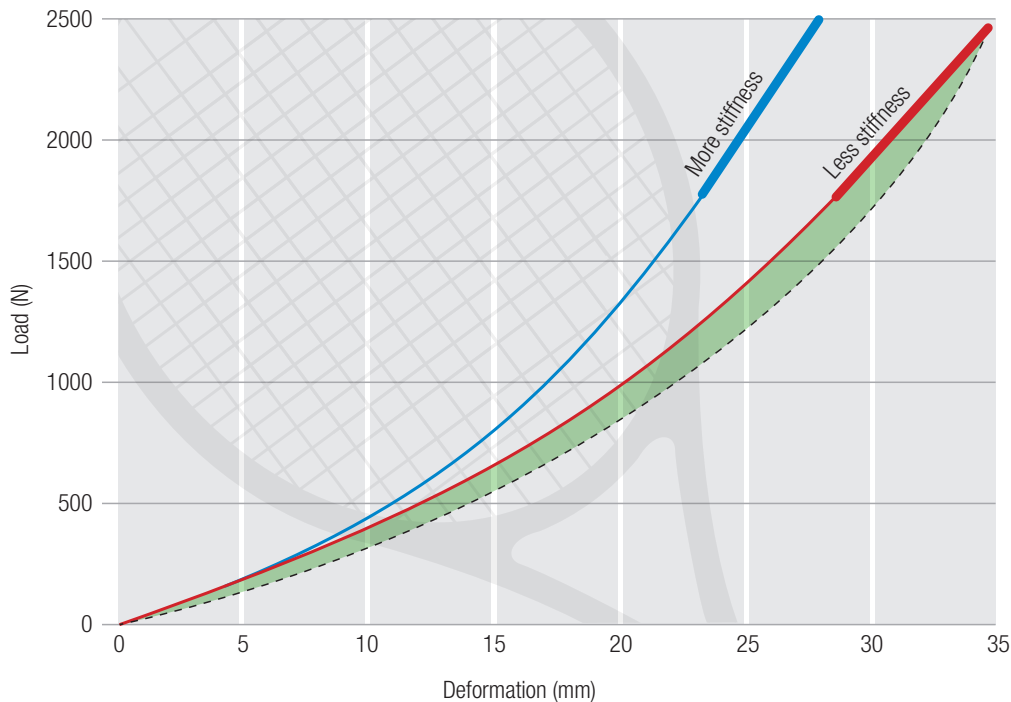
Ball and string



▲ **String pattern** On impact with the racket strings, the ball deforms and the strings shift past each other. The elasticity and spin created by the strings for a given tension depend on their pattern, including the direction of the strings relative to the head, the grommets (holes in the frame), and the spacing of the main and cross strings. Greater ball spin can be achieved by using wider string patterns or smoother strings to increase the amount the

strings slide, as well as the sideward deflection during ball contact. Diagonal stringing patterns create less ball spin than traditional patterns.¹ Further changes in string bed performance can be made beyond the pattern. Advanced tennis players often string the long axis (main strings) at a lower tension with gut strings, and the lateral axis (cross strings) at a higher tension with polyester strings, to create more ball spin on impact.

String energy



◀ **String theory** As the ball impacts the strings, they stretch, storing the energy from the impact until they contract back to their normal length and project the ball back through the air. Tennis strings are quite elastic and energy-efficient, returning 90–95% of the total energy at impact to the ball as it leaves the racket. This diagram shows the energy-storing potential in two strings during impact. The energy stored in the string is the area under the curve, so the slope of the force to elongation curve (or stiffness) largely influences energy storage potential. The energy recovered (elasticity) is related to the force as the string returns to its regular length in the frame. The energy loss can be visualized as the green-tinted part of the area between the loading and the restitution / unloading in the less stiff string.

- Polyester (greater stiffness) force per elongation
- Natural gut (less stiffness) force per elongation
- - - Force in restitution / unloading

How do court surface properties affect ball rebound?

Are clay courts slower than hard courts?

It is obvious to tennis players who have played on different surfaces (hard, clay, grass, or carpet) that the speed, spin, and height of a tennis ball bounce depend on the court surface. The ITF tests the speed or pace of tennis courts with a Court Pace Rating (CPR) based on balls bounced on several court locations, using a standardized projection and ball speed measurement system. Balls are projected at a 16° angle to the court at 98 ft/s (30 m/s) with minimal spin. The system measures the speed and angle of the ball and CPR scores are grouped into five different categories: slow, medium-slow, medium, medium-fast, and fast. The “speed” or pace of a particular court surface is a complex combination of the elasticity (coefficient of restitution) and the friction (coefficient of friction) of the ball and court. Bounce and friction and values of courts can vary by up to about 10% and 30%, respectively.

Tennis balls bouncing off clay courts also lose energy sliding on the court surface, and pick up mass from clay and moisture. These factors—as well as the complex interaction of the elastic

and friction properties of the ball and surface—mean that, for equal speeds, spin, and angles of incidence, the horizontal velocity of the rebounding ball will be slower on clay courts than on hard courts. The speed of the ball is also reduced by the higher bounce on a clay court than on a hard court.

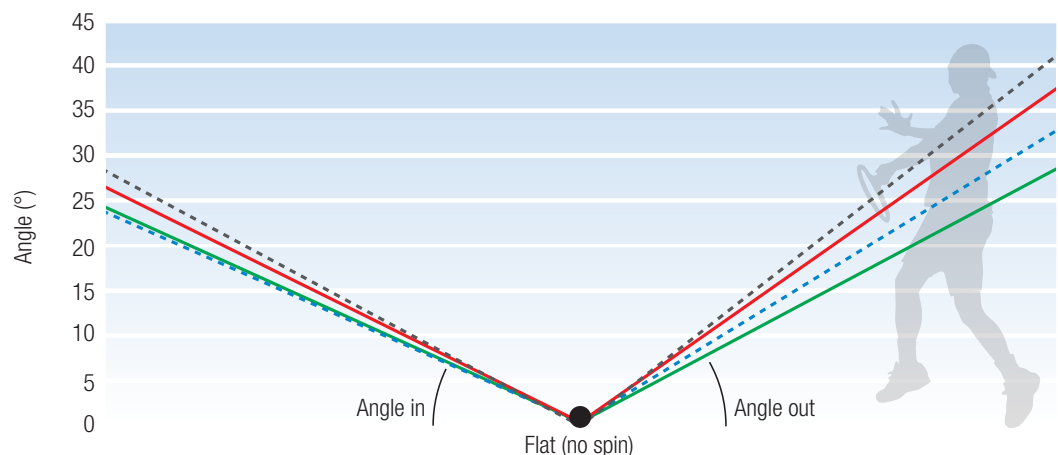
These changes in the speed and height of the bounce are what players perceive as the difference in pace between different courts. Hard-court surfaces can vary because of the different amounts of sand mixed in the acrylic court coating. In addition, balls hitting the lines on both clay and hard courts typically bounce much lower and faster than other shots, making them more difficult to hit.

The physical properties of tennis courts not only affect the bounce of the ball, but also the interaction of the player's shoes and lower body with the surface. Biomechanical research on players performing lateral movements and forehands on differently cushioned tennis court surfaces has reported differences in the rate of force loading on the players' feet.¹

► **On the bounce** Differences in trajectory of balls for no-spin rebounds from several types of court surface used at Grand Slam venues are shown, using high-speed image data from Pallis et al.² A player's sense of the speed of the game will be influenced by the speed and height of the bounce, and also the slowing of their movement on the court surface.

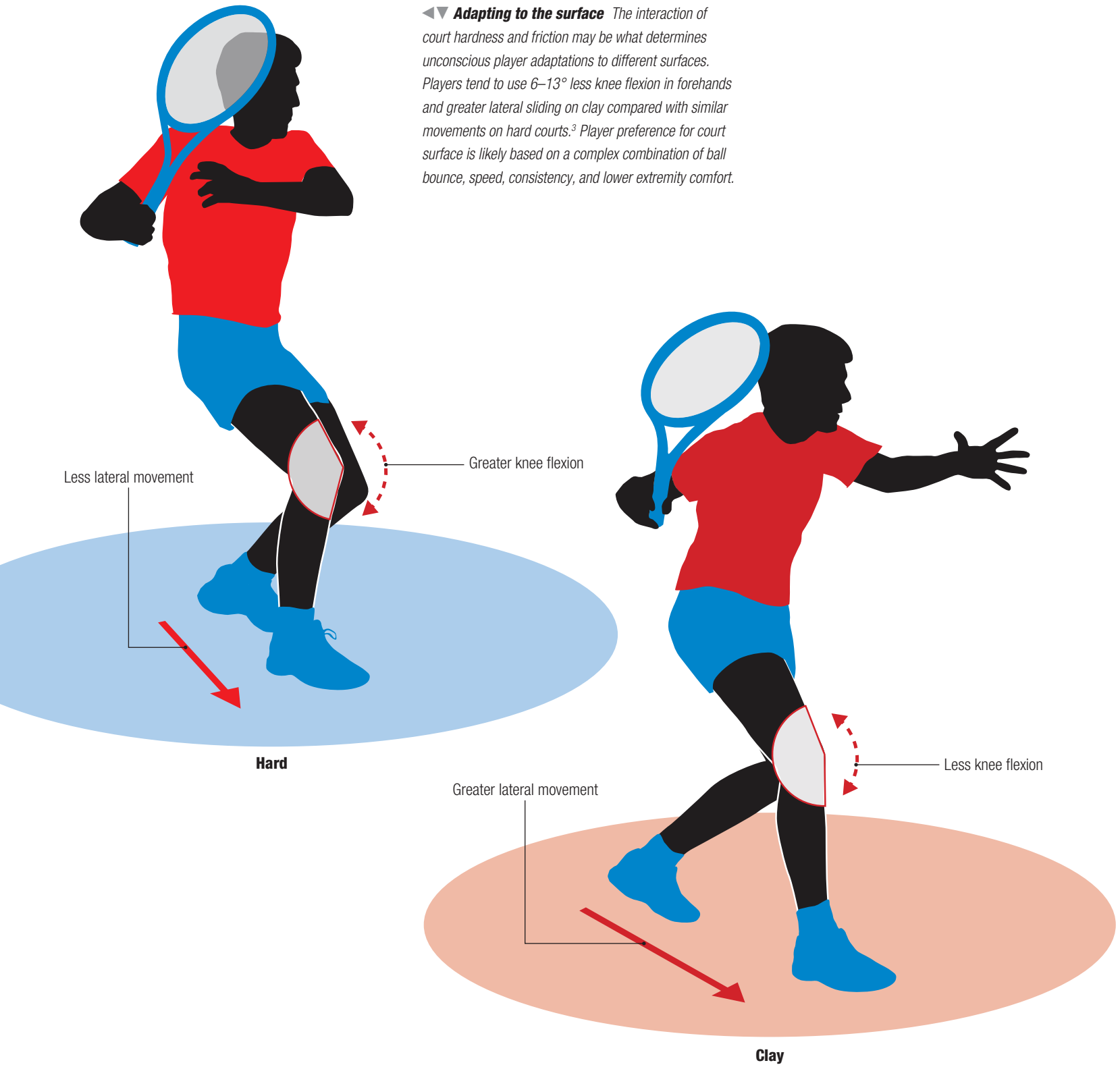
- Green clay, US Open
- Red clay, US Open
- Hard, US Open
- Grass, Wimbledon

Surface differences



Lateral movements

◀▶ **Adapting to the surface** The interaction of court hardness and friction may be what determines unconscious player adaptations to different surfaces. Players tend to use 6–13° less knee flexion in forehands and greater lateral sliding on clay compared with similar movements on hard courts.³ Player preference for court surface is likely based on a complex combination of ball bounce, speed, consistency, and lower extremity comfort.



How do ball characteristics affect performance?

Which tennis balls should I use?

It used to be that tennis players had few choices in tennis balls—use the old, worn balls or buy a new can. Over the years new types of ball have been created: the now familiar “optic” yellow balls—and balls in other colors—replaced white felt balls; heavy-duty felt balls for hard courts; pressureless balls with a stiffer rubber core to create bounce rather than internal air pressure; large (type 3) balls; and developmental balls.

The type 3 ball is 6% larger in diameter than the regular ball, but with the same mass, and was approved by the ITF in 1999. This ball was developed to slow the game down by adding air resistance to compensate for the more powerful tennis rackets of the modern game. Research into the muscle activations used to hit the ball and impact acceleration (shock wave) on contact has shown no difference between the type 3 and regular balls.¹ Despite this, the type 3 ball has not been popular and is no longer widely available.

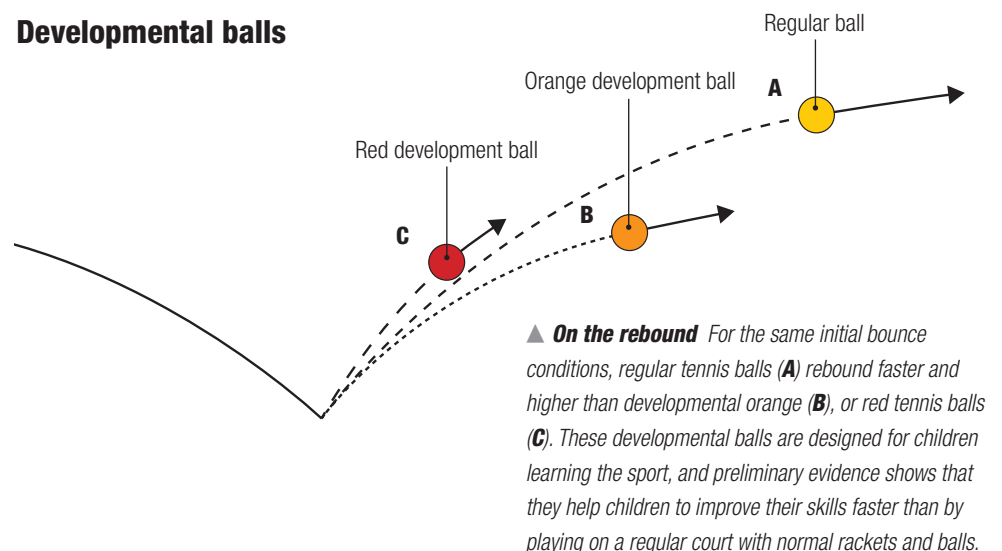
Developmental balls are used for three stages of coaching young players: stage 1 balls are red and designed for children aged 5 to 8; stage 2 orange balls are for 8- to 10-year-olds; and stage 3 green balls are used by children of ages 9 and older. These balls are larger and slower, and are designed to bounce at heights appropriate to each age group, making play easier for children. Matching the hitting height to children’s strokes has been proven to help them learn the sport.

Players know that regular balls go “dead” or do not have the bounce of new balls after many sets of play. The durability of the ball and felt to withstand the punishing demands of the sport—and maintain consistent flight and bounce—is important. For this reason, the ITF added durability tests for all approved tennis balls in 2009. Balls are bounced at high speed before and after being passed through a felt-wearing device—designed to closely match the wear of nine games of tennis play—with the aim of assessing the balls’ durability.



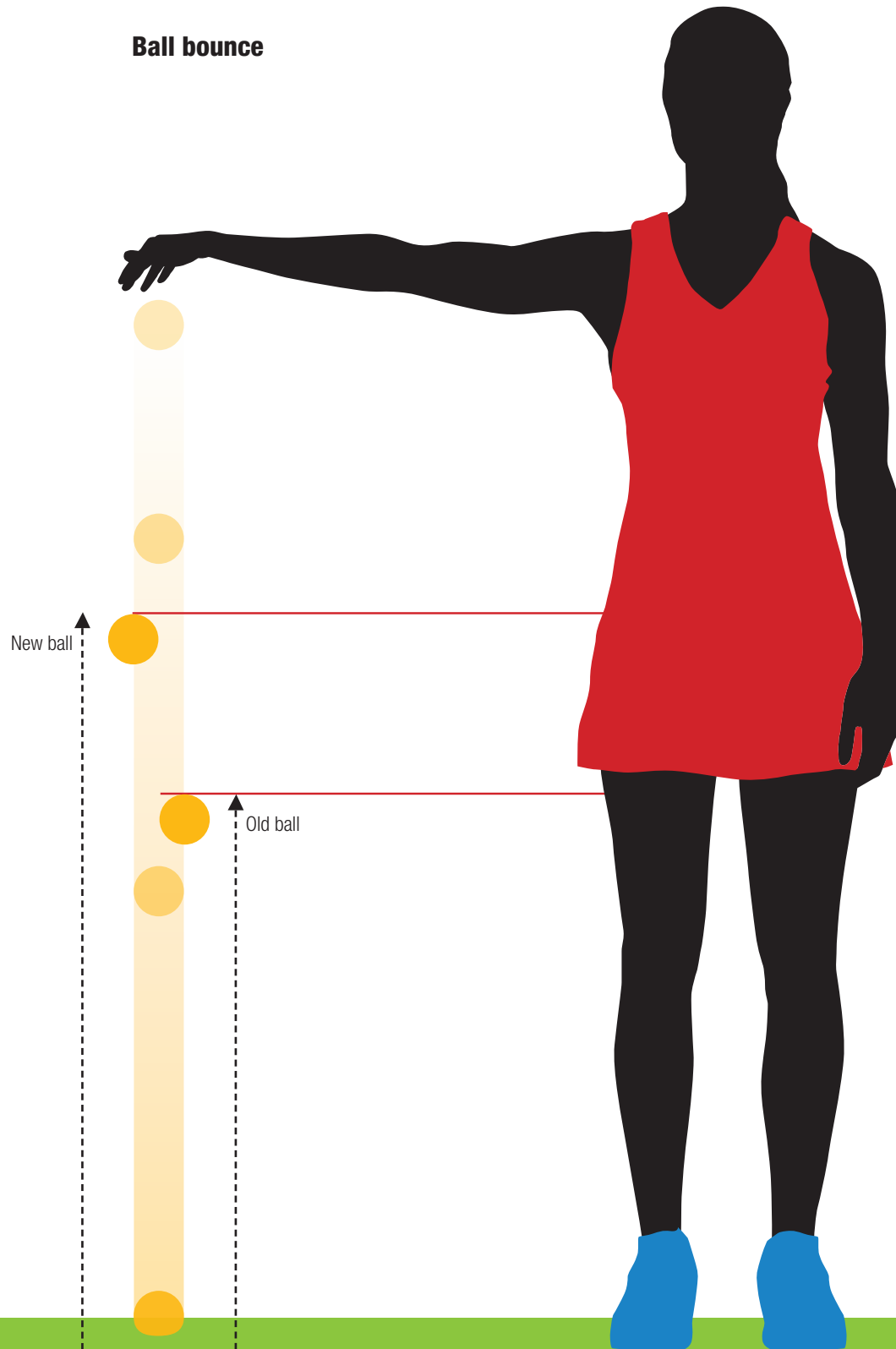
▲ **Ball comparison** A type 3 ball (on the right) has a 6% larger diameter than the regular type 2 tennis ball, but the same mass, so it tends to slow down more in flight as a result of the additional air resistance.

Developmental balls



▲ **On the rebound** For the same initial bounce conditions, regular tennis balls (A) rebound faster and higher than developmental orange (B), or red tennis balls (C). These developmental balls are designed for children learning the sport, and preliminary evidence shows that they help children to improve their skills faster than by playing on a regular court with normal rackets and balls.

Ball bounce



◀ **Dead ball** New balls will bounce to waist height when dropped from shoulder height onto a hard court, while an old, "dead" ball will bounce substantially lower.

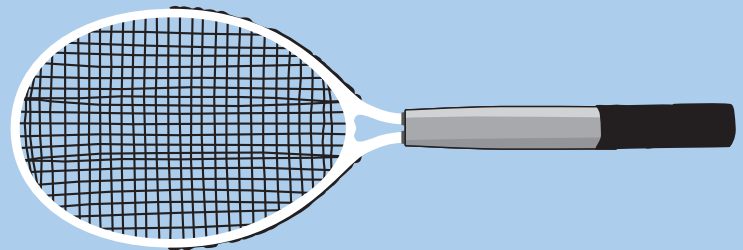
equipment: the racket

The tennis racket has a considerable influence on player performance. Over the years there have been many improvements in the materials, design, and manufacturing of rackets. Advances, including stronger and lighter materials, have allowed larger racket heads and an increasing variety of head designs. Some of these new designs (with larger heads and wider frames) have been effective in improving performance and were a commercial success, while others were not.

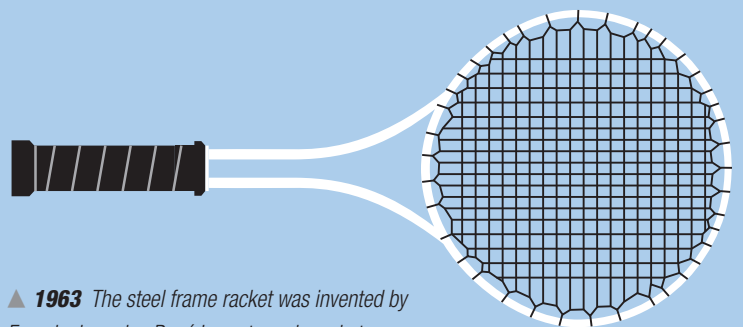
Early rackets were made from strips of hardwood and were susceptible to warping from play, environmental conditions, and tension in the strings. They had teardrop-shaped heads and grooved wooden grips, often of 5–6 in (12.7–15.2 cm) circumference rather than the 4–5 in (10–12.7 cm) seen today. From the 1880s, most racket frames were made of laminated wood, and rackets retained roughly the same design for about 80 years. However, the development of new materials and designs accelerated from the 1960s onward.

The larger racket heads (oversize and midsize) were developed in the late 1970s, following Howard Head's patent of oversized racket frames. Materials that were lighter and stronger than wood (including aluminum and graphite) enabled a larger frame and a greater racket face area, leading to higher ball speeds. In the late 1980s, frame designs with wider cross-sections and reduced mass were introduced. Despite their larger size and length, modern tennis rackets are substantially lighter than the standard-size wooden rackets of the past. Recent changes in rackets have been based primarily on advancements in materials, composites of those materials, and the integration of smart technologies. Rackets with damping or piezoelectric systems (as in Head's Intelligence rackets) are intended to reduce the shock forces and

Racket evolution

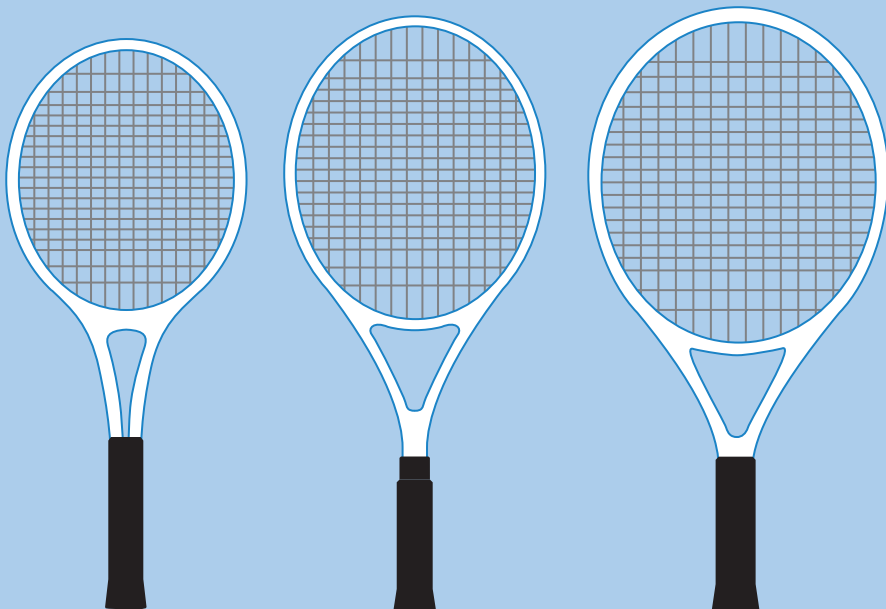


▲ **1920** *The Dayton Steel Company introduced the aluminum head and steel string racket in 1920, but it was not successful because of the excessive wear on tennis balls.*

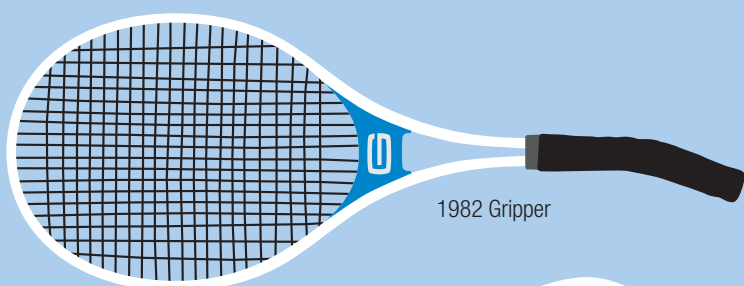


▲ **1963** *The steel frame racket was invented by French champion René Lacoste and used at Wimbledon in 1963. The design was later commercially produced by Wilson as the T2000.*

vibrations transmitted to the player's hand. Advances in sensors and computer processor miniaturization mean that future designs like the Babolat smart racket will strive to provide better performance and to help reduce the risk of injury by giving the player more detailed feedback (see pages 174–175).

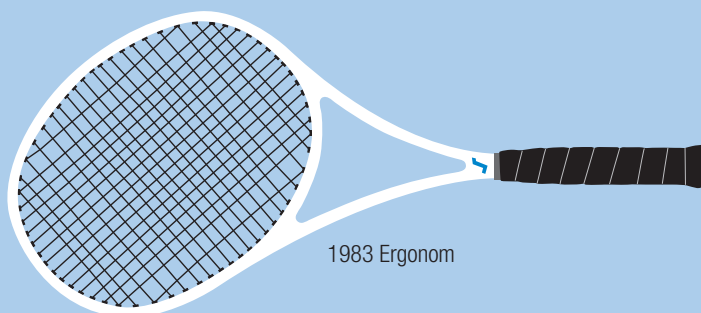


▲ **1977** Prince developed the aluminum Prince Oversize racket based on Howard Head's patent for tennis rackets with larger heads (85–130 sq in or 548–839 cm²). This innovation was a huge commercial success because the racket had a much larger “power zone” for faster ball rebounds, and better accommodated off-center impacts on the racket face. It also spawned a variety of midsize and oversize rackets with larger hitting areas and sweet spots (zones of larger rebound speeds).



1982 Gripper

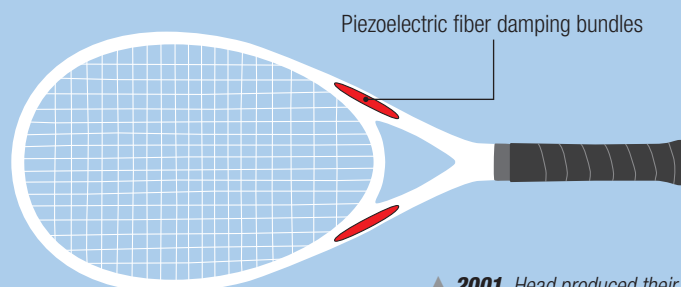
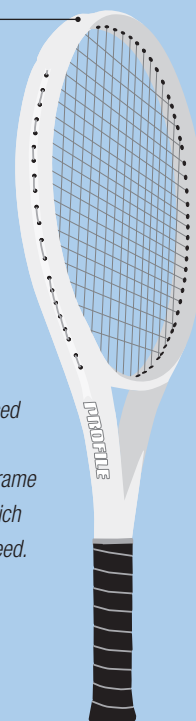
▲► **1980s** The early 1980s saw the emergence of two racket designs based on ergonomics research to foster more natural wrist postures. The designs were not well received by tennis players and were not commercially successful.



1983 Ergonom

Design of Wilson's Widebody frame provides greater resistance to bending, leading to fewer mishits

► **1987** Wilson introduced the first Widebody racket. The greater width of the frame increases its stiffness, which tends to increase shot speed.



Piezoelectric fiber damping bundles

▲ **2001** Head produced their Intelligence line of rackets. ITF rules do not allow rackets to use outside energy to boost racket performance, but Head used piezoelectric fibers to capture, store, and recover the strain energy of the racket deformation at impact to damp out frame vibrations. This damping of the annoying vibrations of impact—which do not affect shot speed—was one of the first uses of sensors to modify the response of a tennis racket.

How does air resistance affect ball flight?

Does the environment affect ball flight?

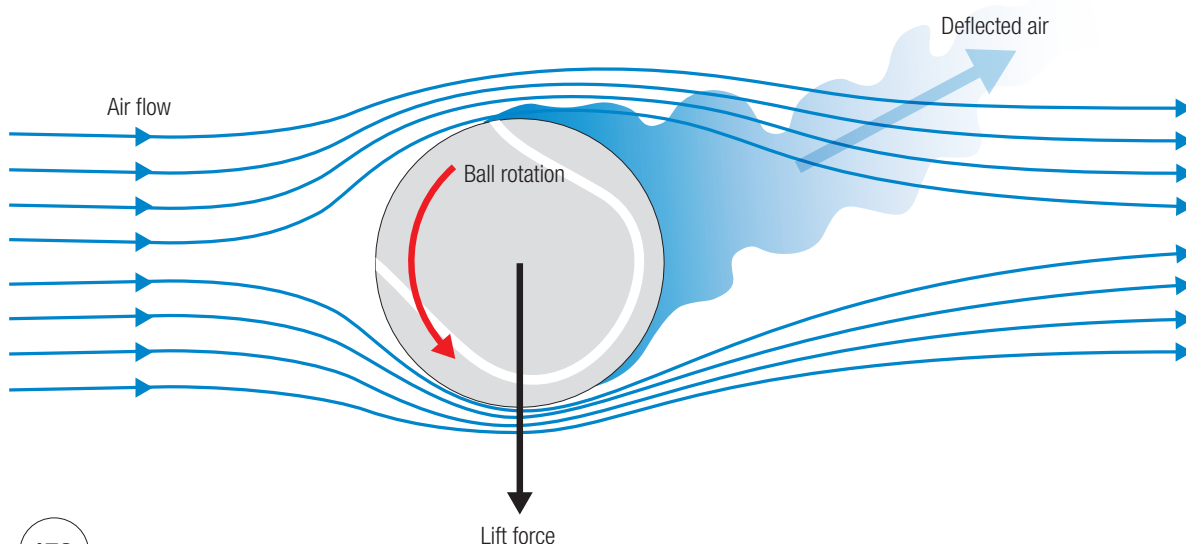
Tennis ball performance is affected by temperature, heat, humidity, atmospheric pressure, and air resistance. The most influential factor, as far as the player is concerned, is how air resistance affects the ball's flight. Tennis balls fly through a sea of air between bounces and strokes. Scientists use wind tunnels to measure the variables that determine the lift (the force that acts at right angles to fluid flow) and drag (the force that acts parallel to fluid flow). A ball's lift mostly affects its up and down motion, and drag primarily slows the ball's horizontal motion. The two variables that most affect the size of these forces are the relative speed of the airflow past the ball and the speed of rotation of the ball.

Hitting a stroke twice as fast as another stroke will result in four times the initial drag air resistance slowing down the ball. The lift force on a spinning tennis ball is created by the uneven airflow and the "wake" behind the ball. In a wind tunnel, a tennis ball with topspin will show a wake of turbulent air

deflected upward by the downward lift force of the airflow — this is why topspin groundstrokes tend to curve downward more than flat or slice strokes. Strokes with backspin have a generally upward lift force that reduces the effect of gravity and creates a "flatter" ball trajectory than minimal spin or topspin strokes. It is this flat trajectory relative to equivalent topspin groundstrokes that causes underspin shots to bounce lower than topspin shots.

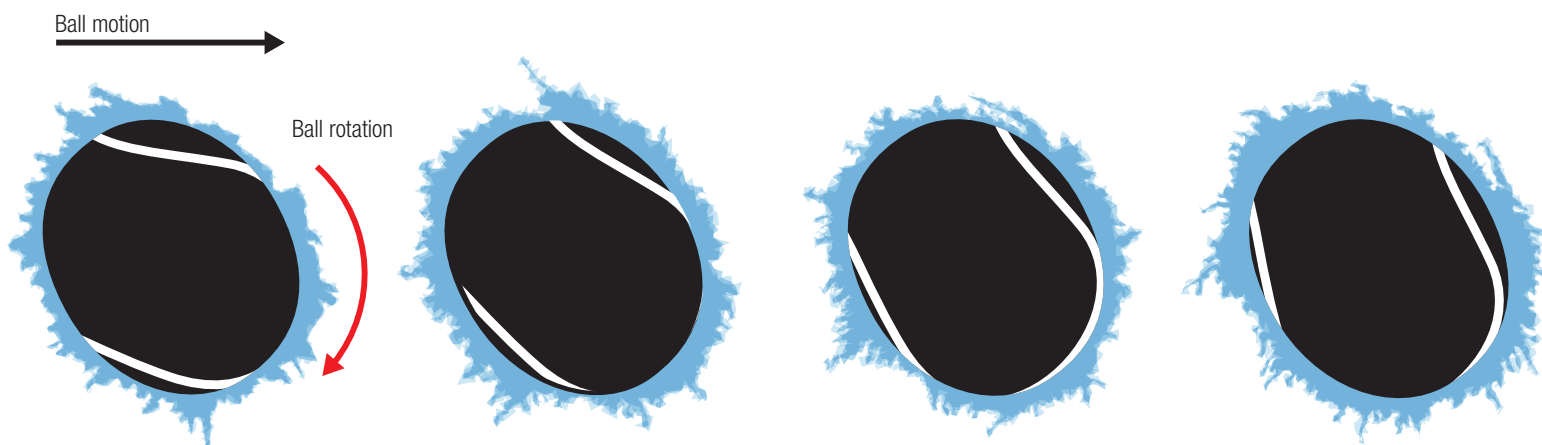
A brand new tennis ball with the felt fluffed up from a few strokes may slow down just as much as a new type 3 ball. Even new balls have small variations in mass (of about 6%) and diameter (of about 3%) — both of these factors have larger effects on air resistance and ball flight than changes to the felt. However, reduction or changes in the felt on a ball will result in increased variation in flight. Recent research has shown that the combination of felt motion in response to ball rotation affects air resistance and consequently ball flight.¹

Topspin trajectory



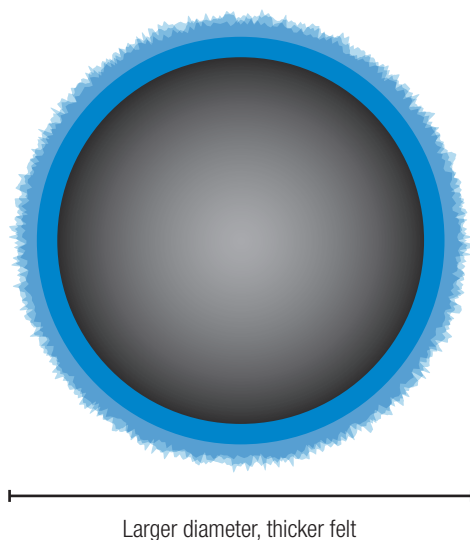
◀ **Topspin** A tennis ball with topspin on the ball creates an uneven wake, deflecting the air upward. The reaction force from the air creates a downward "lift" force that results in the steeper downward trajectory of topspin strokes.

Felt motion

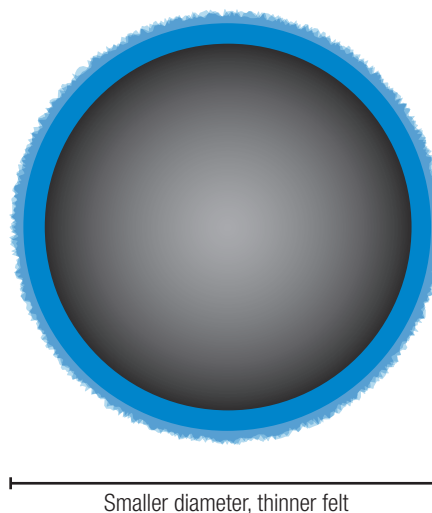


▲ **Felt in flight** Backlit high-speed video images of felt motion during ball flight with topspin.¹

Felt and air resistance



◀ ▼ **Felt variation** Since air resistance is strongly influenced by the cross-sectional area of the ball, a ball that has more felt—or more “fluffed up” felt—will have a larger diameter and so will slow down more than another ball with a smaller diameter. Touring professionals note these subtle differences when selecting balls for their serve.



Need to know

The less dense air at high altitudes reduces the drag on the ball. Similarly, worn felt on an old ball means less drag. Under these circumstances, players might feel that the ball “flies” or goes long (out) more frequently.

maintaining the integrity of the game

The introduction of the double-string tennis racket—also known as the “spaghetti” string racket—in 1977 caused a sensation in the sport when Ilie Năstase used it to bring Guillermo Vilas’ 46-match winning streak to an end. The racket was judged to produce excessive spin on the ball, changing the nature of the game, and so the “spaghetti” stringing pattern was outlawed by the ITF the following year.

While innovations in materials, design, and construction of tennis equipment have increased the enjoyment of the game, as with many technological advances there have been inadvertent consequences. The scientific and technological advancements that are driving innovation in tennis equipment are also being used by the ITF to monitor the effect of these changes and ensure that fair play and the nature of the sport are maintained through the application of the rules of tennis. The ITF’s Science and Technical Department uses state-of-the-art methods to test tennis equipment for compliance with the sport’s regulations, but also to perform research to aid with innovation and improvement.

Using computer simulation, the ITF is able to model how rackets, balls, strings, and environmental conditions all interact with each other, so that any changes in equipment technology do not change the nature of the sport. Simulation can combine data from air resistance, experiments with court geometry, and high-speed video data of typical groundstrokes to model the flight of the ball. For example, this system enables precise comparisons to be made of topspin versus backspin using a specific string design or to compare the regular ball with others (for instance, the type 3 ball). It is also possible to analyze the difference in margin of error if a player were to change string tension, increasing ball speed by 5% and reducing topspin by, say, 4% for a given stroke. Today, the effects of the level of spin on a ball resulting from different string designs and tensions can be accurately measured. This means that the effect of double stringing (multiple layers of strings similar to the “spaghetti” stringing) on the game can now be accurately assessed.

► **Competitive advantage** *Ilie Năstase used the double-string racket to great effect in 1977. Since then, tennis’ governing body, the ITF, has closely monitored, tested, and contributed to advancements in equipment technology, while maintaining the integrity of the game.*



How might sensor technology change tennis equipment?

How will developments in technology help improve my tennis?

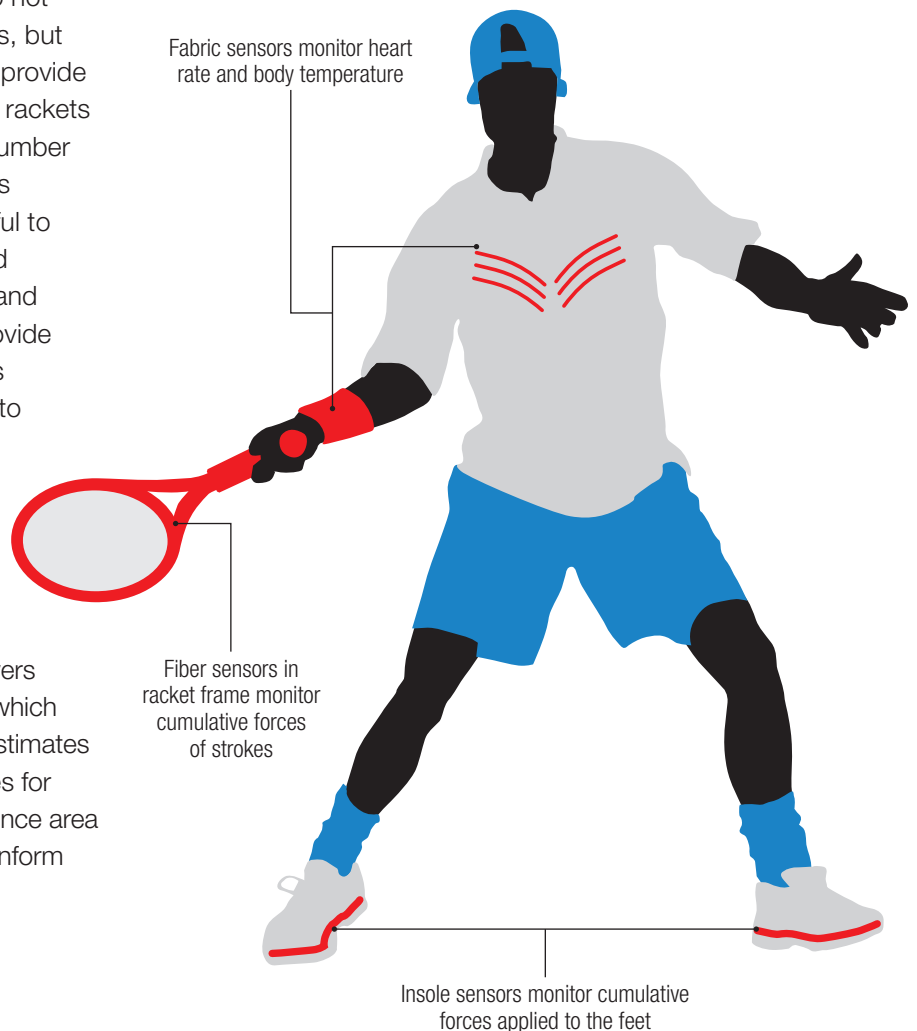
Developments in technologies—such as the miniaturization of computer chips and sensors and their incorporation into mobile devices, equipment, and apparel—mean that the integration of “smart” equipment in tennis is inevitable and, to a limited extent, already happening. The ITF approved the use of player analysis technology (rule 31) for the 2014 rules of the game.

Microsensors and computer processors may soon be able to give tennis players meaningful feedback in the high-force tools of the game: rackets and shoes. The rules of tennis do not allow tennis rackets to add additional energy to strokes, but sensors and processors can be used to calculate and provide feedback to the player. It is anticipated that shoes and rackets might work together to present data on the size and number of repetitive loads during play. Considerable research is needed to determine if these technologies can be useful to players, for instance, by helping to monitor training and prevent injury. Babolat is currently introducing a “Play and Connect” racket that uses sensors in the handle to provide players with matchplay and stroke feedback. Sony has announced the future sale of a “Smart Tennis Sensor” to be attached to the end of a racket or butt cap, which will send data wirelessly to a mobile device or computer running an app for analysis.

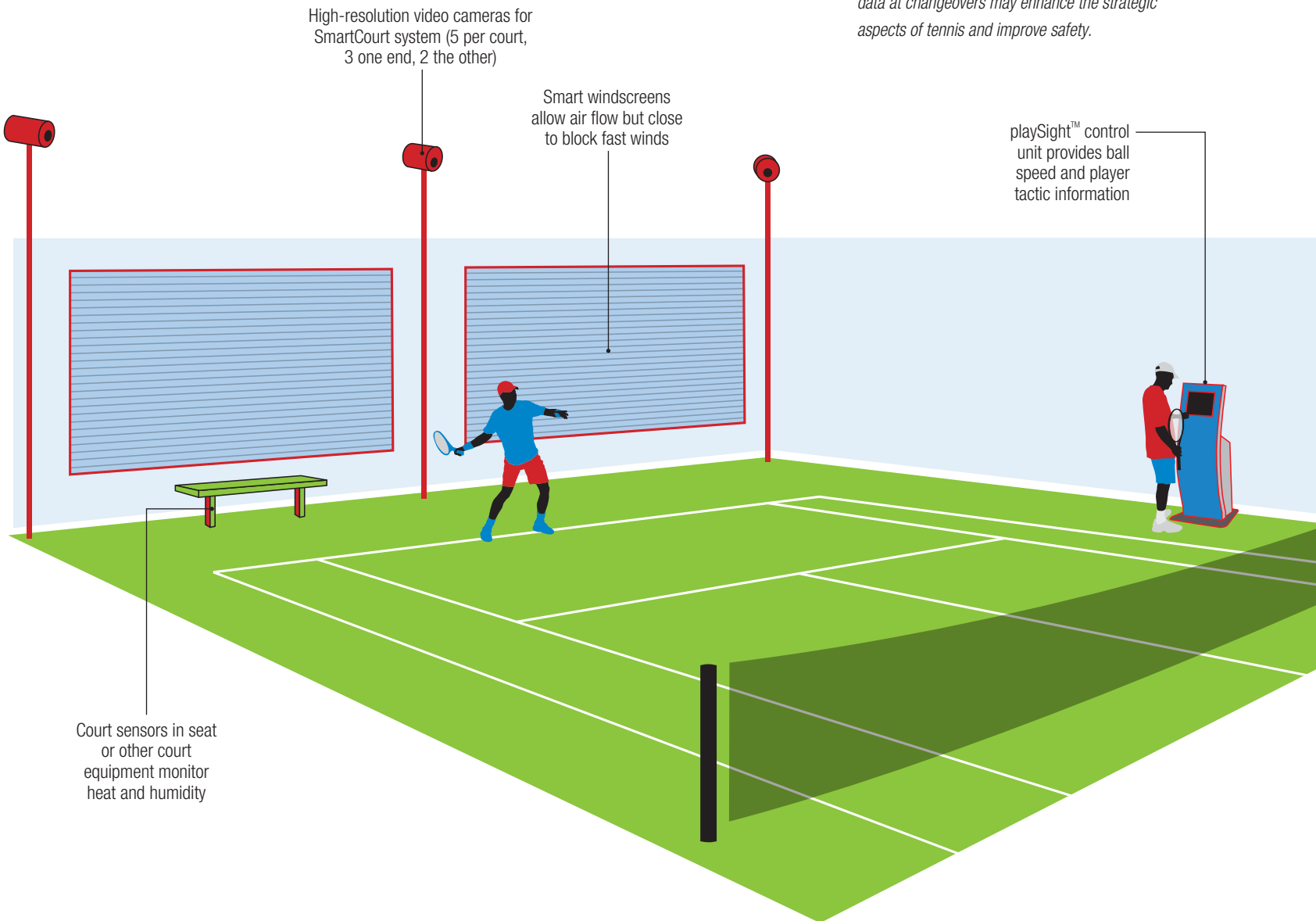
Several tennis clubs have already installed playSight™ SmartCourts that track player and ball motion in three dimensions on a tennis court. A kiosk allows tennis players to interact with the system and review the information, which includes shot location, ball speed, player motion, and estimates of caloric expenditure. The system also provides features for sharing the data with friends or coaches. The sport science area of performance analysis uses data on player motion to inform tactical decisions during competition and training.

Technological innovations need to be developed with care. While a racket that adjusts its performance characteristics to environmental conditions (such as heat and humidity) might be helpful to a player, a racket that dynamically adjusts its own weight distribution or stiffness while a player is automatically adjusting their body for each shot is less desirable. Technology must work for the player, not against their natural abilities.

Player feedback



Smart court



High-resolution video cameras for SmartCourt system (5 per court, 3 one end, 2 the other)

Smart windscreens allow air flow but close to block fast winds

playSight™ control unit provides ball speed and player tactic information

Court sensors in seat or other court equipment monitor heat and humidity

◀ **Super sensors** In the future, tennis equipment may provide meaningful feedback to the player and coach about performance and injury risk. Sensors in the racket and shoes can provide information on repetitive loading to the body. Sensors in the player's shirt or on their wrist can monitor heart rate and body temperature to reduce the risk of heat illness.

▼ **Hi-tech feedback** Sensors integrated into the court environment can measure air temperature, humidity, and wind speed. Enabling players to monitor these data at changeovers may enhance the strategic aspects of tennis and improve safety.

How do shoes affect player motion?

How should I choose a tennis shoe?

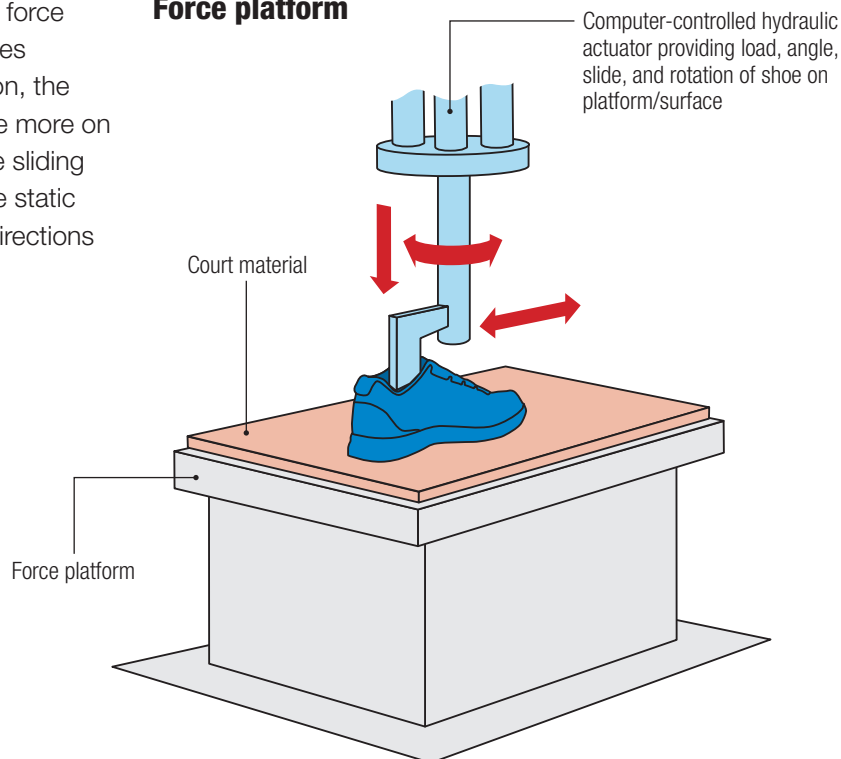
Tennis requires considerable lateral motion, so tennis shoe designs typically include deep and stable heels to support the feet during play. Shoe construction and materials strike a compromise between two objectives: shock absorption and foot motion control. Selecting a softer, well-cushioned shoe will attenuate the shock of each foot strike on the court surface but will also allow the foot to move within the shoe. Tennis players should consider their foot type (flat or high-arched), their playing style, the primary court surface on which they will play, and the fit and comfort during play to help them select their shoes.

Among the most important aspects of a tennis shoe are its frictional properties. Friction in this context is the resistance to linear and rotary sliding of the shoe's sole on the court surface. The maximum static or limiting friction before the shoe slides is equal to the coefficient of friction times the right-angle force between the shoe and surface. When the player creates horizontal forces larger than the maximum static friction, the shoe will begin to slide—for instance, a shoe will move more on a clay-court surface than on a hard-court surface. The sliding or kinetic friction is usually about 30% smaller than the static friction, which means there is less friction to change directions when sliding through a stroke on clay.

► **Shoe testing** Typical experimental setup where a biomechanics force platform is used to measure frictional properties of tennis shoes. Force platforms can measure dynamic forces and moments applied to the surface in all three directions. Hydraulic actuators push the shoe across a section of playing surface fixed to the force platform.

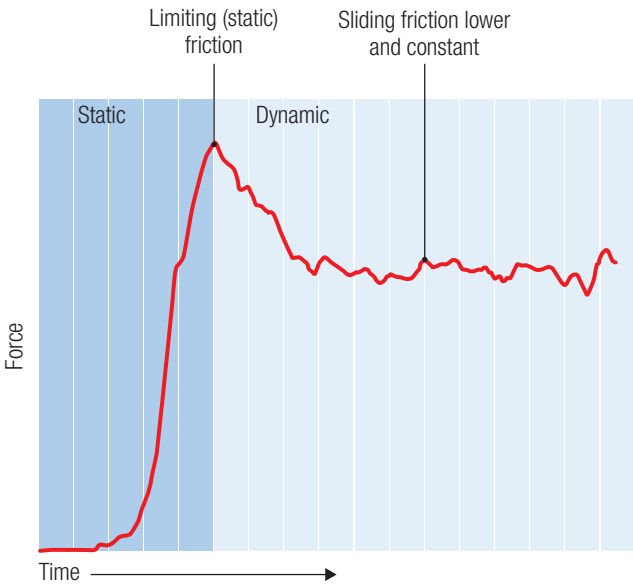
Tennis shoes, like running shoes, have midsoles made from shock-attenuating EVA (ethylene-vinyl acetate) foam. This material gets much of its shock absorption (impact force attenuation) from small air pockets in the foam. Unfortunately, most sport shoes break down over time and will lose much of their shock-absorption capacity. Depending on the distance covered and the intensity of matches, players should consider obtaining new shoes before the outsole wears out. This is particularly true if play is primarily on clay courts, where 50 or more matches will not make appreciable reductions in the outsole tread of many tennis shoes. Remember, the mechanical properties of shoes have a large influence on forces transmitted to the tennis player's foot, and unsuitable or old shoes may lead to injury.¹

Force platform



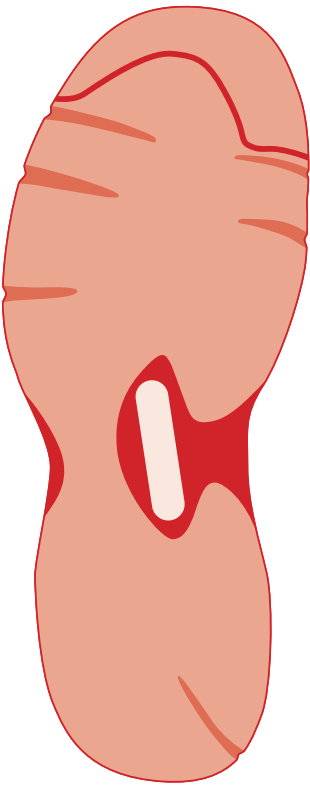
Friction forces

► **Shoe forces** Experimental testing of frictional forces between a shoe and a court surface shows that once the limiting (static) friction value is reached and the shoe begins sliding, the sliding or rotation (kinetic) friction is about two-thirds of the static value.

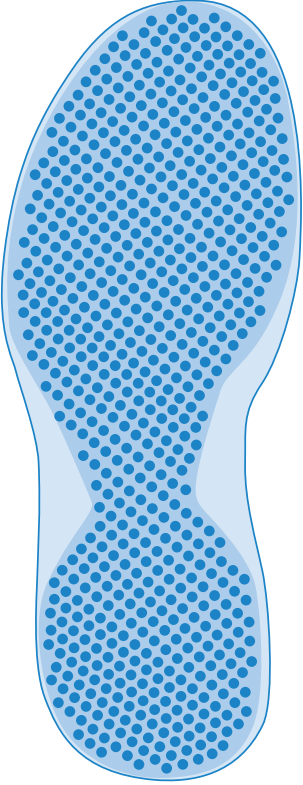


▼ **Sole support** Outsoles of tennis shoes vary depending on their intended court usage. Shoe manufacturers have developed a range of sole styles, although many commercially available shoes are now designed to provide grip on most surfaces. The addition of circular features on the ball of the foot (as in the shoe on the far right) is intended to help the player turn quickly on hard or clay courts.

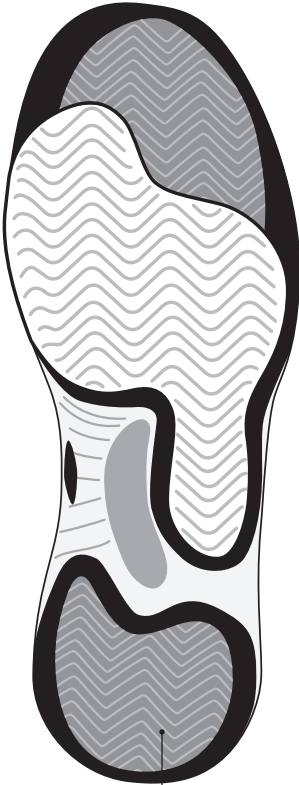
Sole variation



Carpet



Grass



Clay and hard



Notes

CHAPTER 1 learning the game

PAGES 14–15

1. D. Farrow and W. Maschette (1997), "The effects of contextual interference on children learning forehand tennis groundstrokes," *Journal of Human Movement Studies*, 33, 47–67.

2. M. Reid, M. Crespo, B. Lay, and J. Berry (2007), "Skill acquisition in tennis: research and current practice," *Journal of Science and Medicine in Sport*, 10, 1–10.

PAGES 16–17

1. J. J. Gibson (1979), *The Ecological Approach to Visual Perception*, Boston: Houghton Mifflin.

2. M. Reid, D. Whiteside, and B. Elliott (2010), "Effect of skill decomposition on racket and ball kinematics of the elite junior tennis serve," *Sports Biomechanics*, 9 (4), 296–303. DOI: 10.1080/14763141.2010.535843.

3. D. Whiteside, G. Giblin, and M. Reid (2014), "Redefining spatial consistency in the ball toss of the professional female tennis serve," *ISBS Conference Proceedings Archive*, October 2014.

4. M. Reid, D. Whiteside, G. Giblin, and B. Elliott (2013), "Effect of a common task constraint on the body, racket, and ball kinematics of the elite junior tennis serve," *Sports Biomechanics*, 12(1), 15–22.

PAGES 18–19

1. Reid, Machar, Georgia Giblin, and David Whiteside (2015), "A kinematic comparison of the overhand throw and tennis serve in tennis players: How similar are they really?" *Journal of Sports Sciences* 33.7: 713–723.

PAGES 20–21

1. Australian Bureau of Statistics (2012), Australian Health Survey: First Results 2011/12. <<http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4364.0.55.001main+features12011-12>>

2. E. Timmerman, J. De Water, K. Kachel, M. Reid, D. Farrow, and G. Savelsbergh (2015), "The effect of equipment scaling on children's sport performance: the case for tennis," *Journal of Sports Sciences*, 33 (10), 1093–1100.

PAGES 22–23

1. T. Buszard, D. Farrow, M. Reid, and R. S. Masters (2014), "Modifying equipment in early skill development: A tennis perspective," *Research Quarterly for Exercise and Sport*, 85(2), 218–225.

2. ITF (2015), Recommended court and equipment dimensions. <<http://www.tennisplayandstay.com/tennis10s/overview.aspx>>

PAGES 24–25

1. K. Moran, C. Murphy, and B. Marshall (2012), "The need and benefit of augmented feedback on service speed in tennis," *Medicine and Science in Sports and Exercise*, 44(4), 754–760.

2. M. Reid and G. Giblin (2015), "Another day, another tennis coaching intervention ... but does this one do what coaches purport?" *Sport Biomechanics*.

3. C. M. Liao and R. S. W. Masters (2001), "Analogy learning: a means to implicit motor learning," *Journal of Sports Sciences*, 19, 3007–319.

PAGES 26–27

1. K. M. Newell, (1986), "Constraints on the development of coordination," *Motor Development in Children: Aspects of Coordination and Control*, 34, 341–360.

2. W. G. Chase and H. A. Simon (1973), "Perception in chess," *Cognitive Psychology*, 4(1), 55–81.

3. K. A. Ericsson, R. T. Krampe, and C. Tesch-Römer (1993), "The role of deliberate practice in the acquisition of expert performance," *Psychological Review*, 100 (3), 363.

PAGES 28–29

1. D. Farrow and M. Reid (2012), "The contribution of situational probability information to anticipatory skill," *Journal of Science and Medicine in Sport*, 15 (4), 368–373.

PAGES 30–31

1. G. Giblin, D. Farrow, M. Reid, K. Ball, and B. Abernethy (in preparation), "The influence of coaching (perceptual) and playing (motor) expertise on visual search behaviour during an evaluation task," *Perception*.

2. B. Elliott and M. Reid (2004), "Analysing the serve and groundstroke technique on court," *Coaching and Sport Science Review*, 32, 4–6. Available online at: <http://en.coaching.itftennis.com/media/127755/127755.pdf>

CHAPTER 2 technique

PAGES 32–33

1. B. Elliott, M. Reid, and M. Crespo (2009), *Technique Development in Tennis Stroke Production*, International Tennis Federation Ltd, Roehampton, England.

2. P. Roetert and J. Groppe (eds) (2001), *World-Class Tennis Technique*, Human Kinetics, Champaign, IL, USA.

3. H. Brody (2003), "Bounce of a tennis ball," *Australian Journal of Science and Medicine in Sport*, 6, 113–119.

PAGES 34–35

1. C. Bosco and P. Komi (1979), "Potentiation of the mechanical behaviour of the human skeletal muscle through pre-stretching," *Acta Physiologica Scandinavica*, 106, 467–472.

2. G. Wilson, B. Elliott, and G. Wood (1991), "The effect on performance of imposing a delay during a stretch–shorten cycle movement," *Medicine and Science in Sports and Exercise*, 23, 364–370.

3. B. Elliott, R. Marshall, and G. Noffal (1995), "Contributions of upper limb segment rotations during the power serve in tennis," *Journal of Applied Biomechanics*, 11, 433–442.

PAGES 36–37

1. R. Carpenter (1988), *Movements of the Eyes* (2nd Ed), Pion, London, England.

2. D. Kluka (1991), "Visual skills: considerations in learning motor skills for sport," *ASAHPERD Journal*, 14, 41–43.

3. H. Ripoll and P. Fleurance (1988), "What does keeping one's eye on the ball mean?" *Ergonomics*, 31, 1647–1654.

4. D. Lafont (2008), "Gaze control during the hitting phase in tennis: a preliminary study," *International Journal of Performance Analysis in Sport*, 8, 85–100.

PAGES 38–39

1. B. Elliott, A. Marsh, and P. Overheu (1989), "A biomechanical comparison of the multisegment and single unit topspin forehand drives in tennis," *International Journal of Sports Biomechanics*, 5, 350–364.

2. M. Reid and B. Elliott (2002), "The one- and two-handed backhands in tennis," *Sports Biomechanics*, 1, 47–68.

3. K. Takahashi, B. Elliott, and G. Noffal (1996), "The role of upper limb segment rotations in the development of spin in the tennis forehand," *The Australian Journal of Science and Medicine in Sport*, 28, 106–113.

4. H. Brody (2007), "Hitting with underspin," *Medicine and Science in Tennis*, 12, 31–33.

PAGES 40–41

1. The authors acknowledge the assistance of Warren Pretorius (Director, Dartfish USA) in the preparation of this text.

PAGES 42–43

1. A. Baxter-Jones, H. Goldstein, and P. Helms (1993), "The development of aerobic power in young athletes," *Journal of Applied Physiology*, 75 (3), 1160–1167.
2. R. M. Malina, J. C. Eisenmann, S. P. Cumming, B. Ribeiro, and J. Aroso (2004), "Maturity-associated variation in the growth and functional capacities of youth football (soccer) players 13–15 years," *European Journal of Applied Physiology*, 91 (5–6), 555–562.
3. R. M. Malina, S. P. Cumming, A. P. Kontos, J. C. Eisenmann, B. Ribeiro and J. Aroso (2005), "Maturity-associated variation in sport-specific skills of youth soccer players aged 13–15 years," *Journal of Sports Sciences*, 23 (5), 515–522.
4. B. Elliott (2011), "The player development pathway: A biomechanical perspective," *Portuguese Journal of Sport Sciences*, 11 (Suppl. 2), 27–30.
5. T. S. Macfarlane, C. A. Larson, and C. Stiller (2008), "Lower extremity muscle strength in 6- to 8-year-old children using hand-held dynamometry," *Pediatric Physical Therapy*, 20 (2), 128–136.
6. T. D. O'Brien, N. D. Reeves, V. Baltzopoulos, D. A. Jones, and C. N. Maganaris (2010), "Mechanical properties of the patellar tendon in adults and children," *Journal of Biomechanics*, 43 (6), 1190–1195.
7. O. Fricke, J. Weidler, B. Tuttlewski, and E. Schoenau (2006), "Mechanography—a new device for the assessment of muscle function in pediatrics," *Pediatric Research*, 59 (1), 46–49.
8. C. Quatman, K. Ford, G. Myer, and T. Hewett (2006), "Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study," *American Journal of Sports Medicine*, 34 (5), 806–813.
9. J. Loko, R. Aule, T. Sikkut, J. Erelina, and A. Viru (2003), "Age differences in growth and physical abilities in trained and untrained girls 10–17 years of age," *American Journal of Human Biology*, 15, 72–77.
10. K. Newcomer, M. Sinaki, and P. Wollan (1997), "Physical activity and four-year development of back strength," *American Journal of Physical Medicine and Rehabilitation*, 76 (1), 52–58.
11. M. Sinaki, P. Limburg, P. Woolan, J. Rogers, and P. Murtaugh (1996), "Correlation of trunk muscle strength with age in children 5 to 18 years old," *Mayo Clinic Proceedings*, 71 (11), 1047–1054.
12. B. Elliott, M. Reid, and M. Crespo (2009), *Technique Development in Tennis Stroke Production*, International Tennis Federation Ltd, Roehampton, England.
13. G. Fleisig, R. Nicholls, B. Elliott, and R. Escamilla (2003), "Kinematics used by world class tennis players to produce high-velocity serves," *Sports Biomechanics*, 2 (1), 51–64.
14. T. Ellenbecker and E. P. Roetert (2003), "Age specific isokinetic glenohumeral internal and external rotation

strength in elite junior tennis players," *Journal of Science and Medicine in Sport*, 6, 63–70.

15. A. Perry, X. Wang, B. Feldman, T. Ruth, and J. Signorile (2004), "Can laboratory-based tennis profiles predict field tests of tennis performance?" *Journal of Strength and Conditioning Research*, 18 (1), 136–143.

16. D. Whiteside, B. Elliott, B. Lay, and M. Reid (2013), "The effect of age on discrete kinematics of the elite female tennis serve," *Journal of Applied Biomechanics*, 29 (5), 573–582.

PAGES 44–45

1. S. Akutagawa and T. Kojima (2005), "Trunk rotation torques through the hip joints during the one- and two-handed backhand tennis strokes," *Journal of Sports Science*, 23, 781–793.
2. T. Fujisawa, T. Fuchimoto, and M. Kaneko (1997), "Joint movements during the tennis forehand drive: An analysis of rotational movements on a horizontal plane," *XVth Congress of the International Society of Biomechanics*, Japan, 354.
3. O. Girard, J. Micallef, and G. Millet (2005), "Lower-limb activity during the power serve in tennis: effects of performance level," *Medicine and Science in Sport and Exercise*, 37, 1021–1029.
4. M. Sweeney, M. Reid, and B. Elliott (2012), "Lower limb and trunk function in the high performance tennis serve," *Asian Journal of Exercise and Sport Science*, 9, 13–20.

PAGES 48–49

1. M. Seeley, M. Funk, W. Denning, R. Hager and T. Hopkins (2011), "Tennis forehand kinematics change as post-impact ball speed is altered," *Sports Biomechanics*, 10, 415–426.
2. C. Martin, R. Kupla, P. Delamarche, and B. Bideau (2013), "Professional tennis players' serve: correlation between segmental angular momentums and ball velocity," *Sports Biomechanics*, 12, 2–14.
3. K. Takahashi, B. Elliott, and G. Noffal (1996), "The role of upper limb segment rotations in the development of spin in the tennis forehand," *The Australian Journal of Science and Medicine in Sport*, 28, 106–113.

4. M. Reid and B. Elliott (2002), "The one- and two-handed backhands in tennis," *Sports Biomechanics*, 1, 47–68.

5. J. Landlinger, T. Stoggl, S. Lindinger, H. Wagner, and E. Muller (2012), "Differences in ball speed and accuracy in tennis groundstrokes between elite and high-performance players," *Sports Biomechanics*, 14, 301–308.

6. R. Bahamonde (2000), "Changes in angular momentum during the tennis serve," *Journal of Sports Science*, 18, 579–592.

PAGE 50–51

1. B. Elliott, R. Marshall, and G. Noffal (1995), "Contributions of upper limb segment rotations during the power serve in tennis," *Journal of Applied Biomechanics*, 11, 433–442.
2. G. Fleisig, R. Nicholls, B. Elliott, and R. Escamilla (2003), "Kinematics used by world class tennis players to produce high-velocity serves," *Sports Biomechanics*, 2, 51–71.

3. D. Whiteside, B. Elliott, B. Lay, and M. Reid (2013), "The effect of age on discrete kinematics of the elite female tennis serve," *Journal of Applied Biomechanics*, 29 (5), 573–582.

4. B. Elliott, K. Takahashi, and G. Noffal (1997), "The influence of grip position on upper limb contributions to racket head velocity in a tennis forehand," *Journal of Applied Biomechanics*, 13, 182–196.

CHAPTER 3 performance analysis and game intelligence

PAGES 56–57

1. J. Brouwers, V. De Bosscher, and P. Sotiriadou (2012), "An examination of the importance of performances in youth and junior competition as an indicator of later success in tennis," *Sport Management Review*, 15, 461–475.

2. M. Reid, M. Crespo, L. Santilli, D. Miley, and J. Dimmock (2007), "The importance of the International Tennis Federation's junior boys' circuit in the development of professional tennis players," *Journal of Sports Sciences*, 25, 667–672.

3. M. Reid, M. Crespo, and L. Santilli (2009), "Importance of the ITF junior girls' circuit in the development of women professional tennis players," *Journal of Sports Sciences*, 27, 1443–1448.

PAGES 58–59

1. C. Simmons and G. C. Paull (2001), "Season-of-birth bias in association football," *Journal of Sports Sciences*, 19 (9), 677–686.

2. A. Dudink (1994), "Birth date and sporting success," *Nature*, 368 (6472), 592.

3. S. Edgar and P. O'Donoghue (2005), "Season of birth distribution of elite tennis players," *Journal of Sports Sciences*, 23 (10), 1013–1020.

4. N. Delorme, J. Boiché, and M. Raspaud (2010), "Relative age effect in elite sports: methodological bias or real discrimination?" *European Journal of Sport Science*, 10 (2), 91–96.

5. F. Loffing, J. Schorer, and S. P. Cobley (2010), "Relative age effects are a developmental problem in tennis: but not necessarily when you're left-handed!" *High Ability Studies*, 21 (1), 19–25.

PAGES 60–61

1. M. Reid, S. Morgan, T. Churchill, and M. K. Bane (2014), "Rankings in professional men's tennis: a rich but underutilized source of information," *Journal of Sports Sciences*, 32 (10), 986–992. DOI: 10.1080/02640414.2013.876086.

2. M. Bane, M. Reid, and S. Morgan (2014), "Has player development in men's tennis really changed? An historical rankings perspective," *Journal of Sports Sciences*, 32 (15), 1477–1484. DOI: 10.1080/02640414.2014.899706.

3. R. Rodenberg and D. Stone (2011), "The short and long-run labor market effects of age eligibility rules: evidence from women's professional tennis," *Journal of Labor Research*, 32 (2), 181–198. DOI: 10.1007/s12122-011-9108-7.

4. C. L. Otis, M. Crespo, C. T. Flygare, P. R. Johnston, A. Keber, D. Lloyd-Kolkin, J. Loehr, K. Martin, B. M. Pluim, A. Quinn, P. Roetert, K. A. Stroia, and P. C. Terry (2006), "The Sony Ericsson WTA Tour 10 year age eligibility and professional development review," *British Journal of Sports Medicine*, 40 (5), 464–468. DOI: 10.1136/bjsm.2005.023366.

PAGES 64–65

1. A. Filipcic, A. Panjan, M. Reid, M. Crespo, and N. Sarabon (2013), "Tournament structure and success of players based on location in men's professional tennis," *Journal of Sports Science and Medicine*, 12, 354–361.

2. M. Reid, M. Crespo, L. Santilli, D. Miley, and J. Dimmock (2007), "The importance of the International Tennis Federation's junior boys' circuit in the development of professional tennis players," *Journal of Sports Sciences*, 25, 667–672.

3. M. Reid, M. Crespo, and L. Santilli (2009), "Importance of the ITF junior girls' circuit in the development of women professional tennis players," *Journal of Sports Sciences*, 27, 1443–1448.

PAGES 66– 67

1. P. O'Donoghue and B. Ingram (2001), "A notational analysis of elite tennis strategy," *Journal of Sports Sciences*, 19 (2), 107–115.

2. S. M. Ma, C. C. Liu, Y. Tan, and S. C. Ma (2013), "Winning matches in Grand Slam men's singles: an analysis of player performance-related variables from 1991 to 2008," *Journal of Sports Sciences*, 31 (11), 1147–1155.

3. R. Cross and G. Pollard (2009), "Grand Slam men's singles tennis 1991–2009: serve speeds and other related data," *ITF Coaching and Sport Science Review*, 16 (49), 8–10.

4. E. J. Drinkwater, D. B. Pyne, and M. J. McKenna (2008), "Design and interpretation of anthropometric and fitness testing of basketball players," *Sports Medicine*, 38 (7), 565–578.

5. D. Burgess and T. Gabbett (2012), "Football (soccer) players," in: R. Tanner and C. Gore (Eds), *Physiological Tests for Elite Athletes* 2nd Edition, Human Kinetics, Champaign, IL, USA.

6. A. S. Watts, I. Coleman, and A. Nevill (2012), "The changing shape characteristics associated with success in world-class sprinters," *Journal of Sports Sciences*, 30 (11), 1085–1095.

7. J. Benne (2014), "NFL Combine 2014: weigh-in results for linebackers," *SB Nation* February 22 2014, available at www.sbnation.com/nfl/2014/2/22/5427038/nfl-combine-2014-weigh-in-results-for-linebackers

PAGES 68–69

1. Hawk-Eye Innovations Ltd (2015) *About Hawk-Eye*, available at www.Hawk-Eyeinnovations.co.uk/page/about-hawk-eye

2. ITF (2013), *The Player Analysis Technology Approval Report*, available at www.itftennis.com/media/166653/166653.pdf

3. OpenCV (2015), *OpenCV Tutorials*, available at docs.opencv.org/doc/tutorials/tutorials.html

4. M. Reid, D. Whiteside, and M. Bane (2015), "What Grand Slam tennis really looks like: implications for training and conditioning," *Journal of Sports Sciences*, (under peer-review).

5. R. Cross (2014), "The footprint of a tennis ball," *Sports Engineering*, 17 (4), 239–247.

6. R. Braun (2012), "A Hawk-Eye for detail: how accurate is electronic judging in sport?" available at theconversation.com/a-hawk-eye-for-detail-how-accurate-is-electronic-judging-in-sport-8136

PAGES 70–71

1. D. Demaj and M. Kovacs (2013), "Spatio-temporal variation of tennis serves during important points: analytics from 2012 Olympic final," *Journal of Medicine and Science in Tennis*, 18, 108–113.

2. F. Loffing, N. Hagemann, and B. Strauss (2009), "The serve in professional men's tennis: effects of players' handedness," *International Journal of Performance Analysis in Sport*, 9, 255–274.

PAGES 72–73

1. C. Morris (1977), "The most important points in tennis," in: S. P. Ladany and R. E. Machol (Eds), *Optimal Strategies in Sports*, North-Holland, Amsterdam, Netherlands, 131–140.

2. F. Klaassen and J. Magnus (2001), "Are points in tennis independent and identically distributed? Evidence from a dynamic binary panel data model," *Journal of the American Statistical Association*, 96, 500–509.

3. T. Barnett (2012), "Game theoretic solutions to tennis serving strategies," *Coaching and Sport Science Review*, 56.

4. J. O'Malley (2008), "Probability formulas and statistical analysis in tennis," *Journal of Quantitative Analysis in Sports*, 4 (2), Article 15.

CHAPTER 4 the mental edge

PAGES 76–77

1. M. Crespo, M. Reid, and A. Quinn (2006), *ITF Tennis Psychology*, International Tennis Federation Ltd, Roehampton, England.

2. A. Girod (2005), *Winning at Tennis: Learn From the Champions*, Éditions BD Book, France.

PAGES 78–79

1. D. Gould, R. Medbery, N. Damarjian, and L. Lauer (1999), "A survey of mental skills training knowledge, opinions and practice of junior tennis coaches," *Journal of Applied Sport Psychology*, 11, 28–50.

2. D. Gould, B. Eklund, and S. S. Jackson (1993), "Coping strategies used by U.S. Olympic Wrestlers," *Research Quarterly for Exercise and Sport*, 64 (1), 83–93.

PAGES 80–81

1. G. Mamassis and G. Doganis (2004), "The effects of a mental training program on juniors pre-competitive anxiety, self-confidence, and tennis performance," *Journal of Applied Sport Psychology*, 16, 2, 118–137.

2. A. Latinjak, M. Torregrosa, and J. Renom (2011), "Studying the effects of self-talk on thought contents with male adult tennis players," *Perceptual and Motor Skills*, 111 (1), 249–260.

3. J. L. Van Raalte, B. W. Brewer, P. M. Rivera, and A. J. Petitpas (1994), "The relationships between observable self-talk and competitive junior tennis players' match performance," *Journal of Sport and Exercise Psychology*, 16, 400–415.

4. A. M. Lee, D. K. Landin, and J. A. Carter (1992), "Student thoughts during tennis instruction," *Journal of Teaching in Physical Education*, 11, 3, 256–267.

5. R. S. Weinberg and D. Gould (1995), *Foundations of Sport and Exercise Psychology*, Human Kinetics, Champaign, IL, USA.

6. R. S. Weinberg (2002), *Tennis: Winning the Mental Game*, H. O. Zimman Inc, Oxford, OH, USA.

7. J. C. Jaenes (1995), "Análisis de la ansiedad y autoconfianza en tenistas jóvenes," in J. C. Caracul, J. C. Jaenes, L. Linares, A. Oña, and E. A. Perez (eds) *Psicología del Deporte en Andalucía*, Edinford, Malaga, Spain, 145–15.

8. T. Covassin and S. Pero (2004), "The relationship between self-confidence, mood state and anxiety among collegiate tennis players," *Journal of Sport Behavior*, 72, 3, 230–243.

9. J. Hewitt and S. Jackson (1986), "Differential attributions for win-loss in competitive tennis," *Perceptual and Motor Skills*, 63 (1), 970.

10. S. O. Kim (1990), "Self-efficacy and causal attribution of college students in a tennis competition," PhD Dissertation, University of Oregon, USA.

11. K. S. Spink and G. C. Roberts (1980), "Ambiguity of outcome and causal attributions," *Journal of Sport Psychology*, 2, 237–244.

12. A. Guallar, I. Balaguer, F. L. Atienza, P. Blasco, I. Castillo, and I. Fuentes (1993), "Expectativas, emociones y atribuciones en tenistas de competición en función del resultado y de la percepción subjetiva del mismo," in S. Barriga and J. M. León (eds) *Aspectos Psicosociales del Ambiente, la Conducta Deportiva y el Fenómeno Turístico*, Eudema, Sevilla, Spain, 201–213.

PAGES 82–83

1. D. König, M. Huonker, A. Schmid, M. Halle, A. Berg, and J. Keul (2001), "Cardiovascular, metabolic, and hormonal parameters in professional tennis players," *Medicine and Science in Sports and Exercise*, 33 (4), 654–658.

2. B. Elliott, B. Dawson, and F. Pyke (1985), "The energetics of single tennis," *Journal of Human Movement Studies*, 11, 11–20.

PAGES 84–85

1. M. Eubank and D. Collins (2000), "Coping with pre- and in-event fluctuations in competitive state anxiety: a longitudinal analysis," *Journal of Sport Sciences*, 18, 121–131.

2. E. Jacobson (1938), *Progressive Relaxation*, University of Chicago Press, Chicago, IL, USA.

3. D. Gould, B. Eklund, and S. S. Jackson (1993), "Coping strategies used by U.S. Olympic Wrestlers," *Research Quarterly for Exercise and Sport*, 64 (1), 83–93.

4. A. N. I. El Gammal (1993), "Anxiety state of tennis players: a comparative study," in T. Reilly, M. Hughes and A. Lees (eds) *Science and Racket Sports*, Blackwell Publishing, London, England, 226–227.

5. K. Farouk (2003), "Anxiety in tennis and its effect on performance," in M. Crespo, M. Reid, and D. Miley (eds) *Applied Sport Science for High Performance Tennis*, International Tennis Federation Ltd, Roehampton, England, 140.

6. J. D. Perry and J. M. Williams (1998), "Relationship of intensity and direction of competitive trait anxiety to skill level and gender in tennis," *The Sport Psychologist*, 12, 169–179.

7. P. Terry, J. Cox, A. Lane, and C. Karageorghis (1996), "Measures of anxiety among tennis players in singles and doubles matches," *Perceptual and Motor Skills*, Oct. 83 (2), 595–603.

8. L. Lauer, D. Gould, P. Lubbers, and M. Kovacs (eds) (2010), *USTA Mental Skills and Drills Handbook*. Monterey, CA: Coaches Choice.

PAGES 86–87

1. M. Crespo and M. Reid (2007), "Motivation in tennis," *British Journal of Sports Medicine*, 41, 769–772.

2. D. Butt and D. Cox (1992), "Motivational patterns in Davis Cup, university and recreational tennis players," *International Journal of Sport Psychology*, 23, 1–13.

3. D. Gould, R. Medbery, N. Damarjian, and L. Lauer (1999), "A survey of mental skills training knowledge, opinions and practice of junior tennis coaches," *Journal of Applied Sport Psychology*, 11, 28–50.

4. D. Gould, N. Damarjian, and R. Medbery (1999), "An examination of mental skills training in junior tennis coaches," *Sport Psychology*, 13, 127–143.

5. J. Duda, I. Balaguer, Y. Moreno et al. (2001), "The relationship of the motivational climate and goal

orientations to burn-out among junior elite tennis players," *Conference Proceedings of the Association for the Advancement of Applied Sports Psychology*, RonJon Publishing, Denton, TX, USA.

6. I. Balaguer, J. Duda, and M. Crespo (1999), "Motivational climate and goal orientations as predictors of perceptions of improvement, satisfaction, and coach ratings among tennis players," *Scandinavian Journal of Medicine and Science in Sports*, 9, 381–388.

7. C. Harwood and S. Biddle (2002), "The application of achievement goal theory in youth sport," in I. Coackerrill (ed) *Solutions in Sport Psychology*, Thompson Learning, London, England, 58–73.

PAGES 90–91

1. M. Crespo, M. Reid, and A. Quinn (2006), *ITF Tennis Psychology*, International Tennis Federation Ltd, Roehampton, England.

2. R. M. Nideffer (1976), *The Inner Player*, Thomas Crowell, New York, USA.

3. N. J. Smeeton, A. M. Williams, N. J. Hodges, and P. Ward (2005), "The relative effectiveness of various instructional approaches in developing anticipation skill," *Journal of Experimental Psychology: Applied*, 11, 98–110.

PAGES 92–93

1. M. Crespo, M. Reid, and A. Quinn (2006), *ITF Tennis Psychology*, International Tennis Federation Ltd, Roehampton, England.

2. F. L. Atienza, I. Balaguer, and M. L. Garcia-Merita (1998), "Video modeling and imaging training on performance of tennis service of 9- to 12-year-old children," *Perceptual and Motor Skills*, Oct. 87 (2), 519–529.

3. A. Girod (2003), "Visualisation in tennis," *ITF Coaching and Sport Science Review*, 30, 7–8.

4. A. Guillot, S. Desliens, C. Rouyer, and I. Rogowski (2013), "Motor imagery and tennis serve performance: the external focus efficacy," *Journal of Sports Science and Medicine*, 12, 332–338.

5. R. Weigert, W. Campos, S. da Silva, F. Okazaki, and B. Keller (2007), "Imagery intervention in open and closed tennis motor skill performance," *Perceptual and Motor Skills*, 105, 458–468.

6. J. M. Malouff, J. A. McGee, H. T. Halford, and S. E. Rooke (2008), "Effects of pre-competition positive imagery and self-instructions on accuracy of serving in tennis," *Journal of Sport Behavior*, 31, 3.

7. A. Fourkas, V. Bonavolontà, A. Avenanti, and S. Aglioti (2008) "Kinesthetic imagery and tool-specific modulation of corticospinal representations in expert tennis players," *Cerebral Cortex*, 18 (10), 2382–2390.

CHAPTER 5 physical development

PAGES 96–97

1. M. Reid and R. Duffield (2014), "The development of fatigue during tennis match play," *British Journal of Sports Medicine*, 7–11.

2. C. D. Johnson and M. P. McHugh (2006), "Performance demands of professional male tennis players," *British Journal of Sports Medicine*, 40, 696–699.

3. J. Fernandez, A. Mendez-Villanueva, and B. M. Pluim (2006), "Intensity of tennis match play," *British Journal of Sports Medicine*, 40, 387–391.

PAGES 98–99

1. M. Krzysztof and A. Mero (2013), "A kinematic analysis of three best 100 M performances ever," *Journal of Human Kinetics*, 36.

2. M. Kovacs, W. B. Chandler, and T. J. Chandler (2007), *Tennis training: enhancing on-court performance*, Racquet Tech Publishing Vista, CA, USA.

3. M. S. Kovacs (2009), "Movement for tennis: the importance of lateral training," *Strength and Conditioning Journal*, 31 (4), 77–85.

4. M. S. Kovacs, E. P. Roetert, and T. S. Ellenbecker (2008), "Efficient deceleration: The forgotten factor in tennis-specific training," *Strength and Conditioning Journal*, 30 (6), 58–69.

PAGES 100–101

1. G. Schmolinsky (1996), *The East German Textbook of Athletics*, Sports Books Publishers, Toronto, Canada.

2. P. G. Weyand et al. (2000), "Faster top running speeds are achieved with greater ground forces, not more rapid leg movements," *Journal of Applied Physiology*, 89, 1991–1999.

3. J. P. Hunter, R. N. Marshall, and P. J. McNair (2005), "Relationship between ground reaction force, impulse and kinematics of sprint-running acceleration," *Journal of Applied Biomechanics*, 21 (1).

PAGES 102–103

1. M. L. Day, M. R. McGuigan, G. Brice, and C. Foster (2004), "Monitoring exercise intensity during resistance training using the session RPE scale," *Journal of Strength and Conditioning Research/National Strength and Conditioning Association*, 18, 353–358.

2. C. Foster, J. A. Florhaug, J. Franklin, L. Gottschall, L. A. Hrovatin, S. Parker, P. Dolezal, and C. Dodge (2001), "A new approach to monitoring exercise training," *Journal of Strength and Conditioning Research/National Strength and Conditioning Association*, 15, 109–115.

3. F. Singh, C. Foster, D. Tod, and M. R. McGuigan (2007), "Monitoring different types of resistance training using session rating of perceived exertion," *International Journal of Sports Physiology and Performance*, 2, 34–45.

4. M. Kellmann (2010), "Preventing overtraining in athletes in high-intensity sports and stress/recovery monitoring," *Scandinavian Journal of Medicine and Science in Sports*, 20 Suppl. 2, 95–102.

PAGES 104–105

1. A. J. R. Cochran, M. E. Percival, S. Tricarico, J. P. Little, N. Cermak, J. B. Gillen, M. A. Tarnopolsky, and M. J. Gibala (2014), "Intermittent and continuous high-intensity exercise training induce similar acute but different chronic muscle adaptations," *Experimental Physiology*, 99 (5), 782–791.

2. K. A. Burgomaster, K. R. Howarth, S. M. Phillips, M. Rakobowchuk, M. J. Macdonald, S. L. McGee, and M. J. Gibala (2008), "Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans," *Journal of Physiology*, 586, 151–160.

3. J. Fernandez-Fernandez, R. Zimek, T. Wiewelhove, and A. Ferrauti (2012), "High-intensity interval training vs. repeated sprint training in tennis," *Journal of Strength and Conditioning Research*, 26 (1), 53–56.

PAGES 106–107

1. M. S. Kovacs, E. P. Roetert, and T. S. Ellenbecker (2008), "Efficient deceleration: the forgotten factor in tennis-specific training," *Strength and Conditioning Journal*, 30 (6), 58–69.

2. U. Proske, et al. (2004), "Identifying athletes at risk of hamstring strains and how to protect them," *Clinical and Experimental Pharmacology and Physiology*, 31 (8) 546–550.

3. W. Garrett (1996), "Muscle strain injuries," *American Journal of Sports Medicine*, 24 (S2–8).

4. A. Lees (2002), "Technique analysis in sports: a critical review," *Journal of Sports Sciences*, 20, 813–828.

5. W. B. Young, M. H. McDowell, and B. J. Scarlett (2001), "Specificity of sprint and agility training methods," *Journal of Strength and Conditioning Research*, 15 (3), 315–319.

PAGES 108–109

1. M. S. Kovacs (2009), "Movement for tennis: the importance of lateral training," *Strength and Conditioning Journal*, 31 (4), 77–85.

2. J. M. Sheppard and W. B. Young (2006), "Agility literature review: classifications, training and testing," *Journal of Sports Sciences*, 24, 919–932.

3. E. P. P. Roetert, M. P. C. Kovacs, D. P. Knudson, and J. L. P. Groppe (2009), "Biomechanics of the tennis groundstrokes: implications for strength training," *Strength and Conditioning Journal*, 31, 41–49.

4. M. Reid and K. Schneiker (2008), "Strength and conditioning in tennis: current research and practice," *Journal of Science and Medicine in Sport/Sports Medicine Australia*, 11, 248–256.

5. P. Jones, T. M. Bampouras, and K. Marrin (2009), "An investigation into the physical determinants of change of direction speed," *Journal of Sports Medicine and Physical Fitness*, 49, 97–104.

PAGES 112–113

1. ITPA (2012), *Certified Tennis Performance Specialist (CTPS) Workbook and Studyguide*, ITPA, Atlanta, GA, USA.

2. M. H. Stone and H. S. O'Bryant (1987), *Weight Training, a Scientific Approach*, Burgess, Minneapolis, MN, USA.

3. W. J. Kraemer, et al. (2003), "Physiological changes with periodized resistance training in women tennis players," *Medicine and Science in Sports and Exercise*, 35 (1), 157–168.

4. M. Rhea and B. Alderman (2004), "A meta-analysis of periodized versus non-periodized strength and power training programs," *Research Quarterly for Exercise and Sports*, 75, 413–422.

5. T. O. Bompa (1993), *Periodization of Strength*, Veritas Publishing, Don Mills, Ontario, Canada.

6. V. Zatsiorsky (1995), *Science and practice of strength training*, Human Kinetics, Champaign, IL.

PAGES 114–115

1. A. Ferrauti, K. Weber, and H. K. Striider (1997), "Effects of tennis training on lipid metabolism and lipoproteins in recreational players," *British Journal of Sports Medicine*, 31, 322–327.

2. Marks B. L. (2006), "Health benefits for veteran (senior) tennis players," *British Journal of Sports Medicine*, 40, 469–476.

3. C. E. Garber, B. Blissmer, M. R. Deschenes et al. (2011), "Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise," *Medicine and Science in Sports and Exercise*, 43, 1334–1359.

4. A. Murphy, R. Duffield, and M. Reid (2014), "Tennis for physical health; acute age- and sex-based physiological responses to Cardio tennis®," *Journal of Strength and Conditioning Research*, 28 (11), 3172–3178.

CHAPTER 6 nutrition and recovery

PAGES 118–119

1. L. Burke (2008), "Nutrition for racket sports," in *Practical Sports Nutrition*, Human Kinetics, Champaign, IL, USA, 241–264.

2. M. K. Ranchordas, D. Rogerson, A. Ruddock, S. C. Killer, and E. M. Winter (2013), "Nutrition for tennis: practical recommendations," *Journal of Sports Science and Medicine*, 12 (2), 211–224.

PAGES 120–121

1. L. M. Burke, J. A. Hawley, S. H. Wong, and A. E. Jeukendrup (2011), "Carbohydrates for training and competition," *Journal of Sports Sciences*, 29 Suppl. 1, S17–27.

2. M. S. Kovacs (2006), "Carbohydrate intake and tennis: are there benefits?" *British Journal of Sports Medicine*, 40 (5), e13.

3. L. Burke (2008), "Nutrition for racket sports," *Practical Sports Nutrition*, Human Kinetics, Champaign, IL, USA, 241–264.

4. A. E. Jeukendrup (2013), "Oral carbohydrate rinse: placebo or beneficial?" *Current Sports Medicine Reports*, 12 (4), 222–227.

PAGES 122–123

1. M. S. Kovacs (2008), "A review of fluid and hydration in competitive tennis," *International Journal of Sports Physiology and Performance*, 3 (4), 413–423.

2. L. Burke (2008), "Nutrition for racket sports," in *Practical Sports Nutrition*, Human Kinetics, Champaign, IL, USA, 241–264.

3. M. F. Bergeron (2014), "Hydration and thermal strain during tennis in the heat," *British Journal of Sports Medicine*, 48 Suppl. 1, i12–17.

4. S. M. Shirreffs and M. N. Sawka (2011), "Fluid and electrolyte needs for training, competition, and recovery," *Journal of Sports Science*, 29 Suppl. 1, S39–46.

PAGES 124–125

1. R. Duffield, A. Murphy, A. Kellett, and M. Reid (2014), "Recovery from repeated on-court tennis sessions: combining cold-water immersion, compression, and sleep recovery interventions," *International Journal of Sports Physiology and Performance*, 92, 273–282.

PAGES 126–127

1. I. M. Wilcock, J. B. Cronin, and W. A. Hing (2006), "Physiological response to water immersion: a method for sport recovery?" *Sports Medicine*, 369, 747–765.

2. R. Duffield, A. Murphy, A. Kellett, and M. Reid (2014), "Recovery from repeated on-court tennis sessions: combining cold-water immersion, compression, and sleep recovery interventions," *International Journal of Sports Physiology and Performance*, 92, 273–282.

3. S. Halson and C. Argus (2012), "Recovery for endurance training and competition," in I. Mujika (ed), *Endurance Training – Science and Practice*, Iñigo Mujika Sport Physiology and Training, Vitoria-Gasteiz, Spain.

PAGES 128–129

1. R. Duffield, A. Murphy, A. Kellett, and M. Reid (2014), "Recovery from repeated on-court tennis sessions: combining cold-water immersion, compression, and sleep recovery interventions," *International Journal of Sports Physiology and Performance*, 92, 273–282.

2. C. M. Bleakley and G. W. Davison (2010), "What is the biochemical and physiological rationale for using cold-water immersion in sports recovery? A systematic review," *British Journal of Sports Medicine*, 443, 179–187.

3. J. Vaile, C. O'Hagan, B. Stefanovic, M. Walker, N. Gill and C. D. Askew (2011), "Effect of cold-water immersion on repeated cycling performance and limb blood flow," *British Journal of Sports Medicine*, 4510, 825–829.

PAGES 132–133

1. T. Reilly and M. Piercy (1994), "The effect of partial sleep deprivation on weight-lifting performance," *Ergonomics*, 371, 107–115.

2. M. Lastella, G. D. Roach, S. L. Halson, and C. Sargent (2014), "Sleep/wake behaviours of elite athletes from individual and team sports," *European Journal of Sport Science*, 1–7.

3. C. Samuels (2008), "Sleep, recovery, and performance: the new frontier in high-performance athletics," *Neurologic Clinics*, 261, 169–180, ix–x.

4. S. L. Halson (2014), "Sleep in elite athletes and nutritional interventions to enhance sleep," *Sports Medicine*, 44 Suppl. 1, 13–23.

PAGES 134–135

1. T. M. Best, R. Hunter, A. Wilcox, and F. Haq (2008), "Effectiveness of sports massage for recovery of skeletal muscle from strenuous exercise," *Clinical Journal of Sport Medicine*, September, 18 (5), 446–460.

2. C. H. Samuels (2012), "Jet lag and travel fatigue: a comprehensive management plan for sport medicine physicians and high-performance support teams," *Clinical Journal of Sport Medicine*, 223, 268–273.

3. T. Reilly and B. Edwards (2007), "Altered sleep-wake cycles and physical performance in athletes," *Physiology and Behaviour*, 90 (2–3), 274–284.

4. W. E. Leatherwood and J. L. Dragoo (2013), "Effect of airline travel on performance: a review of the literature," *British Journal of Sports Medicine*, 479, 561–567.

CHAPTER 7 staying healthy

PAGES 138–189

1. B. Elliott (2006), "Biomechanics and tennis," *British Journal of Sports Medicine*, 40, 392–396.

2. W. B. Kibler (2014), "Understanding the kinetic chain in tennis performance and injury," *Aspetar Sports Medicine Journal*, October.

3. C. Martin, B. Bideau, N. Bideau, G. Nicolas, P. Delamarche, and R. Kulpa (2014), "Energy flow analysis during the tennis serve: comparison between injured and non-injured tennis players," *American Journal of Sports Medicine*, 42 (11), 2751–2760.

4. W. B. Kibler, J. E. Kuhn, K. E. Wilk, A. Sciascia, S. Moore, K. Laudner, T. Ellenbecker, C. Thigpen, and T. Uhl (2013), "The disabled throwing shoulder: spectrum of pathology – 10-year update," *Arthroscopy*, 29 (1), 141–161.

5. W. B. Kibler, T. Wilkes, and A. Sciascia (2013), "Mechanics and pathomechanics in the overhead athlete," *Clinical Sports Medicine*, 32 (4), 637–651.

6. M. Kovacs and T. Ellenbecker (2011), "An 8-stage model for evaluating the tennis serve," *Sports Health*, 3, 504–513.

7. C. Martin et al (2013), "Identification of temporal pathomechanical factors during the tennis serve," *Medicine and Science in Sports and Exercise*, 45, 2113–2119.

PAGES 140–141

1. H. Van der Hooven and W. B. Kibler (2006), "Shoulder injuries in tennis players," *British Journal of Sports Medicine*, 40, 433–440.

2. W. B. Kibler and S. J. Thomas (2012), "Pathomechanics of the throwing shoulder," *Sports Medicine and Arthroscopy Review*, 20, 22–29.

3. W. B. Kibler, J. E. Kuhn, K. E. Wilk, A. Sciascia, S. Moore, K. Laudner, T. Ellenbecker, C. Thigpen, and T. Uhl (2013), "The disabled throwing shoulder: spectrum of pathology – 10-year update," *Arthroscopy*, 29 (1), 141–161.

PAGES 142–143

1. B. Elliott et al (2003), "Technique effects on the upper limb loading in the tennis serve," *Journal of Science and Medicine in Sport*, 6, 76–87.

2. G. S. Fleisig (1996), "Biomechanics of overhand throwing with implications for injuries," *Sports Medicine*, 21, 233–239.

3. W. B. Kibler and A. D. Sciascia (2004), "Kinetic chain contributions to elbow function and dysfunction in sports," *Clinical Sports Medicine*, 23, 545–552.

PAGES 146–147

1. T. S. Ellenbecker, B. Pluim, S. Vivier, and C. Snitman (2009), "Common injuries in tennis players: exercises to address muscular imbalances and reduce injury risk," *Journal of Strength and Conditioning*, 31, 50–58.

2. T. S. Ellenbecker and E. P. Roetert (2003), "Age-specific isokinetic glenohumeral internal and external rotation strength in elite junior tennis players," *Journal of Science and Medicine in Sport*, 6 (1), 63–70.

PAGES 148–149

1. P. Roetert and T. Ellenbecker (2007), *Complete Conditioning for Tennis*, Human Kinetics, Champaign, IL, USA.

2. D. G. Behm and A. Chaouachi (2011), "A review of the acute effects of static and dynamic stretching on performance," *European Journal of Applied Physiology*, 111 (11), 2633–2651.

3. T. S. Ellenbecker (2014), "Musculoskeletal evaluation of elite junior tennis players," *Aspetar Sports Medicine Journal*, 3, 548–556.

PAGES 152–153

1. S. M. Lephart and F. H. Fu (2004), *Proprioception and Neuromuscular Control in Joint Stability*, Human Kinetics, Champaign, IL, USA.

2. G. Fleisig, R. Nicholls, B. Elliott, and R. Escamilla (2003), "Kinematics used by world-class tennis players to produce high-velocity serves," *Sports Biomechanics*, 2 (1), 51–64.

CHAPTER 8 equipment and technology

PAGES 160–161

1. B. Kneib, H. Schlarb, and U. Glitsch (1998), "Influence of racket length on tennis stroke," in H. J. Riehle and M. M. Vieten (eds), *Proceedings II of the 16th Symposium of the International Society of Biomechanics in Sports*, 214–216, University of Konstanz, Konstanz, Germany.

2. S. Haake, S. Choppin, and S. Goodwill (2007), "The evolution of the tennis racket and its effect on serve speed," in S. Mille and J. Capel-Davies (eds), *Tennis Science and Technology 3*, 257–271, International Tennis Federation Ltd, Roehampton, England.

PAGES 162–163

1. R. Cross and C. Lindsey (2013), *Spin and String Patterns – Old, New and Illegal*, Tennis Warehouse, San Louis Obispo, CA, USA. Available online at http://twu.tennis-warehouse.com/learning_center/spinpatterns.php

PAGES 164–165

1. V. Stiles and S. Dixon (2007), "Biomechanical response to systematic changes in impact interface cushioning properties while performing a tennis-specific movement," *Journal of Sports Sciences*, 25, 1229–1239.

2. J. Pallis, R. Methda, S. Pandya, P. Roetert, A. Lutz, and D. Knudson (2000), *Tennis Sports Science*, Cislunar Aerospace, San Francisco, CA, USA. <http://learn.fi.edu/wright/again/wings.avkids.com/wings.avkids.com/Tennis/index.html>

3. L. Damm, D. Low, A. Richardson, M. Carre, and S. Dixon (2013) "The effects of surface traction characteristics on frictional demand and kinematics in tennis," *Sports Biomechanics*, 12, 389–402.

PAGES 166–167

1. J. Blackwell and D. Knudson (2002), "Effect of the type 3 (oversize) tennis ball on serve performance and upper extremity muscle activity," *Sports Biomechanics*, 1, 187–192.

PAGES 170–171

1. R. Cross and C. Lindsey (2014), *Tennis Ball Trajectories—Aerodynamic Drag And Lift In Tennis Shots*, Tennis Warehouse, San Louis Obispo, CA, USA. Available online at http://twu.tennis-warehouse.com/learning_center/aerodynamics2.php

PAGES 176–177

1. S. J. Dixon and V. H. Stiles (2003), "Impact absorption of tennis shoe–surface combinations," *Sports Engineering*, 6, 1–10.

Glossary

abduction A movement of an arm or a leg that is away from the mid-line of the body, such as a right arm moving outward to the right.

activation The process of inducing activity in the body's muscles involving increased heart rate and respiration so that muscles are ready for action. See *arousal*.

active recovery A period of light or moderate exercise that raises the heart rate and cuts lactic acid levels in the blood.

adduction A movement of an arm or a leg that is toward the mid-line of the body, such as a right arm moving inward to the left.

aerobic With oxygen—this refers to the use of oxygen in generating the energy that muscles need to work by “burning” glucose and fats. Carbon dioxide and water are produced.

anaerobic Without oxygen—the process of converting chemical “fuel” stored in cells into energy to power muscles without using oxygen. Lactic acid is produced.

anthropometry The scientific study of the measurements and proportions of the human body. From the Greek *anthropos* (man) and *metron* (measure).

arousal The physiological state of being ready for action, which includes both physiological activation, with increased heart and respiratory rates, and also

increased awareness and concentration. See *activation*.

Association of Tour Professionals (ATP)

The governing body of the international professional game of men's tennis.

automaticity An automatic movement or response that is usually learned through repetition so that it can be done without conscious thought.

Bernoulli's theorem Principle stating that when the flow speed of a fluid (such as air) increases, its pressure decreases. When topspin is applied to a ball, the speed of the air above the ball is lower than that of the air below the ball—the air pressure above is therefore greater than that below, which results in a downward force.

biofeedback A process that enables individuals to use information about the performance of the body to help control bodily functions such as heart rate and muscle tension.

biomechanics The scientific study of the structure, movement, and function of biological systems, including humans, using the methods of the branch of physics known as mechanics.

body mass (BM) The total mass of a human body without clothes and accessories—in simple terms, your weight.

cardiovascular (conditioning) The process of enhancing heart and blood circulation function and thus muscle

performance through regular and sustained exercise.

cardio-respiratory The combination of heart, blood circulation, and respiratory processes that supply oxygen to muscles during exercise.

ceiling of adaptation The limit—or ceiling—to fitness improvement as the body adapts to exercise and becomes fitter.

circadian (rhythm) What most of us call our body clock: a biological process with a 24-hour rhythm that is linked to the day/night cycle.

coefficient of friction A physical property that determines the amount of frictional force available to help movement; a higher coefficient means more grip for a sports shoe on a playing surface.

coefficient of restitution A physical property that determines how bouncy a ball will be on any given surface; the higher the coefficient, the bouncier the ball.

cognitive This refers to the mental skills required to track and predict the movements of balls and other players and also the ability to remain calm and to manage anxiety.

cold water immersion (CWI) A cold bath—typically 50–59°F (10–15°C)—that aids recovery following exercise by cooling the body, minimizing muscle damage and reducing inflammation.

contrast water therapy (CWT) A regime of alternately immersing a part of the body, usually one or both legs, or the whole body, in cold and warm water baths to aid post-exercise recovery.

core Usually defined as the body minus the arms and legs. The muscles of the abdomen and back are known as the core muscles—appropriate exercise develops core strength.

court pace rating (CPR) A mathematically defined term that combines the friction of a court's surface with the bounciness of the ball to determine how much speed balls lose when bouncing.

cryotherapy The use of cold to treat injury and aid recovery; includes ice packs, frozen gels, chilled splints, spray-on coolants, and cryotherapy chambers. From Greek *cryo* (cold) and *therapeia* (curing).

dyskinesia An abnormal movement of a part of the body; in tennis it is often associated with shoulder problems—known as scapula dyskinesia.

download (training) A period of less intensive training built in to a fitness program that allows an athlete's body to recuperate and build up energy reserves.

drill, practice A series of specific exercises or the repeated practicing of particular movements aimed at developing a specific capability or skill such as agility or serving technique.

drive, leg The part of a serve that positions the racket down, behind, and away from the lower back and enables power from the leg to be transferred through the body and to the racket in order to drive the ball.

dynamometer (isokinetic) The measurement of strength by quantifying the external force exerted by a muscle or muscle group during isokinetic contraction.

electrolyte Chemicals that ionize when dissolved in water; includes many salts and nutrients that are important for health and fitness.

epinephrine Also called adrenaline. A hormone secreted by the medulla of the adrenal glands that readies the body for action. It relaxes airways and tightens blood vessels to improve breathing and stimulate the heart. Used to treat exercise-induced anaphylaxis.

erector spinae A muscle group that acts to straighten the back and allow for twisting of the body. It extends vertically up the back from near the base of the spine.

ergogenic A technique, substance, or piece of equipment that enhances performance; can include exercise, psychological preparation, nutrients, and clothing.

ergonomics The scientific study of how people interact with the world around them, enabling the design of equipment

that maximizes human performance and efficiency.

feedback, augmented Information from an external source, which cannot be detected directly by the individual, and that can be used to help develop skills.

feedback, intrinsic Information from an individual's own senses that can be used to help develop skills.

flexion An inward bending movement around a joint in a limb that decreases the angle at the joint between the bones of the limb.

fluid deficit A measure of dehydration, or lack of body fluids, which may be due to excess fluid loss from, say, sweating and/or inadequate fluid intake.

frontal plane Also known as a coronal plane. An imaginary vertical plane that divides the body into front and back. Perpendicular to the transverse (horizontal) and sagittal planes.

glenohumeral The ball and shoulder joint that connects the arm with the body at the shoulder and allows for circular arm motion.

glenoid The cavity in the shoulder blade bone into which the top of the bone of the upper arm fits.

gluteal (muscle) A group of three muscles that make up the buttocks.

glycogen A form of glucose—a sugar—that acts as a store of energy to power the muscles.

goniometer A device that measures angle between objects. Used in tennis to measure joint movement, particularly at the elbow and shoulder.

grand unified theory (GUT) The idea of perfection in tennis, which would flow from the combination of all the right moves being perfectly executed.

grommet A part of the tennis racket that protects the strings from damage due to rubbing with the material of the frame; consists of a strip of material, usually plastic, containing tube structures which sink into the string holes of the frame and provide a barrier between the strings and the frame.

ground reaction force The upward force exerted by the ground, usually through the foot, that counteracts the downward force of the weight of the body.

high-intensity interval training (HIIT) Intense periods of exercise separated by short rest intervals. The resulting increase in metabolic rate is maintained for some time after the end of the exercise.

hip flexors The collection of muscles that work together to enable the hip joint to flex.

hot water immersion (HWI) A recovery and pain management technique involving immersion of part or the whole of the body in hot water—typically at or slightly above normal body temperature.

humerus The long bone in the arm that runs from the shoulder to the elbow.

hydrostatic pressure The pressure exerted by any fluid in a confined space; thought to play a role in immersion and hydrotherapy treatments.

hydrotherapy The use of water in the medical treatment of various conditions

and injuries. It includes immersion treatments and also water-based therapeutic exercise.

hyponatremia Low sodium levels in the body which, in athletes, can be caused by excess water intake during exercise diluting the concentration of electrolytes in the blood. Can be fatal.

ideal performance state (IPS) The best possible level of psychological and physiological preparedness combining optimal heart and respiration rates, muscle tension, and mental focus.

ilio-psoas group Core muscles connecting the spine with the hip flexors that are used in walking, running, and serving. Associated with groin injuries and lower back pain.

interference, contextual The increased difficulty caused by mixing the practice of different skills within a single training session rather than repeatedly practicing one skill.

International Tennis Federation (ITF) World governing body of tennis overseeing administration, regulation, and organizing of international competitions as well as structuring, developing, and promoting the game.

kinematics Branch of mechanics focusing on the pure motion of objects and points without consideration of mass and force; biomechanics involves the study of the movement of parts of the body.

kinesiology The study of the mechanics of body movement, and the relationship between physiological processes and anatomy, involving analysis of motion, mass, and force.

kinetic chain The idea that a series of linked body parts must work together to

produce a single movement. Different movements involve different chains of linked body part actions.

kinesthetic The ability to sense movement in the limb and body that enables a player to “feel” whether a movement is being correctly performed. See *feedback*, *intrinsic*.

labral injury (SLAP) Damage to the rim of soft tissue that lines the socket in the shoulder blade (known as the glenoid).

lateral epicondylitis (tennis elbow) A painful inflammation of the tendons joining the forearm muscles to the outside of the elbow, caused by repeating the same motion. A common sports injury in tennis.

lattismus dorsi A pair of large muscles in the back that joins to a number of vertebrae in the spine and connects to the humerus of the upper arm.

locomotor The system, or combination of body parts and actions, that enables a player to move from one place to another on a tennis court.

lordosis A natural inward curvature of the spine in the lower back.

lymphedema Swelling in the tissues of the body.

maximal velocity The maximum possible speed of movement for an individual; typically used in tennis to describe the maximum possible speed of movement of an arm during a serve.

medial epicondylitis A painful condition on the inside of the elbow and lower arm due to inflammation of, or damage to, tendons.

metabolism The system of chemical reactions within cells that maintain life, the speed of these reactions determines

metabolic rate and can be increased by exercise and other activities.

modeling, finite element A mathematical technique used to create computer simulations of the physical interactions between player, ball, racket, and court.

musculo-skeletal The combined structure of muscles, bones, tendons, and joints that provide shape and structure and enable movement in a (human) body.

micro-sensor Computer processor found in high-technology tennis rackets.

morphology The branch of biology that deals with the shape, form, and structure of living organisms without considering their function.

neural Refers to the nervous system and the way in which nerves transmit signals around the body.

node Collective term for the various movements that are required to play tennis; includes: foot position, knee motion, hip and trunk movement, and shoulder rotation.

oblique muscle Large trunk muscle that sits on both sides of the abdomen; outermost of a number of abdominal muscles.

pathomechanics The biomechanics—that is, movement—of damaged and broken bones and joints, including bones that have slipped out of position or have become dislocated.

pectoralis major Muscles commonly known as the pecs; large, thick, fan-shaped muscles in the front of either side of the chest.

periodization Long-term cyclic structuring of training and practice to maximize performance for a particular

time—such as a competition. A method of systematically increasing exercise intensity while manipulating its volume over a predetermined time period. Sometimes called linear (or staired) periodization or referred to as traditional or block periodization.

phytochemical Large group of plant-derived chemical compounds. Although not established as essential nutrients, phytochemicals may confer health benefits. From the Greek *phyto* (plant).

piezoelectric system Electronic system that converts vibrations and shocks into electrical signals that can be monitored, such as in intelligent rackets.

plyometric Exercises and workouts designed to improve muscle elastic strength, particularly in the legs; often involving jumps.

pronation Rotation of the hand, wrist, and forearm so that the hand shifts from upward/forward facing to downward/backward facing.

proprioception Sensory information that enables players to know where they are and how they are moving; important for maintaining balance.

propulsion phase (of serve) The phase of the serve during which forward motion is transferred to the ball; characterized by forward and downward rotation of the player's trunk as the racket is brought rapidly forward in an overarm swing.

rating of perceived exertion (RPE) A subjective measure of exertion required to perform an activity such as exercise.

relative age effect The idea that within a cohort of younger players defined by an age band, the additional development and experience of the relatively older

members of the group may confer an advantage in performance, and may also increase their level of participation in comparison with other relatively younger members of the group.

repeated sprint ability (RSA) The ability of players to repeatedly and explosively move around the court; developed by specific training protocol involving repeated short sprints separated by brief periods of recovery.

rotation, external The rotation of the upper arm in the shoulder joint that, during a serve, moves the forearm back behind the player, stretching the muscles of the shoulder in preparation to swing the racket forward.

rotation, internal The rotation of the upper arm in the shoulder joint as the shoulder muscles contract, accelerating the racket forward during a serve or forehand shot; internal shoulder rotation is the main source of racket speed in serves.

rotation, shoulder The rotation of the upper arm within the shoulder joint that occurs during shots and serves.

rotator cuff A group of muscles and associated tendons in the shoulder that connect the upper arm (humerus) to the shoulder blade (scapula) and that twist, stretch, and contract during shoulder rotation.

saccadic Rapid eye movements that enable players to shift their gaze from one point to another point.

sagittal plane An imaginary vertical plane that passes from front to back, dividing the body into right and left halves. Perpendicular to the frontal (coronal) and transverse (horizontal) planes.

scapula, scapular Shoulder blade.

scapulohumeral rhythm Normal coordinated pattern or sequence of movement of the upper arm (humerus) within the shoulder (scapula).

self-talk Inward-directed language which, when uttered aloud, results in players talking to themselves; positive self-talk is a psychological tool for bolstering confidence and improving performance.

separation angle Biomechanical measure of the rotation of the shoulders relative to the hips.

somatic (anxiety) Anxiety that manifests in physical symptoms.

stroboscopic software Software that enables players and coaches to analyze video and see movement and racket paths presented on screen as a series of superimposed frozen frames—as if captured by a camera using a strobe light.

stroke production Term for the collection of specific movements—such as leg drive, trunk rotation and arm motion—required for a player to execute a particular shot.

subscapularis Large shoulder muscle; one of the four rotator cuff muscles found in the joint between the shoulder (scapula) and the upper arm (humerus).

tendinitis Inflammation of a tendon, the thick cord of connective tissue that joins muscle to bone.

theraband Resistance exercise tool consisting of a flexible, elastic band or bar of plastic or rubber that offers resistance when bent or pulled.

torque Twisting force that causes rotation; the greater the force, the faster the rotation. In tennis this is particularly relevant to the rotation of the trunk around the hips and to the rotation of the arm at the shoulder.

tracking, smooth pursuit The ability of an eye to smoothly follow a slow-moving object such as a tennis ball rolling along the ground.

transition time The time between a professional player earning his or her first point and achieving a Top 100 ranking.

transverse plane Also called the horizontal plane, axial plane, or transaxial plane. An imaginary horizontal plane that divides the body into upper and lower parts. Perpendicular to the frontal (coronal) and sagittal planes.

transversus abdominis Pair of large muscles, innermost of the abdominal muscles, that line each side of the abdomen—sometimes called the inner abs.

triglycerides Type of fat found in the blood; used by the body to store energy from food.

trunk Torso of the body; anatomically defined as the length of the vertebral column; excludes limbs and head.

trunk rotation, shoulder-over-shoulder A motion that enables a player to strike a ball strongly by using both legs to drive, rotating the trunk, elevating the back hip, faster than the front hip and so placing the back shoulder above the front shoulder.

ulnar collateral ligament Strong band of connective tissue between bones. The same name is used for: the ligament in the elbow connecting the lower arm bone (ulnar) to the upper arm bone (humerus); the ligament in the thumb running along the ulnar side of the joint at the base of the thumb; and the ligament in the wrist connecting the ulnar with parts of the wrist and hand.

visualization The act of imagining an outcome or result of an action—such as the placing of a shot, the execution of a particular move, or even the result of a match. Visualizing a successful outcome is a psychological tool for bolstering confidence and improving performance.

wicking Fabric that provides moisture control for the skin by using the physics of capillary action to draw away moisture.

Women's Tennis Association (WTA) The governing body of the international professional game of women's tennis.

X-angle Measurement of the hip–trunk separation angle.

Notes on contributors

EDITORS

Miguel Crespo is a research officer at the International Tennis Federation Development Department, Spain. He oversees the ITF's coach education program and has co-authored and edited many ITF publications.

Bruce Elliott is a world leader in sport biomechanics, particularly tennis stroke production. He is an Emeritus Professor and Senior Research Fellow in biomechanics in the School of Sport Science, Exercise and Health at the University of Western Australia. He has published over 230 peer-reviewed articles and over 60 book chapters or books, in the area of sports biomechanics with a particular focus on tennis. A former professional tennis coach Bruce has been an invited speaker at numerous International Tennis Federation and Tennis Australia conferences for coaches. He co-edited the two International Tennis Federation books—*Biomechanics of Advanced Tennis* and *Technique Development in Tennis Stroke Production*—with the editors of this book.

Machar Reid is one of international tennis's preeminent voices in sport and coaching science. He is currently the Innovation Catalyst at Tennis Australia; having previously served as its inaugural High Performance Manager (2011–14) and Sport Science & Medicine Manager (2008–2010). Throughout Machar's time at Tennis Australia, he has led the sport in its embrace of contemporary science, and most particularly, in data, performance and skill analysis. These efforts have helped to restore Australian tennis players to the upper echelons of the sport. Prior to this time, Machar forged a successful career working directly with a number of top 30 ranked professional male and female players as well as with the International Tennis Federation as a touring coach and coach educator. He ranks among a select few to have emphatically crossed over from coaching and sports administration to sports science, having published over 100 peer-reviewed articles and books/book chapters in the field.

CONTRIBUTORS

Michael Bane works in analytics research and development at Tennis Australia's high performance unit. Michael's study permeates a variety of projects, from talent development to performance analysis. Michael hopes that his work will help demonstrate the utility of machine learning, which has only seen limited application in tennis, and lead to its successful application at the elite level.

Louise Burke is a sports dietitian with 35 years of experience in the education and counseling of elite athletes. She has been Head of Sports Nutrition at the Australian Institute of Sport since 1990 and was team dietitian for the Australian Olympic Teams for the 1996–2012 Summer Olympic Games. Her publications include over 200 peer-reviewed research papers and book chapters, and 21 books on sports nutrition.

Rob Duffield is an Associate Professor at the University of Technology Sydney. Rob has over 100 publications in the areas of fatigue, recovery, exercise in the heat and sports performance. Over the last 8 years, he has regularly collaborated with Tennis Australia on performance-focused research.

Todd Ellenbecker is the Vice President of Medical Services for the ATP World Tour and helped develop their injury prevention screening program for male professional tennis players. Todd is also the Clinic Director and National Director of Clinical Research for Physiotherapy Associates in Scottsdale Arizona. He has conducted and published musculoskeletal research primarily in the area of shoulder rehabilitation and tennis medicine and science. He serves on the editorial boards of the *International Journal of Sports Physical Therapy* and *Sports Health*.

Damian Farrow holds a joint appointment with Victoria University and the Australian Institute of Sport (AIS) as a Professor of Skill Acquisition. He has an extensive record of tennis science research focused on the development of anticipatory skills and skill practice organization. A former tennis coach, Damian has worked with Tennis Australia as a scientific advisor and coach educator for over 20 years.

Shona Halson is a Senior Physiologist at the Australian Institute of Sport, where her role involves service provision, education, and scientific research. She has a PhD in Exercise Physiology and has been involved in conducting research into the areas of recovery, fatigue, sleep, and travel.

Aaron Kellett is the Physical Performance Manager with Tennis Australia, where his role is to lead the overall performance and strategic direction of the physical performance team within Australian Tennis.

W. Ben Kibler is an orthopedic surgeon who specializes in sports medicine and shoulder injuries. He was a founding member and past president of the Society of Tennis Medicine and Science. He served on the USTA sports science committee for 27 years, is a sports science advisor for the PTR, and has been a consultant for both ATP and WTA for over 20 years.

Duane Knudson is professor of biomechanics at Texas State University. He is internationally known for his research on the biomechanics of tennis, publishing over three dozen peer-reviewed articles and seven chapters on tennis strokes and equipment. He also authored the book *Biomechanical Principles of Tennis Technique* with Racquet Tech Publishing.

Mark Kovacs is the executive director of the International Tennis Performance Association (ITPA), which is the worldwide leader in education/certification in all aspects of tennis fitness/science. He has led the Sport Science & Coach Education Departments for the USTA and was also the Director of the Gatorade Sport Science Institute. He has coached and trained dozens of top professional tennis players including John Isner, Robby Ginepri, Jared Donaldson, Sloane Stephens, and Madison Keys.

Paul Lubbers is currently the Sr. Director of Coaching Education and Performance for the United States Tennis Association. In his role with the USTA he works to provide educational experiences and opportunities for America's top tennis coaches as well as manage and direct Performance and Sport Science training activities and education for top juniors and professional tennis players.

Index

A

abdominal muscles 154, 155
acceleration, center of mass and 100–101
aerobic fitness 96–97
 and interval training 104–105
age
 and professional rankings 60–61
 “relative age effect” 58–59
agility training 106–107
air resistance 158, 170–171
analogies, coaching by 25
anxiety, strategies for 84–85
Arthurs, Wayne 26
automaticity, acquiring 46

B

backspin 38
balance training 109
ball flight, air resistance and 158, 170–171
ball impact
 and string tension 162–163
 tracking 36–37
ball rebound, court surface and 164–165
ball toss practice 16
balls 166–167
birth months, effect of 58–59
blocked practice 14–15
breathing, centered 85

C

C-shape swing 25
carbohydrates 118, 119, 120, 121
cardiovascular fitness 96–97
center of mass 100–101
centered breathing 85
chest straps 82
children
 court size 20–21
 developmental balls 166
 maturation and skills 42–43

net heights 21
racket size 22–23
 see also junior tennis
“choking” 90
coaches
 analysis of techniques by 30–31
 feedback from 24–25
cold water immersion (CWI) 126, 128–129
compression garments 124–125, 126
computer modeling 158–159, 172
concentration 76, 77, 90–91
confidence 77, 80–81
contrast water therapy (CWT) 126
coordination 52–53
core stability 154–155
courts
 and ball rebound 164–165
 scaling for juniors 20–21
 smart courts 174, 175
 and training success 56
cramp 123
cryotherapy 128–129
CWI (cold water immersion) 126, 128–129
CWT (contrast water therapy) 126

D

debriefs 130
deceleration ability 106–107
dehydration 122–123
diet *see* nutrition
“dig step” 100–101
Djokovic, Novak 53, 96, 130
Draper, Scott 46
dynamic stretching 148, 149, 150
dynamometers 144, 145

E

elastic energy 34–35
elbow injuries 142–143
elite tennis
 game statistics 66

player characteristics 67
 “relative age effect” 58–59
Ellenbecker, Todd 150
emotional control 77
 see also anxiety
erector spinae muscles 154, 155
ergogenic supplements 119
exercises
 core stability 154–155
 muscle imbalance 146–147
 proprioception 152–153
 stretching 148–149
eye-tracking technology 31

F

fabric sensors 83
Federer, Roger 11, 46, 70, 110
finite element modeling 158, 159
five-ball pickup 107
fluid intake 122–123
focus 78–79
force sensors 158, 159
forehand
 internal rotation 50–51
 leg drive 44–45
 linear velocity 52–53
 trunk movement 48–49

G

game plans 62
gluteals (“glutes”) 154, 155
goal setting 77
goniometers 144, 145
Grand Slam tennis
 game statistics 66
 player characteristics 67
 “relative age effect” 58–59
gravity, center of 100–101
Groth, Sam 50
ground reaction force 99

H

hand-grip dynamometers 144

Hawk-Eye 68–71
Head, Howard 168–169
health benefits 114
heart rate monitors 82–83
high contextual interference 14
high-intensity interval training (HIIT) 104–105
Hot Shots 22
hot water immersion (HWI) 126
hydration 122–123
hydrotherapy 126

I

ice baths *see* cold water immersion (CWI)
ideal performance states (IPS) 88
“in the zone” 88
injuries
 elbow 142–143
 shoulder 140–141
insoles, high-tech 159
internal rotation 50–51
interval training 104–105
IPS (ideal performance states) 88
Isner, John 96
isokinetic dynamometers 144, 145

J

jetlag 134–135
joint movement, control of 152–153
junior tennis
 “relative age effect” 58–59
 and senior success 56–57
 see also children

K

Kibler, Dr. Ben 150
kinetic chain breakdown 138–139
knee serve 17
Kyrgios, Nick 62

L

labral injury (SLAP) 140, 141

Lacoste, René 168
lateral epicondylitis (tennis elbow) 142, 143
lattissimus dorsi 154
lead tape 161
learning transfer 18–19
leg drive 44–45
linear periodization 112–113
load monitoring 102–103
low contextual interference 14
lymphedema 124

M

Mahut, Nicolas 96
mass, center of 100–101
massage 126
medial epicondylitis 142, 143
mental skills
 concentration 76, 77, 90–91
 focus 78–79
 motivation 76, 77, 86–87
 relaxation strategies 84–85
 self-confidence 77, 80–81
 training programs 76–79
 visualization 92–93
Mini-Tennis 22
mobile eye recorders 31
motion sensors 158, 159
motivation 76, 77, 86–87
Murray, Andy 70
muscle imbalance, exercises for 146–147

N

Nadal, Rafael 96
Năstase, Ilie 172
nets, height for juniors 21
new opponents 62
non-linear periodization 112
notational analysis 66
nutrition
 daily diet 118–119
 for matchplay 120–121

O

one percenters 130

P

periodization programs 112–113
Play and Stay 22
player rankings
 and national tournaments 64–65
 transitional time for 60–61
players, physical characteristics 67
“point importance” 72–73
power training 109
practice
 acquiring automaticity 46
 blocked *versus* random 14–15
 learning transfer 18–19
 purposefulness 26
 task decomposition 16–17
 see also coaches
preparations for matches
 and Hawk-Eye 70
 new opponents 62
Prince Oversize rackets 169
proprioception exercises 152–153
psychology *see* mental skills

Q

Quickstart 22

R

rackets
 evolution of 168–169
 head size/weight 160–161
 scaling 22–23
 “spaghetti” string rackets 172
 string tension 162–163
rallies, number of shots in 66
Raonic, Milos 50
Rating of Perceived Exertion (RPE) scale 102
recovery strategies 126–127
 and compression garments 124–125

“relative age effect” 58–9
relaxation strategies 84–85
rotator cuff injuries 140, 141
RPE (Rating of Perceived Exertion) scale 102

S

saccadic eye movements 36
Sampras, Pete 26
scoreboard pressure 72–73
self-confidence 77, 80–81
self-talk 80–1
sensor technology 158, 159, 169, 174–175
 heart rate monitors 82–83
serving
 arabesque landing 25
 ball toss practice 16–17
 internal rotation 51
 kinetic chain 138–139
 knee serve 17
 leg drive 44, 45
 predicting location 28–29
 trunk movement 49
shoes 176–177
shoulders
 injuries 140–141
 internal rotation 50–51
 muscle training 152–153
sidespin 39
sit-and-reach box 145
SLAP (labral injury) 140, 141
sleep 132–3
smart courts 174, 175
“spaghetti” string rackets 172
spider drill 107
spin 38–39
“split step” 34, 100–101
sports drinks 120, 121
sports psychology *see* mental skills
stable base, maintaining 108–109
stair periodization *see* linear periodization

static stretching 148, 150
strength levels 108–9
stretching exercises 148–149, 150
strings, tension 162–163
supplements 119

T

TARGET strategies 87
task decomposition 16–17
technology and equipment 174–175
tennis elbow 142, 143
Tennis10s 22
topspin 38–9, 170
tournaments, player rankings and 64–65
tracking the ball 36–37
training diaries 103
travel
 jetlag 134–135
 strategies for 130
trunk movement 48–49

U

undulating periodization *see* non-linear periodization

V

velocities, players' 98–99
video analysis 40–41
Vilas, Guillermo 172
visualization 92–93

W

Western grip 53
 and injuries 143
Williams, Serena 50
Williams, Venus 50
Wilson Widebody rackets 169
workload monitoring 102–103
wrist monitors 83

X

X-angle 138

Table of measurements

Distance

1 in = 25.4 mm = 2.54 cm
1 cm = 10 mm = 0.394 in
1 ft = 0.305 m
1 m = 3.281 ft
1 mile = 1.609 km
1 km = 0.621 mile

Speed

1 ft/s = 0.305 m/s = 0.682 mph = 1.097 km/h
1 m/s = 3.281 ft/s = 2.237 mph = 3.6 km/h
1 mph = 1.609 km/h = 1.467 ft/s = 0.447 m/s
1 km/h = 0.621 mph = 0.911 ft/s = 0.278 m/s

Acceleration

1 ft/s² = 0.305 m/s²
1 m/s² = 3.281 ft/s²

Force

1 lb = 4.448 N
1 N = 0.225 lb

Mass*

1 oz = 28.350 g
1 g = 0.0357 oz
1 lb = 453.6 g = 0.454 kg
1 kg = 1000 g = 2.205 lb

* At the surface of the Earth

Converting mass to weight on Earth

1 kg = 2.205 lb = 9.807 N
1 N = 0.225 lb = 0.102 kg

Area

1 cm² = 0.155 in²
1 in² = 6.452 cm²
1 ft² = 0.0929 m²
1 m² = 10.764 ft²

Volume

1 in³ = 0.0164 liter
1 liter = 61.0237 in³
1 ft³ = 0.0283 m³
1 m³ = 35.315 ft³
1 gallon = 3.785 liter
1 liter = 0.264 gallon

Temperature

°F = (°C × 9/5) + 32
°C = (°F – 32) × 5/9

Abbreviations

in	inch
ft	foot
mm	millimeter (0.001 m)
cm	centimeter (0.01 m)
m	meter
km	kilometer (1000 m)
ms	millisecond (1000 s)
s	second
h	hour
y	year
oz	ounce
lb	pound
N	newton
kg	kilogram
g	gram
°F	degrees Fahrenheit
°C	degrees Celsius
K	kelvin
Hz	hertz (cycles per second)

Acknowledgments

No book reaches its end nor realizes its potential without the considerable, and often silent, contribution of many. We would like to thank all of the scientists that have examined aspects of our sport, while also extending our gratitude to the game’s coaches and players who provide that very canvas. A final thanks goes to the teams at Tennis Australia (Dave Whiteside, Dani Gescheit, Tim Buszard, Al Murphy, Eliza Keaney, Darren McMurtrie, and Georgia Giblin), an innovative group of sports scientists and analysts that have variously contributed their own expertise, and at Ivy Press (chiefly, Caroline Earle, Nick Rowland, and Rob Yarham), who have worked tirelessly to bring the book to life.

Machar Reid, Bruce Elliott, and Miguel Crespo

The Ivy Press would like to thank the following for permission to reproduce copyright material:

Corbis: Toby Melville/Reuters: 47; Mark Spowart/Demotix: 63; Neil Tingle: 55.

Getty Images: AFP: 173; Jan Kruger: 151; Caryn Levy: 27.

Shutterstock, Inc./www.shutterstock.com: Neale Cousland: 4–5, 9, 33, 75, 89, 95, 131; picamaniac: 117; Rena Schild: 111; XiXinXing: 13; Sutichak Yachiangkham: 157; Leonard Zhukovsky: 137. Every effort has been made to trace copyright holders and to obtain their permission for the use of copyright material.

The publisher apologizes for any errors or omissions in the lists above and will gratefully incorporate any corrections in future reprints if notified.

Table of measurements

Distance

1 in = 25.4 mm = 2.54 cm
1 cm = 10 mm = 0.394 in
1 ft = 0.305 m
1 m = 3.281 ft
1 mile = 1.609 km
1 km = 0.621 mile

Speed

1 ft/s = 0.305 m/s = 0.682 mph = 1.097 km/h
1 m/s = 3.281 ft/s = 2.237 mph = 3.6 km/h
1 mph = 1.609 km/h = 1.467 ft/s = 0.447 m/s
1 km/h = 0.621 mph = 0.911 ft/s = 0.278 m/s

Acceleration

1 ft/s² = 0.305 m/s²
1 m/s² = 3.281 ft/s²

Force

1 lb = 4.448 N
1 N = 0.225 lb

Mass*

1 oz = 28.350 g
1 g = 0.0357 oz
1 lb = 453.6 g = 0.454 kg
1 kg = 1000 g = 2.205 lb

* At the surface of the Earth

Converting mass to weight on Earth

1 kg = 2.205 lb = 9.807 N
1 N = 0.225 lb = 0.102 kg

Area

1 cm² = 0.155 in²
1 in² = 6.452 cm²
1 ft² = 0.0929 m²
1 m² = 10.764 ft²

Volume

1 in³ = 0.0164 liter
1 liter = 61.0237 in³
1 ft³ = 0.0283 m³
1 m³ = 35.315 ft³
1 gallon = 3.785 liter
1 liter = 0.264 gallon

Temperature

°F = (°C × 9/5) + 32
°C = (°F – 32) × 5/9

Abbreviations

in	inch
ft	foot
mm	millimeter (0.001 m)
cm	centimeter (0.01 m)
m	meter
km	kilometer (1000 m)
ms	millisecond (1000 s)
s	second
h	hour
y	year
oz	ounce
lb	pound
N	newton
kg	kilogram
g	gram
°F	degrees Fahrenheit
°C	degrees Celsius
K	kelvin
Hz	hertz (cycles per second)

Acknowledgments

No book reaches its end nor realizes its potential without the considerable, and often silent, contribution of many. We would like to thank all of the scientists that have examined aspects of our sport, while also extending our gratitude to the game’s coaches and players who provide that very canvas. A final thanks goes to the teams at Tennis Australia (Dave Whiteside, Dani Gescheit, Tim Buszard, Al Murphy, Eliza Keaney, Darren McMurtrie, and Georgia Giblin), an innovative group of sports scientists and analysts that have variously contributed their own expertise, and at Ivy Press (chiefly, Caroline Earle, Nick Rowland, and Rob Yarham), who have worked tirelessly to bring the book to life.

Machar Reid, Bruce Elliott, and Miguel Crespo

The Ivy Press would like to thank the following for permission to reproduce copyright material:

Corbis: Toby Melville/Reuters: 47; Mark Spowart/Demotix: 63; Neil Tingle: 55.

Getty Images: AFP: 173; Jan Kruger: 151; Caryn Levy: 27.

Shutterstock, Inc./www.shutterstock.com: Neale Cousland: 4–5, 9, 33, 75, 89, 95, 131; picamaniac: 117; Rena Schild: 111; XiXinXing: 13; Sutichak Yachiangkham: 157; Leonard Zhukovsky: 137. Every effort has been made to trace copyright holders and to obtain their permission for the use of copyright material.

The publisher apologizes for any errors or omissions in the lists above and will gratefully incorporate any corrections in future reprints if notified.