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Outside the Research Lab

Physics in sport

Sharon Ann Holgate

VOLUME THREE

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Outside the Research Lab

Volume 3: Physics in sport

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Science writer and broadcaster, doctor of physics

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For Alice, who played an increasingly mean round of mini golf as she grew up

Contents

Preface

If someone had asked me a few years ago if I liked sport, my answer would have been ‘no’. Perhaps this is not surprising given my greatest sporting achievements to date are third place in my school egg and spoon race, and managing a reasonably decent round of crazy golf. But more recently I decided to analyse what I watched most of on the TV. To my great surprise, by far the largest percentage of my viewing time is spent watching sport. Clearly I DO like sport!

I also realised that I still enjoy watching sports that I followed as a child including various types of motor sport, ice skating, and show jumping. As it happens one of my standout childhood memories involves show jumping. In 1983, after appearing at the Royal International Horse Show at the White City stadium (which had hosted the 1948 London Olympics) on board a horse drawn bus as part of a parade of historic vehicles, I was allowed access to the ringside. So I stood with my Mum just outside the ring literally right next to one of the fences during a show jumping competition. Seeing the sport from that close-up ground level perspective rather than the view normally witnessed by the spectators was an incredible experience. The height and width of the fence looked enormous to my teenage eyes, and I remember being fascinated with the power of the horses jumping over the obstacle. I was also struck with the careful way the horses launched themselves and the shape they made in mid-air as they attempted to clear the jump. Clearly the physics of the sport had captured my attention, even though I did not realise it at the time.

Similarly, further analysis of the sports I now sit glued to reveals they are all sports that I find particularly interesting from a physics perspective. This led me to come up with the idea for this book which explores some of the physics and technology inherent to a selection of the sports which have captured my attention. I am hoping that this book—as with the others in my *Outside the Research Lab* series—will provide students and other readers with an interesting insight into some of the diverse applications for physics outside of research laboratories. To help achieve this goal, I have chosen to cover the fastest, and arguably the most brutal, motorsport in the world—drag racing, and the tactical sport of fencing. Fencing can boast a speed record too as the tip of a fencing blade is the next-to-fastest moving thing in sport, second only to the bullets used in rifle shooting. I have also discovered some of the physics used behind the scenes at the London 2012 Olympics and Paralympics, as well as a technological approach to helping diagnose injury and optimise performance for horses used in various sports including show jumping. In each case I have interviewed competitors, coaches, or experts in or supporting that sport, who have generously given their time to explain how physics and technology impact what they do, and also provided some stunning images.

To keep the book accessible for readers with a wide range of backgrounds, I have only included a small number of equations, and have explained the less familiar scientific terminology and notation. In addition, the more detailed physics is presented in boxes that are interspersed among, but separate from, the main text.

I make no apology for choosing to write about topics that I have a personal interest in—and in some cases have previously written articles about—as I suspect I won't be alone in my enthusiasm for these subjects! I hope they will not only provide an interesting general read, but also some useful examples of how the physics encountered in taught courses relates to the real world. As someone who has written extensively about careers, I also hope the contents of this book might inspire readers as yet undecided on their future career, or looking for a change in direction, to think about career options that they might not otherwise have considered. Finally, I hope this book can encourage people to either follow or take up sports beyond those most commonly encountered.

Acknowledgments

As with the earlier volumes in this series, I could not have written this book without the help of many people. I would first like to thank my editor Nicki Dennis for approaching me to write for the IOP Concise Physics series, and for her help throughout the creation of this volume. Thanks are also due to Brent Beckley, Karen Donnison, Ana San and Mitra Sayadi at Morgan & Claypool, and Chris Benson at Institute of Physics Publishing.

In addition, I'd like to extend my gratitude to all the interviewees who have kindly given their time, expertise and advice, and allowed me to reproduce some fantastic images. I could not have written this book without your enthusiasm and support. I would also like to thank the various experts, press officers, and friends who helped me to secure interviews and kindly provided me with additional information and images. These include Jennifer Goethel and Scott Smith at the NHRA (National Hot Rod Association), David Akroyd-Jones, Michinobu Fujita, Yuka Fujita, Natalie Hogg, Steve Keevil, and Oliver Lam-Watson. Thanks are also due to David Culpeck, Julian Mayers, Ian Rennison and Tracey deWhalley for their help in various ways with this project.

As ever, friends and family members have been a tremendous support, in particular Dawson Chance, Emma Winder, and my mother Joan.

About the author

Sharon Ann Holgate

© Sharon Ann Holgate. Photo by Stuart Robinson.

Sharon Ann Holgate has a doctorate in experimental physics from the University of Sussex in the UK, where she was a Visiting Fellow in Physics and Astronomy for nine years, and is a Chartered Scientist and Chartered Physicist. She has worked for twenty one years as a freelance science writer and broadcaster, with broadcast credits including presenting on the BBC World Service and BBC Radio 4, presenting video podcasts for medical research charity the Myrovlytis Trust and appearing on a 'Boffins Special' of the *Weakest Link*. Her articles have appeared in *Science*, *Science Careers*, *New Scientist*, *The Times Higher Education Supplement*, *E&T*, *Flipside*, *Focus*, *Physics World*, *Interactions*, *Materials World*, *Modern Astronomer*, and *Astronomy Now*, while her first book *The Way Science Works* (a children's popular science book co-authored with Robin Kerrod) was shortlisted for the Aventis Prizes for Science Books Junior Prize. She was a contributor to the popular science books 30-*Second Quantum Theory* and 30-*Second Energy*, and her undergraduate textbook *Understanding Solid State Physics* is currently in use as a core text in universities around the world. Her previous books for this IOP Concise Physics series are *Outside the Research Lab Volume 1: Physics in the arts, architecture and design* and *Outside the Research Lab Volume 2: Physics in vintage and modern transport.* She has also written careers material, case studies, and press releases for the Institute of Physics and careers material and brochures for The Institute of Physics and Engineering in Medicine, and given talks at venues including the Science Museum in London. Dr Holgate was the Institute of Physics Young Professional Physicist of the Year for 2006, won a Merit Award in the 1994 Daily Telegraph Young Science Writer of the Year competition, and was shortlisted for the radio programme category of the Association of British Science Writers' Awards in 2005. Outside of work she collects contemporary ceramics, is a regular visitor to art galleries and museums, and enjoys learning about fashion history and steam locomotives. Further information may be seen at www.sharonannholgate.com.

IOP Concise Physics

Outside the Research Lab

Volume 3: Physics in sport

Sharon Ann Holgate

Chapter 1

Introduction

When you hear about the latest physics breakthroughs on the news, or attend university or college physics courses, it can be easy to think of physics as nothing other than an academic subject. But physics does much more than just describe how matter and energy behave, and so reveals how almost everything around us, and even within us, works. In fact physics-based technologies are integral to many of the work and leisure activities we carry out every day without giving science a second thought.

In this book we will explore the use of physics in various sports. We will see how professional athletes, coaches and amateurs in different sports use physics, and physics-based technologies, to participate in that sport and raise their performance levels as high as possible.

For instance, we will see in chapter 2 that electronic scoring systems and a wide variety of protective clothing made from specialist materials are used in competitive fencing (see figure 1.1), while motion capture technology can reveal how to improve the fencing lunge (see figure 1.2). In wheelchair fencing the additional equipment required and the ability to gain a competitive edge are also based on high-tech materials and knowledge of physics respectively (see figure 1.3).

Chapter 3 reveals the vital part physics plays in the world's fastest motorsport, drag racing. As we will hear, the incredible speeds reached by dragsters (see figure 1.4(a) and (b)) over the quarter mile track subject both drivers and cars to large forces and a lot of vibration, and require a parachute to slow down from.

In the final chapter, chapter 4, we hear how knowledge of radiation physics was essential for creating a safe environment for both staff and patients in the x-ray and CT scanning facilities (see figure 1.5) at the medical centre at the Queen Elizabeth Olympic Park at the London 2012 Olympics and Paralympics. This chapter also describes an electronics-based system for measuring asymmetry in the gait of sporting horses (see figure 1.6). The system enables a more accurate diagnosis of

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Figure 1.1. George Harris fencing in the men's sabre category at the British Universities & Colleges Sport (BUCS) Individual Championships in 2018. Both fencers are connected via wires to the electronic scoring system. (© George Harris. Reproduced with permission.)

Figure 1.2. The full body mark-up used by principal lecturer Lindsay Bottoms from the University of Hertfordshire in the UK, and colleagues, for their investigations into the physics of the fencing lunge. (© Lindsay Bottoms. Reproduced with permission.)

Figure 1.3. Metal or carbon fibre frames are used to hold the wheelchairs in place, keeping the fencers set at the correct distance and angle from one another, during wheelchair fencing. This image shows Dimitri Coutya from the UK on his way to a gold medal in the category B epee competition at the 2017 World Championships in Rome, Italy. (© Vivien Mills. Reproduced with permission.)

(a)

(b)

Figure 1.4. (a) Alec Coe in his 184 mph [296 km h^{-1}] dragster smoking the tyres before a drag run at the Shakespeare County Raceway in the UK. (© Alec Coe. Reproduced with permission.) (b) Brittany Force in action in a Top Fuel dragster at the NHRA (National Hot Rod Association) in the United States in 2018. Top Fuel dragsters reach over 300 mph (482 km h^{-1}). (© NHRA. Reproduced with permission.)

Figure 1.5. The CT scanner, and the two MRI scanners, used for medical scans on athletes during the London 2012 Olympics and Paralympics were housed in temporary buildings outside the Polyclinic in the Queen Elizabeth Olympic Park in Stratford, east London. (© Donald McRobbie. Reproduced with permission.)

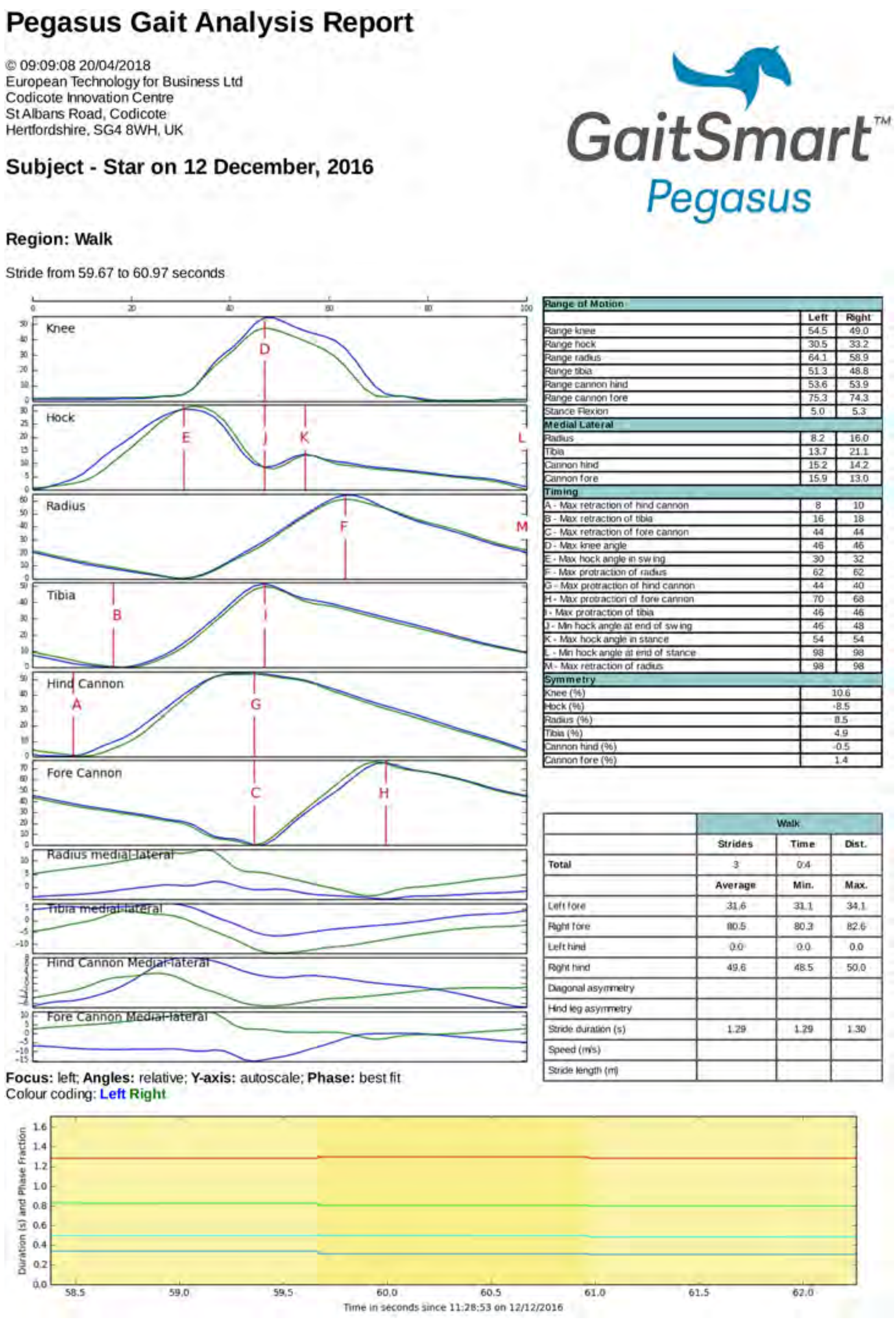
veterinary problems and the chance to optimise training for show jumpers, race horses and dressage horses.

Within the chapters, I record conversations with athletes, coaches, scientists and engineers working in and on various aspects of sport. Athletes and coaches have given an insight into their sport and how physics impacts on it, while scientists and engineers have revealed how their expertise is applied in the sporting arena. Additional details about the physics mentioned, and related physics topics, are presented in boxes interspersed among the main text.

Throughout this book I have used the SI system of units when describing the sizes of measurable physical quantities—which include mass, length, pressure, electric current, and time. (The only exceptions to this are in instances where specialist vehicles are being discussed, and alternative units are more appropriate as they are widely used in that context.)

The SI system of units—Système Internationale d'Unités to give it its full title—is, as its name suggests, the internationally agreed system for detailing the sizes of physical quantities. One of its main advantages is removing any confusion that can be created by using different systems of units to describe the size of the same quantity, and hence having to convert numbers from one unit to another; such as, for instance, converting a temperature measured in Fahrenheit into its SI unit of Celsius. Table 1.1 shows a selection of physical quantities along with their associated SI units, while table 1.2 lists the prefixes used to describe multiples of SI units.

As table 1.2 reveals, some symbols are uppercase, and others are lowercase. It is important not to muddle the two as the same letter can represent very different sized units. For example, lowercase m stands for *milli* while M denotes *mega*. Different countries can vary in how they use SI units. In some countries for instance drinks are labelled in 'cl' while in other countries the labels show the quantity in 'ml'. So a 25 cl



Pegasus Gait Analysis Report

© 09:09:08 20/04/2018
European Technology for Business Ltd
Codicote Innovation Centre
St Albans Road, Codicote
Hertfordshire, SG4 8WH, UK

Subject - Star on 12 December, 2016

Region: Walk

Stride from 59.67 to 60.97 seconds

Range of Motion		
	Left	**Right**
Range knee	54.5	49.0
Range hock	30.5	33.2
Range radius	64.1	58.9
Range tibia	51.3	48.8
Range cannon hind	53.6	53.9
Range cannon fore	75.3	74.3
Stance Flexion	5.0	5.3
Medial Lateral		
Radius	8.2	16.0
Tibia	13.7	21.1
Cannon hind	15.2	14.2
Cannon fore	15.9	13.0
Timing		
A - Max retraction of hind cannon	8	10
B - Max retraction of tibia	16	18
C - Max retraction of fore cannon	44	44
D - Max knee angle	46	46
E - Max hock angle in swing	30	32
F - Max protraction of radius	62	62
G - Max protraction of hind cannon	44	40
H - Max protraction of fore cannon	70	68
I - Max protraction of tibia	46	46
J - Min hock angle at end of swing	46	48
K - Max hock angle in stance	54	54
L - Min hock angle at end of stance	98	98
M - Max retraction of radius	98	98
Symmetry		
Knee (%)	10.6	
Hock (%)	-8.5	
Radius (%)	8.5	
Tibia (%)	4.9	
Cannon hind (%)	-0.5	
Cannon fore (%)	1.4	

	Walk		
	Strides	**Time**	**Dist.**
Total	3	0.4	
	Average	**Min.**	**Max.**
Left fore	31.6	31.1	34.1
Right fore	80.5	80.3	82.6
Left hind	0.0	0.0	0.0
Right hind	49.6	48.5	50.0
Diagonal asymmetry			
Hind leg asymmetry			
Stride duration (s)	1.29	1.29	1.30
Speed (m/s)			
Stride length (m)			

Focus: left; **Angles:** relative; **Y-axis:** autoscale; **Phase:** best fit
Colour coding: **Left Right**

Figure 1.6. Gait analysis data for the horse Star while walking. (The second page of this report is shown in figure 4.8.) (© Diana Hodgins. Reproduced with permission.)

Table 1.1. Some physical quantities and their respective SI units.

Physical quantity	Name of SI unit	Symbol of SI unit
mass	kilogram	kg
time	second	s
length	metre	m
electric current	ampere	A
electric potential	volt	V
force	newton	N
pressure	pascal	Pa
power	watt	W
frequency	hertz	Hz
energy	joule	J

Table 1.2. Prefixes used to describe multiples of SI units (a) getting smaller, where 10^{-3} is a shorthand way of writing 0.001, and 10^{-6} is equivalent to 0.000 001, and so on. Part (b) shows the prefixes for getting bigger, where 10^2 is equivalent to 10 × 10 i.e. 100, and 10^3 is mathematical shorthand for 10 × 10 × 10 i.e. 1000, and so on.

(a)

Factor	Prefix	Symbol
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a
10^{-21}	zepto	z
10^{-24}	yocto	y

(b)

Factor	Prefix	Symbol
10	deca	da
10^2	hecto	h
10^3	kilo	k
10^6	mega	M
10^9	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E
10^{21}	zetta	Z
10^{24}	yotta	Y

Table 1.3. The Greek alphabet.

Capital letter	Lowercase letter	Name
Α	α	alpha
Β	β	beta
Γ	γ	gamma
Δ	δ	delta
Ε	ε	epsilon
Ζ	ζ	zeta
Η	η	eta
Θ	θ	theta
Ι	ι	iota
Κ	κ	kappa
Λ	λ	lambda
Μ	μ	mu
Ν	ν	nu
Ξ	ξ	xi
Ο	o	omicron
Π	π	pi
Ρ	ρ	rho
Σ	σ	sigma
Τ	τ	tau
Υ	υ	upsilon
Φ	φ	phi
Χ	χ	chi
Ψ	ψ	psi
Ω	ω	omega

bottle of mineral water holds the same volume of liquid as a 250 ml bottle of mineral water.

As Greek letters are used to describe some of the quantities covered in this book, table 1.3 provides a quick reference point for the Greek alphabet.

Each chapter concludes with some suggestions for further reading and a selection of web links—including links to video footage and additional photographs—that will enable the respective sport, and in some cases the physics topics covered, to be explored further.

It is difficult to predict exactly what impact physics based technology or research will have on sport in the future. But if the last one hundred years are anything to go by, it seems likely that the influence of physics, and the technologies it helps create, will continue shaping not only the elite sport we watch, but the sports many of us participate in during our leisure time.

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Chapter 2

Cut and thrust—the physics of fencing

2.1 Introduction

If we are asked to think about fencing, many of us might imagine sword fights from our favourite films or plays, or historic battles that we learned about at school. But while the sport of competitive fencing has its roots in centuries-old weaponry and tactics, it is just as reliant on modern technology. Scoring is achieved using an electronic system, while the protective equipment worn by fencers is made from specialist materials that can prevent blade penetration.

In this chapter, thanks to Ian de Whalley, an avionics engineer and fencer, we will first hear about the scoring technology and protective equipment used in the sport. Team GB wheelchair fencer Oliver Lam-Watson also demonstrates how the different swords used in fencing are held.

Then thanks to master's student and university fencer George Harris we will discover some of the physics that comes into competitive fencing. We will also see what principal lecturer in exercise physiology Lindsay Bottoms from the University of Hertfordshire in the UK discovered about the mechanics of the fencing lunge when investigating lunging from a biomechanical perspective.

Finally, coach and retired competitive wheelchair fencer Viv Mills explains the physics and technology inherent in wheelchair fencing. As Viv reveals, while the weapons, protective equipment, and scoring system are the same as in able-bodied fencing, the different actions necessitated by fencing from a wheelchair involve additional physics and technology.

2.2 Equipment

As with many sports, participating in fencing relies on high-tech equipment and clothing. However fencing is more complex than most as it is essentially three different sports rather than one. These take the name of the three respective types of swords used—the epee, the foil, and the sabre—each of which requires different equipment and techniques.

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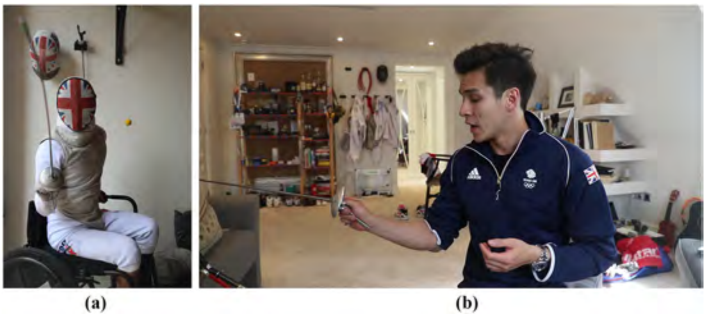
The heaviest of the weapons is the epee which is more rigid than either the foil or the sabre and weighs in at a maximum of 770 g. The foil is a much more flexible sword weighing less than 500 g and with a blade up to 110 cm long, the same length as that of the epee blade. The sabre (see figure 2.1) is slightly shorter at 105 cm and weighs less than 500 g. Fencers score a hit on their opponent with any part of the sabre blade. By contrast for both foil and epee the aim is to land the tip of the blade on the opponent.

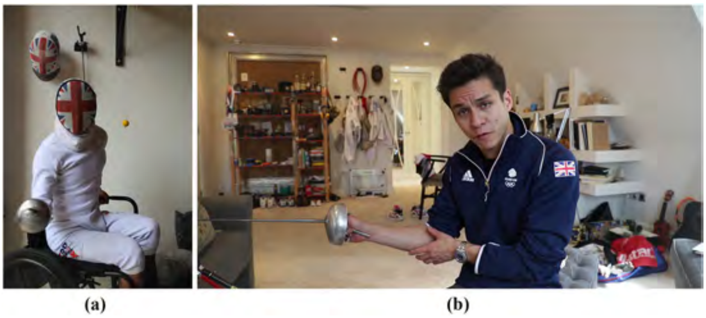
While the foil is a lightweight sword derived from the small swords historically used at court, the epee is a modern derivation of a rapier which was a duelling sword. The sabre has its origins in the swords carried by the cavalry and used for slashing. The grip for the weapons is slightly different for left-handed users compared with right-handed users, and differs for each different type of weapon. The different way of holding each sword is demonstrated by Team GB wheelchair fencer Oliver Lam-Watson in figure/video 2.2 for foil, figure/video 2.3 for epee, and figure/video 2.4 for sabre.

Whether fencing with a foil, epee or sabre, a protective mask, plastron, glove (for the fencing hand) and jacket need to be worn. The exact design of the mask depends on the weapon being used, but all variants ensure that no damage can occur to a fencer's eyes. The main component of all types of fencing mask is a metal mesh, with a maximum spacing between the mesh wires of 2.1 mm and wires no smaller than 1 mm in diameter. 'It would be dangerous if there was penetration of the mask mesh, and if a blade were to then go in through the eye. So masks are massively stronger than they need to be. Also, the rules say that a damaged mask must be thrown away,' explains Ian de Whalley, an electronics engineer in the avionics industry who fences competitively, and has won the Surrey County

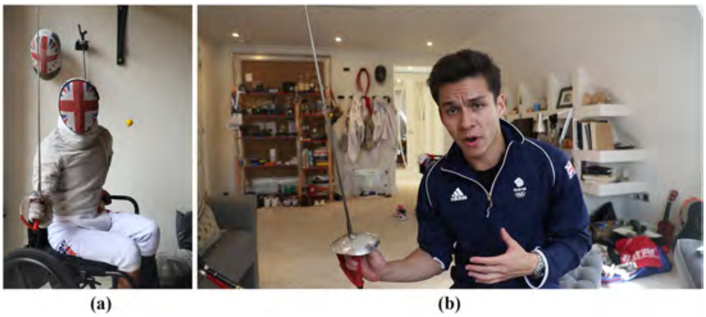
Figure 2.1. George Harris fencing in the men's sabre category at the British Universities & Colleges Sport (BUCS) Individual Championships in 2018. The wires connecting the fencers to the electronic scoring system can be seen coming from the back of the jackets. (© George Harris. Reproduced with permission.)



Figure/Video 2.2. (a) Still image and (b) video demonstrating how the foil is held by Team GB wheelchair fencer Oliver Lam-Watson; (a) shows the kit for foil, which is discussed in more detail later in this section, and includes a lamé conductive over-jacket that covers the body but not the arms, and lamé on the bib of the mask. (© Oliver Lam-Watson. Reproduced with permission.) Video available at https://iopscience.iop.org/book/978-1-64327-670-0.



Figure/Video 2.3. (a) Still image and (b) video demonstrating how the epee is held by Team GB wheelchair fencer Oliver Lam-Watson; (a) shows the kit for epee, which unlike foil and sabre does not include lamé. (© Oliver Lam-Watson. Reproduced with permission.) Video available at https://iopscience.iop.org/book/978-1-64327-670-0.



Figure/Video 2.4. (a) Still image and (b) video demonstrating how the sabre is held by Team GB wheelchair fencer Oliver Lam-Watson; (a) shows the kit for sabre, which is discussed in more detail later in this section, and includes a lamé conductive over-jacket that covers the body and the arms, a mask which is conductive, and a glove with a lamé cuff. (© Oliver Lam-Watson. Reproduced with permission.) Video available at https://iopscience.iop.org/book/978-1-64327-670-0.

fencing championships in the UK seven times. 'Masks have a bib that comes down below the chin. That provides cover over the neck but it is not attached to the jacket—it allows your head to move freely. For foil, epee and sabre the bib is target,' he continues.

The trunk is protected via a tough jacket made from heavy cotton, nylon or Kevlar®, which completely covers the body and both arms and has a strap going between the legs with a catch at the back. 'We also have a half-undershirt called a plastron. This provides a layer with no seam under the armpit because the armpit is an area of particular vulnerability as it is a potential way in to vital areas [of the body],' says Ian, adding that the plastron is such an important piece of kit that referees check it for every fencer before the first bout of fencing commences.

In addition, fencers can also opt to wear chest protectors under their jackets to spread the load from hits. Chest protectors are made from low-density polyethylene, which is a strong, impact absorbing thermoplastic. (See box 2.1 for more on polyethylene.)

Box 2.1. Polyethylene

Polyethylene, which is commonly known as polythene, is one of the most widely used thermoplastics. Thermoplastics are polymers that become soft when they are heated, and only harden up if they cool down. Other common examples of thermoplastics include PVC, polystyrene and PTFE.

All polymers are solid materials made from very large molecules, which are themselves composed of many smaller, identical building blocks of molecules known as monomers. A 2D diagram of the polymer polyethylene together with its monomer ethylene is shown in figure 2.5.

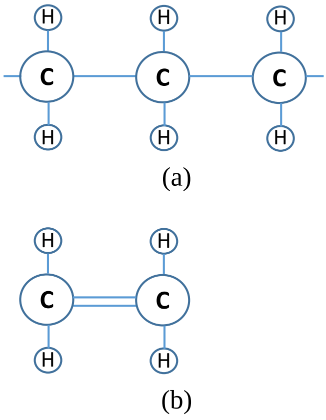


Figure 2.5. (a) A 2D representation of polyethylene. Each 'C' represents a carbon atom, while 'H' depicts a hydrogen atom. (b) Polyethylene's monomer ethylene. Polymers are known as hydrocarbons when they are made up from carbon and hydrogen atoms.

There are two forms of polyethylene: low-density polyethylene and high-density polyethylene. While high-density polyethylene (see figure 2.6(a)) has linear polymer chains, low-density polyethylene has branched polymer chains (see figure 2.6(b)).

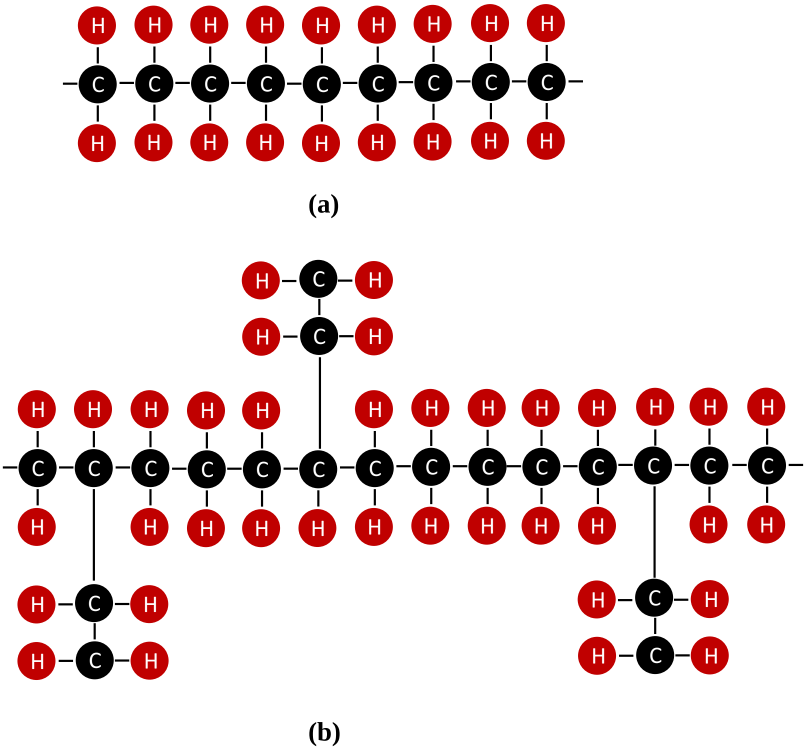


Figure 2.6. (a) High-density polyethylene; (b) low-density polyethylene.

The difference in the structure of the polymer chains accounts for the difference in density of the two forms. Linear polymer chains can pack closely together and so produce a high density material. Conversely the side branches of branched polymer chains prevent such close packing, leading to a relatively low density material.

Buckets and children's toys are among the common objects made from high density polyethylene, while drinks bottles and plastic bags can be manufactured from low density polyethylene.

Breeches are another piece of safety equipment worn for all types of fencing. 'Breeches cover some significant areas so there is a regulation on the fabric [in terms of what pressure it must be able to withstand]. For example I have 800 newton breeches,' explains Ian, adding that although most fencers talk about the equipment in terms of newtons, this is not a relevant unit of measure on its own. 'It's only relevant to the pressure over a specific area. So you might refer to a 1600 N (newton) mask, but the rules [for fencing] actually tell you the probe shape for the tests which need to be done in a lab for the manufacturer [when obtaining that figure].'

Perhaps surprisingly, given the level of protection it gives, fencing clothing can be quite thin and lightweight. 'The [clothing] equipment that I have is actually cool and thin. One reason why the clothing is quite thin is because you're working hard and you get really hot. They're not padded so in terms of comfort, if somebody does hit you with their blade the breeches don't entirely help. What they help with is confidence that there won't be any penetration, for example by a broken blade,' says Ian.

Gloves are used in all three types of fencing. They must cover the hand and are usually padded over the knuckles. 'The glove is different for sabre because sabre is the stiffest blade and a broken sabre would be more dangerous if it hit between your fingers. So the sabre glove is controlled for its performance. You have to have an 800 newton sabre glove. For foil and epee you can wear whatever [fencing] gloves you like as there is no penetration test,' he continues. For all weapons however, the glove's gauntlet needs to cover around half of the fencer's forearm on the sword arm. This is to stop their opponent's weapon going up inside the jacket sleeve.

While foil, epee, and sabre have different rules and equipment, an electronic scoring system is used for all types of competitive fencing. So in addition to the weapons, and the specialist clothing, there is also the need for electrical equipment.

This consists of five main components: conductive clothing (for foil and sabre only) known as lamé, body wires to connect a fencer's weapon (and lamé), long retractable wires on spools that connect each fencer to the scoring system, the central judging apparatus (which fencers tend to refer to as the 'box'), and a metal piste which the fencing takes place on. The weapons are wired up so that hits on the target area of the opponent alter the flow of electricity through the electrical circuit linking each fencer and their weapon—via a 'ground lead' to the retractable spool of wire—to the score board. This allows each hit to be registered and scored.

While the scoring system, piste, and retractable wire are common to all three sports, the use of lamé—fabric with conducting metal wires embedded that allows the scoring system to register 'on target' hits—and the wiring up are not the same, as Ian explains.

'The lamé conductive over-jacket is different for foil and sabre, and lamé is not used for epee because everything is target. For foil the lamé covers the body but not the arms. [See figure 2.2(a).] The bib [of the mask] is also target, but not the rest of the mask. So there is lamé on the bib but the rest of the mask is insulated. For sabre the lamé covers the body and the arms, and the entire mask is conductive. [See figure 2.4(a).] The cuff of a sabre glove is also lamé because that is target.'

The wired system has 'three wires for each fencer,' explains Ian. The spool is clipped to the fencer's back and has a 3-way connector. From there wires run under the fencer's clothing along their arm, out at the wrist then to the weapon's connector. The lamé is connected by a large crocodile clip.

When fencing with a foil, in which you score by making a hit on your opponent's jacket or bib, the foil blade has a spring in the tip that when depressed registers a hit. 'Foil uses a 'push to break' switch. In other words the two connections to the [sword's] point break a circuit when the point is depressed,' says Ian. 'The rectangular blade has one wire in a fine groove; the other connection is the blade itself. The third wire goes to the conductive lamé jacket. If the point is touching the opponent's guard or the metal piste then nothing happens. But if the point of the foil touches the opponent's lamé then a coloured lamp lights, a buzz sounds and the clock stops. If the point touches the opponent elsewhere—which is off target—for example their arm, then a white lamp lights, a buzz sounds and the clock stops.' An off target hit followed by an on target hit will cause a white light to be displayed with a coloured light, while for an on target hit followed by an off target hit only a coloured light will show. 'From 300 ms after a touch is registered, the opponent's circuit is ignored. This timeout significantly adjusts the nature of the sport, balancing the advantage of attacker versus defender.'

An epee hit registers when the point of the blade is pressed in. This is because you can score by striking any part of the opponent not just the trunk as in foil, so it is easier to measure the hit via the weapon rather than via the opponent's clothing.

'Epee is a 'push to make' switch. In other words the two connections to the point [of the epee] close a circuit when the point is depressed', explains Ian. 'The V-section blade protects two fine wires, while a third wire goes to the guard of the epee. If the point [of the epee] is touching the opponent's guard (or the metal piste) then nothing happens. But if it is touching the opponent anywhere [else] then a coloured lamp lights, a buzz sounds and the clock stops. A short time after a touch is registered, the opponent's circuit is blocked. The time during which a double hit can be scored is critical at epee,' he says, adding that if both fencers score within 1/25 of a second of each other, that is counted as a double hit.

For sabre, any part of the blade can score. 'There is no switch in the sabre—anywhere on the blade making contact with the opponent's lamé, glove or mask completes the circuit. There are two wires to the sabre and one to the lamé,' explains Ian. Unlike the foil and epee, there is no wire running along the sabre. Instead, conduction through the metal of the blade completes the circuit. 'The blade section is nearly triangular near the guard and has a thin rectangular section for the lighter part. If you touch anywhere other than the opponent's lamé there is no effect [on the score board].'

Wireless systems are used in elite fencing, but local competitions still use the wired systems. 'It's still rare to see wireless scoring systems. Many fencers have confidence in the performance of the wired systems. In epee, for example, if you hit your opponent's guard it is necessary that it does not register a hit, whereas if you hit your opponent's hand, say, that does register a hit. If your opponent's hand is sweaty and conductive [since sweat is salty water] and is holding the metal handle of their epee, the amount of electrical discrimination between hitting the guard versus hitting the hand is tricky to have a threshold on. Life is much easier if you've got an electrical circuit and can pass a current around it. There is also a practical problem of fencers accidentally walking off with the organiser's expensive equipment. So wireless is mostly used for the Olympics and other major events,' says Ian, who maintains wiring and scoring equipment for his local fencing club.

'It's amazing how often my experience with fencing equipment is relevant for avionics manufacture,' he continues. For example, Ian has to mitigate corrosion in his day job, which also occurs in fencing when different metals come into contact with sweat—the sweat acts as an electrolyte leading to corrosion of the metals.

‘Fencers get sweaty, and that is salty. Sweat causes metals such as copper, and the nickel that is under the plating [in the connectors for the wiring system] to corrode. In particular, the body wire at the end of the [fencer’s] wrist, where it comes out from under the clothing, has a termination to a connector which plugs into the foil, epee or sabre. That point has a number of places which corrode. If it is copper wire it corrodes really badly, and there are usually brass pieces in the connector that corrode too. So what the elite fencers often have to do is buy new kit for top level competitions to meet all the rules, especially for the resistance limit. With a corroded wire or connector, meeting that limit is not reliable,’ says Ian.

‘The materials used are so important. When we buy [fencing] equipment we take it on trust that the manufacturer has done the necessary types of plating, and that’s where it overlaps into the world of avionics,’ he continues, explaining that when choosing connectors for avionics applications he needs to study not only the specific design of the contacts in connectors, but also how the plasticity and elasticity of the metal in different places affects the forming [process] for the contacts. In addition, Ian needs to look in detail at the plating process for the connectors. For example, he must be certain that any plating is thick enough to prevent corrosion.

‘The abrasion of plating in use matters. In my fencing equipment the end of the connector that goes into the foil actually gets worn down quite a lot because you take it in and out many times. So club fencers, and anyone training [who unlike elite fencers are not constantly buying new equipment], wear the plating away and then the end corrodes. On an aircraft there is a connector between the engine and the wing, because the engines are interchangeable and have lots of electronics in them. You have to have a very good connector because it is subjected to a wide temperature range and a harsh environment, and it has to be reliable. You can’t have that corroding. Interestingly, corrosion is not just due to flying along high over a sea. Some city air contains pollutants which seem to be surprisingly reactive to some of the metals used in [avionics] connector plating,’ explains Ian.

Fretting, which is the gradual wearing away via rubbing of surfaces in contact, is another shared problem. ‘On the end of the foil [weapon] is a switch, and the parts of that switch have to be touching each other to complete the circuit. The forces of the blade’s touch are quite high because there is a big acceleration of the point when it taps against the other blade. Even a light tap is probably a very high acceleration in *g*. So the metal surfaces are pressed together by a spring but are being moved sideways against each other which will roughen [fret] the surface. Most of the designs of switch are actually pretty good, but over time a fault that appears is you get a white light come up [on the scoring apparatus] when you tap the blade. A similar equivalent in avionics will be when you have high vibration and bits of metal in contact with each other. If there is any movement between those bits of metal then the surface abrades. Because the dust [created as a result] is microscopic you get a relatively rapid oxidisation, and a powder of what looks like dirt but actually is metal oxide. That is insulating and can get between things that should be conducting. The best way to stop this happening is to make sure that bits of metal don’t move relative to one another,’ says Ian.

Metal fatigue also occurs in both fencing and avionics. ‘With metal fatigue the [fencing] blades start off straight and stiff, but after a long time get kinks and bends.

Eventually they become soft and then you know they are going to break soon [even though] the metal used is incredibly tough. In foil, for example, we often use maraging steel [low carbon steel with aluminium, cobalt, molybdenum, and titanium added] blades, which are very stiff,' Ian explains. In fencing, he continues, fatigue occurs from the bending of the blade when hits are scored, while in avionics design the potential for metal fatigue must be considered since most aircraft are mainly made from metal and are also subject to forces.

2.3 Fencing technique

Knowledge of physics can help fencers improve their technique and performance, as data science and analytics master's student George Harris, who has been fencing as a hobby since childhood, reveals.

'I began fencing when I was quite young. My interest started when my parents were clearing out the loft and my Dad's fencing equipment from his time at university was brought down. He showed me all the kit,' recalls George, who promptly joined a fencing club with his re-enthused father.

'Despite fencing for a long period of time I have only just started my competitive career recently,' continues George, who now belongs to two fencing clubs: Kingston Fencing Club and Brunel [University] Fencing, and has regular coaching sessions. 'I have managed to gain consistent results and am showing development in my fencing,' he says, adding that he participated in the British Universities & Colleges Sport (BUCS) national 'Individual Championships' competition in 2017, 2018 and 2019 (see figures 1.1, 2.1 and 2.7).

'One thing my coach always tries to put into my fencing is a good sense of timing. By timing, I mean that you understand when you have to attack and defend. If your opponent is always using the same timing to attack and defend you can then change

Figure 2.7. George Harris (seen here on the left wearing one pink sock) fencing in the men's foil category at the British Universities & Colleges Sport (BUCS) Individual Championships in 2017. In this shot George is about to finish his lunge, which successfully hit his opponent. (© Natalie B. Hogg. Reproduced with permission.)

yours so that your attacks always hit and theirs do not. Another useful skill to have in fencing is good hand eye coordination. It makes it a lot easier to control your weapon.'

George, who studied astrophysics for his first degree, says that as he became more experienced at fencing he realised that analysing the physics of the movements he was making could improve his technique.

'When I was learning [to fence] the physics of forces were never explained in detail. As I grew older and understood physics more I started to infer [the physics] from what I was doing. For example when I was a younger fencer I had a tendency to move upwards a lot with my lunge. What I didn't realise at the time was this was actually slowing down my lunge, as I was using more force to push upwards than was needed meaning my acceleration forwards towards the target was slower. I have since corrected this and now have quite a fast lunge. The same also applies for footwork,' he explains. (Box 2.2 describes a research study into the physics of the fencing lunge.)

Box 2.2. The physics of the fencing lunge

As far as inspiration goes, being a victim of crime must certainly rank as an unexpected starting point for a research study into sport science. But this was the impetus for Lindsay Bottoms, a principal lecturer in exercise physiology at the University of Hertfordshire in the UK, to start researching the biomechanics of fencing.

'I did fencing as a hobby on and off and had a love–hate relationship with it. But the critical point came when I was doing my PhD and my fencing kit got stolen from my car. I had to make a decision. Because it was so expensive to replace, did I just quit, because I'd kept saying I wasn't going to do it anymore, or did I actually start taking it seriously?', recalls Lindsay. She settled on purchasing a new kit and becoming competitive.

'I owe a massive thank you to whoever stole my fencing gear as it actually made me look at fencing [scientifically],' continues Lindsay, who on finishing her PhD got her first lecturing job at the University of Central Lancashire (UCLAN) in the UK, and was by then concentrating hard on fencing in her spare time. 'I suddenly realised I needed something to research for work, and as I was getting into my fencing competitively I thought I'd research fencing. It seemed like a nice fit as I'd suddenly got access to a lot of participants [for the experiments] which made it a lot easier. Also, the results helped me and other fencers,' she says, adding that with 33 medals available in fencing at the Olympics it is an area 'worth researching'.

For her first study, conducted in 2012 in conjunction with Jonnie Sinclair, a senior lecturer in Sport Exercise & Nutritional Sciences at the University of Central Lancashire, Lindsay looked at the fencing lunge of club level epeeists by analysing data collected via a 3D motion capture system (see figure 2.8). The system at UCLAN has eight cameras arranged around the room that enable researchers to create a 3D model of the human skeleton, and obtain angles and velocities of limbs. There was also a force plate embedded into the floor which connects up into the camera system so that they are synced together, explains Lindsay.

Each of the 14 similarly aged (26.2 ± 1.3 years) right-handed epee fencers participating in the experiment had markers attached to their body (see figures 1.2 and 2.8) and their swords. They were then asked to lunge five consecutive times at a dummy (see figure 2.9). The participants all used their right leg as the front leg for the lunge.

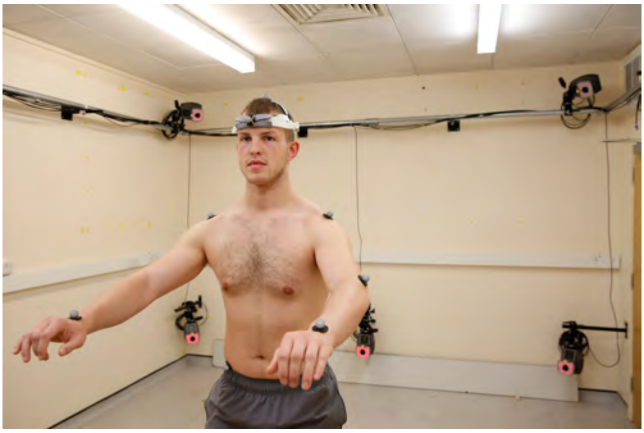


Figure 2.8. A lab at the University of Hertfordshire containing the same type of camera system and markers used to capture data in the University of Central Lancashire-based experiments on the fencing lunge. (© Lindsay Bottoms. Reproduced with permission.)

Figure 2.9. Lindsay Bottoms hitting the dummy during a lunge. This is the movement the participants in the experiment performed. (© Lindsay Bottoms. Reproduced with permission.)

'To record the movement of the lunge we used a full body marker set up where you put markers on the head all the way through to their shoes. This means that you can see the majority of the joints in the body, and the bones, so you get a full skeletal mark-up of the person. After we put all the markers on, we calculated the distance such that when the volunteer lunged their front foot would land onto the force plate. We gave them a dummy to aim for so that it was a bit more realistic than just lunging [at nothing]. We even put markers on the sword so we could get the sword velocity,' says Lindsay.

'If you get the sword velocity, you can then work out from the 3D kinematic of the body what movement is contributing to that sword velocity. In fencing you want a really fast lunge. When you do a lunge you extend your leg out at the front and straighten your back leg. Some of that [movement] is involved in increasing the speed of the sword.'

To work out the details of the movement, eight different types of 3D kinematic measures including joint angles, velocities and range of movement from the hip, knee and ankle were extracted from the data and put through a statistical analysis. The results revealed that the sword velocity is determined by how much the knee joint of the back leg is bent at the start of the lunge, the amount which the back leg (in this case the participants' left leg) straightens during the lunge, and the amount of bending of the hip joint in the front leg as that leg moves forward.

These results indicate that being lower in the stance before the lunge enables greater power to be produced during the lunge. Also, it suggests that if fencers work on the strength and conditioning of both the back and front muscles in their legs, that is, their hamstring and quadriceps muscles, they should improve the power of their lunge and hence their overall performance.

Lindsay used this knowledge to improve her own fencing lunge by targeted work conditioning her muscles. 'It's about working out what we need to condition to get the speed of the lunge to increase, and this [experiment] gave us that information,' she says. Some of her later studies revealed that the amount of bending at the shoulder and the speed of the arm extension also impact on the velocity of the sword.

While Lindsay still carries out some studies on fencing performance from a physiological and biomechanical perspective, her main area of research involves investigating the health benefits of exercise. 'What I would like to do in the future is to combine the two and use fencing as a mode of exercise for looking at health benefits. One of the issues for health is trying to get people interested in exercise or sport. The thing that I love about fencing is that it can appeal to lots of different people. Fencing can attract sporty people because it's physical, but also people who aren't necessarily sport orientated because it's got a bit of an artistic drama-type element to it. That's why I think there is quite a good opportunity to actually use fencing as a form of exercise for benefitting health.'

When a fencer extends their arm towards their opponent this is the attack. When a fencer blocks an attack from their opponent via their own weapon this is called a parry. A riposte is a move made by the fencer after they have parried away an attack from their opponent. Although the same parts of the body are used—mainly the legs, core muscles, shoulder, wrist and fingers—the fencing technique is different for each of the three swords: foil, sabre and epee. Understanding the physics of the movements for the attack, parry, and riposte for each weapon can enhance a fencer's ability, as George reveals.

'In sabre, attacks happen more aggressively than [with the] other weapons, and the attack can sometimes push your parry out of the way. By changing the blade angle when you parry you can defuse the energy of the strike, so that the attacker's blade slides down the defenders into the guard. If you notice your opponent isn't parrying correctly you can use this to your advantage also. In epee the whole body is target and double points can be scored. This means a more defensive style is encouraged as you want to hit without being hit, although there are some very aggressive epeeists at the high level.'

‘Sabre is very much the opposite. The rules in sabre favour the attack, which encourages fencers to be aggressive,’ he says. ‘Foil is the in-between weapon. It requires you to sometimes be defensive and then aggressive. Since foil is a point weapon it is harder to land the point on target, making it easier to counter attack so that the attacking opponent misses.’

2.4 Wheelchair fencing

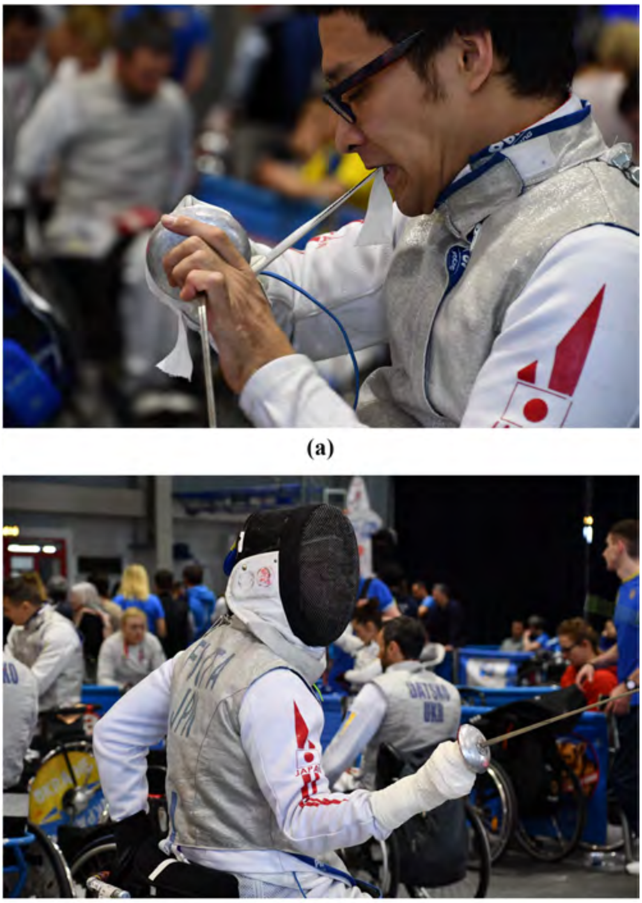
Wheelchair fencing was developed by Sir Ludwig Gutmann, a neurosurgeon at Stoke Mandeville Hospital in the UK who devised various sports in the 1940s and 1950s to help his patients with spinal cord injuries recover. In 1954 he organised the ‘International Stoke Mandeville Games’—a forerunner of the Paralympics—which included wheelchair fencing. While the early competitors used regular wheelchairs and other people to hold them in place, as we will see in this section, the current equipment is much more high-tech.

In modern wheelchair fencing there are three classifications: category A, category B and category C, explains Viv Mills, a British wheelchair fencing coach and retired competitive fencer (see figure 2.10) who began the sport after being seriously injured while on duty as a police officer. ‘Athletes in category A have impairments to their legs or balance, but good control of their trunk, while athletes in category B have

Figure 2.10. Coach and retired competitive wheelchair fencer Viv Mills about to compete in foil in her first national championships at Stoke Mandeville in the UK in 2009. (© David Akroyd-Jones Physability. Reproduced with permission.)

impairments that affect their trunk as well as their legs. Category C athletes are impaired in all four limbs to the extent they can't hold their weapon correctly. The three classifications were originally based on the level of spinal cord injury. The category C is based on someone with a cervical spinal injury. Typically you will see the category C fencers with the weapon bandaged onto their hand,' says Viv. (Figures 2.11 and 2.12 show category C fencer Michinobu Fujita from Japan preparing to compete, and during competition respectively.)

'The category C fencers don't compete in the Paralympics, only the A and B fencers [do]. Some fencers are classified as category C fencers, but they fence as category B fencers so that they have the chance to qualify for and compete in the Paralympics. While in individual competitions the [A and B] classes are kept separate, both categories come together in the team events. Teams consist of three fencers, and each person fences all three fencers from the opposing team,' continues Viv.


(a)

(b)

Figure 2.11. Michinobu Fujita preparing to fence at the IWAS (International Wheelchair & Amputee Sports Federation) Wheelchair Fencing World Cup in Pisa, Italy in 2019. (a) Michinobu bandaging his hand onto his epee, and (b) warming up ready for competing in foil. (Both images © Yuka Fujita. Reproduced with permission.)

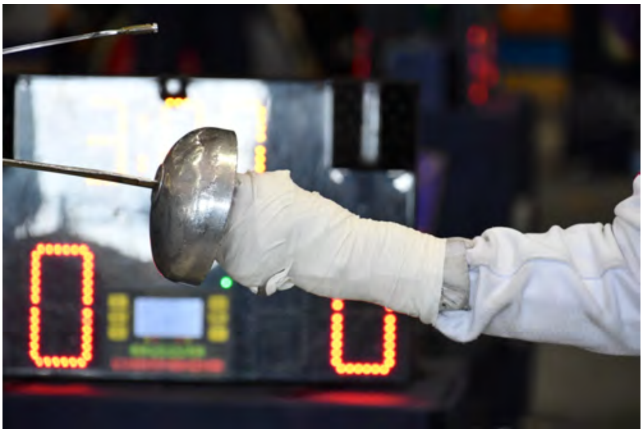


Figure 2.12. Close-up of Michinobu Fujita's fencing arm during the 2019 World Cup competition in Pisa, Italy. (© Yuka Fujita. Reproduced with permission.)

'I took up wheelchair fencing in 2009. I wanted to get back into some sort of sport, having played hockey and cricket at a reasonable level before my injury. I'd watched the Beijing Paralympics on TV. The opening credits showed two fencers beating the living daylights out of each other, and I thought 'I need to have some of that'. It took me six months to find out what wheelchair fencing was and where I could do it,' she recalls.

Viv soon began competing, and went on to win two World Cup bronze medals. The first was in foil at Montreal, Canada in 2010, the second came in sabre in 2012 in Hong Kong. She decided to retire from competitive fencing after the 2012 World Cup, but remained in the sport helping to raise its profile through charity work and coaching other fencers.

'I coach all ages from 4 years to 88—that's the oldest person I've coached. I teach all abilities from profoundly disabled to able-bodied, and I've coached fencers at the Commonwealth championships and [other] international wheelchair fencers, as well as some of the junior fencers from my club who go to their first local competition.'

'The main rules, equipment [swords and protective masks and bibs], and scoring technology are the same for able-bodied and wheelchair fencing,' continues Viv. 'The fencers sit in specially adapted wheelchairs, which are clamped into a fencing frame [see figure 2.13]. The frame is configured according to whether the fencers are right- or left-handed,' continues Viv, explaining that if a right-handed fencer has a left-handed opponent, the fencers sit side by side (see figure 2.14) while two right-handed or two-left handed fencers sit diagonally opposite to one another (see figure 2.15).

There are several different designs of frame. But all have plates for the wheelchairs to sit on and clamps to hold the wheelchair wheels which are similar to wheel clamps used for vehicles incorrectly parked. (See figures 2.13(b) and (c).) 'The wheelchair frames perform the role of keeping the fencers stable, the correct distance apart and set at the correct angle,' explains Viv. The frames themselves are not fixed to the floor, so during bouts the helpers have to move the frame and the fencers back

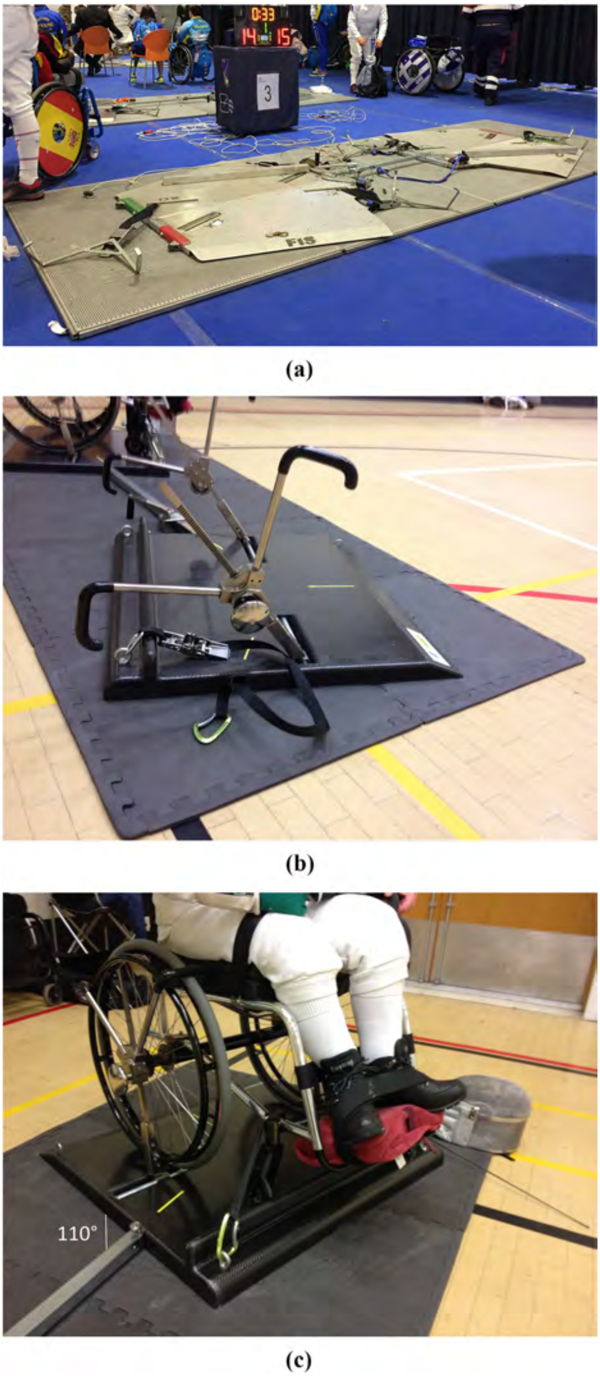


Figure 2.13. Wheelchair frames for fencing. (a) An Italian-made, lightweight, foldable, aluminium frame on castors; (b) shows one of the clamps to hold the wheelchair wheels on a French-made carbon fibre frame; (c) wheelchairs are fixed at the statutory angle indicated of 110° (±2°) relative to the central bar of the frame in the horizontal plane. (All photos courtesy of Vivien Mills. Reproduced with permission.)

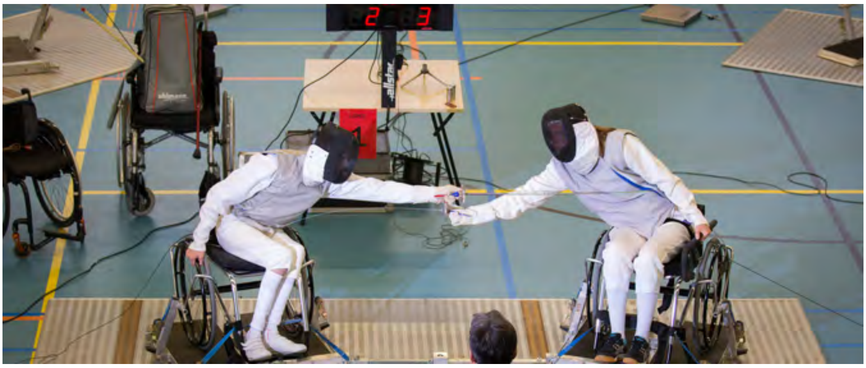


Figure 2.14. A right-handed wheelchair fencer with a left-handed opponent in an international tournament on October 11, 2014 in Gouda, The Netherlands. (© Rob van Esch/Shutterstock.com.)

Figure 2.15. Two right-handed wheelchair fencers competing in the Asian Para Games in 2018 at Jakarta, Indonesia. (© FocusDzign/Shutterstock.com.)

into position. Perhaps surprisingly, the frames do not prevent the fencers from falling out of their wheelchairs. ‘You do come out frequently. I’ve crashed out of my wheelchair many a time,’ says Viv.

The distance the wheelchairs are set apart from one another on the frame depends on the reach of the fencers, as they must be able to reach each other to score points. This distance is ascertained by each fencer extending their fencing arm whilst holding their weapon but without making a lunging movement, while their opponent bends their fencing arm. For foil each fencer needs to be able to reach the inside bend of their opponent’s elbow, while for both sabre and epee a fencer must be able to touch the outside of their opponent’s elbow. (The first section of the first video in the web links at the end of this chapter shows the setup before the fencing begins.) The rules also state the wheelchairs must be fixed at a statutory angle of 110° (±2°) relative to the central bar of the frame in the horizontal plane (see figure 2.13(c)).

‘There are various frames all made by different manufacturers. One type of innovative frame is an Italian made lightweight, foldable, aluminium frame on castors,’ says Viv, explaining that this frame (see figure 2.13(a)) makes it easy to set up for both left- and right-handed fencers. ‘The best frame by far is a French model which is carbon fibre [see figure 2.13(b) and box 2.3], but the most impressive feature is the clamp,’ continues Viv, explaining that this is tightened via the central part of it being spun round.

Wheelchair fencing uses specially made sports wheelchairs, which can have bespoke adjustments. For example, fencers can choose different heights for the back rest or the arms so long as these fall within the heights specified by the sport’s regulations.

‘The thing that my [fencing] wheelchair has which most other people’s don’t have is a fifth wheel on the back, which is an anti-tip wheel’, says Viv. ‘I’ve also got slightly cambered [angled away from the vertical] wheels, with 4 degrees of camber,’ she adds, explaining that ordinary wheelchairs have 2 degrees of camber while fencing wheelchairs will have either 4 or 6 degrees of camber on their wheels. This is created by the axle at the back of the wheelchair which itself is angled away from the vertical such that the attached wheels are then also at an angle. ‘For wheelchair

Box 2.3. Carbon fibre

Carbon fibre is a composite material. The two or more materials that make up a composite provide a combination of properties not available from any single material. One of the most common examples of a composite is reinforced concrete (see figure 2.16), which is widely used by the building industry and has steel rods embedded in it to make the concrete much stronger when it is under tension.

Figure 2.16. Creating reinforced concrete by pouring concrete over steel rods. Concrete itself is also a composite material, comprising a mixture of sand, cement, an aggregate such as gravel or crushed stones, and water. (© seroma72/Shutterstock.com).

Carbon fibre, which has a range of uses from prosthetic limbs to high performance cars, is made up from carbon fibres embedded in resin. ‘Prepreg’ is a dry, woven mat of carbon fibre pre-impregnated with activated resin (see figure 2.17).

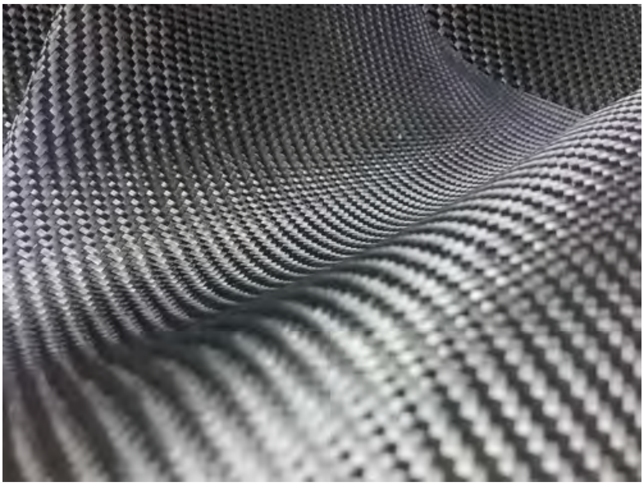


Figure 2.17. Prepreg carbon fibre. (© TLaoPhotography/Shutterstock.com).

While most prepreg has carbon fibres running in different directions, very expensive prepreg with uni-directional fibres is used for highly specialised applications such as Formula 1 wishbones (which are part of the suspension). These must withstand a high load path in one direction and so need all the fibres lined up in that direction in order to cope with the forces.

In general, to make parts from prepreg the carbon fibre mat is cut to shape and then laid carefully into a mould (see figure 2.18). The weave needs to be angled such that there are lots of fibres running in the direction of the highest load path for the forces that will act on the finished component. Layers of mat are built up to give the required

Figure 2.18. Creating a carbon fibre component for a racing car. (© fabiodevilla/Shutterstock.com).

thickness for the finished part before the mould surface is covered with 'breather cloth' that allows any trapped air to be pushed out of the prepreg. The mould is sealed inside a vacuum bag, which once evacuated is placed into an oven or autoclave under pressure to fully cure the resin. When the curing is complete the mould is taken out of the oven, and the carbon fibre part is carefully removed.

basketball and rugby that angle is what gives them the stability to enable them to do the sharp turns. On my wheelchair the camber has helped to offset some of the force you get in the diagonal [plane].'

This force comes from the lunge movement, which many wheelchair fencers—depending on their impairment—make by holding onto the arm of the wheelchair with their free arm and pushing forward with that arm, explains Viv. 'So you are pushing with one arm while you are reaching with the fencing arm [that is holding the sword]. This happens at a slightly diagonal angle, and what happens with the physics of the chair is that over the years the chair becomes warped because of the torque [see box 2.4] on it caused by the fencer's movement. So when you go to push the wheelchair you realise it is all wobbly because the forces have pushed the steel into a buckled position. You can actually see the chair starting to lean over.' The forces involved in the lunging movement are large enough that they can also buckle the frame holding the wheelchairs in position, she adds.

'I've had my wheelchair for nine years now, and it is still going [thanks to its fifth wheel]. Most wheelchairs have died after about three or four years because they just snap in half eventually because of the pressure,' explains Viv, who is hoping someone will research exactly what forces are involved as this would yield very useful information for competitors and coaches, and for steering future design of fencing wheelchairs. 'The physics of it, I think, is fascinating. The force that goes through that wheelchair at a diagonal angle is phenomenal.'

'The main muscle groups involved in wheelchair fencing are around the hips (the obliques and core), and fast twitch muscles in the forearm, upper arm and the shoulders. If your hips work you have a much better chance of winning matches because you move very much faster,' continues Viv.

'In wheelchair fencing the physics of what is going on is crucial to the fencer understanding where the power comes from, where injuries can occur and how the wheelchair is going to be punished. The wheelchairs always snap in the same places, and fencers need to be aware to look for signs of weakness.'

'In general wheelchair fencers will be pushing with one arm and lunging with the other. So [to assist the lunging movement] you can lower the backrest on the wheelchairs and also alter the position and shape of the arm of the wheelchair on the side of the participants' fencing arm.'

In order for the electronic scoring system to work, 'the frame sits on a metal piste—the same metal piste used by able-bodied fencers—which is earthed so that if a weapon tip hits the floor the scoring box will not be activated. [As with able-bodied fencers]

Box 2.4. Torque

If we describe an object as being in static equilibrium we mean that it is not being subjected to any net force that is moving it from one place to another and also that there is no net force twisting or rotating it. When the latter scenario holds this is known as rotational equilibrium, while in the former the object is said to be in translational equilibrium.

Force is a vector quantity so both its magnitude (size) and direction need to be specified. For translational equilibrium, the vector sum of all the forces acting on the object must be zero i.e.

$$\sum F = 0 \tag{2.1}$$

Similarly for rotational equilibrium, the applied forces must add up to zero, so the forces cannot be applied such that the object twists round.

The upper diagram in figure 2.19 shows a lever in equilibrium about its pivot point labelled P. In this case force F_1 multiplied by the distance L_1 between the point at which the force F_1 acts and the pivot point P is equal to force F_2 multiplied by L_2. i.e.

$$F_1L_1 = F_2L_2 \tag{2.2}$$

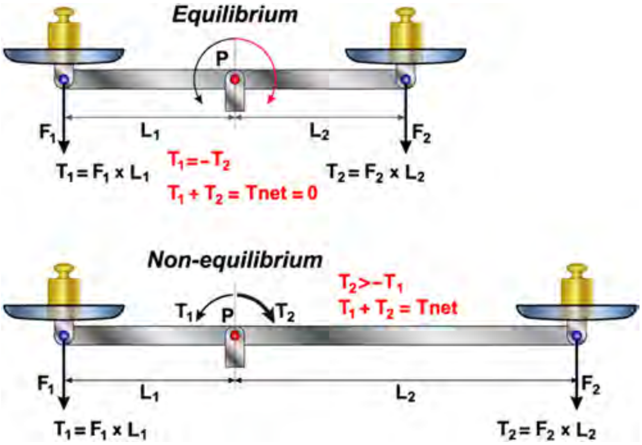


Figure 2.19. A lever in (top) equilibrium and (bottom) non-equilibrium. (© Fouad A. Saad/Shutterstock.com)

The product of a force and its perpendicular distance from the point of rotation is known as the torque or moment. Torque, T, measured in newton metres (N m), therefore describes the ability of an object to twist, or the amount of leverage. So equation (2.2) can be written as

$$T_1 = -T_2 \tag{2.3}$$

because although both torques are equal in magnitude, the torque of F_1 with respect to the pivot point P is anticlockwise, while the torque of F_2 is in the opposite direction i.e. clockwise. Writing one torque as negative allows this difference to be expressed mathematically. Equation (2.3) is therefore saying that in rotational equilibrium the sum of all the clockwise torques acting on an object must equal the sum of all the anticlockwise torques.

This equation can also be written as

$$T_1 + T_2 = 0 \tag{2.4}$$

thereby giving another way of mathematically expressing the condition for rotational equilibrium.

When a lever is not in equilibrium, such as in the non-equilibrium example situation shown in the bottom diagram in figure 2.19, then equation (2.4) no longer holds. Instead, one torque will be greater than the other giving rise to a net torque which results in the lever rotating about its pivot point.

the fencers are wired up to the scoring box via a body wire which is passed through the fencer's jacket, and a hole in their glove. One end of the body wire is plugged into the weapon and the other end is plugged into the scoring box,' explains Viv.

'In wheelchair fencing the target area for epee is anywhere above the waist. To ensure that only hits on the target area count the fencers wear a large conductive lamé apron, which covers the non-target area of the fencers and their wheelchairs. Ground wires are used to earth the aprons, attaching them to the metal piste so you don't score when you hit them,' she continues.

'Foil and epee are stabbing weapons, so a lot of the movements to hit an opponent are similar for both weapons. Foil is like holding a pen [with your thumb and forefinger] and the three [remaining] fingers are the enablers. When using an epee you have one finger up and three gripping. The curvature of the weapon blade is important. It determines how much flick you can get out of the blade. The flicking motion in fencing is a little bit like fly fishing. The speed of a fencing tip is considered the second fastest missile in sport, second to the bullet in shooting.'

'The sabre, however, is a cutting weapon and the technique is totally different. You use your thumb and forefinger to grip a sabre. The three fingers particularly the little finger are used to refine the movement. The hand has to be angled, so the forearm is used far more, but the speed and power comes from the fingers, so a lot of the strain is in the fingers and the wrist,' says Viv, adding that strength and dexterity in the fingers is essential for fencing success.

Viv says she explains the physics involved in the lunge to the fencers she coaches as this helps them improve their performance. 'When I'm coaching I tell everybody that the first thing you need to do is to look at your disability and work out what you can do with your disability—which bits can you move and how can you get to move them. You then need to understand what your opponent can do disability-wise. So for example if your opponent is an amputee and they have only got one arm it means that they haven't got anything to hold on the [wheelchair] arm with. So they can't lean out as much.'

'In able-bodied fencing there is a big difference in the strength of the fencing arm compared with the non-fencing arm, but in wheelchair fencing there is no difference in the arms, because both arms are used in performing the fencing technique,' says Viv. In order to ultimately execute a very fast lunge, 'I teach fencers to lunge very, very slowly [at first] to get the movement correct and build up muscle memory.'

'Knowledge of the physics and the biomechanics involved is very important especially as each wheelchair fencer needs to maximise the parts of the body that are functioning,' continues Viv. 'The best wheelchair fencers also modify their wheelchairs to enable the maximum usage of their bodies.'

Further Reading

Bottoms L, Greenhalgh A and Sinclair J 2013 Kinematic determinants of weapon velocity during the fencing lunge in experienced épée fencers *Acta Bioeng. Biomech.* **15** 109–13

Sinclair J, Bottoms L, Taylor K and Greenhalgh A 2010 Tibial shock measured during the fencing lunge: the influence of footwear *Sports Biomech.* **9** 65–71

Sinclair J K and Bottoms L 2015 Gender differences in limb and joint stiffness during the fencing lunge *Cent. Eur. J. Sport Sci. Med.* **11** 39–44

Sinclair J and Bottoms L 2013 Gender differences in the kinetics and lower extremity kinematics of the fencing lunge *Int. J. Perform. Anal. Sport* **13** 440–51

Weblinks (live as at June 2019)

Video footage of a match from the wheelchair fencing men's team epee competition from the Rio 2016 Paralympic Games which shows the set up procedure for the fencers, explains how the team competition works, and features my favourite fencer Kamil Rzasa from Poland
https://www.paralympic.org/video/wheelchair-fencing-pol-v-ita-men-s-team-epee-third-match-rio-2016-paralympic-games
International Wheelchair & Amputee Sports Federation, Wheelchair Fencing
http://www.iwasf.com/iwasf/index.cfm/sports/iwas-wheelchair-fencing/
British Disability Fencing
https://britishdisabilityfencing.co.uk/
Fencing kit manufacturer Leon Paul London
https://www.leonpaul.com/
Oliver Lam-Watson's YouTube channel
https://www.youtube.com/channel/UCkNz1NgAfZFyi4LtFL-P_Kg
Oliver Lam-Watson's Instagram
https://www.instagram.com/oliverlamwatson/?hl=en
British Universities & Colleges Sport, Fencing
https://www.bucs.org.uk/page.asp?section=19299&sectionTitle=Fencing
USA Fencing
https://www.usafencing.org/
British Fencing
https://www.britishfencing.com/

Chapter 3

Foot to the floor—the physics of drag racing

3.1 Introduction

If we pull away from traffic lights quite rapidly we might feel the effect of g force on our bodies pushing us back slightly into the driving seat as we accelerate. But this is nothing compared with the forces acting on the drivers of dragsters. The acceleration that is an integral part of drag racing is brutal in comparison, and it takes careful preparation of both car and driver to cope with the speeds with which everything happens in order to achieve a successful drag run.

In this chapter, retired drag racer Alec Coe describes what it feels like to race in arguably the most extreme form of motorsport there is. I met Alec in 2009 at an American and Custom Car Show in the UK, and interviewed him for a 2013 feature in *Flipside* magazine. As we will see, Alec built up knowledge of physics in action that was essential in enabling him to complete his runs as safely as possible.

We also look at some of the physics that enables the fastest dragsters in the world, Top Fuel dragsters, to reach their incredible speeds.

3.2 View from a drag racer

Perhaps surprisingly, retired British drag racer Alec Coe (see figures 1.4(a) and 3.1) says he never did anything special to prepare for withstanding the g forces when he rocketed away from the start line of a drag race.

‘Because we have got a full roll cage, and our head is covered with the helmet and the balaclava, and we are wearing a fire suit and harnesses, all we can move is our hands and feet. So as we’re accelerating [see box 3.1] we make sure our head is back against the roll cage, so you don’t get that crack back. When the parachute opens and the car slows down, you get the opposite effect and your head does come forwards. But we’ve got a big neck restraint on, which stops our neck moving about. The neck restraint is basically a thick cushion that goes round our neck, which holds the neck still and keeps the head straight,’ explains Alec, who says he first ‘fell in love with cars’ at the age of four when visiting his uncle’s scrapyard in Cambridge.

doi:10.1088/2053-2571/ab2332ch3

Figure 3.1. Alec Coe in his dragster starting a run, with poor traction causing the car to turn, at the Shakespeare County Raceway in the UK. (© Alec Coe. Reproduced with permission.)

Box 3.1. Acceleration, deceleration and *g*-forces

Acceleration is the rate of increase of velocity while deceleration is the rate of decrease of velocity. Deceleration is represented as negative acceleration. Acceleration is measured in metres per second per second. This is written as metres per second squared ($m\ s^{-2}$). Table 3.1 shows some acceleration values in metres per second squared.

Table 3.1. Some acceleration values.

Cause of the acceleration	Acceleration in $m\ s^{-2}$
Lamborghini Gallardo LP 560-4 Spyder from 0 to 100 $km\ h^{-1}$	6.94
Acceleration due to gravity on surface of earth	9.76–9.86 (varies with location)
Alec Coe's dragster	33.53
F16 fighter jet pulling out of a dive	80
Ejecting from an aircraft	150

When we accelerate, the acceleration causes an extra force to act on our body. This is known as a g force where $1g$ is equal to the acceleration of free fall caused by the Earth's gravitational field.

Weight is the force due to gravity. Since our weight, W (measured in newtons, N) is our mass, m (in kg), multiplied by g (in $m\ s^{-2}$), then a force of $4g$ would feel to us as though we were four times heavier than normal.

Here he saw American vehicles from United States Air Force bases in the UK which had been left behind and were waiting to be scrapped. Through his childhood he also became familiar with the 1930s US cars used by a local funeral director, and as a teenager had the chance to drive an American Dodge articulated lorry with trailer on private ground.

By the time he was 19, Alec was firmly hooked on American automobiles, and after hearing about the Santa Pod Raceway in Bedfordshire in the UK (home of the FIA European Drag Racing Championships) thought to himself 'I've got to do this'. He promptly bought his first dragster and raced at Santa Pod for a year.

'Lots of Americans came over including [8 times National Hot Rod Association U.S. Nationals winner, drag racing legend] Don Garlits and I got to see them,' recalls Alec, who sold his dragster after his children were born but still attended drag racing meetings as a spectator. 'My sons loved it,' he says, adding that he began racing again when his youngest son was 17 and bought his own dragster which both he and Alec drove.

'After a year of competing I bought another car as I didn't want to share the driving. I wanted to drive all the time. We were in four different championships. I won two and my son won two. We wiped the board with everyone that year! In the third year [of racing] we started having a bit of engine trouble with my car and the chassis cracked. So it was time to get a new chassis made and £30 000 later we had a car,' explains Alec, who says the dragster took specialist builders around nine months to complete.

He then returned to racing, competing regularly at the Shakespeare County Raceway in the UK (which closed in 2018 after 44 years operating as a drag strip). Race meetings would follow a similar pattern as Alec recalls. 'We always got there on a Friday ready for racing on a Saturday. On the Friday I did the unpacking, then my son and nephew [working as mechanics] would check every single nut and bolt on the car externally, and check to make sure the top bit of the engine was together.' These checks are very important, says Alec, because for each drag run 'the car is flat out and everything is under such great stress that things do come loose with the vibration running down the track.'

For safety reasons, the three crew helping Alec on race days would have specific jobs allocated to them. 'If too many people work on the car it gets confusing as to who has checked what. If I stepped in sometimes and did a job, the next time they might think I'd already checked something when I hadn't. So I kept out of it.'

'The hardest work [in the preparation] is moving the car around when it's in the pits because it is heavy, and the back axle has got a locked differential so both wheels have to turn at the same speed. Normally when you push a car round a corner one wheel can turn quicker than the other. But as our cars are locked, even though one [wheel] is trying to do a different speed round the bend it can't. [Instead] the tyres are trying to turn the car which makes it feel heavier. So setting up and packing away at the start and end of the weekend is quite hard work,' recalls Alec.

His dragster (see figure 3.2), which he has now sold, contained an engine imported from the US that was based on 'a small-block Chevrolet engine which was in the

Figure 3.2. Side view of Alec Coe's dragster. (© Alec Coe. Reproduced with permission.)

Corvettes. But ours was a purpose built block with specialist pistons and valves. Everything in these [dragster] engines is better quality [than in a production car], finely machined, and optimised specifically for drag racing. If you drove one of these cars on the street it would leave anything else standing.'

'Every half a mile we would put brand new engine oil in the car, which it needs because even when the engine is brand new it's under real stress. Also because we were running on methanol, even though it keeps the engine cool, the methanol gets through into the oil and makes the oil a caramel milk colour. So it degrades the oil very quickly,' continues Alec.

'About half an hour before a race we would warm the engine up to get it to a good temperature. The engines like to run nice and warm. If you try to run them from cold, they don't perform as well,' says Alec, adding that by the end of a run the engine is 'really cooking'.

'Different cars start in different ways. Mine had an on-board starter motor but a plug-in battery and button lead from the outside of the vehicle to keep the weight down. The crew man connected it all up. All I had to do was turn the fuel on then flick the master switch on. As soon as it's started you take the battery lead off … and it's running.'

Although Alec would sit in the car to start it up and so allow the engine to warm, he then got out while the engine was turned off again and the dragster was towed towards the start line. 'It's too dangerous to drive these sorts of cars in the pits because of the power, and if we were to drive them down to the start line they'd get overheated,' he explains. 'Once we were near the start we'd get the tow car out of the way, start up the engine and drive round onto the track into what they call the "burn-out box".'

This is a section of track with standing water positioned under the rear wheels of the dragster which enables the wheels to spin freely. It is used 'to heat your tyres up—once you've done the burn-out you can't put your hands on the tyres as they'd blister your hands—and to clean all the dirt off as well,' says Alec, explaining that cleaning off dust or embedded stone, which the very soft tyres readily pick up when they are hot, is important for safety reasons. This is because dirty tyres can lose traction, and since both rear wheels are turning at the same speed due to the locked differential, if one wheel is dirtier than the other and loses traction the car will start to turn instead of staying straight. To keep in a straight line Alec says you also need the tyres to be pumped up exactly the same, to avoid causing a height difference between them which could turn the dragster to the right or left.

‘You drive into the water box and when your rear wheels are in it you floor the accelerator. The wheels spin on the spot and the car starts creeping forward. If you imagine being on a dry patch of tarmac and flooring it [the accelerator] there is instant load on the gear box and back axle. Because the wheel has got something to grip onto means the dragster is working harder. But if it’s in water, the wheels will freely spin on the water. So it is gentler on the gearbox and the axle.’

‘You smoke the tyres once it leaves the water box and gets onto the dry tarmac surface,’ continues Alec, explaining that although the driver is spinning the wheels on the spot the dragster slowly creeps out of the water box just because the wheels are spinning so hard. ‘As it moves onto the tarmac the wheels are still spinning and spinning. You can smoke the tyres along one third or half the track, [during] which time you’re picking up speed as well [see figures 1.4(a) and 3.3]. My car did 184 mph [296 km h^{-1}] flat out at the quarter mile, so doing a burn-out the wheel speed must have been nearly 200 mph [322 km h^{-1}],’ he explains, adding that because of their flexibility the tyres increased in height by 4–6 inches [10–15 cm] during burn-outs.

Figure 3.3. Tyres smoking on the dry tarmac race track after a burn-out in the water box. (© Alec Coe. Reproduced with permission.)

The tyres are designed to expand as this increase in tyre size helps the car to keep accelerating. ‘If you have small wheels on you get far better acceleration [off the start line] but when you get to the half-track it won’t accelerate any more. If the wheels are growing the faster you go,’ says Alec. This is because the increase in tyre size is effectively working like an automatic gearbox enabling the engine to keep running at the optimum rpm for creating power and acceleration. (Section 3.3 describes this effect in more detail.)

Once the burn-out process is complete, ‘you stop and reverse back and one of the crew men sprays de-icer on the bug catcher—where the air goes in when you open the throttle. If you look at the picture [see figure 3.4] the bug catcher is where it has got ‘Old Git’. Those three round flaps open and let the air in. It needs a lot of air because we’re doing about 2.5 gallons (11 l) of fuel on a quarter mile, so that’s 10 gallons (45 l) to the mile. Because that air is forced in there so hard it tends to freeze, so we have to spray de-icer on the bug catcher so it doesn’t freeze open. Otherwise you’d never stop the engine.’

‘Once you’ve reversed back, you sit there looking at the ‘Christmas tree’, which is the traffic light [see figure 3.5]. There’s a starter man on the track and he presses a button when he thinks we’re ready. Then the countdown will go on the tree. It will go from two white lights that mean you’re in stage ready, to one amber light and when you see that amber light you have to go. You have to press the throttle because even though the amber light is showing it’s only a split second before the green light comes on, and if you wait for the green your reaction time is quite bad and it could lose you a race,’ says Alec.

Figure 3.4. Views of Alec Coe’s dragster. The three round flaps emblazoned with ‘Old Git’ let air into the engine. (© Alec Coe. Reproduced with permission.)

Figure 3.5. A race track starter with the traffic light in the background. (© Stephen Mcsweeny/Shutterstock.com.)

‘As soon as you see the amber light and you floor it, by the time your eyes have straightened onto the track you’re probably doing 60 mph [97 km h^{-1}]. So you have to be aware of how you’re positioned and how the car feels as it is launching because by the time you’re doing 60 mph and you’re 100% in control, your car might be going the wrong way. So it’s just instant reaction to keep it straight.’

Alec says drag racers can do quite a lot to steady the car if it begins to go a bit off-course. ‘Sometimes you think you’re doing a really straight run but it’s all over the place. You don’t realise, because it’s so quick, how much you are moving and steering.’

Practising during race meetings by doing solo timed runs helped Alec prepare himself for being able to react to the lights at the sort of speed required to win races. In this case the timing clock begins as the dragster passes the start line. ‘You get the time come up from when you leave the line to when you get to the finish. So you could sit there for 10 seconds and then go. But if you’re racing against somebody, they’ve [already] finished!’

‘While learning I was taught to sit there [at the tree], do it at my own speed and not feel panicked into going. Nobody is pressuring you,’ says Alec, who held onto that philosophy throughout his racing days. ‘I would sooner sit in a car with all my gear on, all strapped in, helmet on ready to go for 15 minutes before. Because if you leave getting down to the start line to the last couple of minutes, you tend to get a bit stressed out. Your heart starts beating and you can make silly mistakes.’

According to Alec, while sitting at the lights and thinking through the run it is important to ‘get in your own zone’ and not worry about anybody else. ‘You just think about you and the car because the car is the master. The car is so violent you’ve got to know that if it goes bad, back out quick and waste the run.’

‘You’ve got to be ready, calm, relaxed, and in control,’ he continues. ‘You shut your eyes and you think about what you’re going to do. Then the calmness is there. Your heart starts racing before the engine is fired up because you’re getting anxious and excited, but the minute the engine fires up and you’re in total control your heart slows down. You’re calm and you go round and race.’

The kick of the *g* forces does play havoc with your body though admits Alec. '[But] because you're strapped so tight and can't move, physically your body can't go anywhere. My car does 0–60 mph [0–97 km h^{-1}] in 0.8 s and the moment you hit the throttle the excitement and the adrenaline is so much that you just love every second of it. It's just the most amazing feeling in the world. Some of the roller coaster rides are quick, but you're not in control. You're a passenger. We're way faster than any F1, road or track car. Drag racing is the fastest motorsport in the world. It's being in control of that and knowing that you're going to be hitting 184 mph within seconds,' enthuses Alec, whose fastest run along a quarter of a mile strip from a standing start was 7.58 s.

'The car always leaves the line with its front wheels in the air, but the wheelie bar [protruding from the back of the car and visible in figure 3.3] stops the car from flipping over,' continues Alec. 'If the car goes dead straight there is no problem—the front wheels gradually come down. But if it turns left or right you've then got to fight the steering wheel. Our front axle is full of lead to try and give it a bit more weight to keep the front down. But it's still not enough. So we can't use all the power we've got because if we did the front wheels wouldn't come back down [onto the track],' he explains, adding that not every design of dragster ends up with its front wheels airborne at the start of a run.

Alec's dragster has a two speed gear box. 'There is a shift light so when the engine reaches 7000 revs per minute (rpm) the shift light comes on and you change gear. You can change gear in literally a split second, but if you're trying to steer you don't want to let go [of the steering wheel]. So you've got to get the steering wheel and car straight [in order] to let go with one hand to change gear.' Having two gears also helps if the car begins to go off course, explains Alec, as quickly knocking the car into second gear slows it down.

At the end of the run there is, of course, the need to decelerate, which subjects the driver to even more *g* force than the start. But Alec says you are not particularly aware of the forces acting on your body. 'You're so pumped up you don't feel a thing except the excitement. By the time you get to the end of the track you're really buzzing and things are just flying by you at such a speed. Then you let go [of the steering wheel] with one hand to pull the parachute handle, which is on the opposite side to the gear lever.' (Figure 3.6 shows a dragster braking via its parachute.)

'There is a gantry over the top of the track. You wait until the car is through that then you pull your parachute lever. A split second later the chute will come out and it's got the opposite effect to the acceleration [see box 3.2]. It really pushes you forward. You do feel it, but again you're still pumped up and excitable.'

'When you get to the top end [of the track] if the parachute doesn't open you can't use the footbrake to slow the car down. The footbrake makes the car twist the opposite way to the way it was moving, and because of the speed you're going the wheels are turning so fast that the flexibility of the tyre makes the tyres start to bounce,' explains Alec, adding that you are running at 4½ to 5½ pounds (31–38 kPa) of pressure in the tyres compared with the 30 pounds (207 kPa) used in a normal car tyre.

Figure 3.6. Driver Tony Schumacher slows his Top Fuel race car during the Tire Kingdom NHRA Gatornationals race at the Gainesville Speedway in Gainesville Florida USA on March 12th 2011. The deployed parachute helps bring the race car to a halt. (© Action Sports Photography/Shutterstock.com.)

Box 3.2. Parachutes and drag

We are used to objects slowing down and eventually stopping if there is no propelling force acting. This is because they will always encounter a frictional force that acts in the opposite direction to the motion. This frictional force comes from the surface it is in contact with—for example a road or track—and from any fluid it is passing through—for example air. Both will provide a force that resists the motion. Resistance created by fluid (a liquid or gas) is known as drag.

While many sports cars will have their designs optimised to reduce drag so as to reach the optimum performance levels, dragsters by contrast need to maximize drag in order to slow down and stop at the end of their runs. A parachute is the only option for slowing down from the immense speeds reached on the Quarter Mile track. So the main forces at play are similar to those which act on a skydiver when they deploy their parachute (see figure 3.7).

Before opening their parachute, skydivers experience drag from the air resistance. However their weight is greater than the drag force so the result is that their downward speed increases. If they continue falling they will eventually reach a speed known as the terminal velocity. They are unable to fall any faster than this, but since this is around 120 mph (193 km h^{-1}) for a skydiver, this would indeed be terminal if they continued at this speed all the way down to the ground. To avoid catastrophe they deploy a parachute.

The open parachute provides a much greater amount of air resistance. Since the skydiver still weighs the same as they did before deploying the parachute, this new upwards acting force slows them down considerably—generally to around 15 mph (24 km h^{-1}) thereby enabling safe landing. A similar arrangement of forces acts on the dragster so the deployed parachute can slow the car enough for the brakes to be safely applied.

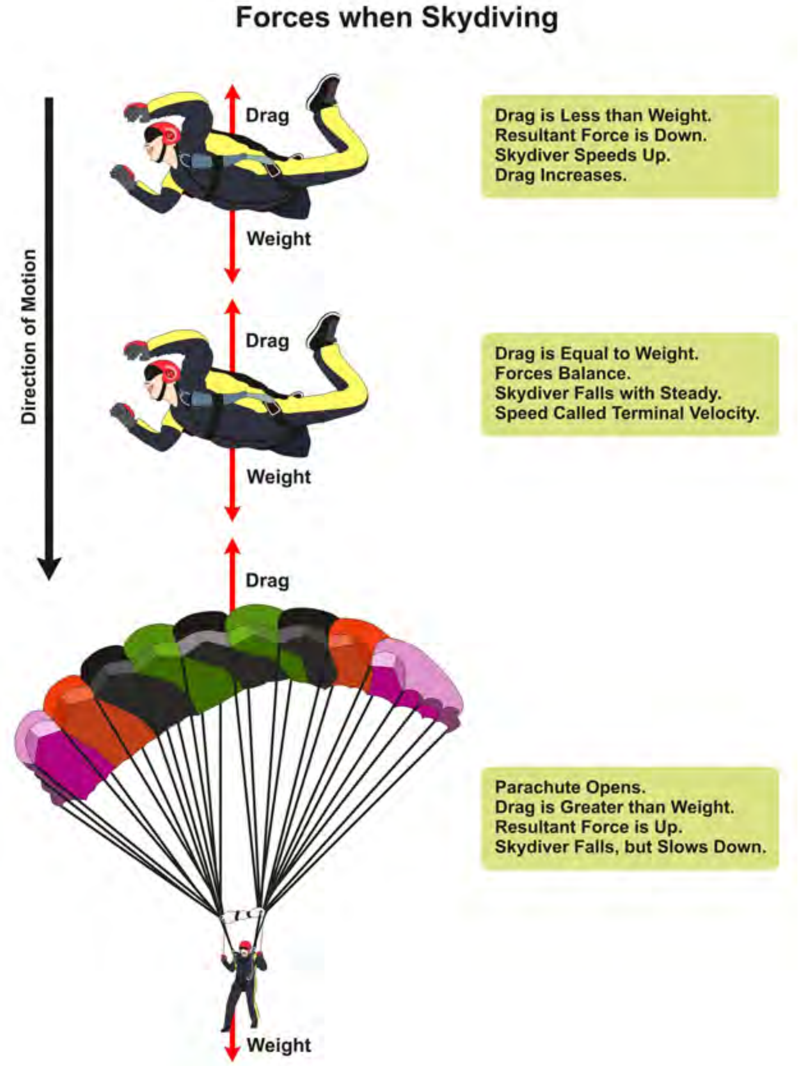


Figure 3.7. The forces acting on a skydiver. (© udaix/Shutterstock.com.)

‘It starts at literally half an inch [of bouncing above the track], then within 50 yards [46 m] it is up to 1 foot [0.3 m]. You’re still probably doing 140 mph and the whole car is bouncing on all four wheels and starts to rock from side to side. I’ve only had it happen twice but it is painful and it taught me a lesson: never use the brakes until you’re doing about 40 mph. Forces then slow you down naturally,’ he says.

‘Once you get to the end, you get out of the car, turn everything off to make it safe, pack your chute away then tow the car back to the pits,’ continues Alec, admitting that it is at this point that you tend to notice minor injuries. ‘You do get bounced around inside the car to a certain degree. Five to ten minutes after [the run] you start thinking ‘Ooh that hurts!’ Then you have a look and find you’ve got a big bruise on the side of your leg. But at the time you don’t give a monkey’s what happens because you are having so much fun.’

3.3 Top Fuel dragsters

There are many different classes of dragster, ranging from junior dragsters powered by lawnmower engines, up to the fastest class known as ‘Top Fuel’ dragsters (see figures 1.4(b) and 3.8) which hit speeds of over 300 mph (482 km h^{-1}).

Top Fuel dragsters have 500 cubic inch supercharged V8 engines, and run on fuel which is a mixture of 90% nitromethane and 10% methanol. This fuel releases oxygen when it burns. In general the more air put into an engine, the more fuel can be burned—resulting in more power. The fuel used in Top Fuel dragsters, combined with the supercharger pumped air, enables their engines to generate about 8000 bhp (brake horsepower). (See box 3.3 for more on horsepower.)

One of the reasons dragsters go so fast is because of the high power-to-weight ratio. The power of a car engine is the rate at which it turns the chemical energy provided by the fuel into mechanical energy that drives it along. The greater a car’s power-to-weight ratio, in other words the engine power divided by the weight of the car, the faster it will go. A Top Fuel dragster has a power-to-weight ratio around five-and-a-half times more than that of a Formula 1 race car.

Top Fuel dragsters use special types of tyres that are soft and expand as the dragster shoots along. Because the side walls of the tyres are extremely flexible, as the wheels revolve faster and faster, the tyres grow due to centrifugal force. The considerable rolling radius change gives an additional gear ratio. Normally, gears enable a car engine to work at a sensible number of revolutions per minute (rpm) by adjusting the speed of the wheels as the car goes faster or slower. Top Fuel dragsters

Figure 3.8. Audrey Worm in action at the NHRA (National Hot Rod Association) 2018 championships in the United States. (© NHRA. Reproduced with permission.)

Box 3.3. Horsepower

In general, power is the rate at which work is done or energy is transferred from one system to another. The power of a car's petrol engine for instance is the rate at which the engine converts the chemical energy from the fuel into mechanical energy that moves the car.

Although it is not part of the SI system of units, horsepower, the imperial unit of power, is still commonly used when describing the output of engines. It has the symbol hp and 1 hp is equal to 745.7 W. Horsepower was first used as a unit by the British inventor James Watt (1736–1819). While the SI unit of power, the watt (W), is named after James Watt and is defined as a power of one joule per second, horsepower is defined as 550 foot-pound force per second, which is 33 000 foot-pounds per minute.

A value of 1 horsepower (1 hp) is approximately the rate at which a breed of heavy horse known as a Clydesdale can do work. Thanks to experiments in the late 18th century it was found that an average heavy horse harnessed up to a 330 pound weight could pull that weight up a shaft at a rate of 100 feet per minute. Historically, describing the outputs of engines in terms of horsepower therefore gave a guide as to how much more powerful that engine was than a heavy horse.

A variant on horsepower, brake horsepower (bhp) is equivalent to the theoretical horsepower developed by an engine minus the power lost by working against friction in the engine. So bhp gives a measure of the hp at the engine's output. Table 3.2 compares the horsepower ratings for some different cars.

Table 3.2. Comparative horsepower ratings for some different cars.

Vehicle	Horsepower (hp)
Elemental Rp1 track day car	320
Koenigsegg Regera supercar	1500
Top Fuel dragster	8000

have no gear box, relying instead on their expanding tyres to alter the gear ratio as the run proceeds and keep their engine operating at the optimum rpm—about 8000 rpm—to give maximum power right through the run. This increase in tyre size also stops the wheels slipping on the track once the car is picking up speed on its run.

At the end of a run, the dragster's parachute needs to reign in all the speed that has been built. Just after launch a Top Fuel dragster will be accelerating at about 5–6g, and it will cross the line at around 320 mph (515 km h^{-1}) so similar g forces will be experienced when the driver deploys the parachute at the end of the run. Parachutes are particularly effective at slowing things down from very high speeds because the drag is proportional to the square of the velocity. Parachutes are used for dragsters instead of a conventional braking system as the latter would be much heavier. The comparatively lightweight parachute helps keep the dragster's power-to-weight ratio as high as possible, allowing the blistering speeds loved by both drivers and spectators.

Further Reading

Barrow J D 2012 *100 Essential Things You Didn't Know You Didn't Know About Sport (The Bodley Head)* **ch 19** pp 48–9

Holgate S A 2013 Boxed content for *Pedal to the Metal!*, Flipside, November 2013 www.sharonannholgate.com/cars.htm

Weblinks (live as at June 2019)

Alec Coe driving at Shakespeare County Raceway in 2010
https://www.youtube.com/watch?v=wi224pubURI
The Supercharged Outlaws at Mallory Park May 2011(includes footage of Alec Coe's dragster)
https://www.youtube.com/watch?v=uJLxsWHi5d8
Alec Coe on Facebook
https://www.facebook.com/MadRsDragRacing/
How a Top Fuel Dragster Works
https://www.youtube.com/watch?v=-VF0JwxQqcA
Slow Motion Drag Racing
https://www.youtube.com/watch?v=XttOe4rerLo
Short biography of US drag racing legend Don Garlits
http://garlits.com/don-garlits-biography/
Top Fuel dragster race slow motion
https://www.youtube.com/watch?v=Lt6iltuxD48

Chapter 4

Supporting role—physics behind the scenes in sport

4.1 Introduction

When we watch major sporting events either on TV or by attending in person, we don't often give a lot of thought to the work that goes on behind the scenes in order to bring us the live action. However, physics and technology-based support services are often inherent to enabling competitive sport whether via healthcare technologies for the participants or the equipment required in training or carrying out the sport.

In this chapter we will first look at the radiation protection services required for the medical scanning facilities that were put in place for the London 2012 Olympic and Paralympic Games. As Donald McRobbie, radiation protection advisor for the London Games reveals, medical physics played an important role in ensuring safe facilities for both patients and staff.

We will then hear from engineer Diana Hodgins, co-founder and technical director of European Technology for Business Holdings Limited, who market a gait analysis device for horses and humans that Diana first developed in 2006. Its sporting uses so far are in the equine world, analysing the gait of race horses, endurance horses, show jumpers and dressage horses in order to help improve their training and ultimately their performance.

4.2 Radiation protection at the London 2012 Olympics and Paralympics

At any major sporting event there must be healthcare facilities, and at the London 2012 Olympic and Paralympic Games the Stratford Polyclinic (see figure 4.1) in the Queen Elizabeth Olympic Park (see figure 4.2) was able to provide medical scanning thanks to two MRI scanners and a CT scanner. Each scanner was housed in its own separate portable building (see figure 4.3) outside the healthcare facility since they were to be sold after the Games concluded. The healthcare facility itself however is

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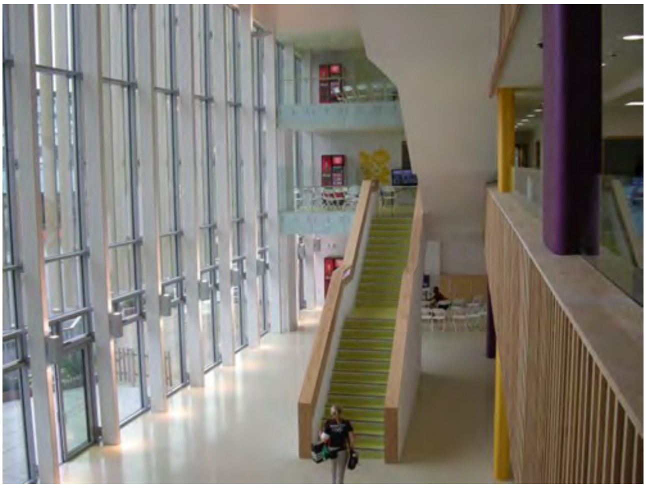


Figure 4.1. Inside the London 2012 Polyclinic. (© Donald McRobbie. Reproduced with permission.)

Figure 4.2. An aerial view of the Queen Elizabeth Olympic Park in London. (© James E Sealey/Shutterstock.com.)

one of the legacies of the Games and is still in use by the NHS (National Health Service) today.

While there was no public access to the medical facilities, 'non-athlete members of the Olympic family could receive treatment at the Polyclinic. This would include coaches, physios, team doctors, and administrative staff,' explains Donald McRobbie, a medical physics consultant, and honorary Associate Professor, Discipline of Medical Physics, School of Physical Sciences at the University of Adelaide in Australia, who was the radiation protection advisor for the London 2012 Olympics and Paralympics.

Figure 4.3. Portable scanner buildings outside the London 2012 Polyclinic. The most common parts of the body scanned during the London 2012 Olympics and Paralympics were the spine, knees and ankles (see Further Reading at the end of this chapter). (© Donald McRobbie. Reproduced with permission.)

Whenever a healthcare facility in the UK is going to be using radiation in any capacity, including for diagnostic x-rays, then stringent legal regulations must be adhered to. These regulations apply equally to permanent health centres, and those set up at major sporting events, explains Donald, who at the time of taking on the London 2012 responsibility was the Director of the Radiological Sciences Unit at Imperial College Healthcare NHS Trust, and an honorary Senior Lecturer in Imaging at Imperial College, London.

'I was approached directly by LOCOG (the London Organising Committee of the Olympic and Paralympic Games) regarding [radiation protection] consultancy to the Games' medical services. We were asked to quote for our services and were appointed by LOCOG. My team of medical physicists then provided medical physics support for the medical, dental, and veterinary clinics within the Games,' recalls Donald.

His team's duties were many and varied. In addition to developing radiation and MR (magnetic resonance) safety policies and procedures for the clinics, they had to carry out critical examinations (required by regulation) and risk assessments for the x-ray equipment. This equipment consisted of a CT scanner, a general digital x-ray room, and dental x-ray equipment, as well as veterinary x-ray equipment and facilities. They also tested the radiation shielding of the x-ray facilities, and carried out equipment acceptance testing of the medical imaging x-ray and MR equipment.

'Acceptance testing is carried out to ensure that the performance of the imaging equipment meets its technical specifications, and establishes baseline values for ongoing quality control. For x-ray equipment this will include testing of the radiation output and energy, the radiation dose delivered to the patients and (where relevant) staff, other safety features, as well as the end product image quality. For MRI the testing relates more to the final image quality, the uniformity of magnetic fields used, and safety features including the extent and containment of the ‘fringe field’. The fringe field is the magnetic field that extends beyond the scanner, but reduces very rapidly with distance from the scanner. Close to the scanner it is responsible for the attractive force on ferromagnetic objects, further away from the scanner it can interfere with electrical and electronic equipment including cardiac pacemakers’, explains Donald.

Another important duty for Donald’s team was providing radiation monitoring for the medical and dental staff, who were volunteers drawn from the UK’s NHS, and auditing the radiation doses received by patients and staff. Choosing the most suitable type of dosimeter—which measures the dose an individual has received—was a decision that took long and hard consideration says Donald.

‘The problem was that the duty to monitor staff falls upon the employer. However, the staff were volunteers, not LOCOG employees. We decided it was inappropriate for the staff to bring their usual personal dosimeters from their NHS Trusts as any dose accrued from Games’ work would be indistinguishable from their NHS work. In addition we did not consider that this fulfilled LOCOG’s legal responsibilities. It was also impracticable to set up a radiation badge service for the extent of the Games. So we decided that only staff within x-ray rooms during exposure required monitoring and this was achieved using electronic personal dosimeters [EPDs]. In practice this only involved the CT and veterinary staff. The EPD could be read out and an individual exposure record kept for each member of staff,’ says Donald, adding that there was only one incidence of a higher than usual exposure which his team were able to investigate as a result of the monitoring.

Donald’s team also had responsibility for investigating radiation incidents, and providing medical physics experts in line with the Ionising Radiation (Medical Exposure) Regulations (IRMER). ‘Developing the IRMER procedures was a major task as the use of radiation in the Games did not fit the usual definition of medical exposures. Also the provision of radiation protection and monitoring of staff as volunteers from many organisations did not fit with the usual definitions. So much work was spent on policy, including several meetings with the Health Protection Agency to ensure the Games were compliant,’ he says.

All these tasks come under the general remit of a radiation protection adviser (RPA), who helps their employer by ‘assisting with and advising on an organisation’s compliance with radiation regulations,’ explains Donald, adding that at that time the regulations in place were the Ionising Radiations Regulations 1999.

Donald says he began his aspects of the planning for the London 2012 scanning provision in the summer of 2010, but the medical committee for the Games was already active by that point and had ordered the imaging equipment.

‘Normally the RPA would be consulted over the design of the x-ray and MR rooms and medical physicists would be involved with the procurement process. But because the main Stratford Polyclinic was built as a permanent site to be used by the NHS in legacy after the Games with selling on of some of the equipment, this had already been done prior to our involvement.’

Additionally, specification for radiation shielding, and magnetic shielding for the MRI, was undertaken by a contractor in the Netherlands. ‘Our role was to verify these calculations and to test the effectiveness of the shielding. In both areas significant defects were detected and we advised on their eventual remediation prior to the Games opening, and ensured they met the appropriate standards,' continues Donald.

The main aim for all radiation protection scenarios is to keep doses to the staff and the public as low as reasonably practicable. Although the dose is tightly controlled, it can never be zero. For example, as Donald explains, there are several routes via which diagnostic x-rays leak into the x-ray room.

When an x-ray tube is switched on it will emit a beam that enables the x-ray of the patient to be taken. This is known as the primary beam. However, not all of the beam passes through the patient and reaches the detector. As well as some x-rays (see box 4.1) being absorbed by the patient's cells, a proportion of the beam is scattered from the patient or passes through them but misses the detector. There can also be some leakage of x-rays from the x-ray tube itself.

'X-ray leakage from the tube is limited by regulation, and national and international standards. It can occur around the mechanical joints in the external structure. X-rays penetrate metal so there will always be a small amount of leakage. This however is much less than the level of scattered radiation,' explains Donald, whose team measured the scattered radiation under controlled conditions via hand-held ionisation chambers and a bucket of water. The water acts as a 'scattering medium equivalent to a patients' tissue. The operator wears protective lead apparel—either an apron or a skirt and jacket,' he adds.

'Ionising radiation such as x-rays interacts with matter through three major physical means: Photoelectric absorption (where the x-rays are completely absorbed—mainly at lower energies), Compton scatter (where some energy is absorbed but the x-ray continues in a deflected path) and pair production (which is not relevant in diagnostic x-ray as the energies are too low),' continues Donald.

Box 4.1. X-rays

X-rays are a type of electromagnetic radiation with a wavelength (represented by the symbol λ) in the range of 10^{-11} m to 10^{-9} m, which is shorter than that of UV radiation.

Electromagnetic waves (sometimes shortened to e-m waves) including light and x-rays, do not disturb the particles of the solid, liquid, or gas they are travelling through. Instead they are comprised of vibrations of the electric and magnetic fields in the area they are moving through.

By contrast sound waves are an example of an elastic wave, which is a wave made up from the vibrations of the particles of whatever solid, liquid, or gas it is travelling through. The vibration passes from one particle to the next particle and so on, so that the wave travels onwards.

Waves can be grouped into two types, longitudinal and transverse. Waves such as sound waves that travel along in the same direction as the vibration that makes up the wave are known as longitudinal waves while electromagnetic waves such as x-rays are a type of transverse wave (see figure/video 4.4) which means a wave that moves along at right angles to the direction of motion of the vibrations that it is made from.

Because x-rays can pass through many forms of matter they are useful for looking at bones and some other structures inside the human body. While natural x-ray sources exist, the x-rays used in medicine, for carrying out research experiments, and for industrial testing of structures are created in an x-ray tube powered by electricity.

Figure/Video 4.4. Demonstrating the difference between longitudinal and transverse waves using a slinky spring and a skipping rope. To create longitudinal waves with a slinky spring one hand needs to remain still while the other hand is used to repeatedly push on the spring and so generate longitudinal waves that travel along the spring from one coil to the next. To create transverse waves with a skipping rope, one person needs to hold one end of the rope still while the other person moves their hand from side to side to generate transverse waves that travel along the rope towards the still end. (© Sharon Ann Holgate.) Video available at https://iopscience.iop.org/book/978-1-64327-670-0.

Not surprisingly, the closer a person is to the radiation source, the greater the amount of radiation exposure they will receive. To shield people and equipment from x-rays, high density materials such as lead are used.

‘The primary beam from the x-ray tube will scatter off materials in the path of the beam—primarily the patients’ tissues. For intense beams such as in CT, a significant amount of the scattered radiation will re-scatter from anything [it hits] but most significantly from the walls and ceiling—[since] scatter is proportional to the scattering area. This is known as ‘tertiary scatter’. Tertiary scatter was initially a problem with the mobile CT which was elevated from the ground [via metal stilts] but not shielded underneath as the Dutch radiation consultants did not know the portable building would be elevated. We measured scatter off the ground which was reaching public areas,’ says Donald. His team had to carry out calculations on the dose that both the patients and the staff received from the CT scanners, and also on what radiation dose was leaking outside the building. These calculations revealed the need for additional lead lining in the floor which then made it safe.

Radiation protection procedures also needed to be put in place at the Veterinary Centre at Greenwich (see figure 4.5), where the equestrian events took place, as they x-rayed horses in the facility. Equine x-rays involve three different people: the groom who steadies the horse, a vet or a nurse holding the x-ray unit and another vet or nurse holding an x-ray plate. For these equine x-rays, because of the hand-held equipment, the controlled area (i.e. where radiation exposure is high enough that staff should avoid being in that area) is circular with a 2 m radius centred on the point where the x-ray enters the horse. Radiation doses received by the staff are much higher than in a hospital setting just because of the design of the portable x-ray equipment that is used, explains Donald.

Donald also worked as the MRI safety expert for the Polyclinic. Unlike x-rays, MRI (see box 4.2) does not involve ionising radiation. 'The main safety issue with MRI is in regards to limiting access for persons carrying ferromagnetic objects and medical implants including cardiac pacemakers. Normally an exclusion zone

Figure 4.5. The Veterinary Centre for the London 2012 Olympics and Paralympics. (© Donald McRobbie. Reproduced with permission.)

Box 4.2. MRI

Magnetic resonance imaging (MRI) is used to reveal high quality images of soft tissues inside our bodies. To capture an MRI scan, the patient lies inside the bore of the scanner which contains a powerful permanent magnet or electromagnet. This magnet produces a magnetic field of at least 1.5 T, which is 30 000 greater than the Earth's magnetic field.

Approximately 65% of the human body is water, and MRI images are obtained via the spins of protons within the hydrogen atoms in our water molecules. The interaction between the proton spins, the scanner's magnet, and applied radio waves creates small changes in the magnetic field which are electronically detected. When the radio waves are switched off the proton spins return to how they were behaving before the radio waves were turned on. The time that this takes an individual proton depends on the type of tissue it is surrounded by. So by recording these times too, software can then be used to construct a detailed image that reveals the soft tissues in the body.

Although MRI scans do not show bones, they are extremely useful for looking at the musculo-skeletal system and the central nervous system. Figure 4.6 shows an MRI scan of an injured knee. The main clinical applications of MRI include planning for some types of surgery, imaging sports injuries and spinal injuries, and assisting with cancer diagnosis.

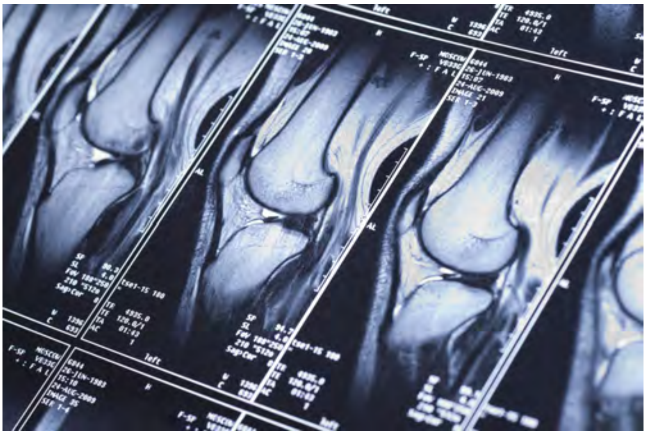


Figure 4.6. An MRI image of a knee showing damage to the cross-shaped ligaments caused by a sporting injury. (© Kondor83/Shutterstock.com.)

restricting the fringe field to less than 0.5 mT is established. This required the addition of magnetic shielding to the portable building—these calculations were carried out by GE (General Electric) or their Dutch consultants. Unfortunately they did not model that the shielding would increase the extent of the 0.5 mT fringe field contour within the structure. This required our assessment of the risks and further organisational procedures to be devised to ensure the wellbeing and safety of the staff.'

'Additionally, the MR building was situated on the main access road to the Olympic Park so the influence of moving vehicles had to be considered. For the MRI we devised local rules to ensure the staff, athletes and members of the public were safe. We also carried out a detailed safety survey and audit of the facilities, and I paid a spot inspection visit during the Games,' recalls Donald.

Overall Donald says he found the organisational aspects of his contribution to the London 2012 health care provision the most challenging part. 'Organisationally it was complex. We had to deal with LOCOG itself, the Medical Imaging and Veterinary Committees, the sponsor and equipment provider General Electric, the clinic managers, security (access to the site was highly controlled), the accreditation body, and the volunteer staff from many organisations,' he recalls, adding that 'additionally the overarching International Olympic Committee is not a national body and was unfamiliar with local regulatory requirements.' However despite these challenges, Donald says his work at London 2012 was a definite career highlight.

4.3 Gait analysis for sporting horses

In 2006, engineer and keen horsewoman Diana Hodgins became inspired by the project she was then working on. This involved using movement sensors for patients with the aim of replacing gait laboratories. She felt she could simplify the process, and set about designing a small portable device which enabled gait analysis for both humans and horses to be conducted outside of a laboratory for the first time. The horse version of this system is known as ‘Pegasus’ and can be used for analysis of horse movement in any equine sport, as well as for diagnosing injuries. It is marketed by European Technology for Business Holdings Limited (ETBH), the company Diana formed with her engineer husband in 1997 to develop specialist sensor-based devices for medical applications.

Each of the eight identical strap-on sensors in the system (see figure 4.7) contains an inertial measuring unit (IMU). Each IMU in turn comprises three orthogonal gyroscopes and a 3-axis accelerometer. So these six sensors within each IMU are able to detect orientation in two axes at right angles to each other. The Pegasus system collects raw sensor data at a rate of 102.4 Hz, sending this data straight to a PC or laptop via a USB cable. Software fuses this data together to give the orientation of horses’ legs in two planes—the sagittal plane and the coronal plane. The sagittal plane is the side view and looks at the flexion and extension, while the coronal plane is the view from the front which looks at any out-of-plane movement in the legs. Using this system a full gait analysis can be performed in less than 10 minutes in any type of weather or lighting conditions, and in the horse’s usual environment. Pegasus enables problems to be picked up before they become so bad that they can be readily seen or heard, and gives a quantifiable measure of the problem in a level of detail impossible to achieve by eye. ‘It is a completely different way of looking at horse movement,’ says Diana, who has been awarded an MBE (Member of the Order of the British Empire) for her services to small and medium sized businesses.

Figure 4.7. Eight Pegasus sensors strapped onto a horse’s legs ready for carrying out a gait analysis. Each sensor contains an IMU. (© Diana Hodgins. Reproduced with permission.)

'You can extract a lot of data by knowing the orientation of each of these sensors in relation to each other in a gait cycle,' explains Diana. In the trot gait the legs work in diagonal pairs. The left fore limb and the right hind limb form one coupled pair, while the right fore limb and left hind limb form another coupled pair. Each coupled pair is half a stride out compared with the other, which you can hear as a horse trots. In order to look at a horse's trot gait in detail (see figure 4.8) the system takes one coupled pair and shifts the plotted data by half a stride. This results in the curve plot of the data for one coupled pair overlaying the data plot for the other pair of legs. So any disparity in the movement of the horse's legs during the gait shows up as asymmetry between the plotted curves.

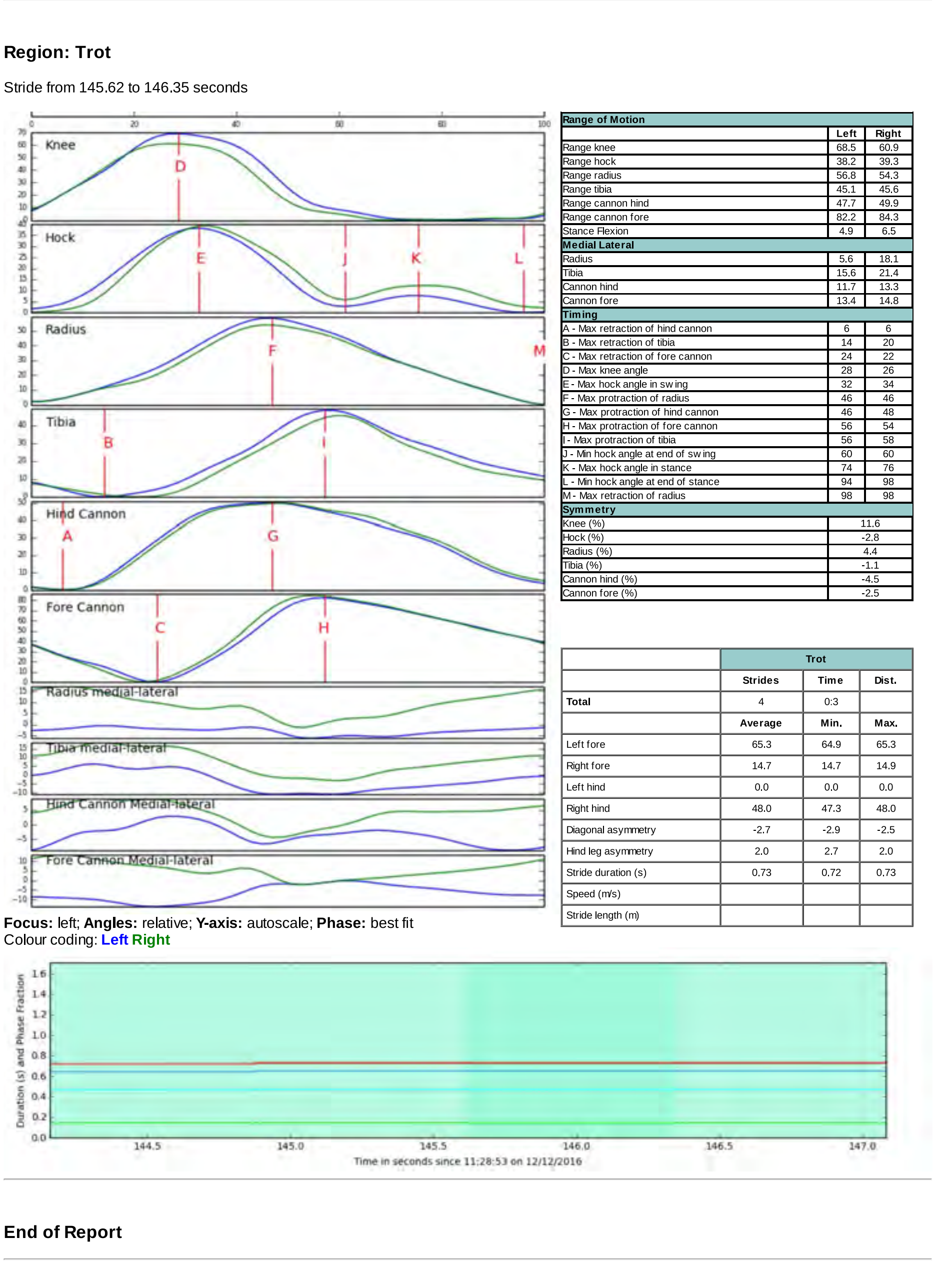
'You hear hoof down at the same time, but if you look at the movement of the hind limb and the fore limb prior to hoof down they are very different,' continues Diana. 'In a horse the knee locks when it loads. This leads to a flat line in the stance part of the graph [where the legs are momentarily stationary]. But the hock bends when it's loaded. The hock angle is very like the human knee angle. So you get a swing phase and then you get a loading phase, and it flexes twice. Horses have an extra flexion at the fetlock that we don't have. They are very complex.'

If a fore limb is hurting a horse when landing on it, it will adjust its gait to land on its hind limb first to take the initial load, then rock onto the fore limb. Similarly, if it has pain in its hind limb it will put the fore limb down first and then rock back onto the hind limb to take some of the loading off of the painful limb. 'It uses the fact it's got two legs coming down in trot to adjust. You'll see that because all those lines [on the Pegasus system read-out] shift one way or the other,' explains Diana.

'[With these graphs] you can immediately see where the horse's hoof comes down, where it is locking, and whether it is bending or loading it properly,' she continues. Any asymmetry in the gait is revealed in the graphs by the overlaid curves shifting in relation to one another, in a similar way to a sine wave lagging or leading another (see box 4.3).

'Timing is very, very important with a horse. We can immediately see if its gait is asymmetric. Nobody else has produced graphs like this,' says Diana. 'Equine biomechanics books are very basic. When people have analysed gait in the past they've looked at joints in isolation. Nobody has looked at all four legs together. But because our technology is so far ahead it could take people years to adopt it. However, it enables early stage problems to be picked up, and there have also been academic studies and papers written on the device.' (See Further Reading at the end of this chapter.)

The trot is the gait that is always used by vets for analysis, as none of the other gaits are suitable for detecting injury, explains Diana. In the walk gait, three legs are on the ground simultaneously so it's not obvious if something is wrong. The canter is difficult to analyse because horses tend to canter differently and the gallop, like the canter, is not meant to be symmetrical. The trot, by contrast, should be a



Region: Trot

Stride from 145.62 to 146.35 seconds

Range of Motion		
	Left	**Right**
Range knee	68.5	60.9
Range hock	38.2	39.3
Range radius	56.8	54.3
Range tibia	45.1	45.6
Range cannon hind	47.7	49.9
Range cannon fore	82.2	84.3
Stance Flexion	4.9	6.5
Medial Lateral		
Radius	5.6	18.1
Tibia	15.6	21.4
Cannon hind	11.7	13.3
Cannon fore	13.4	14.8
Timing		
A - Max retraction of hind cannon	6	6
B - Max retraction of tibia	14	20
C - Max retraction of fore cannon	24	22
D - Max knee angle	28	26
E - Max hock angle in swing	32	34
F - Max protraction of radius	46	46
G - Max protraction of hind cannon	46	48
H - Max protraction of fore cannon	56	54
I - Max protraction of tibia	56	58
J - Min hock angle at end of swing	60	60
K - Max hock angle in stance	74	76
L - Min hock angle at end of stance	94	98
M - Max retraction of radius	98	98
Symmetry		
Knee (%)	11.6	
Hock (%)	-2.8	
Radius (%)	4.4	
Tibia (%)	-1.1	
Cannon hind (%)	-4.5	
Cannon fore (%)	-2.5	

	Trot		
	Strides	**Time**	**Dist.**
Total	4	0:3	
	Average	**Min.**	**Max.**
Left fore	65.3	64.9	65.3
Right fore	14.7	14.7	14.9
Left hind	0.0	0.0	0.0
Right hind	48.0	47.3	48.0
Diagonal asymmetry	-2.7	-2.9	-2.5
Hind leg asymmetry	2.0	2.7	2.0
Stride duration (s)	0.73	0.72	0.73
Speed (m/s)			
Stride length (m)			

Focus: left; **Angles:** relative; **Y-axis:** autoscale; **Phase:** best fit
Colour coding: **Left** **Right**

End of Report

Figure 4.8. Trot data for the horse Star obtained by the Pegasus system. (The first page of this report is shown in figure 1.6.) The system reveals details of all phases of the trot gait from the swing phase where the legs move, to the stance phase at the end of the cycle. (© Diana Hodgins. Reproduced with permission.)

Box 4.3. Waves lagging and leading

Many physical phenomena depend on the behaviour of waves. A sine wave can be used to represent both transverse and longitudinal waves. While the real-life shapes of waves are not restricted to sine functions, a mathematical series of sine waves, known as a Fourier series, can represent waveforms of any shape. As a natural example, a plot of the measured values for the hock angle in the swing phase of a horse's trot gait is in fact a smooth curve with a similar form to a sine wave.

The period, T, is the time, measured in seconds, s, taken for one complete vibration or cycle of movement—in other words, a full movement to and fro of the particles or fields transmitting the wave that finishes back at their starting point.

If two waves are compared with one another and one wave is further through its cycle than the other it is said to be 'leading' the other wave. Wave W1 in figure 4.9 for example leads wave W2. Conversely, a wave which is behind another wave in its cycle is said to be 'lagging' behind.

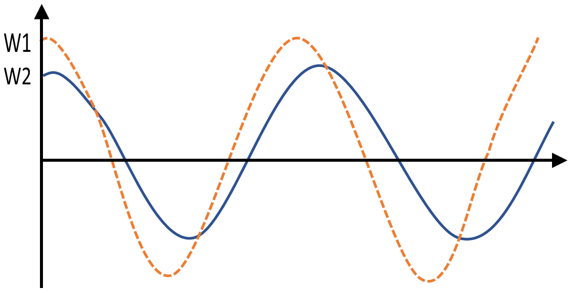


Figure 4.9. In this diagram wave W1 leads wave W2. This situation can equally be described by saying that wave W2 lags behind W1.

symmetrical gait, enabling problems to be revealed more easily. (See box 4.4 for more about the trot gait, as revealed by the Pegasus system.)

Pegasus devices are currently being used in a horse rehabilitation centre in the UK for detecting injuries. But the system can also measure a horse's stride length, speed, and stride duration, making it a useful tool for flagging up where performance improvements in equine sport can be made, explains Diana. For instance in many sports, it is useful to see how well horses gallop, and the Pegasus system is used in some professional racing yards to analyse the gallop gait.

It can also help with training in show jumping. In 2011 and 2012 Diana worked with British Showjumping's world performance team using her system to help young riders in the team's development programme improve their training and optimise their performance.

As a horse begins its stride when launching into either the canter or gallop, it will choose one front leg or the other to lead with. This is known as 'left rein' and 'right

Box 4.4. The trot gait analysed by the Pegasus system

One complete cycle of the trot stride takes around 700 ms. During this cycle each of the four limbs will be on the ground for approximately 300 ms, and the hock joint moves from maximum extension to maximum flexion in 250 ms. While the human eye can resolve separate images if they are separated out in time by around 90–100 ms, it cannot do so when multiple events occur simultaneously such as the fore and hind limbs of a horse touching the ground at the same time.

When horses have a problem moving, for example when they have a painful limb, they tend to compensate for this by altering the loading time on the contralateral limb, in other words on the limb opposite and diagonal to the problem limb. The difference in this loading time compared with normal is generally only around 20 ms, which is a few percent of the total stride time. The human eye cannot see this difference, neither can it be picked up on a normal video running at 25 Hz since this has 40 ms between each frame. Likewise, videoing or watching a horse is unlikely to reveal when they have a problem flexing their hock as the point of maximum flexion occurs so quickly.

As the Pegasus system monitors all four limbs simultaneously at a data collection rate of 102.4 Hz, it provides accurate data on how each of the limbs are moving in relation to one another. Problems can be swiftly diagnosed by comparing the freshly gathered data with a database of data from healthy horses that are moving normally.

rein', with the left and right referring to the respective fore legs used. In canter for example the legs go into diagonal pairs and the horse will have one of its fore legs as the leading leg for the gait depending on what rein it is on.

'In show jumping you assume they exercise equally on both reins but in fact they tend to train far more on one rein than the other,' explains Diana. This, she says, means that the horse ends up building more muscle strength on one side. This situation isn't helpful in competition as depending on the positioning of the fences in the courses they need to jump, the horses may have to use both sides.

'The Pegasus system looks at the timing of the limbs in relation to a reference. The horse should enter a certain gait on a left lead or right lead. What you don't want the horse doing is changing the lead [leg] part way along a straight [between fences]. When they're actually about to jump over the obstacles they change from the coupled pair to bringing both hind legs down together so they can take off [see figures 4.10(a) and (b)] but they will land on one [fore] leg. So the horse thinks to itself: 'What am I going to land on and go off doing?' If they misjudge the distance to the jump, and have to put another short stride in this can throw them off balance. With this system we can have a look at both the left lead gallop and the right lead,' says Diana, adding that training can subsequently be adjusted to avoid favouring one side.

Figure 4.10. (a) and (b) Two views of horses clearing a show jump. Notice that the horse tucks in its front legs as a pair and extends out its back legs as a pair. (a) shows Peder Fredricsson at the International horse jumping event in the Sweden International Horse Show at Friends Arena in November 2016 (© Stefan Holm/ Shutterstock.com); while (b) shows a rider jumping at the Winter Equestrian Festival at the Palm Beach International Equestrian Center in Wellington, Florida, United States in January 2017. (© Perry Correll/ Shutterstock.com.)

The Pegasus system has also been used with endurance racing horses, and in training for dressage (see figure 4.11). ‘In dressage you are meant to keep the same stride duration and change the stride length. Experienced dressage riders will be able to maintain the same stride duration, but a beginner won’t and they will get marked down for this. With Pegasus you can see whether a rider is changing the stride duration [instead of the stride length] in order to keep the rhythm steady,’ says Diana, adding that the same technology and core algorithms for analysing the data are used for ETBH’s GaitSmart$^{\text{TM}}$ system for looking at human gait. This is used by several health centres in the United Kingdom, predominantly in falls clinics as most falls in the elderly are due to an abnormal gait explains Diana, adding that ‘because humans only have two legs it’s easier to do the interpretation.’

Figure 4.11. Emilie Nyerod at the dressage event in the Sweden International Horse Show at Friends Arena in November 2016. (© Stefan Holm/Shutterstock.com.)

Further Reading

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Weblinks (live as at June 2019)

Donald McRobbie
https://drdonaldmcrobbie.com/
The London 2012 Olympic Games
https://www.olympic.org/london-2012
The London 2012 Paralympic Games
https://www.paralympic.org/london-2012

Pegasus equine gait screening
http://pegasus.uk.com/wordpress/
GaitSmart^{TM}
https://www.gaitsmart.com/
British Showjumping
http://www.britishshowjumping.co.uk/