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Going for gold

Sport and science

Science Enhancement Programme

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Contents

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The cover image shows a computer-generated image of cyclists on the BMX track outside the velodrome at the London 2012 Olympic park. (Image courtesy of ODA.)

Science and sport

The London 2012 Olympic games open at the end of July. Science plays a significant part in sports, and this is reflected in this issue of Catalyst. Science can help athletes to train better, and it can contribute to the development of new equipment and clothing.

At the same time, science and engineering have played a big part in the construction of the Olympic Park and other venues, and in the transport systems used to move large numbers of people – athletes, officials and spectators – from one place to another.

And the winners get to take home their medals, a product of chemistry. Did you know that an Olympic gold medal is mostly silver?

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dlritter

Michael Gleeson

Fighting Fit

How exercise affects your immunity and susceptibility to infection

dlritter

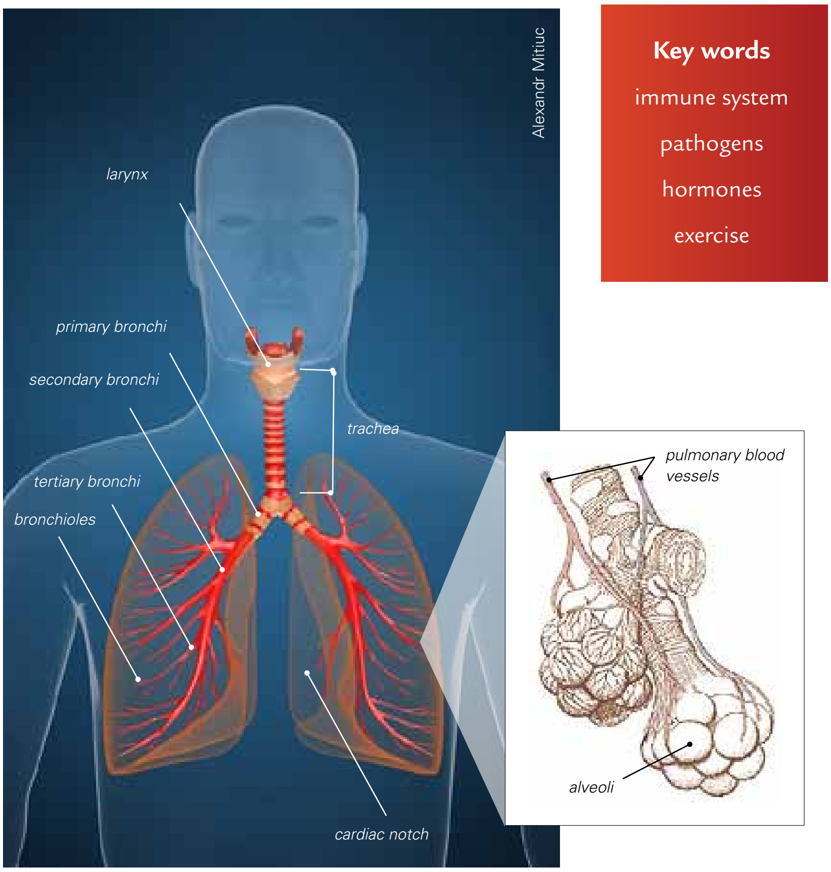
We all suffer from colds at some time but recent research indicates that a person's level of physical activity influences their risk of respiratory tract infections such as a cold, most probably by affecting immune function. Moderate levels of regular exercise seem to reduce our susceptibility to illness compared with an inactive lifestyle but long hard bouts of exercise and periods of intensified training put athletes at increased risk of colds and flu.

Key words
immune system
pathogens
hormones
exercise

Immune function and infection risk

Infections of the nose, throat, windpipe (trachea) or the two airways that branch from the trachea as it reaches the lungs (bronchi) are the most common infections that people get.

These upper respiratory tract infections (URTIs) include the common cold, sinusitis and tonsillitis, and most are due to an infection with a virus. The average adult has two to three URTIs each year and young children have twice as many. We are constantly exposed to the viruses that cause these infections, but some people seem more susceptible to catching URTIs than others.



Alexandr Mitiuc

Every day, our immune system protects us from an army of pathogenic microbes that bombard the body. Immune function is influenced by an individual's genetic make-up as well other external factors such as stress, poor nutrition, lack of sleep, the normal aging process, lack of exercise or overtraining. These factors can suppress the immune system, making a person more vulnerable to infection.

Exercise and the immune system

Exercise can have both positive and negative effects on the functioning of the immune system and can influence a person's vulnerability to infection. Researchers have found a link between moderate regular exercise and reduced frequency of URTIs compared with an inactive state and also between excessive amounts of exercise and an increased risk of URTIs. A one year study of over 500 adults found that participating in 1-2 hours of moderate exercise per day was associated with a one third reduction in the risk of getting a URTI compared with individuals that had an inactive lifestyle.

Other studies have shown that when forty minutes of moderate exercise is repeated on a daily basis there is a cumulative effect that leads to a long-term improvement in immune response. This research showed that people who exercise 2 or more days a week have half as many days off school or work due to colds or flu as those who don't exercise. Other factors that were correlated with a reduction in infection risk included a high intake of fruit, being married, being male, having a moderate or high level of fitness and having a low level of mental stress.

However, more is not always better in terms of exercise volume as other studies have reported a 2- to 6-fold increase in risk in developing an URTI in the weeks following marathon (42.2 km) and ultra-marathon (90 km) races. This is due, in part, to increased levels of stress hormones like adrenaline and cortisol (see box below) that suppress white blood cell functions. After strenuous exercise, athletes enter a brief period of time in which they experience weakened immune resistance and are more susceptible to viral and bacterial infections, in particular URTIs.

Another problem for athletes is that their exposure to pathogenic (disease-causing) microorganisms in the environment may be higher than normal due to increased rate and depth of breathing during exercise (increasing exposure of the lungs to airborne pathogens), exposure to large crowds and frequent foreign travel.

Pathogens

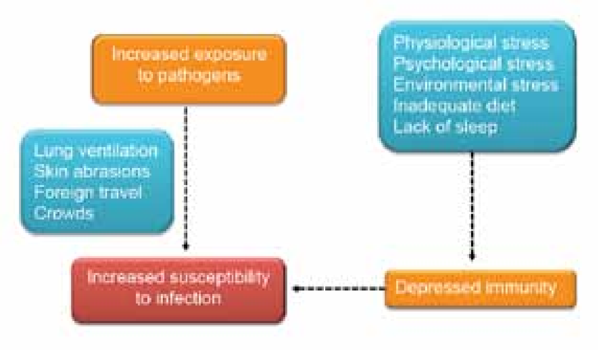
A pathogen is an agent causing disease or illness to its host, such as an organism or infectious particle capable of producing a disease in another organism. Pathogens are mostly microscopic, such as bacteria, viruses, protozoa, and fungi, thriving in various places such as air, dust, dirty surfaces, soil, etc. Not all bacteria are pathogens; in fact, most of them are harmless and only a few are pathogenic. Examples of pathogenic bacteria are *Mycobacterium tuberculosis* (causing tuberculosis), *Streptococcus pneumoniae* (causing pneumonia) and *Salmonella* (causing food-borne illnesses). Examples of diseases caused by pathogenic viruses are smallpox, influenza, mumps, measles, chickenpox and rubella. The common cold is also usually caused by a viral infection.


Evah

Sneezing - one way that viruses are spread from person to person.

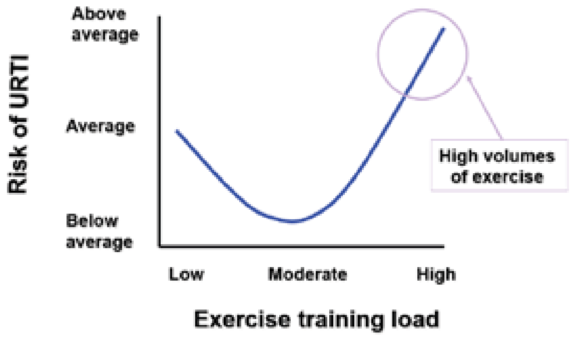
Ray Butler/CDCP

Mycobacterium tuberculosis, *the bacterium that causes tuberculosis.*



Causes of increased infection in athletes

Some of the reported sore throats may not be due to infectious agents but to non-infectious airway inflammation caused by allergies or inhalation of pollutants. A 'J'-shaped model has been used to describe the relationship between the amount of physical activity that is undertaken and risk of URTI.



The 'J-shaped' model of exercise and upper respiratory tract infection (URTI) risk

This increased sensitivity to infection with high exercise may be due to a depression in immune system function of the individual. Studies have shown that prolonged strenuous bouts of exercise cause a temporary suppression of various immune cell functions and that performing such exercise on a regular basis with limited recovery can result in a longer lasting and more severe depression of immunity.

These studies involve the collection of blood samples from volunteers before and after prolonged exercise. The blood can be analysed using automated cell counters to measure the numbers of the total white blood cells and the various subsets (e.g., neutrophils, monocytes and lymphocytes). A machine called a flow cytometer can be used to count numbers of the different lymphocyte types (e.g., natural killer cells, B cells and T cells) and can also be used to measure certain white blood cell functions.

Most people are more susceptible to colds in winter but numerous studies on athletes indicate that they tend to be most susceptible to picking up infections at times close to competition. This usually follows a period of intensive training and added mental stress with the anxiety of wanting to perform well. The worry for athletes is that even a mild infection can impair their ability to perform at the highest level. Preventing infections is therefore very important to them and they can help themselves by ensuring good personal hygiene, good nutrition and minimizing other life stresses.

Photosani

Fit today, flu tomorrow?

The message from research

The message from current research is that moderate exercise has a positive effect on the immune system. So to keep colds at bay we should all go out for a brisk walk or participate in sports at least several times per week. Being active on a regular basis also comes with other health benefits including a reduced risk of developing metabolic diseases (e.g. type 2 diabetes) and cardiovascular diseases (e.g. coronary heart disease) later in life. The higher infection risk that comes with very high (some might say excessive) levels of exercise is the small price that athletes pay for being a potential Olympic gold medallist.

Michael Gleeson is Professor of Exercise Biochemistry at Loughborough University, UK

Hormones, exercise and immune function

Adrenaline, often known as the 'flight or fight' hormone, is produced by the adrenal glands in response to physical activity. It is constantly produced in small amounts to maintain normal blood pressure. During exercise, larger amounts of the hormone are released into the bloodstream where it prepares the body for increased physical activity by speeding up the heart rate, diverting blood flow to the muscles, widening the airways, dilating the pupils and raising the blood sugar level. However, adrenaline can also suppress some immune cell functions.

Corticosteroids are hormones are produced by the inner part of the adrenal glands (called the adrenal cortex) and have a wide range of physiological functions. They include glucocorticoids – the most important of which in humans is cortisol. Cortisol is known as a stress hormone as it is secreted at higher levels in response to stressful situations. Elite athletes are exposed to the psychological stress of competition (worry/anxiety). During endurance events and over-training, the body is exposed to the physiological stress of prolonged exercise, and performing exercise in extreme environments – heat, cold and altitude – can put additional stress on the body. Elevated secretion of glucocorticoids in these situations suppresses the immune system.

Nick Treby

Building a white water canoe course

The white water site in May 2008, before the start of building work

Key words
sound waves
noise
acoustics
construction

Building things is really complicated. Not only do you have to be out in the cold and wet and have a huge range of practical skills, but you need great science skills too. ***Nick Treby*** *explains.*

If the chemical composition of the mortar isn't right, the bricks won't stick together. If you haven't calculated the forces acting on the steel support structure, the roof could fall off. If the steel is too thin it will bend and the building will fall down.

And there's lots of science that few people ever think about. What materials should I use so that a fire won't spread? How do I get fresh air in and out of the building without it getting cold or feeling draughty? How much lighting do we provide so it's not too bright (and costs lots of money to operate) and not too dark?

There are scientists and engineers whose lives are devoted to these issues, the things you never notice unless they get them wrong. I am an expert in something like that – acoustics.

When you go the cinema you'd know if you could hear the action film next door whilst you were watching the silent film *The Artist*. Or if the auditorium was so reverberant that you couldn't understand a single word of the dialogue. Or if you were sitting below a noisy air-conditioning grille.

But what about a white water canoe course, being built in a country park for the Olympic Games?

The white water site in May 2008, before the building work

Get digging

This project was a huge landscaping job. Diggers, excavators, dozers, you name it, it was needed to dig out a 10 000 m^2 lake, a 300 m long canoe slalom course and a 160 m long training course.

That is potentially a very noisy activity. And it can't be done over a few weeks. It's made trickier because people live right around the edge of the site, and you can't disturb them in the day, or at night.

So the scientist has to calculate how much noise all this work will generate at these people's homes. We then calculate how the noise will travel to the homes.

It's quite easy to find out how noisy these machines are. We can measure it, and there are standards that tell you.

Sound measuring equipment

But we need to know what happens to the sound waves once they leave the machines. It's physics on a grand scale, in 4 dimensions (3 dimensions of direction, and time as well).

Noise annoys

Noise is measured in decibels (dB). Every time you double the distance away from the machine making the noise, the noise goes down by 6 dB. So if the machine is 100 dB at 10 m, it's 94 dB at 20 m, 88 at 40 m, 82 at 80 m and so on. Every time the noise level goes down 10 dB, it is half as loud. If it just changed 3 dB, you probably wouldn't even notice. After working out your distances you take a bit more off depending on the ground. If the ground is soft it will soak up more noise than if it is hard. (That's why everything outdoors sounds different on a snowy day.)

It is affected by the wind and the temperature. It's affected by anything in the way that might screen it, or might reflect the sound towards it. And it's affected by the distance. So we know how noisy it is at the homes.

But how do we know if the people next to the canoe course will be affected by this? If it's already noisy, because of cars and lorries, then they might not notice the construction work. But if it's quiet they will. This one was in between.

Researchers have spent many years doing experiments to find out how much noise disturbs people who are trying to sleep, or to work, or watch TV. And they've found out whether people will just be a bit disturbed by it (so would put up with it for a while) or whether it will affect them physiologically – causing stress, anxiety and even heart disease.

Lorry noise

Now when you dig out all that earth, you have to take it away. By lorry. And so we had to calculate how much extra noise all those lorries would make on the road between the Canoe Course and the main Olympic Park.

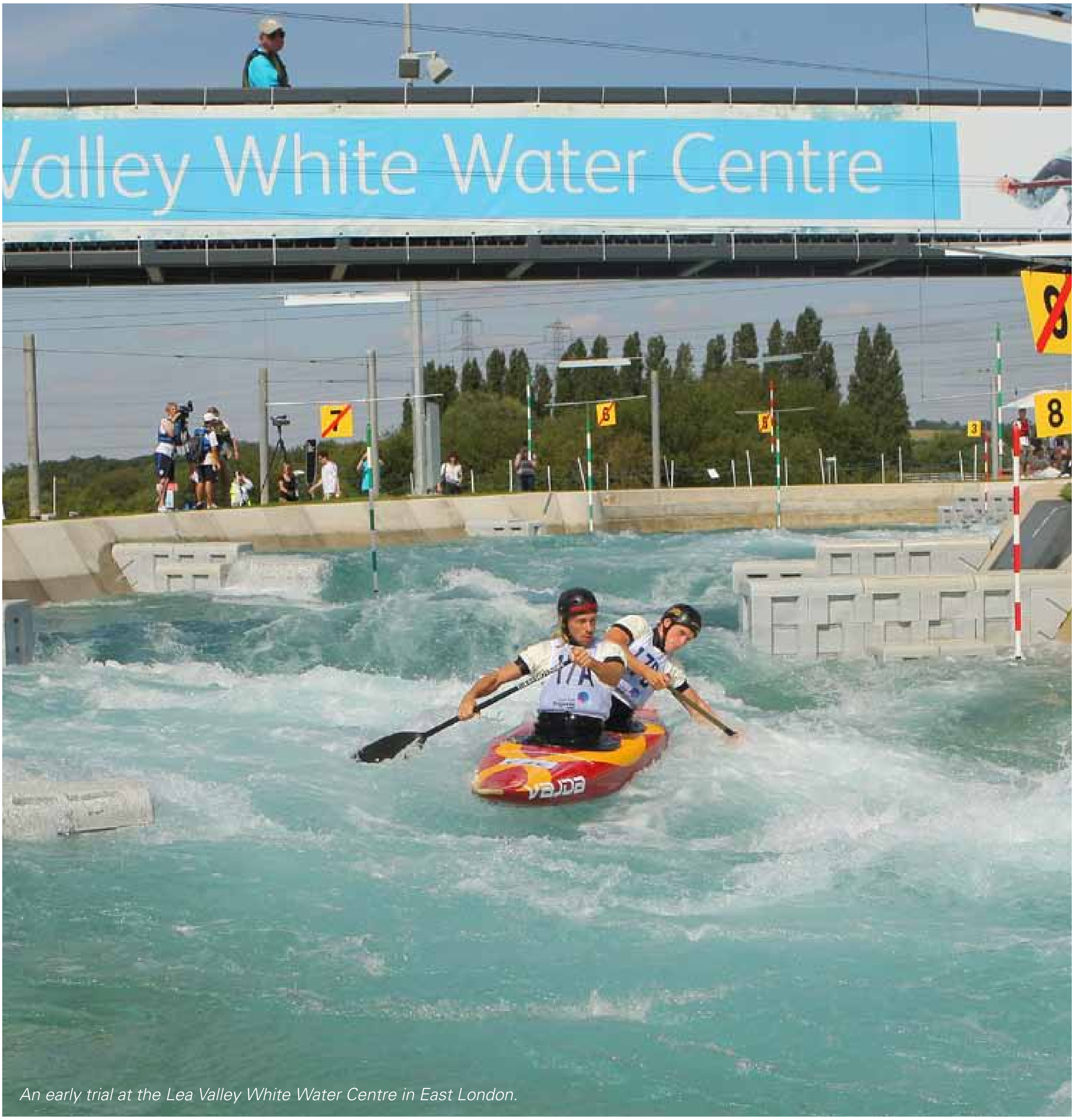
Noise from lorries is generated by their wheels interacting with the road. As the wheels go round they squash air out, which makes a noise. This is the main noise source at high speeds. At low speeds you will hear their diesel engines rumbling away. So we can calculate how much noise they make, and the effect on people. We need to know the distance from the road to the houses, the speed of the lorries, the number of lorries, the type of road surface, the gradient and lots of other things. We can do all this using the physics that explains how a sound wave travels.

Pumping water

Once the digging has been done, there are lots more acoustic things to consider. The pumps need to move 15 m^3 every second. That's a lot of water, and needs big pumps. It wouldn't be a good day out if whilst watching the Olympics you were deafened by the pumps, and felt the ground shake when they were running. So we set noise limits for the pumps, and a pump engineer helps to design and build them so they are quiet and vibration isolated.

15 m^3 of water weighs 15 tonnes

A pump being lowered into position



An early trial at the Lea Valley White Water Centre in East London.

The competitors need somewhere quiet to prepare and get changed. So there's a building where we help design the walls and windows so they have a nice calm place to get ready. Because we know what happens when a sound wave hits a window, we can calculate how much is bounced back and how much passes through. So we know how noisy it will be inside, and can make the windows thicker if we need to, or save money by making them thinner.

An audio engineer will work out where to put the loudspeakers for the tannoy, so the supporters can hear what is going on during the event.

So even for a canoe course, there are plenty of noise issues that have to be considered. And understanding wave motion – which you can see when you shake a slinky spring – means that we can make sure that when it comes to the Olympic Games nobody notices the acoustics!

About the author

Nick Treby read Engineering Acoustics and Vibration at Southampton University, and has subsequently gone on to an 18 year career in Acoustic Consultancy. He mainly works on buildings, but has visited petrochemical plants, golf courses, oil rigs, sports stadia and anywhere else that has a need for acoustic advice. He is a Senior Consultant at Spectrum Acoustic Consultants Ltd, who work all over the world from their offices in Bedfordshire, Lancashire and Switzerland.

Pedal Power

Jon Clarke

Key words
mechanics
speed
power
cycling

Why can't I cycle faster? ***Jon Clarke*** *applies physics to this question.*

I cycle a lot, both for work and pleasure. This year I was given a cycle computer which measures speed, and that has reinforced questions that have struck me recently.

- Why can't I reach 30 miles per hour (13 m/s) on a level road no matter how hard I cycle, yet elite women's races routinely hit 37 mph (17 m/s)?
- Why does a slight headwind make cycling such hard work compared to a slight tailwind?
- Why is my average speed so consistently around 14 mph (6 m/s), whether that's sprinting as hard as I can for 40 minutes to my friend's house, or riding for 7½ hours to visit the seaside?

I gradually realised that physics has a lot to say about each of these questions.

Shanaze Reade and Victoria Pendleton: two of the UK's top women team sprint cyclists, celebrating gold at the 2008 Track Championships.

Which variable?

Force: Was I limited by not being able to push the pedals hard enough? If you push down with more force than your body's weight then you accelerate upwards. Standing on one bent leg, I can easily straighten it, lifting my whole body's weight. Cyclists are not strapped down onto their seats, so pushing a lot harder is not useful, because it will simply lift you off the bike. I already seem to be capable of exerting more force than is useful, so that doesn't seem to be the limitation.

Energy: Had I emptied the chemical store of my body, so I could no longer do mechanical work? Even after cycling as hard I could for a minute or two, I can still carry on cycling. I might need to get my breath back, and let my body clear any build-up of lactic acid, but clearly I do still have energy available to me, otherwise I wouldn't be able to get home afterwards! So this isn't it.

Power: Is it that I can't do work at a high enough *rate*? Is it possible that I can't shift energy from my chemical store fast enough? The rate at which people can use oxygen during respiration to power their muscles is measured by their VO_2 max, and this is considered a critical measurement for elite athletes. The organisation which supports the British Olympic team invests heavily in measuring power and using it effectively during training. So power does look particularly relevant.

Calculating power

Imagine a cyclist providing a driving force F and moving with speed v. Both of these variables can be measured for a cyclist. Their power P can then be calculated from

$$P = F \times v$$

where P is in watts (W), F is in newtons (N), and v is in metres per second (m/s).

insidestory

A touring bike like mine.

What force must I provide?

Lots of people have used *models* to represent the forces involved in cycling. A cyclist will need to overcome rolling resistance, air resistance, and a component of their weight if they are cycling up a hill. For simplicity, I will focus only on level roads, so we can ignore the weight. The models agree that the air resistance is far larger than the rolling resistance at my cruising speed of around 20 mph (9 m/s), so I will now consider only the air resistance.

This is modelled as having a force that increases with the *square* of the speed, that is, doubling the speed means the force due to air resistance increases by a factor of four.

Arne Trautmann

Cycling in the gym – no air resistance to overcome here.

What power must I provide?

Remember that power is force times speed, so if the force increases as speed squared, then the power increases as speed *cubed*. Expressed mathematically:

$$P \propto v^3$$

So doubling the speed increases the power required by a factor of 2 × 2 × 2 = eight!

Cycling as hard as I can on a level road with no tail wind, I reach a maximum speed of 25 mph (11 m/s). One model calculates that this corresponds to a power of 330 W. For me to reach 30 mph (13 m/s, the UK speed limit in residential areas), I would need to provide:

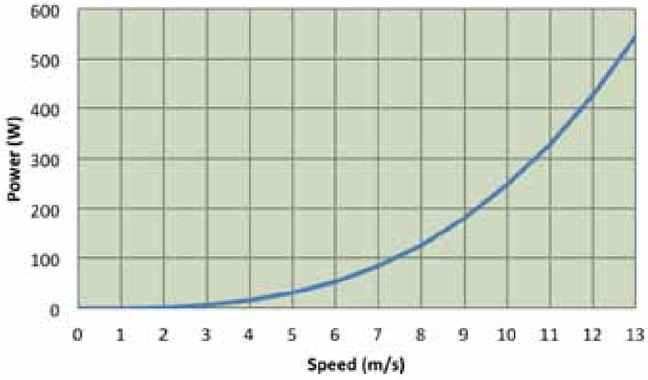
$$P = 330 \times \left(\frac{30}{25}\right)^3 = 570 \text{ W}$$

a massive 70% more power just to go 20% faster! I've already been cycling pretty intensively for two years – I'd need to train and gain the fitness of an Olympic athlete just to reach that extra 5 mph! The graph shows how the power needed to overcome air resistance increases with speed.

What if I drop my speed by 20% to 20 mph? Now we have

$$P = 330 \times \left(\frac{20}{25}\right)^3 = 170 \text{ W}$$

So dropping my speed by 20% means I can cruise along with a significant (and restful!) drop in power of 50%. No wonder my average speeds are so similar even over very different distances.



The power required to overcome air resistance increases more and more rapidly as speed increases.

BeverlyLR

Commuting by bike in San Francisco: a quick and healthy way to get around.

The same idea applies to tailwinds and headwinds. London's average wind speed is 10 mph (4.4 m/s). Cycling *with* the wind at my cruising speed of 20 mph (8.8 m/s) gives a relative speed of just 10 mph (4.4m/s) requiring a trivial,

$$P = 330 \times \left(\frac{10}{25}\right)^3 = 21 \text{ W}$$

less than I require to simply stay alive, whereas cycling against it means we're back to a relative speed of 30 mph again, needing that unachievable 570 W. No wonder I like it when the wind's behind me!

Note that the same physics applies to wind turbines. Siting them where wind speed is twice as high, for instance on a hillside compared to the centre of a city, will produce a massive eight times as much electrical power.

How do they do it?

World-class athletes like Shanaze Reade and Mark Cavendish make their achievements through years of hard training, so they are capable of higher power than me, using equipment such as specially built bikes which minimise their air resistance and, in some events, "drafting" behind other cyclists to take advantage of the air being pushed forwards by the rider in front.

So with a little disappointment, I can see that I'll never defeat the physics to cruise along at 30 mph, but I have also learnt that if I feel like taking it easy whilst riding somewhere I can do so safe in the knowledge that it won't make much difference to my speed. I've also have learnt far more respect for anyone with the fitness needed to reach that speed!

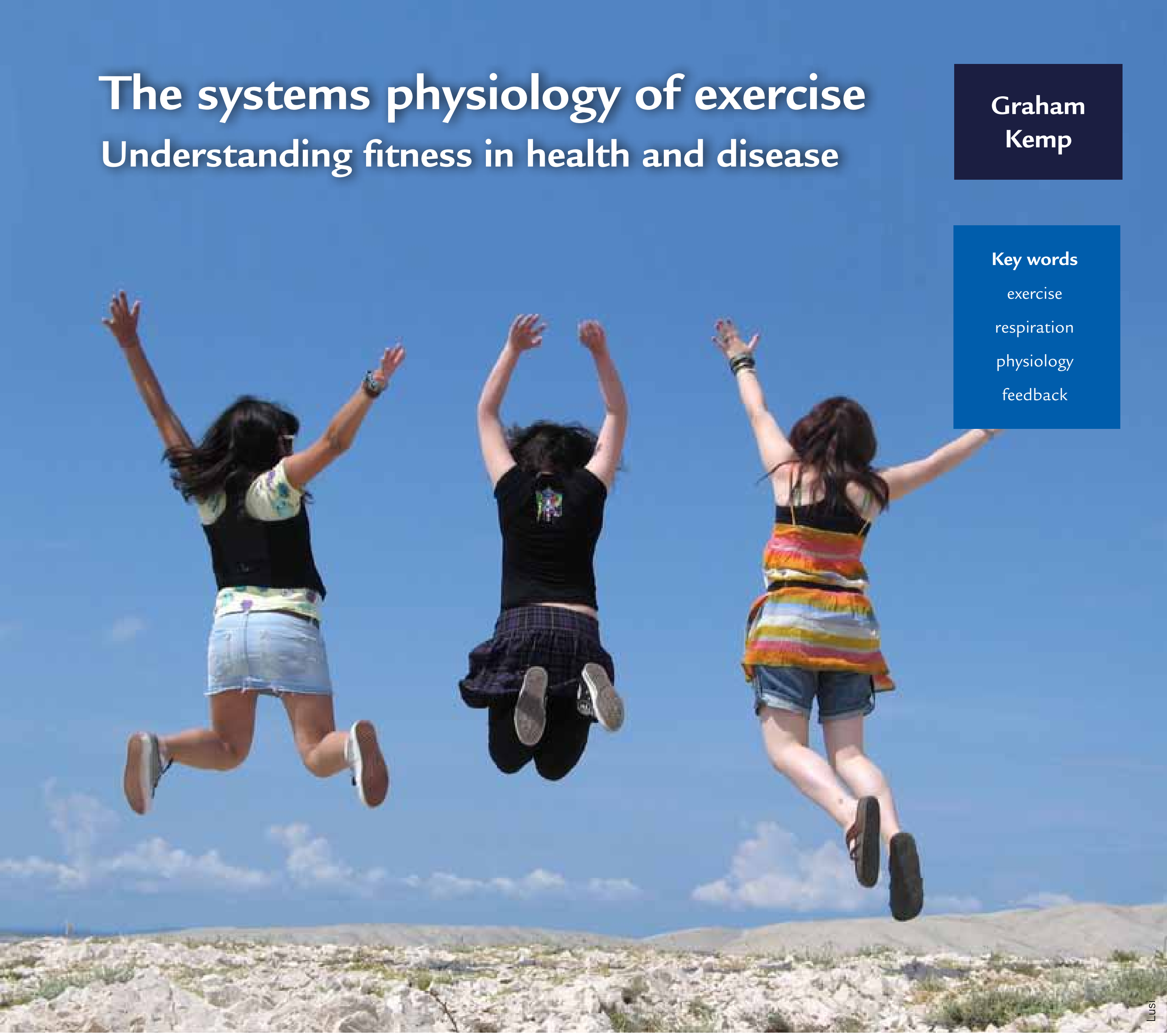
Jon Clarke cycles to work at the Institute of Physics in London.

The systems physiology of exercise

Understanding fitness in health and disease

Graham Kemp

Key words
exercise
respiration
physiology
feedback



Lusi

The ability to exercise is fundamental to life. Poor fitness contributes to reduced life expectancy and reduced ability to exercise reduces quality of life in the ill or aged. At the other end of the scale, excellent exercise performance can win Olympic gold. The hope of scientists is that understanding the mechanisms which limit 'exercise tolerance' (Box 1 on page 12) can contribute to enhanced performance for the sportsperson, and to health and to quality and length of life for everyone. How can we best approach this?

How the body works

Systems physiology is about understanding the body at work. We can understand the body in many ways as a machine. When a signal from the brain makes muscles contract, the force is transmitted to, for example, the floor beneath a foot according to the mechanical properties (length, elasticity) of the tendons and bones involved. The force and speed of the muscle depend on the properties of its component fibres, for example, 'slow twitch' muscle fibres have more endurance, and 'fast twitch' fibres have greater speed and power.

Muscles contain a storage carbohydrate, glycogen, which is the main fuel for the rapid, high-force contractions of fast twitch fibres. As exercise carries on they switch to using glucose and then fatty acids delivered by the blood, which also delivers the oxygen. For sustained exercise this aerobic (oxygen-requiring) energy supply system is crucial (Box 2 on page 13).

The Big Picture on pages 10-11 shows seven different techniques used to measure physiological changes during exercise.

^{31}P MRS (phosphorus magnetic resonance spectroscopy)

measurement of changes in pH and the concentration of phosphocreatine (PCr), an important temporary energy store in the body

Spirometry

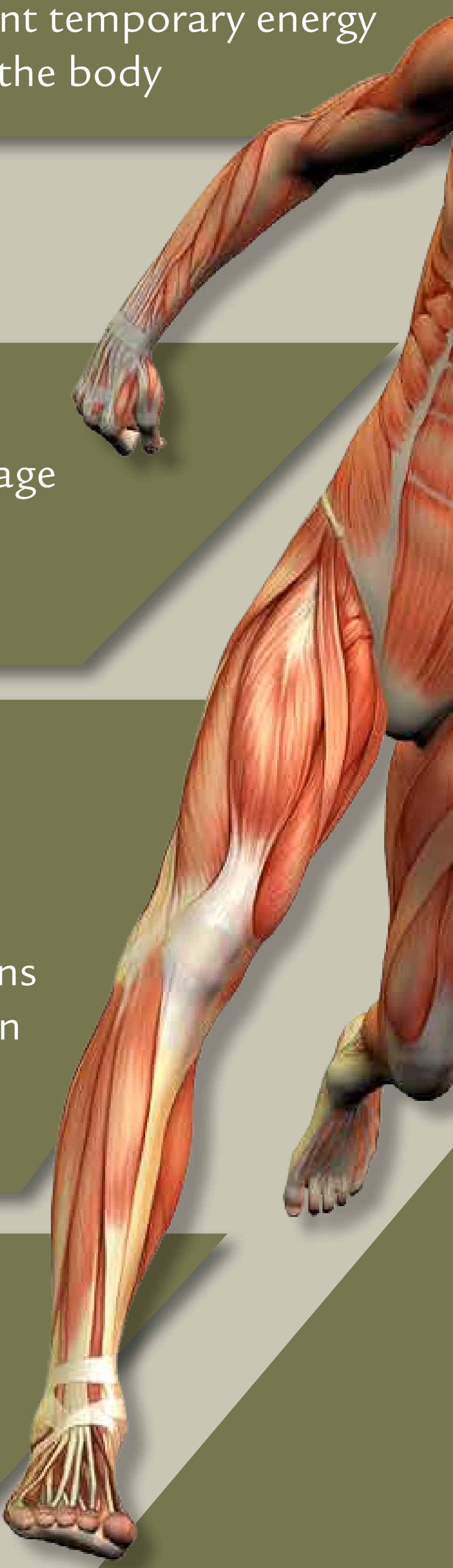
measurement of oxygen usage via a simple face mask; a non-invasive technique

Needle biopsy

measurement of enzyme content, gene activation patterns, mitochondrial function and concentrations of chemicals in blood taken from muscle tissue

Arteriovenous sampling

direct measurement of such things as oxygen use



Peter Galbraith

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NIRS (near infrared spectroscopy)
measurement of muscle oxygen content

Blood sampling
measurement of concentrations of circulating chemicals (metabolites) including lactate made in anaerobic respiration

Whole Body
measurements of running speeds, power output

Measuring the system

The Big Picture (pages 10-11) shows the major ways in which we can measure physiology in the exercising human. Some difficulties exist with these methods. Subjects, especially if they are patients rather than volunteers, are much more willing to participate with non-invasive techniques such as spirometry. Needle biopsy is especially difficult and, although in theory very good for looking at changes over time, the multiple samples that would be needed pose ethical and practical problems.

In addition, none of these techniques tells us everything we want to know about this system – this would be ethically and practically impossible. However, quantitative analysis of the data (i.e. analysis which pays attention to the actual values of concentrations and rates, and the size of changes) with a knowledge of the underlying physiology and supported by computer modelling, can give us much valuable information.

Understanding the system

We now know a great deal about the anatomy of this system, the nature of its protein components, and the chemistry of the pathways of synthesis and breakdown of storage compounds, fuel oxidation and energy transformation. During sustained exercise, oxygen must be delivered from the atmosphere and fuel from the stores (liver glycogen, adipose tissue triglyceride) at a sufficient rate.

Regulation is very important. In the muscle cell we understand how energy supply is switched on in exercise and then off again. Two important principles are the idea of steady states versus kinetics (time-dependent changes), and the engineering concept of **feedback**.

When a muscle is instructed by the brain to contract, its energy (ATP, see Box 3 opposite) needs to increase rapidly. In the time it takes for processes of ATP production to catch up, the shortfall is met by phosphocreatine (PCr), which can be considered a temporary energy store. PCr stabilises at new steady-state level when ATP production matches ATP demand. When exercise ends the ATP demand falls to its low resting-muscle value, and the temporary excess ATP supply is used to replenish PCr.

Using ^{31}P magnetic resonance spectrometry, we can follow these PCr concentration changes. As PCr falls in response to ATP hydrolysis the concentration of ADP (see BOX 3) rises, stimulating ATP production. ADP is the ‘error signal’ in the feedback loop, matching ATP supply to demand. This explanation is broadly accepted, but current research is examining several unanswered questions. Is ADP really the key signal? Are there also direct signals activating ATP synthesis (‘parallel’ or ‘feedforward’ activation)? How much account must we take (e.g. by mathematical simulation approaches) of the complexity of metabolic reactions within the mitochondrion itself?

Box 1

Exercise tolerance is the level of physical exertion an individual may be able to achieve before reaching a state of exhaustion. Exercise tolerance tests are commonly performed on a treadmill under the supervision of a health professional who can stop the test if signs of distress are observed.

The system as a whole

More generally, to understand how the system works, we need to grasp it as a whole; not only to understand how the parts work in isolation but also how they interact. There is nothing magic about this, but there is sometimes extraordinary complexity. At the same time the results can often seem quite simple. For example, physiological processes often behave in a first-order way, typical of systems in which the force which restores a system to its original condition is proportional to the size of the original change which moved it away from steady state. This applies to post-exercise PCr recovery, as described above, where the PCr resynthesis rate is roughly proportional to how much further it has to recover to reach the resting value.

The resulting recovery can be described by a rate constant (inversely proportional to the time taken for 50% recovery). This is related to the mitochondrial capacity of the muscle, the maximum rate at which it can make ATP. The faster PCr recovery is, the larger the recovery rate constant, the larger the estimated mitochondrial capacity.

Mitochondrial capacity is a complex property, depending on the many organs and processes involved; lungs, heart, blood vessels, muscle capillaries, muscle mitochondrial enzymes and other proteins (Box 2). It is generally reduced in diseases that affect any of these, and it is increased by aerobic (endurance) training. This makes it a useful concept in clinical and sports-science research, but we would like to understand how these factors interact, in a model that incorporates all we know of how the parts of the system work, and of the interactions between them.

For example, how much does limitation in cardiac performance affect the performance of several muscle groups (e.g. in bicycle exercise) compared to a single muscle group (e.g. in single knee extension)? How much does reduction in muscle mitochondrial numbers contribute to intolerance to exercise in chronic heart disease?

This knowledge will also help us to decide what to do in a specific case. In a disease, for example, a drug improving muscle metabolism directly is unlikely to be beneficial if the main factor limiting exercise tolerance is cardiac function, however in sport if a 5% increase in muscle mitochondrial function increases overall performance by just 1%, this may be just what it takes to win Olympic gold! Only a quantitative systems understanding can answer these questions.

Box 2
The parts of the machine

The **lungs**, which acquire oxygen from the air and let it diffuse into the pulmonary capillaries.

The **heart**, which pumps blood round the circulatory system.

The muscle **vascular system**, which distributes the blood so that oxygen can diffuse across the capillary wall into the cell, and then through the cytoplasm to the mitochondria.

The **subcellular organelles** where the cellular respiration (the oxidation of fuels) takes place.

The way forward

If we can develop this kind of approach, not only will we understand our measurements better, but we will also be better able to predict what changes may influence overall performance, and by how much. This is the practical goal of a system physiology approach, and it has many applications in health and sports science. While we can only fully understand the whole, we are of course allowed to focus. We may want to concentrate (as I have done here) on muscle use of oxygen and fuel. We may be more interested in timescales of seconds to minutes (as I have been here) rather than the millisecond events of nerve stimulation, the hours-to-days effects of gene activation, or the days-to-months events of growth and development.

Ideally the scientist progresses from experiment through analysis, simulation and prediction to new experiments. This requires the collaboration of scientists with a range of skills: these may be sports scientists, medical doctors, computer scientists, biochemists, biophysicists, physiologists, cell biologists, pharmacologists and neuroscientists. Systems thinking provides a model of how individual contributions sum to a greater whole, which is a key principle of scientific knowledge itself.

Graham Kemp is a professor in the Institute of Ageing and Chronic Disease at the University of Liverpool.

Box 3

Respiration generates adenosine triphosphate (ATP) from adenosine diphosphate (ADP) and phosphate. ATP is the ‘energy currency’ of the cell, and is hydrolysed (i.e. broken down) to release energy where it is needed – for example, when the highly structured proteins actin and myosin interact to generate force in a contracting muscle. ADP is a by-product of this breakdown.

Mike Follows

Life below the surface

The science of diving

Richard Carey

Key words
diving
pressure
upthrust
Boyle's law

Diving is exciting but it can be dangerous. ***Mike Follows*** *explains how understanding a little physics can help divers get out of trouble.*

Scuba diving is the closest any of us will come to a career as an astronaut. Indeed, scuba diving is an important part of astronaut training. Both NASA and ESA (the US and European space agencies) have a Neutral Buoyancy Laboratory (NBL) where they train astronauts. The neutral buoyancy achieved underwater is like the apparent weightlessness of Earth orbit or deep space.

A pressure of 230 bar is 230 times atmospheric pressure.

ASC-CSA

Canadian astronaut David St Jacques undergoes training in a neutral buoyancy tank.

SCUBA is short for Self-Contained Underwater Breathing Apparatus. A 12-litre cylinder charged to a pressure of 230 bar provides enough breathing gas for a dive time of around one hour to a maximum depth of around 30 metres. The cylinder is attached to a buoyancy compensator that is worn like a jacket and the diver is able to breathe quite normally from a demand valve (sometimes called a second stage).

By the time British-born NASA astronaut Nick Patrick had flown his last mission aboard the Shuttle his 'dive-log' totalled 430 hours – 100 dives in the NBL and 100 in open water in preparation for his three spacewalks. He sums up the significant difference between the scuba diving and spacewalking environments like this: "One is blue and wet, and the other is black and a vacuum." Actually, the underwater world is much more beautiful, with weird and wonderful sea creatures to see and wrecks to explore.

Some people are afraid to take up scuba diving because they fret about the extremely remote possibility that they may be mistaken for dinner by a predatory shark. Yet according to the Shark Attack File (www.sharkattackfile.net) there has been an average of about half a dozen fatal shark attacks per year over the last decade while, for every human killed by a shark, our species slaughters over 70 million sharks. Actually, divers need look no further than the nearest mirror to see their biggest potential hazard – themselves. Part of the allure of


PhutureUK

'Blue water' diving – more colourful than space

scuba diving is that the underwater world is an alien environment. This means that diving is classed as a hazardous sport yet it is actually very safe, courtesy of the comprehensive training available from scuba diving organisations like BSAC and PADI and the reliable life-support equipment available.

Although scuba divers often become over-reliant on the dive computers they wear on their wrists, they need to learn some basic physics in order to pass their theory exams. In fact, an understanding of Archimedes' Principle, Boyle's Law, heat transfer and Snell's Law helps keep scuba divers safe. Reflecting on the physics helps divers become more skilled.

Buoyancy

Even though divers can ascend and descend diagonally, fins attached to the feet are used for propulsion in the horizontal direction. Vertical motion is achieved by controlling buoyancy and this is the most important skill to be mastered by a scuba diver – ascending too rapidly can lead to a burst lung or DCI (decompression illness).

According to the Archimedes Principle, any object immersed in a fluid receives an upthrust equal to the weight of the fluid it displaces. This can be applied to diving: a diver will descend if her weight exceeds that of the water displaced and rise if her weight is less. A diver achieves neutral buoyancy if her weight exactly equals the weight of water displaced and this mimics the apparent weightlessness experienced by astronauts (see Box on right).

Divers carry several kilograms of lead to ensure that they can sink. However, they control their buoyancy (and hence whether they go and up or down) by varying how much water they displace. They achieve this by controlling how much gas they put into their buoyancy compensator (BC). The BC acts like a lifejacket when the diver is on the surface and provides a convenient place to mount the cylinder that carries the breathing air for the diver.


Royster

A diver's buoyancy compensator, used to control the speed of ascent and descent

Floating up, sinking down

Whether a diver will float upwards or sink depends on his density relative to the density of the water around him. Here's why:

The downward force (weight) acting on a diver of volume V depends on his mean density D and the gravitational field strength g:

$$\text{weight} = V \times D \times g$$

Under water, the diver displaces his own volume of fluid, and he experiences an upward force (upthrust) that depends on the density of water D_w:

$$\text{upthrust} = V \times D_w \times g$$

The resultant force is the difference of these:

$$\begin{aligned}\text{resultant force} &= \text{weight - upthrust}\\ &= V \times (D - D_w) \times g\end{aligned}$$

A positive value means that the diver will sink – his density is greater than that of water. A negative value means that he will rise, while a zero value means that weight and upthrust are equal and opposite. The forces on the diver are balanced and he will be neutrally buoyant.

Under pressure

Fluids – liquids and gases – are substances that flow. Pressure falls as one ascends in a fluid (e.g. gaining altitude in an aircraft). Descending through a fluid leads to an increase in pressure, as a result of the increasing weight of fluid pressing down on you. The change in pressure is more obvious in water than air because its density is roughly 1000 times as great. Even if you just hold your breath and duck dive to the bottom of a deep swimming pool, you may feel a pain in your ears as the pressure on the outer ear increases while the air trapped in the middle ear is compressed. Divers need to learn how to 'equalise' so that the pressure is the same on both sides of the eardrum.

Equalising is easy for a novice to remember, because it hurts when they don't. However, just as gases are compressed on descent, they expand on ascent according to Boyle's Law. The air in your lungs will be at the same pressure as the surrounding water. Panicking divers will sometimes bolt for the apparent sanctuary of the surface. If they also hold their breath as people are apt to do when alarmed, they put themselves in acute danger of bursting a lung or inducing decompression illness (known as 'the bends'). Scuba trainees are taught to never hold their breath.

The more time that is spent breathing air at higher pressure, the more gas is dissolved in the blood and body tissues. As a diver ascends, pressure is reduced. But, if this takes place too quickly, the gas forms bubbles as it comes out of solution. In the most extreme case, it is like opening a bottle of fizzy drink. These bubbles often form in joints and the accompanying pain is so intense that the victim can be 'bent' double. Depending on the severity of the bend, other symptoms range from a skin rash, paralysis and even death. Divers are taught to use decompression tables that tell them how long they can spend at different depths to reduce the risk of reducing a bend, though they often delegate this task to their wrist computers. The tables used by BSAC are based on the research started in 1905 by Dr John Scott Haldane, whose experiments decompressing goats reduced the incidence of decompression illness (DCI) in Royal Navy divers.

Air consumption

It is important for all divers to be able to estimate how long their air supply will last. A miscalculation could leave you with choosing between drowning and making a dash for the surface, risking a burst lung or DCI in the process. Boyle's law tells us that, as we dive to greater depths, the same air will occupy a smaller volume. Since the volume of your lungs does not change as you dive, filling your lungs when at a depth of 30 m, where the pressure is four times atmospheric pressure, requires four times as many air molecules. So, as you dive deeper you use more air. A cylinder of air that would last for one hour at the surface may last for only 15 minutes at 30 m.

Racks of diving gas cylinders

Heat transfer

For most people the mental image of scuba diving involves wetsuits and warm tropical waters, referred to by British divers as 'blue-water' diving. But how does a wetsuit work? Wetsuits are made of synthetic rubber (usually neoprene) that has been foamed to create gas bubbles. These bubbles are isolated from each other so that the suit does not absorb water as a sponge might.

In warm water, a diver may risk wearing just a swimsuit.

A layer of water becomes trapped between the diver's skin and the wetsuit. Warmed by heat from the diver, the trapped water soon reaches body temperature. A tight-fitting suit makes it less likely that cold water will flush out this layer of warm water and, because the material stretches, it can be very close fitting.

The neoprene fabric is a poor thermal conductor and the tiny air pockets make it like cavity-wall insulation, reducing conduction still further. But donning a wetsuit simply reduces the heat leaked by the diver to the surrounding water. It does not stop it altogether. Colder water demands a thicker wetsuit. However, when diving in temperate waters, like those around the British coast, the temperature gradient becomes so steep that a wetsuit has to be so thick that it becomes impractical. Apart from a few diehards, divers normally switch to a drysuit, which traps air between the diver and the water. This makes sense because air is a much poorer conductor: air conducts heat 25 times more slowly than water. Water leaking into a drysuit essentially turns it into a 'wetsuit' and is usually the cue for a diver to 'call' (i.e. end) the dive and get back on terra firma.


Richard Carey

A diver's neoprene drysuit; the latex cuff and neck seal keep water out.

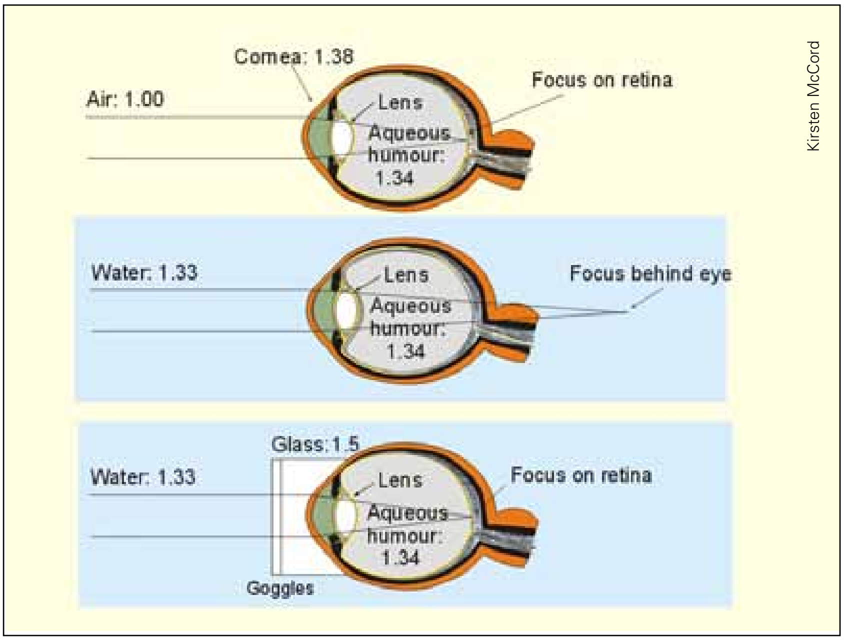
The effectiveness of a drysuit versus wetsuit in British waters was amply illustrated by Hywel Dyer and Jamie Lewis who lost contact with their dive boat on 8 September 2007. Divers are taught to drink plenty of fluid to reduce the risk of DCI so their bladders were probably full when they surfaced from their dive to discover that their boat was nowhere to be seen. They were eventually rescued by helicopter after being adrift for nine hours off the Pembrokeshire coast. However, not long before they were airlifted to safety, Dyer was no longer able to suppress the urge and urinated into his drysuit, providing a liquid path for his body heat to pass into the sea. Heat takes the path of least thermal resistance, just as most electric current flows along the path of least electrical resistance. Dyer had created a 'thermal short-circuit' which made him "very cold, very quickly". Lewis managed to resist the urge and "this eventually meant the difference between him walking off the helicopter (into hospital A&E) while I got stretchered," added Dyer.

The eyes have it

Our eyes have evolved for vision in air. When light enters our eyes it slows down and the curvature of both the cornea (at the front of the eye) and the lens ensures that it is refracted (changes direction) and is brought to a focus on the retina at the back of the eye. When we open our eyes underwater, everything looks blurred because images are no longer brought to a focus on the retina; water has almost the same refractive index as the aqueous and vitreous humours inside the eye so virtually no refraction takes place. This is resolved by donning a mask that covers the eyes and nose. It is 'cleared' by exhaling through the nose and displacing the water, leaving a pocket of air between our eyes and a flat piece of toughened glass.


M Follows

A diver's mask covers both eyes and nose so that it can be 'cleared'.



Kirsten McCord

How a mask or goggles allows a diver to see clearly under water; the figures show the refractive index of each material.

Colours towards the red end of the visible spectrum are absorbed more by water, so that everything looks bluer the deeper you descend. Particularly if visibility is poor, it can also become quite dark, so divers should carry a torch as a precaution.

Skin protection

Tropical waters can be around 30 °C so snorkelers in particular are often tempted to wear nothing more than a swimsuit. Kept cool by the water, they do not notice that they are being 'burned' by the ultraviolet (UV) radiation. The pigment called melanin cannot be produced quickly enough to screen this radiation, leading to a risk of melanoma or skin cancer. A wetsuit offers good protection against UV.

Mike Follows is a BSAC Dive Leader and Open Water Instructor

Peter Campbell

Going electric

Taking the train to the Games

A 'Javelin' high-speed train

Sustainability has been a high priority for the London organising committee for the 2012 Olympic and Paralympic Games. The declared aim is 'for 100 per cent of spectators to get to the Olympic Park by public transport, or by walking or cycling.' Railway lines with a combined capacity of 240 000 passengers per hour will serve the Olympic Park, most of them using Stratford station.

Long before preparations for the 2012 Game began, rail services through Stratford had been electrified. Electrified trains have many advantages over the diesel-powered trains which they replaced:

- zero emissions at the point of use, so no adverse impact on local air quality
- electric motors are lighter, so train weight does less damage to the track
- 20–35% less carbon emissions per passenger mile

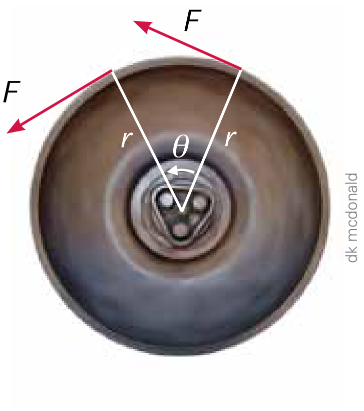
Stratford station, with the Olympic Park under construction beyond it.

All of these railway lines through Stratford station are electrified.

- North London overground line, powered by a 750 V DC third rail system from Richmond to Acton Central, 25kV 50 Hz AC overhead lines from Acton Central to Stratford
- Docklands light railway, powered by a 750 V DC third rail system
- Jubilee and Central underground lines, powered by a four-rail system. A third rail at +420 V DC is beside the track, and a fourth rail at -210 V DC is centrally between the running rails, giving a traction voltage of 630 V DC
- Great Eastern mainline and suburban overground lines serving east London and Essex, powered by a 750 V DC third rail
- 'Javelin' high-speed rail service to serve Stratford International from St Pancras and Ebbsfleet International stations, during the Games only. Powered by 25 kV 50 Hz AC overhead lines.

Torque and work done

Railway engineers commonly use the concept of ‘torque’ or turning effect, because the motive force on the track depends on wheel size. Just as with simple machines like levers and pulleys, the turning effect depends on the size of the force and how far from the pivot or axle it is applied.



dk mcdonald

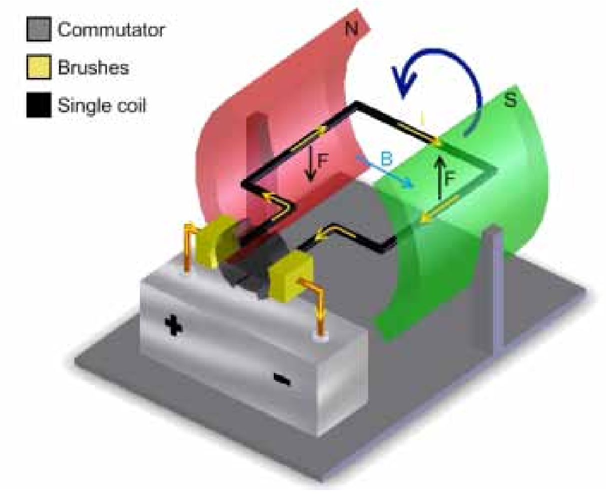
Torque is the product Fr. The work done by a drive wheel is given by $W = Fr\theta$, where r is the wheel radius and θ is the angle (expressed in radians) through which it turns.

Most noticeably, work is done when a train accelerates on leaving a station platform or when it climbs a gradient. But work is also done against resistive forces when a train is travelling at constant speed.

Speed control of electrified trains

Electrified trains generally have several motors. For example, all 7-car Jubilee Line underground trains have two units called ‘Driving Motor cars’.

What makes any electric motor turn is the interaction between two independent magnetic fields. One magnetic field is stationary and the other rotates with a current-carrying coil of wire.

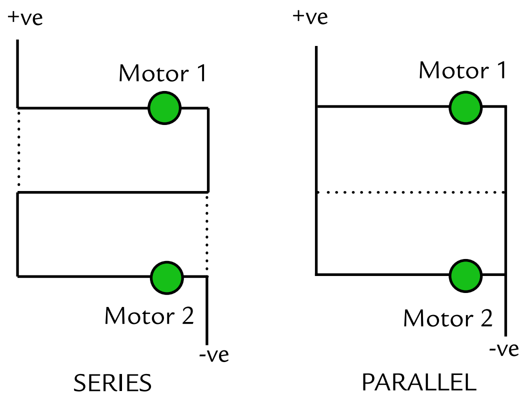


A DC electric motor. The current (yellow arrows) in the coil produces a magnetic field which interacts with the field produced by the stationary magnets (N and S), causing the coil to turn.

But any coil of wire rotating in a stationary magnetic field produces a dynamo effect. A voltage (also called a ‘back EMF’) is therefore induced in the motor coil which opposes the rotation. The faster the coil rotates, the greater the reverse voltage induced.

A simple motor produces maximum torque when it is just starting to turn, because there is no back EMF. As it spins faster, the torque that it can produce falls. This is because the net voltage across the coil falls and so there is less current through it.

To get larger torques as an electrified train speeds up, its motors are arranged so that they can be switched between working in series and parallel. The circuits also include large, switchable resistances that can be used in different ways.



These circuits control motors as the train speeds up. Not shown: in each configuration, every branch also contains resistors.

As the train starts moving, part of what happens is that its electric motors are connected in series (diagram a), so the motor voltage is smaller than the railway supply voltage. As the train approaches its maximum speed, circuits are switched so that they are in parallel (diagram b). This means each motor receives the full supply voltage, compensating for the back EMF induced at higher speed.

Regenerative braking

The dynamo effect within electric motors means that electrified rail systems can re-use the energy that would otherwise be lost when a train is braking. If there is another train drawing power from the system on a nearby section of track, circuits in a braking train can be switched to feed electricity back into the overhead wires, or power rails. The braking train slows down as its kinetic energy changes to electrical energy.

If there is no other train nearby the braking train, then yet another switching arrangement feeds the electricity generated by the braking train through massive on-board resistors, so wasting the energy as heat. This wasteful electrical heating effect can be compared with frictional heating in the brakes of cars and trucks.

Peter Campbell taught physics in London schools and colleges for over 20 years.

Ray Oliver

Olympic alloys

London 2012

The London 2012 velodrome

The development of new alloys is allowing Olympic athletes to improve their performances. When the 2012 Games finish, the winners will take away their own pieces of alloy – gold, silver and bronze medals.

Alloys are mixtures of metals or of a metal with a non-metal, as with steel. Steel is an alloy of iron and carbon. There is no upper limit to the number of possible new alloys with novel and useful properties. Alloys are generally harder, stronger and resist corrosion better than pure metals.

The ArcelorMittal Orbit Tower

The Olympic Park in Stratford contains the largest alloy steel sculpture in Britain. The 115 metre high Orbit Tower was designed by Anish Kapoor with the engineer Cecil Balmond. The name 'Orbit' refers to the electron clouds moving in orbits inside atoms. In metals, positively charged metal ions are held together by a cloud of shared electrons.

63 per cent of the Orbit Tower is made of recycled steel. Steel is a malleable and strong alloy that can be rolled and bent into all the complex shapes needed for the sculpture. It will be the tallest sculpture in the UK.

2000 tonnes of steel and 19 000 litres of paint have been used to build the ArcelorMittal Orbit tower

On two wheels

Designers must consider the properties of the materials used to make both sports equipment and buildings. These include strength, density, toughness, ductility and resistance to fatigue – will it break too easily?

The London Velodrome has been made of thousands of steel alloy sections that support a distinctive-shaped roof. The architect used an unusual cable-net roof in a double-curve to reflect the geometry of the cycling track itself. The whole building uses strong steel alloys to give a lightweight design intended to reflect the advanced designs of the bicycles.

The bikes used at the Olympic Velodrome look very different to ordinary mountain or racing bikes used in road races or off-road. A range of alloys and composite materials can be used. Composites are made from two or more different materials combined to maximise the best properties of each. Examples include carbon fibre and plastics reinforced with fibre glass.

Materials chosen for Olympic cycle construction

Material used	Reason for using this material
Titanium	Very strong but low density
Aluminium alloys	Rigid structures hold their shape well
Magnesium alloys	Very tough
Carbon-fibre composites	Low density and strong

For the Velodrome cyclists, the ordinary tubular metal frame of bikes is replaced by a composite monocoque, a single piece. Other high-performance bikes can use a wide variety of alloys to help athletes achieve top performances: Chromoly, an alloy steel containing chromium and molybdenum, lightweight aluminium alloys or even titanium alloys first used in the aerospace industry.


London 2012

Trying out the BMX track in front of the velodrome

Throwing alloys through the air

Olympic javelin throwers have seen record performances improve as new materials have been developed. A javelin needs to be aerodynamic and must have low vibration in flight so that it travels further. At the Olympics, the javelins are likely to be made of aluminium alloys or aluminium combined with carbon fibre. These materials combine low density with a rigid structure that does not flex in flight, something that can slow down the javelin.


Leryn Franco, Paraguayan javelin thrower


An 800 g javelin

Some of the strongest and largest athletes at the Games are the shot-putters. The sport has a long history, there are reports of British soldiers holding cannon-ball throwing competitions hundreds of years ago. The design of a modern shot-put can vary. They can use the copper-zinc alloy familiar as brass, or be solid iron or even have an outer metallic shell filled with lead. The heavy metal ball weighs 7.26 kg for the men's event and 4.0 kg for the women's.

See the next page for the alloys used in the Olympic torch and medals.

Alloys in the water

Aquatic sports and those on ice in the Winter Olympics play an important role in the Games. Both sailing and rowing rely upon advanced alloys and composites. These have replaced traditional materials used in boat construction such as wood and canvas. Olympic rowers now mostly use carbon-fibreglass composite oars. The high strength and versatility of such composites have allowed oar-blade design to change, giving extra speed in the water. The smooth surface of the material improves its hydrodynamics – how easily it enters and leaves the water, reducing drag.

Sailing boats need a strong and flexible mast to support the sails. Most masts are made of aluminium alloys. Smaller masts can be constructed in a single piece using extrusion, like squeezing toothpaste from a tube. Extrusion is possible since metals like aluminium are both ductile and malleable. A recently developed alloy called Alustar is one-fifth stronger than previous alloys. Designers can save weight and increase sailing speeds by using thinner and lighter metal masts. Aluminium alloys also show good corrosion resistance, essential when sailing in salt water. The presence of an electrolyte such as sodium chloride, common salt, accelerates metallic corrosion.

Alustar is aluminium alloyed with magnesium, manganese, zinc and zirconium.

Ray Oliver is a science teacher and author of many textbooks and industry-related teaching resources.

The beginning and the end

Olympic torch

The London Olympic torch is made of a special aluminium alloy originally produced for the car and aerospace industries. This alloy has good heat resistance, so the flame will not melt it. It is also strong and lightweight, making it easier to carry. The torch has 8000 circles representing each of the Torchbearers.

London 2012

Ben Slocombe, David Smith and Nicole Easy from Hayes School Bromley show off the Olympic torch.

Olympic medals

The London 2012 medals have been designed by David Watkins. He also did the special effects for the film 2001: A Space Odyssey in 1968. The medals are manufactured at the Royal Mint in Llantrisant, S Wales.

medal	composition	comment
gold	1.34% gold 92.5% silver 6.16% copper	plated with a minimum of 6g of gold
silver	92.5% silver 7.5% copper	pure silver (or gold) would be soft and easily damaged
bronze	97.0% copper 2.5% zinc 0.5% tin	harder than copper but easier to melt and mould into shape

At the Sydney Olympics, the bronze for the medals came from old melted-down one and two-cent coins – sustainable medals. The bronze used to make a medal for the London 2012 games is worth about £2.