Royal Academy of Engineering

THIS IS ENGINEERING

WINNING MEDALS

Teacher guide

Does engineering design make a difference?

This resource aims to give students the opportunity to investigate the impact of science, technology, engineering and mathematics (STEM) on wheelchair sport.

WINNING MEDALS:

does engineering design make a difference?

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INTRODUCTION

The aim of this resource is to give students the opportunity to investigate the impact of science, technology, engineering and mathematics (STEM) on wheelchair sport.

The success of any athlete is the result of many hours of training, dedication and sacrifice. However, in the case of wheelchair athletes there is an added dimension – the work of the engineer who designed the wheelchair.

The International Wheelchair Basketball Federation's (IWBF) regulations 'consider the wheelchair to be part of the player'. This phrase highlights the need for engineers to develop wheelchairs that enhance sporting performance and facilitate excellence.

So when a wheelchair athlete wins a medal, to what extent has engineering design made a difference to the wheelchair athlete's performance?

If engineering design does make a significant difference to a wheelchair athlete's performance this might also raise other questions that could be considered by students. For example, amongst a field of elite athletes, do those with access to the best engineering design have an unfair advantage?

INFORMATION FOR STEM ACTIVITY LEADERS

How to use this STEM resource

This STEM resource has been written for the leaders of STEM activities to use with students of secondary school age. However, there is no reason why younger students should not be given the opportunity to investigate the STEM in wheelchair sport and there are some activities that would provide stretch and challenge for older students.

The desired **learning outcome** is for students to create a presentation that provides a justified answer to the 'big question', *does engineering design make a difference to a wheelchair athlete's performance?* It is intended that students arrive at their answer having investigated the practical challenges of making a model wheelchair and through developing their knowledge of the science and mathematics used by engineers to design wheelchairs for sport.

Throughout the resource the student activities are signposted by the heading ***Time to...*** These sections give students the opportunity to observe, think, make, modify and compete. The students should see these activities as opportunities to gather evidence for their final presentation.

The **STEM activity leader's version** of the resource provides prompts, answers and notes to help support teachers, STEM Ambassadors and STEM club leaders. Background information about some of the scientific principles that are central to developing an understanding of sports wheelchair design is also provided so that non-specialist teachers can engage in discussions with students about the influence of science on wheelchair design. The **student version** of the resource includes information about the relevant scientific principles, but none of the prompts, answers or notes.

All of the activities in this STEM resource can be carried out by students in **groups**. For some activities, just like with real-world engineering, it is essential that students work together.

Overview of the student activities

Introductory student activity

The London 2012 Paralympics was both hugely exciting and inspirational to watch. This introductory activity asks students to familiarise themselves with wheelchair sport and think about competition from the wheelchair athlete's perspective. It is also an opportunity for students to start thinking about how and why sports wheelchairs are different to everyday wheelchairs.

Technology and engineering student activity

This activity helps students to develop an understanding of some of the practical challenges faced by engineers when designing and making wheelchairs for sport.

The guide on pages 6–8 shows students how to make a 1:10 scale model wheelchair. It also explains how to make a tabletop track, which students can use to test their models and compete against each other to see whose wheelchair can travel the furthest and the straightest.

Students will naturally wish to modify their models to improve performance. They should, in preparation for their final presentation, note how the changes they made to their models affected performance. For example, changing the length of the model wheelchair will influence its stability. This may help students to understand the impact the engineer has on the wheelchair's and the athlete's performance.

Science and mathematics student activities

These activities show students how science and mathematics can be used to enhance the performance of wheelchairs and that of the athletes that use them. By investigating **torque**, **track** and **turning moments**, students can develop an understanding of some of the scientific principles engineers apply to make wheelchairs easier to accelerate and control.

The main goal for wheelchair athletes who compete on the track is to achieve the highest velocity needed to beat their rivals and break world records. The activities that focus on velocity also allow students to investigate human movement and, once again, how engineers apply scientific knowledge and mathematics to enhance the performance of wheelchair athletes.

Student presentation

Students should use the practical, scientific and mathematical knowledge they have developed during their investigation of wheelchair sport to present an answer to the 'big question', *does engineering design make a difference to a wheelchair athlete's performance?*

Student presentation specification

The presentation must:

- include a justified answer to the 'big question', *does engineering design make a difference to a wheelchair athlete's performance?*

The presentation could:

- refer to more than one wheelchair sport
- highlight both the athlete's and the engineer's responsibilities in the build-up to competition
- identify some of the challenges faced by wheelchair athletes in their preparations for competitions
- describe the skills wheelchair athletes need to master in order to compete at the highest level
- suggest how the engineer enhances the skills of the athlete
- explain some of the technical problems faced by the engineer when designing and making wheelchairs for sport
- suggest how engineers solve the technical problems they encounter
- include other relevant information about wheelchair sport.

The presentation could take a number of forms and can include:

- text
- photographs
- diagrams
- charts
- graphs
- data.

The desired learning outcome is for students to present a justified answer to the 'big question', *does engineering design make a difference to a wheelchair athlete's performance?*

INTRODUCTORY STUDENT ACTIVITY

Time to OBSERVE

What does wheelchair sport look like?

Use the internet to search for a video of wheelchair athletes competing against each other. Typing *'wheelchair basketball'* into the YouTube search box might be your starting point or you could go to **www.youtube.com/paralympicsporttv**.

Time to THINK

Try to identify the athletic skills that are important for wheelchair sport while you watch video footage of wheelchair athletes in action.

[Prompts provided to the STEM activity leader]

Students might identify some of the following skills needed by wheelchair athletes:

- making the wheelchair accelerate (speed up)
- making the wheelchair decelerate (slow down) or stop
- holding and bouncing a ball while also moving and controlling the wheelchair
- changing direction quickly
- throwing while moving or stationary
- avoiding getting knocked over
- getting up quickly after being knocked over
- catching a ball
- hitting a ball with a racquet.

Time to THINK

What might life be like for a wheelchair athlete? What might be the challenges they have to face? What does it take to become a Paralympian?

[Prompts provided to the STEM activity leader]

Students might identify some of the following challenges for wheelchair athletes:

- funding training and competition entry and travel
- training for several hours a day for six or even seven days a week
- coping with injuries sustained during training or competition
- travelling to training and competition venues
- access into and around training and competition venues.

Changes in the design of wheelchairs for sport

The first official Paralympic Games where wheelchair athletes competed against each other took place in Rome in 1960. The wheelchairs used by the Paralympians then looked very different to those used by wheelchair athletes today.

Time to THINK

Make a list of how the wheelchairs in Figure 1 and Figure 2 differ. Why do you think there are differences between the two designs?

Figure 1: 1960s-style wheelchair

Figure 2: Modern basketball wheelchair

TECHNOLOGY AND ENGINEERING STUDENT ACTIVITY

Time to MAKE

Guide to making a model wheelchair

The photographs in this section explain how to make a 1:10 scale (approximately) model of a track wheelchair, which are the wheelchairs used by athletes competing in racing events such as the 400 m, the 800 m and the marathon.

This guide allows a standardised model of a track wheelchair to be made and used in the two practical STEM challenges. However, if the time and skills available are sufficient, it would be more of a challenge to design and build the model wheelchair from scratch.

Practical STEM challenge

Once made, the model can be used in the following practical STEM challenges.

1. How far can you launch a model wheelchair?
2. How straight can you make a model wheelchair travel? (Lane discipline is very important in wheelchair track events)

Materials required

- 3 mm corrugated plastic sheet*
- 3.2 mm aluminium rod*
- 3 mm steel rod*
- 75 mm diameter polythene wheels x 2*
- 39 mm diameter polythene wheel*
- Drinking straw
- Blu-Tack

* Available from **www.mindsetsonline.co.uk**. See page 18 for product codes.

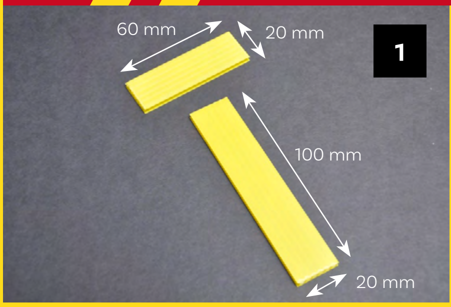
Tools required

- Scissors
- Hot glue gun or double-sided sticky pads
- Pliers
- Hand drill or cordless drill
- 4 mm drill bit

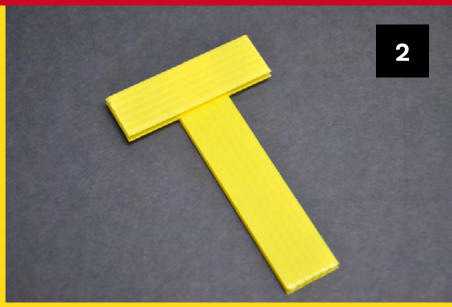
Optional

- Tyres for 39 mm and 75 mm wheels*

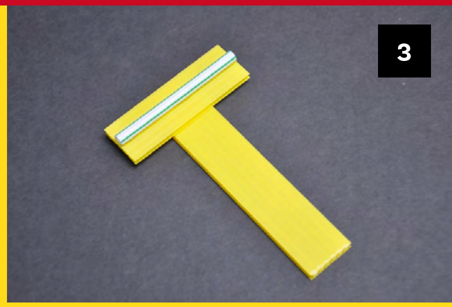
Making instructions



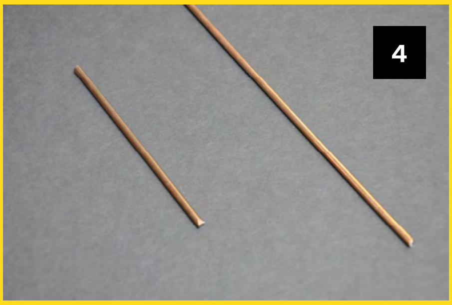
Cut two lengths of corrugated plastic for the wheelchair's chassis.



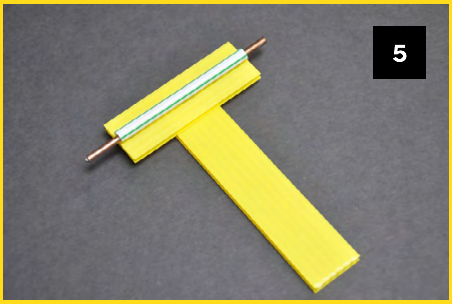
Join the corrugated plastic with hot glue or double-sided sticky pads.



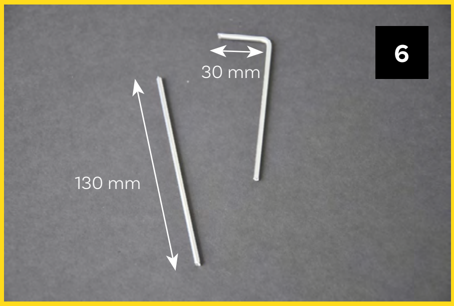
Fix a 60 mm length of drinking straw to the chassis with hot glue.



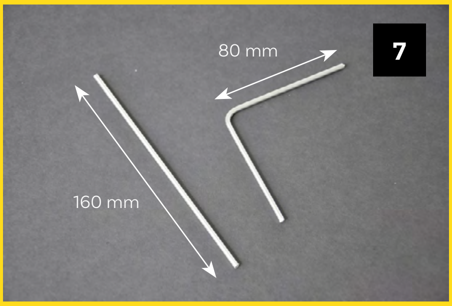
Make a rear axle by cutting an 85 mm length of the 3 mm steel rod.



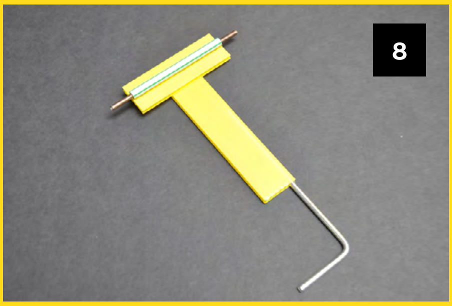
Insert the steel rod axle into the drinking straw on the underside of the chassis.



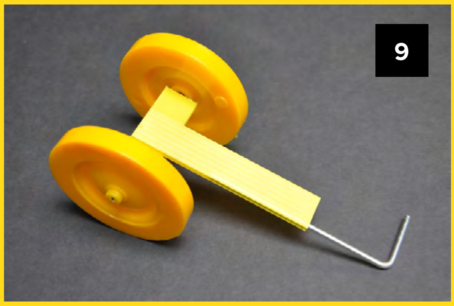
Cut one 130 mm length of the 3.2 mm aluminium rod. Make a 90° bend 30 mm from one end of the rod.



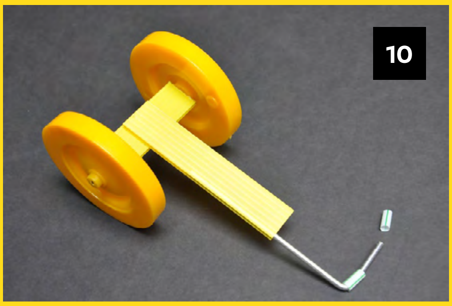
Cut one 160 mm length of the 3.2 mm aluminium rod. Make a 90° bend at its midpoint.



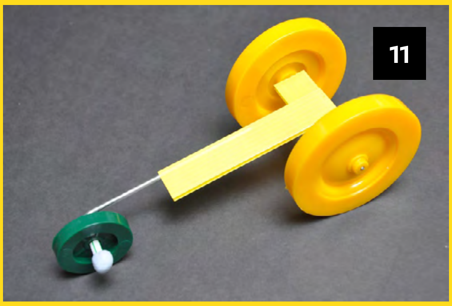
Insert the 130 mm bent aluminium rod into the corrugated plastic chassis. This will become the front wheel's axle.



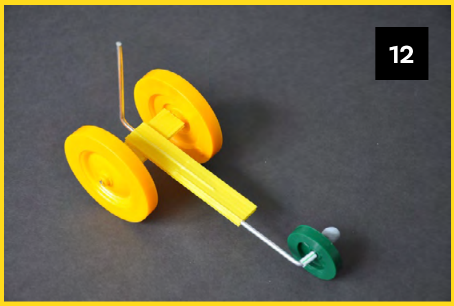
Slide the 75 mm diameter wheels onto the steel axle.



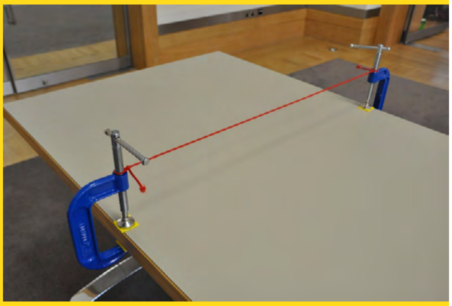
Slide a 10 mm length of drinking straw onto the front wheel's axle.

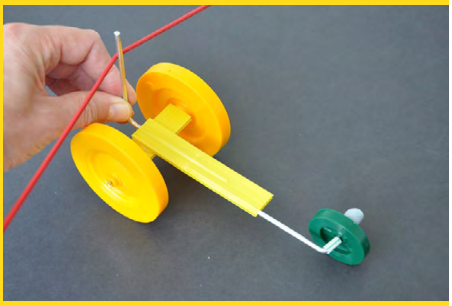


Add the 39 mm diameter wheel to the front axle. If the wheel does not easily slide on and spin freely you will need to use a 4 mm drill to increase the size of wheel's hole.



Insert the 160 mm bent aluminium rod into the rear of the model wheelchair's chassis. This part will help you to launch the model.





Guide to making a launcher and test track

Test track

The prototype wheelchair test track is created by placing a number of tables end to end.

Track barriers

You will need to attach barriers to the edges of the tables to prevent the models from falling off during testing. The barriers can be made from strips of sheet material, such as foam board or corrugated card, and they can be fixed to the edges of the table using Blu-Tack and adhesive tape.

Targets

The students need to be provided with targets for them to aim their prototypes at and test how straight their models travel. The targets could be pictures of gold, silver and bronze medals, with the gold medal position at the centre and the other two medals arranged either side.

Launcher

The prototype wheelchair launcher is made by tying a length of elastic or bungee cord to two G-cramps that have been attached to the edges of a table. The G-cramps shown in this photograph have a 100 mm opening.

Launching

The model wheelchairs are launched by catapulting them along the tabletop track using the elastic or bungee cord, which is tied to the G-cramps.

Success

The most successful prototypes will be those that hit the middle of the target at the end of the test track.

Time to MODIFY

[Notes provided to the STEM activity leader]

Students will be able to improve the performance of their prototype if they give some thought to:

- controlling the force of the launch and turning the energy from the launch method into forward momentum
- preventing the prototype from skidding
- making sure the rear wheels are parallel (this will help the prototype to travel in a straight line)
- adding mass to the prototype to make it more stable
- changing the dimensions of the prototype to make it more stable.

SCIENCE AND MATHEMATICS STUDENT ACTIVITIES

The science and mathematics of sports wheelchair design

Science and mathematics can help to explain the design features of sports wheelchairs. The following sections use science and mathematics to investigate the design of wheelchairs used for sport.

Acceleration

Acceleration is key to the success of any athlete and must be considered when designing a sports wheelchair. This is either because they are competing with others for straight-line speed from a start at rest or because they want to change direction quickly in response to the motion of a ball or other athletes.

In either case, the athlete needs to generate enough upper-body muscle force and apply it at the correct instant to get the whole-body acceleration they require.

Visit **www.youtube.com/paralympicsporttv** and observe how different wheelchair athletes accelerate their wheelchairs. For example, compare wheelchair track athletes, eg, 100 m sprinters, with basketball and tennis wheelchair athletes.

Torque

In order to accelerate, the athlete needs the help of torque, which is a 'moment' (a particular application of force in a rotational or 'twisting' fashion) used to rotate an object about an axis or pivot point (fulcrum).

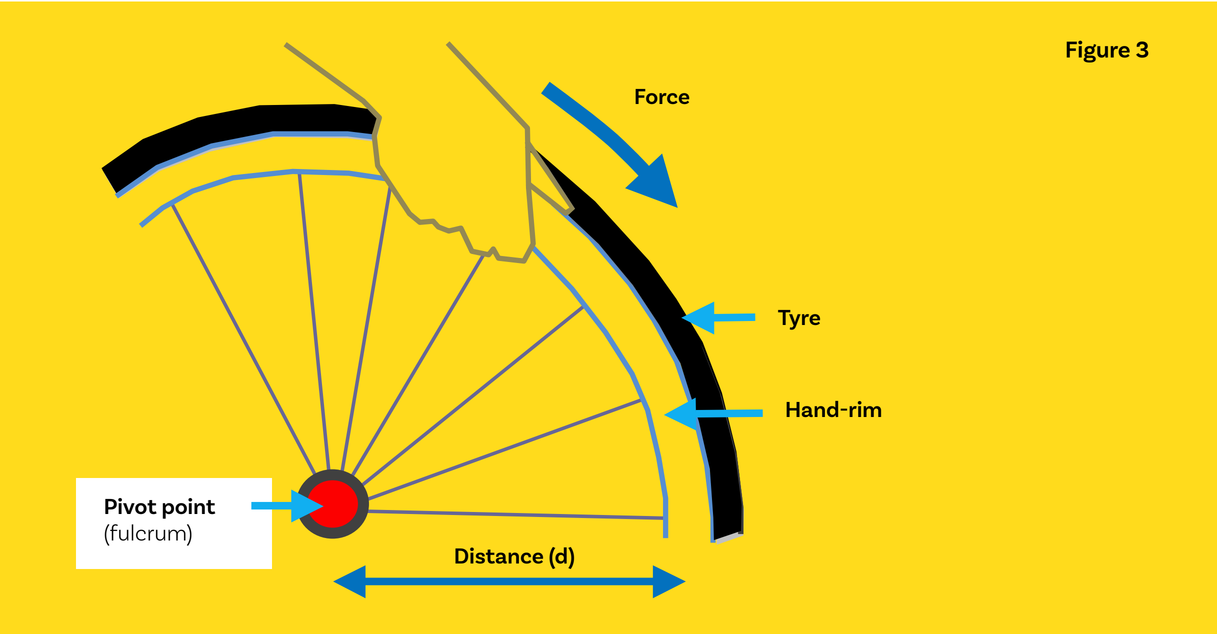
The torque applied to a wheelchair to make it accelerate in a straight line or change direction (also a form of acceleration) is the upper-body muscle force of the athlete applied to the hand-rims of the wheels on the wheelchair. This is a real world example of torque.

Torque (Nm)= **force** (N) **x distance** (m)

Force is measured in Newtons (N)
Distance is measured in metres (m)
Torque is measured in Newton metres (Nm)

Where the distance (d) is the measurement between the point at which the force acts and the pivot point (the fulcrum).

Figure 3



Athletes who can apply or remove the most torque the fastest, and control it best, will be able to accelerate their wheelchairs best. This will make them both faster (linear acceleration) and more agile (rotational acceleration).

The International Wheelchair Basketball Federation (IWBF) regulations stipulate that the wheels of a wheelchair used for basketball must have a diameter no bigger than 69cm.

Time to THINK

Why are larger diameter wheels helpful when it comes to wheelchair basketball?

[Answers provided to the STEM activity leader]

- *Larger diameter wheels allow for larger diameter hand-rims and these, for a given upper-body muscle force, produce more torque.*
- *Larger diameter wheels allow the athlete to have more of their body protected behind the wheels. This is important for sports like basketball where collisions with other wheelchair users are sometimes unavoidable.*

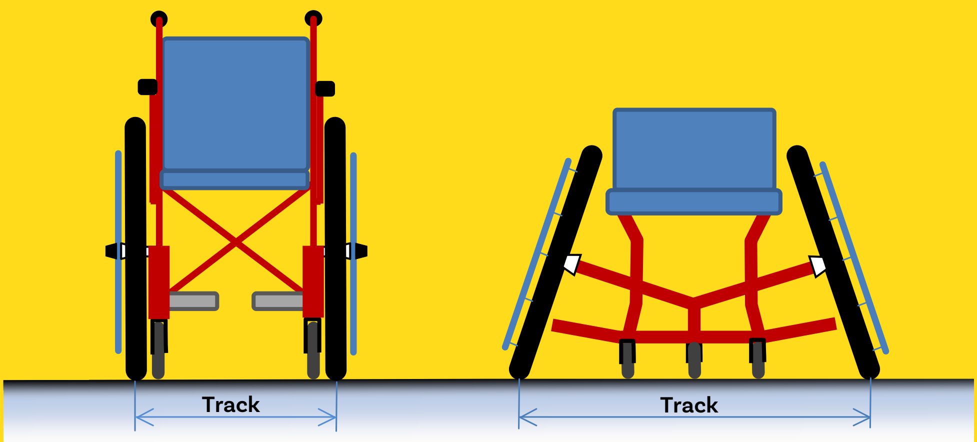
Stretch and challenge

If there was no maximum diameter for the wheels used for basketball wheelchairs, how big do you think the wheels could get before they became too difficult to use?

Track

The distance between the points at which a wheelchair's two tyres touch the ground is called the track. The two drawings below show the difference between the track of an ordinary wheelchair and one used for basketball.

Figure 4



Everyday wheelchair

Wheelchair for playing basketball

Time to THINK

How much bigger is the basketball wheelchair's track?

There are a number of significant differences between wheelchairs that are for everyday use and those that are used for sport. One obvious difference is the way the wheels of a sports wheelchair are angled or 'cambered'. Cambering the wheels of a wheelchair increases its track. Increasing the track of a wheelchair brings a number of advantages to the athlete. But how much bigger is the track of a sports wheelchair? It is possible to work it out using the information we know about the sizes of a standard wheelchair and some basic trigonometry.

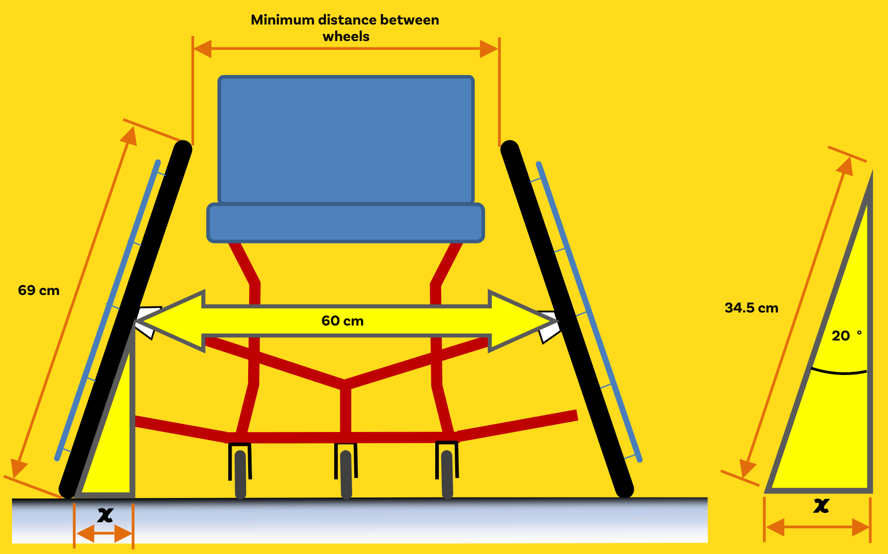


Figure 5

The distance between the wheels of a standard wheelchair is about 60 cm. If we take this as our starting point for the sports wheelchair and assume from observing wheelchair basketball that the camber of the wheels is about 20° we can calculate how much greater its track is using the following equation.

$$\sin(20) = \frac{\chi}{34.5}$$

$\chi = \sin(20) \times 34.5 = 11.7$ cm = 12 cm (if we round up to the next whole number).

So the track of the wheelchair in Figure 5 = 12 + 60 + 12 = 84 cm.

And the minimum width between the wheels, which determines the seat width, is:

60 -12 - 12 = 36 cm,

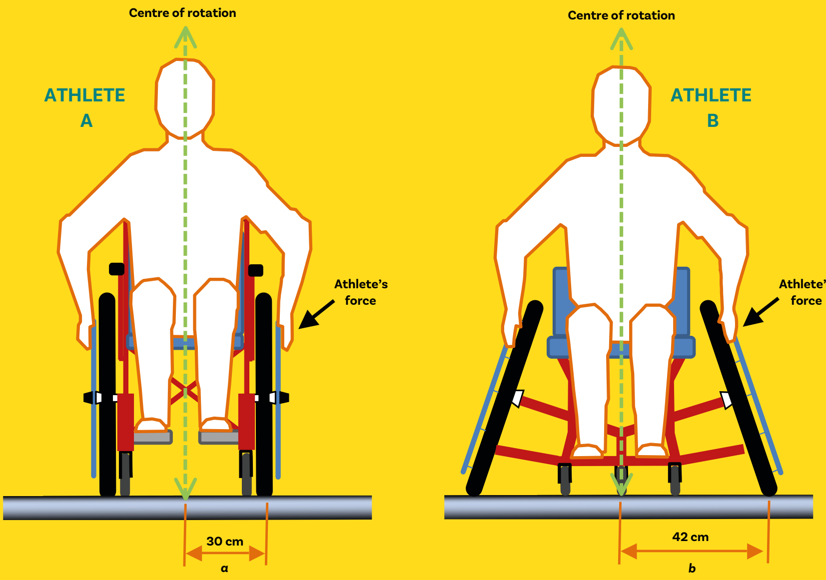
which is ideal because the athlete needs to be able to sit between the wheels (the width of a sports wheelchair's seat is usually 34 cm – 54 cm).

Moments

The cambering of the wheels makes the wheelchair more manoeuvrable because it creates a *turning moment advantage* compared to a wheelchair with vertical wheels.

The turning moment is a form of torque acting about the centre of rotation of a mass. This can be calculated using the torque equation we met earlier.

Figure 6



Turning moment (Nm) = **force** (N) x **distance** (m)

Where force is the effort made by the athlete to turn the wheelchair's wheel and this time the distance is the measurement between the centre of rotation of the wheelchair and the point at which the wheel touches the ground.

The centre of rotation of the wheelchair in a turn is the centreline of the wheelchair.

Time to THINK

How much of an advantage do cambered wheels provide a wheelchair athlete?

[Answers provided to STEM activity leader]

Increasing the distance between the centre of rotation and the turning moment advantage achieved by cambering the wheels of a wheelchair can be discovered by calculating the percentage increase between ***a*** and ***b*** in Figure 6 above:

$$\text{Percentage increase} = \frac{b - a}{a} \times 100$$

$$\text{Percentage increase} = \frac{42 - 30}{30} \times 100 \quad \frac{12}{30} \times 100 = 0.4 \times 100 = 40\ \%$$

40 % of additional turning moment is caused when the 69cm diameter wheels of a wheelchair are cambered by 20 degrees. For the athlete this means the **rate** at which they can change direction increases by 40 % when they apply a sudden muscle force to the hand-rims of the wheelchair. This is a huge gain in rotational acceleration and hence manoeuvrability and agility.

Time to THINK

What are the other advantages of cambering the wheels of a wheelchair used for basketball?

[Answers provided to STEM activity leader]

- The athlete needs to reach out to catch and pass the ball. When reaching out to the side they can topple over. A wider 'track' to the wheelchair produced by wheel camber makes them more **laterally stable** – less likely to topple over to the side. This is like a person who stands with their feet further apart in a strong wind in order not to be blown over. It is like the legs of the stool that are commonly splayed out to make the stool more stable. Formally, widening the track of the wheelchair means that the wheelchair can be tipped over laterally to a higher angle before reaching its toppling point – the point where the centre of mass is directly over the contact point between the wheel and the ground.

- Camber protects the athlete's hands and knuckles in a collision.
- Camber allows the athlete to keep their elbows nearer to their sides which (apart from protecting them) allows them to make more effective use of their arm and upper-body muscles. This is why it is easier to do press ups with our arms in line with our shoulders. Doing press ups with our arms splayed is really hard!

Velocity

Time to THINK

How fast can a wheelchair athlete go?

One way to answer this is to look at the world records for wheelchair athletes. The International Paralympic Committee (IPC) publishes world record data for all of the sports it oversees [1]. The current world records for a selection of track events for T54 classification [2] wheelchair athletes are given below in Table 1.

Table 1

Men (T54)		Women (T54)	
Distance	**Time (seconds)**	**Distance**	**Time (seconds)**
100 m	13.63	100 m	15.82
200 m	24.18 *	200 m	27.52
400 m	45.07 *	400 m	51.91
800 m	91.12	800 m	105.19
1500 m	174.51	1500 m	201.22

* The same athlete

We can discover the average velocity of world class wheelchair athletes using the equation below.

$$\text{velocity (m/s)} = \frac{\text{distance (m)}}{\text{time (s)}}$$

[Answers provided to STEM activity leader]

Table 2 shows the average velocities of the wheelchair athletes who achieved the world records shown in Table 1.

Table 2

Men (T54)			Women (T54)		
Distance	**Time (seconds)**	**Average velocity (m/s)**	**Distance**	**Time (seconds)**	**Average velocity (m/s)**
100	13.63	7.34	100 m	15.82	6.32
200	24.18 *	8.27	200 m	27.52	7.27
400	45.07 *	8.88	400 m	51.91	7.71
800	91.12	8.78	800 m	105.19	7.61
1500	174.51	8.60	1500 m	201.22	7.45

[1] Paralympic world record data can be downloaded in various file formats from **http://www.paralympic.org/Results/world-records/Athletics**

[2] Track athletes competing in the T51 – T54 classifications have activity limitations in both lower and upper limbs. The athletes with a T54 classification have fewer activity limitations than those with lower classification numbers. *The Layman's Guide to Paralympic Classification* can be downloaded from **http://tinyurl.com/cuqb8yd**

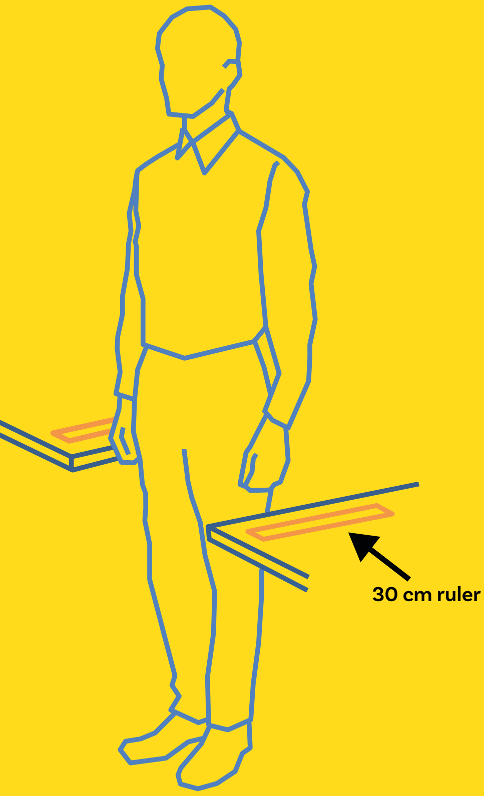


Figure 7

So the fastest world class wheelchair athletes can currently travel at an average of approximately **8 m/s**, which is equivalent to **17.9 miles per hour**.

The athletes achieve these speeds by providing a burst of muscle force to the hand-rims of the wheelchair – an *impulse* – and over long distances *coasting* between impulses. The velocity of the athlete's hands must be equal or greater than the *tangential velocity* [3] of the hand-rim if they are to apply a *positive torque* and increase the rotational speed of the wheel, that is, accelerate the wheelchair – increasing its travelling velocity. If the athlete's hands are travelling slower than the hand-rims they will have the effect of *slowing the hand-rims down*, absorbing torque and therefore *decelerating* (slowing down) the wheelchair.

Visit **www.youtube.com/paralympicsporttv** and observe how T54 wheelchair athletes accelerate their wheelchairs in track events, such as the 100 m and 200 m races.

When accelerating in a straight line, the maximum speed of the wheelchair occurs when the tangential velocity of the hand-rims reaches the maximum velocity of the hand movement that the athlete can produce.

Time to COMPETE

What is the maximum hand velocity possible when powering a wheelchair? Do a controlled test!

- Take two tables and position them with a 50 cm gap between them.
- Lay a 30 cm ruler on the edge of each table as shown in Figure 7.
- Stand between the tables with your hands comfortably by your sides and your palms stretched out.
- See how fast you can move your hands backwards and forwards over the 30cm distance as if you were powering a wheelchair. A friend should count the number of times your hands can make a 30 cm 'trip' down the length of the ruler and back again in 20 seconds.
- Work out an average velocity, in terms of metres travelled per second, for your hands using the equation below.

$$\text{velocity (m/s)} = \frac{\text{distance (m)}}{\text{time (s)}}$$

- At what point do you think your hands have maximum velocity?

[Answers provided to the STEM activity leader]

- The maximum repetition rate of the entire hand motion cycle will rarely be more than 3 Hz (3 cycles per second) as this is the commonly known maximum 'control frequency' of the human. One cycle is represented by a 'trip' down the length of the ruler and then back again. See if the repetition rate is higher when the subject moves their arms 'in phase' with each other (both moving forward at the same time) or in 'anti-phase' (when one moves backwards as the other moves forwards).
- The distance the hand travels in one cycle is 60 cm, so at 3 Hz this is 180 cm which is an average velocity of **1.8 m/s**.

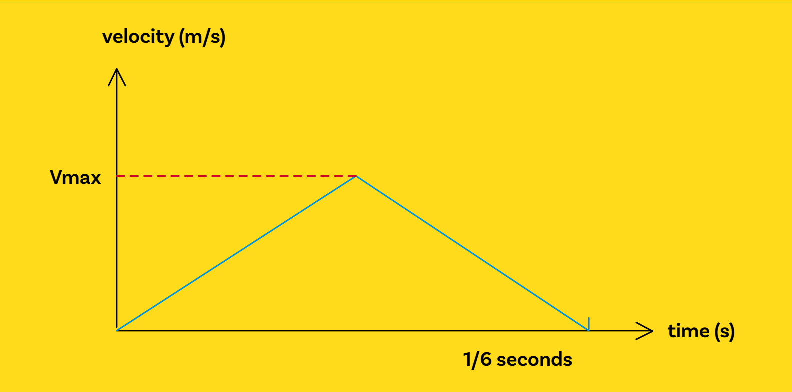
$$\text{velocity (m/s)} = \frac{3 \times 0.60\text{m}}{1\text{ (s)}}$$

[3] The velocity of the hand rim at the point at which the athlete's hand makes contact.

- The maximum velocity of the hand occurs at the midpoint of its travel. Before then it is accelerating from a change in direction. After that it is decelerating in anticipation of another change in direction.

Stretch and challenge

Calculating maximum hand velocity



Making the simplifying assumption that the acceleration of the hand is constant we get the velocity time history above for a 3Hz cycle frequency. Noting that if using calculus the integral of a velocity time history (which is the area of the triangle) is the distance travelled.

We can find out the athlete's maximum hand velocity (Vmax) using the following equation.

Area = ½ x base x height

where:

- area is the distance travelled, which is 30 cm or 0.3 m
- base is the time it takes to travel 30 cm, which is $\frac{1}{6}$ of a second
- height is the maximum velocity (Vmax), which we don't know.

So:

$$0.3 = \frac{1}{2} \times \frac{1}{6} \times V_{max}$$

and if we rearrange the equation so that it reads:

$$V_{max} = 0.3 \times 2 \times 6$$

we find that the maximum velocity is 3.6 m/s.

Students unfamiliar with integration could use the equations of motion $v^2 = u^2 + 2as$ and $s = ut + \frac{at^2}{2}$ to calculate the maximum velocity or else use a spreadsheet to estimate through a process of trial and error.

If the realistic maximum hand velocity is between 3 and 4 m/s how do wheelchair athletes achieve travelling velocities of up to 8 m/s (i.e. twice that of the maximum hand velocity)? They do it by using hand-rims with diameters much smaller than the wheel diameter of 69cm considered here. If they used a hand wheel with a diameter of less than 35 cm on a wheel of 69cm diameter they would be able to achieve travelling velocity of 8 m/s with a maximum hand velocity of 4 m/s. However they would need to produce **twice** the upper-body muscle force to produce the same torque as the athlete using a 69cm hand-rim. **So the design tricks of the engineer can only be exploited by a true athlete!**

Figure 8

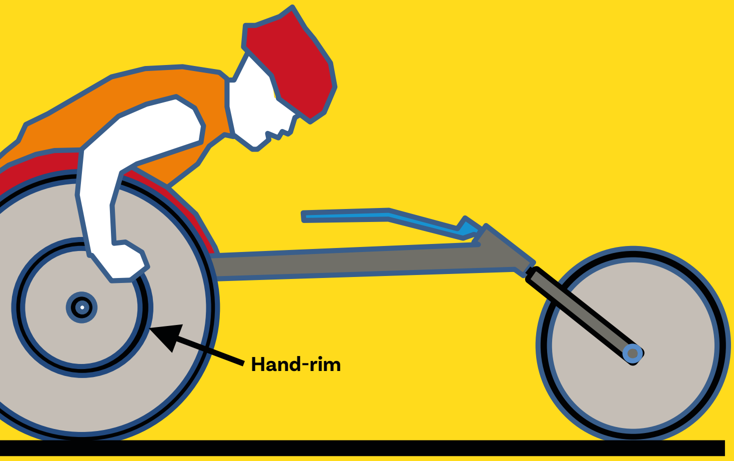
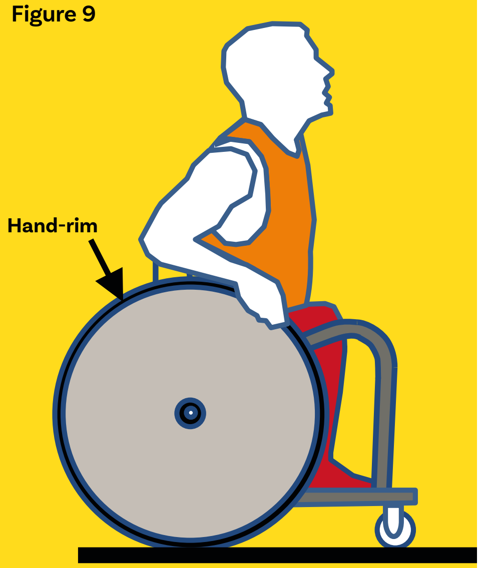


Figure 9



Time to THINK

A Paralympic track athlete can move her hands at a maximum velocity of approximately 4 m/s. How is it that she can make her wheelchair travel faster at an average velocity of 8 m/s?

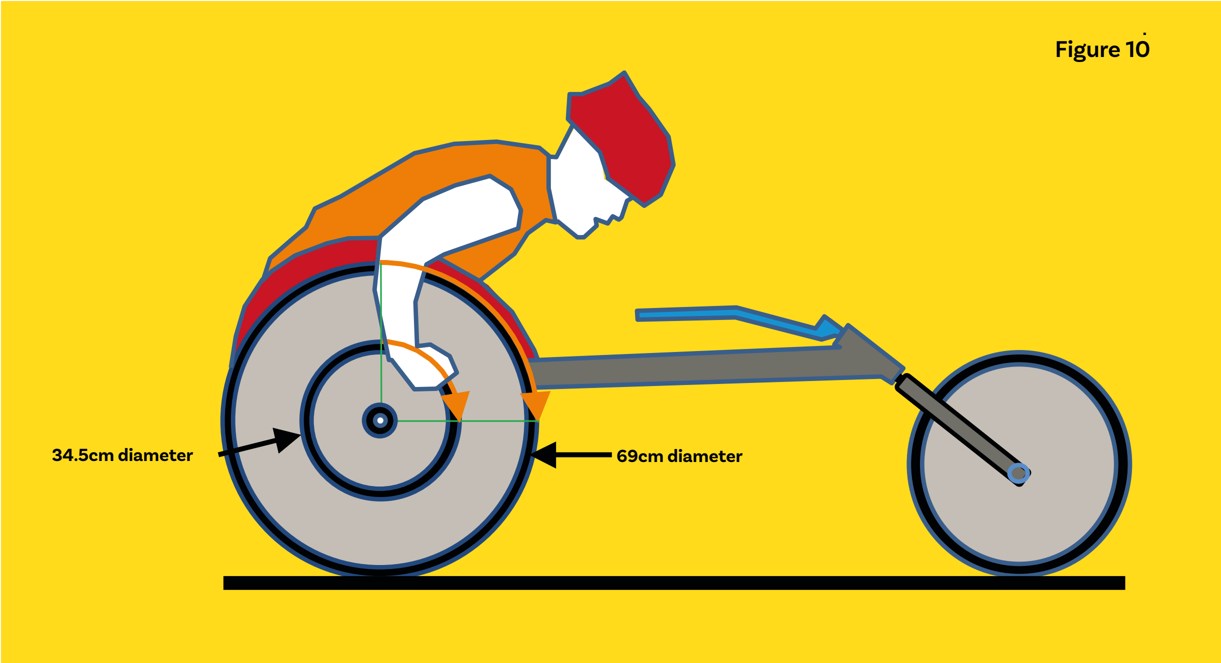
Compare the drawing of the track wheelchair in Figure 8 with the drawing of the basketball wheelchair in Figure 9. Why do you think the hand-rims are different diameters?

[Answers provided to the STEM activity leader]

Although harder to push (because the distance between the fulcrum and the point of effort is small) a hand-rim that is half the diameter of the wheel will cause the wheel to rotate twice the distance of that travelled by the hand-rim. This can be shown graphically and using mathematics.

Figure 10 (above right) uses orange arrows to show that rotating the hand-rim a quarter turn, or 90 °, results in the wheel rotating twice the distance of the hand-rim. This means every rotation of the track wheelchair's hand-rim will result in the track athlete travelling twice as far as an athlete in a basketball wheelchair who uses a hand-rim that is positioned at the outside edge of the wheel.

We can also use mathematics to investigate how far the wheel rotates in relation to the hand-rim by calculating the arcs of two circles.



An arc is part of a circle's circumference. If we compare the arc of a circle equal in diameter to the hand-rim (34.5 cm) with the arc of a circle of diameter 69 cm (which is the same as the wheelchair's wheel) we can find out if making the hand-rim half the size of the wheel makes the wheel travel twice as far.

The arc of a quadrant (a 90° sector) of a circle with a diameter of 34.5 cm (equal to that of the track wheelchair's hand-rim) is calculated using the equation:

$$\text{arc} = \textit{diameter} \times \pi \times \frac{90}{360}$$

34.5 cm x 3.14 x 0.25 = **27.08 cm**.

The arc of a quadrant of a circle with a diameter of 69 cm (equal to that of the wheel) is:

69 x 3.14 x 0.25 = **54.16 cm,**

which is double that of the hand-rim.

This shows that the distance travelled by the track wheelchair's wheel is twice that of the hand-rim. Being able to move the wheels twice as far as the hand-rim travels has the same effect as doubling the speed of the athlete's hands. This is how wheelchair athletes can travel at 8 m/s when their hands can only travel at approximately 4 m/s.

STEM CHALLENGE DAY

Preparation

- Organise students into groups of three. If possible, each group should ideally be made up of one student who is confident in D&T, one who is a confident mathematician and one who is a confident scientist.
- Ensure all the materials and equipment needed are available or have been purchased well in advance of the day. See Table 3 below for a list of the essential materials and components that will probably need to be ordered especially for the day.
- Prepare the tabletop track so students can test their models and compete against each other to see whose can go furthest and in as straight a line as possible. Details about how to prepare the test track can be found on page 8 of this resource.
- Provide copies of the *guide to making a model wheelchair* for the students, which can be found on pages 6–8 of this resource and pages 3–4 of the students' version.

Ordering essential materials and components

The following specific components may not be readily available in schools and other educational establishments. Therefore, it may be necessary to order these items.

A free starter pack is available from the Royal Academy of Engineering and can be requested by emailing **education@raeng.org.uk**. This offer is available while the Academy's stocks last.

Table 3

Description	Product code	Pack size	Supplier
3 mm corrugated plastic sheet	CS6 001J	1 sheet @ 600 mm x 500 mm	**www.mindsetsonline.co.uk**
3.2 mm aluminium rod	CW3 018	50	**www.mindsetsonline.co.uk**
3 mm steel rod	CW3 015	30	**www.mindsetsonline.co.uk**
75 mm diameter polythene wheels x 2	CW3 031	1	**www.mindsetsonline.co.uk**
39 mm diameter polythene wheel	CW3 027A	1	**www.mindsetsonline.co.uk**
Optional Tyre 'O' ring for 75 mm wheel	GRO 010	1	**www.mindsetsonline.co.uk**
Optional Tyre 'O' ring for 39 mm wheel	GRO 005	1	**www.mindsetsonline.co.uk**

Challenge day plan

Time (minutes)	Student/teacher activity	Equipment, materials and resources
10	**Teacher** Introduction to wheelchair sport using video clips. Set student the challenge to answer the 'big question': *does engineering design make a difference to a wheelchair athlete's performance?*	■ ICT access ■ Video projector or interactive white board (IWB) ■ **www.youtube.com/paralympicsporttv**
20	**ACTIVITY: INTRODUCTION** **Students** Complete the introductory activities on pages 4–5 making sure they record their responses to the following tasks and questions: ■ Identify the skills that are important for wheelchair sport ■ What might life be like for a wheelchair athlete? ■ What might be the challenges wheelchair athletes have to face? ■ What does it take to become a Paralympian?	■ Pages 4–5 of this resource and pages 1–2 of the students' version ■ ICT access ■ Internet access ■ Writing paper, pens and pencils
10	**ACTIVITY: MAKING A MODEL WHEELCHAIR** **Teacher** Introduce the technology and engineering practical activity, which is to make a model wheelchair and compete to see whose model can travel furthest and straightest. Demonstrate how to make the model wheelchair. Encourage students to modify the standard design in order to improve performance. Demonstrate how to launch the model wheelchair.	■ Copies of the *guide to making a model wheelchair,* which can be found on pages 6–8 of this resource and pages 3–4 of the students' version. **Model wheelchair components** ■ 3 mm corrugated plastic sheet* ■ 3.2 mm aluminium rod* ■ 3 mm steel rod* ■ 75 mm diameter polythene wheels x 2* ■ 39 mm diameter polythene wheel* ■ Drinking straw ■ Blu-Tack * available from **www.mindsetsonline.co.uk** **Tools required** ■ Scissors ■ Hot glue gun or double-sided sticky pads ■ Pliers ■ Hand or cordless drill ■ 4 mm drill bit **Optional** ■ Tyres for 39 mm and 75 mm wheels*
20	**ACTIVITY: MAKING A MODEL WHEELCHAIR** **Students** In groups, students make model wheelchairs from the components provided.	■ See above.

Time (minutes)	Student/teacher activity	Equipment, materials and resources
20	**ACTIVITY: TESTING AND MODIFYING A MODEL WHEELCHAIR** **Students** Students test their model wheelchairs on the tabletop track. They should be encouraged to modify their model wheelchairs in preparation for the final competition.	■ See above
10	**ACTIVITY: MODEL WHEELCHAIR COMPETITION** **Students** Students take it in turns to launch their group's model wheelchair on the tabletop track. Each group has three attempts to launch their model wheelchair at the targets at the far end of the tabletop track. The winning students are those who get their model wheelchairs nearest to the middle target at the end of the tabletop track.	■ Tabletop test track and launcher (see page 8 of this resource) NOTE: An incline could be used to launch the model wheelchairs rather than the catapult shown on page 8 of this resource.
10	**ACTIVITY: REFLECT ON PRACTICAL ACTIVITY** **Students** Students record what they have learned about some of the practical and technical challenges involved in engineering a wheelchair.	■ Writing paper, pens and pencils
10	**ACTIVITY: INVESTIGATING TORQUE** **Teacher** Introduce the science and mathematics of sports wheelchair design. Discuss the importance of **acceleration** (perhaps ask the students to come up with their own definition for acceleration) and the role of **torque** in acceleration. Make students aware of the equation for **torque** and use the diagram in Figure 3 to illustrate this scientific principle. If appropriate give students the opportunity to investigate **torque** by providing them with scenarios and data, which they can use with the equation. **Students** If appropriate investigate **torque** using the equation and data provided. Record an answer to the question: ■ Why are larger diameter wheels helpful when it comes to wheelchair basketball?	■ Page 9 of this resource ■ Writing paper, pens and pencils

Time (minutes)	Student/teacher activity	Equipment, materials and resources
10	**ACTIVITY: INVESTIGATING TRACK AND TURNING MOMENTS** **Teacher** Introduce the concept of **track** to the students using the images in Figure 4. If appropriate, talk students through Figure 5 and the worked example on page 11 of this resource and page 7 of the students' version. Introduce students to the concept of **moments**. Use Figure 6 and the **turning moment** equation on page 12 of this resource and page 8 of the students' version to illustrate the concept of turning moments in the context of wheelchairs with cambered wheels. Discuss how students might calculate the amount of advantage provided to the athlete by cambering the wheels. **Students** Record an answer to the questions: ■ How much of an advantage do cambered wheels provide a wheelchair athlete? ■ What are the other advantages of cambering the wheels of a wheelchair used for basketball?	■ Pages 10–11 of this resource and pages 6–8 of the students' version ■ Writing paper, pens and pencils ■ Calculators
15	**ACTIVITY: INVESTIGATING VELOCITY** **Teacher** Highlight the importance of velocity for wheelchair athletes. Set students the task of calculating the average velocity of T54 wheelchair athletes. Present the equation for calculating average velocity and the data for T54 athletes at various distances (see page 13 of this resource and page 9 of the students' version). **Students** Calculate and record the average velocity of T54 wheelchair athletes.	■ Page 13 of this resource and page 9 of the students' version ■ Pencil and paper for completing calculations ■ If necessary, a calculator for working out the average velocities
20	**ACTIVITY: INVESTIGATING VELOCITY AND HUMAN CONTROL FREQUENCY** **Teacher** Introduce the idea that there is a limit to the speed at which human beings can move their arms. Explain that this has implications for the velocity at which a wheelchair athlete can travel. It is also a problem that engineers have tackled. Set the students the challenge of investigating how many times a human can move their arms backwards and forwards (just like when accelerating a wheelchair and maintaining its velocity). The student instructions for carrying out this controlled test are available on page 9 of the students' version of the resource. Students may need some support to calculate the average velocity of their hands during the controlled test. **Students** ■ Carry out the controlled test. ■ Calculate the average velocity of their hands during the controlled test. ■ Suggest the point at which their hands have maximum velocity.	■ Page 14 of the STEM activity leader's version of the resource for details of the controlled test ■ Page 9 of the students' version of the resource for details of the controlled test **Controlled test equipment, materials and resources** ■ Classroom table x 2 ■ 30 cm ruler x 2 ■ Stopwatch or timer ■ Pencil and paper for recording data and calculations ■ If necessary, a calculator for working out the average velocity

Time (minutes)	Student/teacher activity	Equipment, materials and resources
	ACTIVITY: INVESTIGATING VELOCITY AND HUMAN CONTROL FREQUENCY (*CONTINUED*) **Teacher** Introduce the idea that the maximum 'control frequency' of humans, and therefore, wheelchair athletes, is 3 Hz (3 cycles per second). Ask students to think about the question, which is on page 16 of this resource and page 10 of the students' version: ■ A Paralympic track athlete can move her hands at a maximum velocity of approximately 4 m/s. How is it that she can make her wheelchair travel faster at an average velocity of 8 m/s? A possible answer is provided on page 17 of this resource. **Students** Think about, discuss and answer the following question: ■ A Paralympic track athlete can move her hands at a maximum velocity of approximately 4 m/s. How is it that she can make her wheelchair travel faster at an average velocity of 8 m/s? **Teacher** Give students the opportunity to present their answers' to the above question. Provide answers using the guidance on page 17 of this resource.	
60	**ACTIVITY: PRESENTATION** **Teacher** Introduce the presentation activity, making students aware of the specification for the presentation on page 3 of this resource and page 11 of the students' version. The focus of the presentation is for the students to provide their group's answer to the 'big question': *does engineering design make a difference to a wheelchair athlete's performance?* Stress the need for students to justify their answer by drawing on the knowledge developed during the practical, science and mathematics activities they have completed. The presentation could take the form of a: ■ Poster ■ PowerPoint presentation ■ Prezi presentation (see **http://prezi.com**) ■ Video ■ Combination of media **Students** Prepare and present an answer to the 'big question': *does engineering design make a difference to a wheelchair athlete's performance?*	**Suggested equipment, materials and resources for poster presentation** ■ A2 or A1 sheet or board ■ Coloured pens, pencils and other drawing media ■ Coloured paper ■ Glue sticks ■ Lettering stencils ■ Self-adhesive lettering ■ Adhesive tape ■ Other appropriate materials and components **Suggested equipment and materials for digital presentation** ■ ICT access ■ Digital camera ■ Video camera ■ Video projector

USEFUL SOURCES OF INFORMATION

The International Paralympic Committee (IPC) – www.paralympic.org
The official website of the Paralympic Movement with links to information and videos about all Paralympic sports.

ParalympicSportTV – www.youtube.com/paralympicsporttv
Access to videos of Paralympic sports.

IPC rules and regulations – www.paralympic.org/Athletics/Rulesandregulations/Rules
The rules and regulation for Paralympic athletics including the design of wheelchairs and equipment.

British Paralympic Association – www.paralympics.org.uk
The official website of the British Paralympic Association.

Wheel Power – www.wheelpower.org.uk
The national organisation for wheelchair sport in the United Kingdom.

Wheelchair sport FAQs – www.wheelpower.org.uk/WPower/index.cfm/resources/faqs/

Draft Wheelchairs – www.draftwheelchairs.com
Wheelchair designer and manufacturer.

RGK – www.rgklife.com
Wheelchair designer and manufacturer.

WC Racing – www.wcracing.net/misc/index.html
A guide to track wheelchair fitting, technique and training.

International Wheelchair Basketball Federation – www.iwbf.org
This organisation provides a wealth of detailed information about the sport of wheelchair basketball, including the rules and regulations for the design of wheelchairs.

British Wheelchair Basketball Association – www.gbwba.org.uk

International Wheelchair Rugby Federation – www.iwrf.com
Information about the sport of wheelchair rugby, including the rules and regulations for the design of wheelchairs.

Great Britain Wheelchair Rugby – www.gbwr.org.uk

Wheelchair athlete Shelley Woods

Picture courtesy of BAE Systems plc

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We're influencing policy through the National Engineering Policy Centre – providing independent expert support to policymakers on issues of importance.

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Front cover image: Wheelchair athlete Shelley Woods
Picture courtesy of BAE Systems plc

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