

Archimedes' poetry: the beauty of pulleys in motion

Introduction: the ingenious simplicity of pulleys

The pulley. Arguably one of the most fundamental and revolutionary inventions in human history. At first glance, it is simply an ordinary wheel on an axle, with a belt or rope running along its groove, yet its use has transformed how we approach engineering, architecture, and even sports performance. The beauty of pulleys lies in their deceptive simplicity: a single change in configuration, such as adding an extra pulley, can significantly alter the forces that are at work, enabling humans to lift exceptionally heavy loads with minimal effort, or in the case of sports training, maximise performance with incredible precision.

In this essay I will discuss the fundamental mathematical concepts behind pulleys, their historical significance, and modern applications, most notably in sports training methods. This will be in part informed by my own project, completed together with Olympic swimmer, Ben Proud, demonstrating how such pulley systems can be used to achieve optimal performance at the highest level of sports.

Historical origins: ancient civilizations to modern engineering

The earliest use of pulleys dates to ancient Mesopotamia and Egypt. The reason behind using such pulley systems was simple: to enable humans to lift loads heavier than they could lift themselves. This basic desire turned out to be pivotal in constructing monumental structures like the pyramids, which even by today's standards remains an incredible feat. Later, the Greeks solidified their study of pulleys, with Archimedes famously demonstrating how a compound pulley system could lift heavy ships with minimal force required on the part of humans. Archimedes also studied and recognised the six classical machines (lever, pulley, screw, inclined plane, wedge, and wheel and axle), which would be the building blocks of almost all machines to come. This innovation would continue throughout the ages, with the desire to build bigger and better pushing innovators towards increased precision during the Industrial Revolution, notably Henry Maudslay's work on block and tackle mechanisms for the Royal Navy at the Portsmouth Block Mills in the 1800s.

The whole concept of pulleys revolves around one important concept: mechanical advantage. This is the factor by which a mechanism multiplies the input force. A single fixed pulley changes only the direction of force, while a movable pulley reduces the effort required. A system that combines this is known as a block and tackle mechanism, where multiple pulleys work in tandem, to provide an exponential mechanical advantage capable of lifting heavy loads.

One elegant equation that captures this is:

$$\text{Mechanical Advantage (MA)} = \frac{\text{Output force}}{\text{Input Force}} = \frac{\text{Number of supporting ropes}}{1}$$

This sole principle has enabled cranes to lift massive ships, elevators to transport passengers every day, and athletes train with precision-engineered resistance.

The physics of pulleys: force, work, and efficiency

The fundamental mechanics of pulleys can be separated into a few key equations. Consider a weight, (W), being lifted by an ordinary pulley system:

1. Weight calculation:

$$W = m \times g$$

Where (m) is mass and (g) is gravitational acceleration (9.81m/s^2).

2. Mechanical advantage:

For a system with (n) supporting ropes, the input force (F_{input}) required is:

$$F_{input} = \frac{W}{n}$$

3. Work done:

Since energy is conserved in this system (neglecting friction), the work input must equal the work output:

$$F_{input} \times d_{input} = W \times d_{output}$$

Where (d_{input}) is the rope pulled and (d_{output}) is the distance the load moves.

These equations prove an insight into why such pulley systems can be so powerful: they essentially trade force for distance. This allows heavier weights to be lifted with substantially reduced effort over a greater distance. Of course, it must be noted whilst one gains MA, energy is conserved, as work done ($Work\ done = Force \times distance$) will remain the same. If friction were to be considered, work done by the swimmer will be greater due to energy losses within the system.

Pulleys in sports: a project with an Olympian

A striking modern application of pulley systems can be found in swimming training. Here, pulleys can be used to balance heavier loads (resistance training) whilst still providing movement specificity. One such mechanism is the swimming power tower, which is

commonly used by elite swimmers like Ben Proud, and utilises a block and tackle mechanism. Whilst using one of these towers during our training session, I was prompted to investigate how this machine worked after an insightful discussion about the resultant force experienced by the swimmer during its use.

The experiment: measuring mechanical advantage

For my project, we used a 20-pulley Swim Power Tower, and attempted to determine its mechanical advantage. The setup consisted of:

- A 100 kg water-filled bucket as resistance
- A harness connecting the swimmer to the pulley system

The specific power tower we used can be seen below.



Calculation:

$$F_{\text{swimmer}} = \frac{m \times g}{n} = \frac{100 \times 9.81}{20} = 49.05 \text{ N}$$

Therefore, to lift 100kg, the swimmer must only apply 49.05 N of force: hence the tower results in a 20-fold advantage, a striking outcome for such a compact mechanism.

Implications for sprint training

The power tower's mechanical advantage allows for:

1. Explosive power development – heavy resistance can be applied without overloading the swimmer and increasing maximal speed.
2. Over speed training – the weight assists recovery on the way back, as the system works in reverse too, enabling faster-than-race-pace repetitions. This is key for top speed in races, as your body can be accustomed to it.
3. Space efficiency – the compact pulley arrangements maximize potential training distance with limited space.

Conclusion

This synergy of maths and biomechanics highlights just how valuable pulley-based systems are in many modern applications like sports, pushing the upper limits of performance. Furthermore, their remarkable adaptability can be demonstrated by a slight modification to the system; adding an extra pulley, for example, can almost entirely transform the purpose or capability, whether for building pyramids or creating world-class athletes.

The project with Ben Proud not only validated the core principle behind pulleys, but also provided an insight into how these systems are able to bridge mathematics and tangible results at high performance levels. For these elite athletes, such systems could be the difference between silver and gold, separated by only a few tenths of a second.

From antiquities to the Olympic pool, pulleys have proven countless times that mechanical elegance lies not always in complexity, but the simple application of mathematical principles.

References:

All images are my own

Simple Machines: https://en.wikipedia.org/wiki/Simple_machine

Henry Maudslay context: How Precision Engineers Created the Modern World by Simon Winchester

General info on pulleys: <https://www.britannica.com/technology/pulley>