Rotating locomotion in living systems

There exist two distinct modes of locomotion using rotation : first , simple rolling ; and second , the use of wheels , which spin relative to a fixed axle or body . Several organisms are capable of rolling . However , despite their utility in human vehicles , true wheels do not appear to play a significant role in the movement of living things (with the notable exception of certain flagella , which function like corkscrews) . Biologists have expounded on the reasons for this apparent absence of biological wheels , and wheeled creatures have appeared often in speculative fiction .

Given the ubiquity of the wheel in human technology , and the existence of biological analogues of many other technologies (such as wings and lenses) , the lack of wheels in the natural world would seem to demand explanation ? and the phenomenon is broadly explained by two main factors . First , there are several developmental and evolutionary obstacles to the advent of a wheel by natural selection ? addressing the question " Why can 't life evolve wheels ? " . Secondly , wheels are often at a competitive disadvantage when compared with other means of propulsion (such as walking , running , or slithering) in natural environments ? addressing the question " If wheels could evolve , why would they be rare nonetheless ? " . Incidentally , this environment @-@ specific disadvantage also explains why some historical civilizations have abandoned wheels .

Known instances of rotation in biology

Rolling

Some organisms use rolling as a means of locomotion . These examples do not constitute the use of a wheel , as the entire organism rotates rather than employing separate parts which rotate independently .

Several species of elongate organisms will form their bodies into a loop in order to roll , including caterpillars , tiger beetle larvae , myriapods , mantis shrimp , and salamanders , while other species adopt more spherical postures , as observed in pangolins , hedgehogs , armadillos , Armadillo girdled lizards , isopods , wheel spiders , and fossilized trilobites . These species may roll passively (under the influence of gravity or wind) or actively , typically by altering their shape to generate a propulsive force . Tumbleweeds are the above @-@ ground portions of certain plants , which separate from their root structure and roll in the wind to distribute their seeds .

Dung beetles form spherical balls of animal excrement , which they roll with their bodies . Although it is the dung ball that rolls rather than the beetle itself , the beetles face many of the same mechanical difficulties that rolling organisms contend with .

Keratinocytes , a type of skin cell , migrate with a rolling motion during the process of wound healing .

Rotifers , although their Latin name means " wheel @-@ bearer " , do not have any rotating structures , but rather a ring of rhythmically beating cilia used for feeding and propulsion .

Wheel @-@ like rotation

Macroscopic

Among animals , there exists a single known example of an apparently freely @-@ rotating structure , though it is not propulsive ? the crystalline style of certain bivalves and gastropods . The style consists of a transparent glycoprotein rod which is continuously formed in a cilia @-@ lined sac and extends into the stomach . The cilia rotate the rod , so that it becomes wrapped in strands of mucus . As the rod slowly dissolves in the stomach , it releases digestive enzymes . Estimates of the speed of rotation of the style in vivo vary significantly , and it is unclear if the style is rotated continuously or intermittently .

Molecular

There are two known examples of molecular rotating structures used by living cells . ATP synthase is an enzyme used in the process of energy storage and transfer , notably in photosynthesis and oxidative phosphorylation . It bears some similarity to the flagellar motors discussed below . The evolution of ATP synthase is thought to be an example of modular evolution , in which two subunits with their own functions have become associated and gained a new functionality .

The only known example of a biological " wheel " ? a system capable of providing continuous propulsive torque about a fixed body ? is the flagellum , a corkscrew @-@ like tail used by single @-@ celled prokaryotes for propulsion . The bacterial flagellum is the best known example . About half of all known bacteria have at least one flagellum , indicating that rotation may in fact be the most common form of locomotion in living systems , though it is restricted to the microscopic environment .

At the base of the bacterial flagellum , where it enters the cell membrane , a motor protein acts as a rotary engine . The engine is powered by proton motive force , i.e. , by the flow of protons (hydrogen ions) across the bacterial cell membrane due to a concentration gradient set up by the cell 's metabolism . (In species of the genus Vibrio , there are two kinds of flagella , lateral and polar , and some are driven by a sodium ion pump rather than a proton pump .) Flagella are quite efficient , allowing bacteria to move at speeds up to 60 cell lengths per second . The rotary motor at the base of the flagellum is similar in structure to ATP synthase . Spirillum bacteria have helical bodies with flagella at either end , and they spin about the central axis of their bodies as they move through the water .

Archaea , a group of prokaryotes separate from bacteria , also feature flagella driven by rotary motor proteins , which are structurally and evolutionarily distinct from bacterial flagella . Whereas bacterial flagella evolved from the bacterial Type III secretion system , archaeal flagella appear to have evolved from Type IV pili .

Some eukaryotic cells , such as the protist Euglena , also have flagella , but eukaryotic flagella do not rotate at the base ; rather , they bend in such a way that the tip of the flagellum whips in a circle . The eukaryotic flagellum , also called a cilium or undulipodium , is structurally and evolutionarily distinct from prokaryotic flagella .

Biological barriers to wheeled organisms

Evolutionary constraints

The processes of evolution , as they are presently understood , can help explain why wheeled locomotion has not evolved in multicellular organisms ; simply put , a complex structure or system will not evolve if its incomplete form provides no benefit to the organism .

According to the modern evolutionary synthesis , adaptations are produced incrementally through natural selection , so major genetic changes will usually spread within populations only if they do not decrease the fitness of individuals . Although neutral changes (which provide no benefit) can spread through genetic drift , and detrimental changes can spread under some circumstances , large changes that require multiple steps will occur only if the intermediate stages increase fitness . Richard Dawkins describes the matter thus : " The wheel may be one of those cases where the engineering solution can be seen in plain view , yet be unattainable in evolution because it lies [on] the other side of a deep valley , cutting unbridgeably across the massif of Mount Improbable . " In such a fitness landscape , wheels might sit on a highly favorable " peak " , but the valley around that peak may be too deep or wide for the gene pool to migrate across by genetic drift or natural selection . Stephen Jay Gould notes that biological adaptation is limited to working with available components , commenting that " wheels work well , but animals are debarred from building them by structural constraints inherited as an evolutionary legacy . "

Natural selection therefore explains why wheels are an unlikely solution to the problem of locomotion ? a partially evolved wheel , missing one or more of its key components , would probably not impart an advantage to an organism . The exception to this is the flagellum , the only known example of a freely rotating propulsive system in biology ; in the evolution of flagella , individual components were recruited from older structures , where they performed tasks unrelated to propulsion . The basal body that is now the rotary motor might , for instance , have evolved from a structure used by the bacterium to inject toxins into other cells . This recruitment of previously evolved structures to serve new functions is called exaptation .

Molecular biologist Robin Holliday has written that the absence of biological wheels argues against creationist or intelligent design accounts of the diversity of life , because an intelligent creator ? free of the limitations imposed by evolution ? would be expected to deploy wheels wherever they would be of use .

= = = Developmental and anatomical constraints = = =

Using human manufacturing processes , wheeled systems of varying complexity have proven fairly simple to construct , and issues of power transmission and friction have proven tractable . It is not clear , however , that the vastly different processes of embryonic development are suited to ? or even capable of ? producing a functioning wheel , for reasons described below .

The greatest anatomical impediment to wheeled multicellular organisms is the interface between the static and rotating components of the wheel . In either a passive or driven case , the wheel (and possibly axle) must be able to rotate freely relative to the rest of the machine or organism . Unlike animal joints , which have a limited range of motion , a wheel must be able to rotate through an arbitrary angle without ever needing to be " unwound " . As such , a wheel cannot be permanently attached to the axle or shaft about which it rotates (or if the axle and wheel are fixed together , the axle cannot be affixed to the rest of the machine or organism) .

= = = = Power transmission to driven wheels = = = =

In the case of a driven wheel , a torque must be applied to generate the locomotive force . In human technology , this torque is generally provided by a motor , of which there are many types , including electric , piston @-@ driven , turbine @-@ driven , pneumatic , and hydraulic . (Torque may also be provided by human power , as in the case of a bicycle .) In animals , motion is typically achieved by the use of skeletal muscles , which derive their energy from the metabolism of nutrients from food . Because these muscles are attached to both of the components that must move relative to each other , they are not capable of directly driving a wheel . In addition , large animals cannot produce high accelerations , as relative inertia increases rapidly with body size .

= = = = Friction = = = =

In typical mechanical systems , some type of bearing and / or lubricant must be used to reduce friction at the interface between two components . Reducing friction is vital for minimizing wear on components and preventing overheating . As the relative speed of the components rises , and as the contact force between them increases , the importance of friction mitigation increases as well . In biological joints such as the human knee , friction is reduced by means of cartilage with a very low friction coefficient , as well as lubricating synovial fluid , which has very low viscosity . Gerhard Scholtz , professor at the Institut für Biologie Vergleichende Zoologie (" Institute for Biology and Comparative Zoology ") at Humboldt University of Berlin , asserts that a similar secreted lubricant or dead cellular material could allow a biological wheel to rotate freely .

= = = = Nutrient and waste transfer = = = =

Another potential problem that arises at the interface between wheel and axle (or axle and body) is the ability of an organism to transfer materials across this interface . If the tissues that make up a wheel are living , they will need to be supplied with oxygen and nutrients and have wastes removed in order to sustain metabolism . A typical animal circulatory system , composed of blood vessels , would not be able to provide transportation across the interface . In the absence of circulation , oxygen and nutrients would need to diffuse across the interface , a process that would be greatly limited by the available partial pressure and surface area , in accordance with Fick 's law of diffusion . For large multicellular animals , diffusion would be insufficient . Alternately , a wheel could be composed of excreted , nonliving material such as keratin , of which hair and nails are composed .

Disadvantages of wheels

Wheels incur mechanical and other disadvantages in certain environments and situations that would represent a decreased fitness when compared with limbed locomotion . These disadvantages suggest that , even barring the biological constraints discussed above , the absence of wheels in multicellular life may not in fact be the " missed opportunity " of biology that it first seems . On the contrary , given the mechanical disadvantages and restricted usefulness of wheels when compared with limbs , the central question can be reversed : not " Why doesn 't nature produce wheels ? " , but rather , " Why don 't human vehicles make more use of limbs ? " The use of wheels rather than limbs in many engineered vehicles can likely be attributed to the complexity of design required to construct and control limbs , rather than to a consistent functional advantage of wheels over limbs .

Efficiency

Rolling resistance

Although stiff wheels are more energy efficient than other means of locomotion when traveling over hard , level terrain (such as paved roads) , wheels are not especially efficient on soft terrain such as soils , because they are vulnerable to rolling resistance . In rolling resistance , a vehicle loses energy to the deformation of its wheels and the surface on which they are rolling . Smaller wheels are especially susceptible to rolling resistance . Softer surfaces deform more and recover less than firm surfaces , resulting in greater resistance . Compared with rolling on concrete , resistance on medium to hard soil can be five to eight times greater , and resistance on sand can be ten to fifteen times greater . While wheels must deform the surface along their entire path , limbs induce only a small , localized deformation at the point of foot contact .

Rolling resistance is also the reason wheels are not seen in certain human civilizations . During the time of the Roman Empire , wheeled chariots were common in the Middle East and North Africa ; yet when the Empire collapsed , wheels fell out of favor with the local populations , who turned to camels to transport goods in the sandy desert climate . In his book Hen 's Teeth and Horse 's Toes , Stephen Jay Gould explains this curiosity of history , asserting that , in the absence of maintained roads , camels required less manpower and water than a cart pulled by oxen .

Efficiency of aquatic locomotion

When moving through a fluid , rotating systems carry an efficiency advantage only at extremely low Reynolds numbers (i.e. , viscosity @-@ dominated flows) such as those experienced by bacterial flagella , whereas oscillating systems have the advantage at higher (inertia @-@ dominated) Reynolds numbers . Whereas ship propellers typically have efficiencies around 60 % and aircraft propellers up to around 80 % (achieving 88 % in the human @-@ powered Gossamer Condor) , much higher efficiencies , in the range of 96 % ? 98 % , can be achieved with an oscillating flexible foil like a fish tail or bird wing .

Traction

Wheels are prone to slipping ? an inability to generate traction ? on loose or slippery terrain . Slipping wastes energy and can potentially lead to a loss of control or becoming stuck , as with an automobile on mud or snow . This limitation of wheels can be seen in the realm of human technology : in an example of biologically inspired engineering , legged vehicles find use in the logging industry , where they allow access to terrain more challenging than what wheeled vehicles can navigate . Tracked vehicles suffer less from slipping than wheeled vehicles , owing to their larger contact area with the ground ? but they tend to have larger turning radii than wheeled vehicles , and they are less efficient and more mechanically complex .

= = = Obstacle navigation = = =

Work by engineer Mieczys?aw G. Bekker implies that the distribution of irregularities in natural terrains is log @-@ normal ; i.e. , small obstacles are far more common than larger ones . Thus , obstacle navigation presents a challenge to wheeled locomotion in natural terrains at all size scales . The primary means of obstacle navigation are to go around obstacles and to go over them .

= = = = Going around obstacles = = = =

Anatomist Michael LaBarbera of the University of Chicago illustrates the poor maneuverability of wheels by comparing the turning radii of walking and wheelchair @-@ bound humans . As Jared Diamond points out , most biological examples of rolling are found in wide open , hard packed terrain , including the use of rolling by dung beetles and tumbleweeds .

= = = = Going over obstacles = = = =

Wheels are poor at dealing with vertical obstacles , especially obstacles on the same scale as the wheel itself . Assuming a vehicle or animal can shift its center of mass , the limiting height of vertical obstacles for a passive wheel is equal to the radius of the wheel . If the center of mass cannot be shifted , the highest obstacle a vehicle can surmount is one quarter to one half the radius of the wheel . Because of these limitations , wheels intended for rough terrain require a larger diameter .

In addition , without articulation , a wheeled vehicle can become stuck on top of an obstacle , with the obstacle between the wheels , preventing them from contacting the ground . Limbs , in contrast , are useful for climbing and are equipped to deal with uneven terrain .

With unarticulated wheels , climbing obstacles will cause the body of a vehicle to tilt . If the vehicle 's center of mass moves outside of the wheelbase or axle track , the vehicle will become statically unstable and tip over . At high speeds , a vehicle can become dynamically unstable , meaning that it can be tipped over by an obstacle smaller than its static stability limit , or by excessive acceleration or tight turning . Without articulation , this can be an impossible position from which to recover .

= = = Versatility = = =

Limbs used by animals for locomotion over terrain are frequently also used for other purposes , such as grasping , manipulating , climbing , branch @-@ swinging , swimming , digging , jumping , throwing , kicking , and grooming . With a lack of articulation , wheels would not be as useful as limbs in these roles .

= = Rolling and wheeled creatures in fiction and legend = =

= = = Rolling creatures = = =

The hoop snake is a creature of legend in the United States and Australia . The snake is said to grasp its tail in its mouth and roll like a wheel towards its prey . The Japanese Tsuchinoko is a similar mythical creature .

The 1944 science fiction short story " Arena " , by Fredric Brown , features a telepathic alien called an Outsider , which is roughly spherical and moves by rolling . The story was the basis for a 1967 Star Trek episode of the same name and possibly also a 1964 episode of The Outer Limits entitled " Fun and Games " , though neither television treatment included a spherical creature .

The Dutch graphic artist M. C. Escher invented a creature that he named Pedalternorotandomovens centroculatus articulosus , which was capable of rolling itself forward . He illustrated this creature in his 1951 lithograph Wentelteefje (also known by the English title Curl @-@ up) .

A 1956 Scrooge McDuck comic by Carl Barks , Land Beneath the Ground ! , introduced Terries and Fermies (a play on the phrase terra firma) , creatures who move from place to place by rolling . The Terries and Fermies have made a sport of their rolling abilities , causing earthquakes in the process .

Tuf Voyaging , a 1986 science fiction novel by George R. R. Martin , features an alien called a Rolleram , described as a " berserk living cannonball of enormous size " , which kills its prey by rolling over it and crushing it , before digesting it externally . Adults of the species weigh approximately six metric tons and can roll faster than 50 kilometers per hour .

In the Sonic the Hedgehog video game series , which first appeared in 1991 , the eponymous Sonic and his sidekick Tails move by rolling .

The 1995 short story " Microbe " , by Kenyon College biologist and feminist science fiction writer Joan Slonczewski , describes an exploratory expedition to an alien world whose plant and animal life consists entirely of doughnut @-@ shaped organisms .

= = = Wheeled creatures = = =

L. Frank Baum 's 1907 children 's book Ozma of Oz features humanoid creatures with wheels instead of hands and feet , called Wheelers .

The 1968 novel The Goblin Reservation by Clifford D. Simak features an intelligent alien race that uses biological wheels .

Piers Anthony 's 1977 book Cluster and its sequels feature aliens called Polarians , which locomote by gripping and balancing atop a large ball . The ball is a living , though temporarily separable , portion of the Polarian 's body .

David Brin 's Uplift Universe includes a wheeled species called the g 'Kek , which are described in some detail in the 1995 novel Brightness Reef . In 1996 's Infinity 's Shore , a g 'Kek is described as looking like " a squid in a wheelchair . " They suffer from arthritic axles in their old age , particularly when living in a high gravity environment .

A 1997 novel in the Animorphs series , The Andalite Chronicles , includes an alien called a Mortron , composed of two separate entities : a yellow and black bottom half with four wheels , and a red , elongated head with razor @-@ sharp teeth and concealed wings .

The 2000 novel The Amber Spyglass , by English author Philip Pullman , features an alien race known as the Mulefa , which have diamond @-@ shaped bodies with one leg at the front and back and one on each side . The Mulefa use large , disk @-@ shaped seed pods as wheels . They mount the pods on bone axles on their front and back legs , while propelling themselves with their side legs . The Mulefa have a symbiotic relationship with the seed pod trees , which depend on the rolling action to crack open the pods and allow the seeds to disperse .

In the 2000 novel Wheelers , by English mathematician Ian Stewart and reproductive biologist Jack Cohen , a Jovian species called " blimps " has developed the ability to biologically produce machines called " wheelers " , which use wheels for locomotion .

The children 's television series Jungle Junction , which premiered in 2009 , features hybrid jungle animals with wheels rather than legs ; one such animal , Ellyvan , is a hybrid of an elephant and a van . These animals traverse their habitat on elevated highways .