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Wheels-in-wheels: Use of gravity in human locomotion

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ABSTRACT

Although a wheel is an ideal method for transportation and the invention of the spoke wheel made a wheel lighter and swifter, a wheel cannot function well on slanted or rough surfaces; these are common in the natural environment. Further, the load support of the wheel is limited to a point of the whole wheel in contact with the ground. Then, we humans may be using the legs as a part of spoke wheel and place our legs and feet on the ground alternatively to support the body weight while the gravitational torque makes the center of mass (COM) rotate around the hip joint when proper stiffness and balance is made. Through a pulley-like action involving the hamstrings and a lever-like action of back muscles via the psoas muscle, the energy expenditure for locomotion can be reduced to the energy for lifting the swing leg to maintain the proper position of the COM. Further, the stabilizing action of the psoas muscle to the spinal column can be achieved between the stance leg and the swing leg by the weight of the lifted swing leg during the forward movement. This lifting action during swing phase can assist an energy-efficient eccentric contraction of the stance leg. The passive tension generated by gravity (own weight and the carried load) can be the reason for the energy efficiency of both head-carrying and the Nepalese porter method. Using this passive gravitational force via actively synchronized neuromuscular action may be universal for animal locomotion.

Background

Down through eons of human history, head-carrying has been a common practice and is known to be very energy-efficient transport method. Presumably, these skills were learned in childhood [1]. Nepalese porters are also known to have the ability to carry a very large load almost equal to their body weight using only a strap and an oversized basket [2]. In both these cases (the head-carrying methods and the Nepalese porter methods), the exact mechanism of their energy efficiency is still not known. To find the possible reason(s) for the energy efficiency, a different approach to the understanding of bipedal human locomotion (especially walking and running) need to be made.

There have been many different theories about human walking; such theories include the Six Determinants of Gait model, the Inverted Pendulum model, the Dynamic Walking model, and the Ballistic Walking model [3–5]. Although each theory provides some insight about human locomotion, none are able to provide a comprehensive explanation of energy efficient human walking and integrate the practical weight and torque energy generated of body parts under gravitational influence during movement.

Hypothesis

Gravitational force is very predictable and unavoidable. In everyday life, we use gravitational force to stabilize objects and structures (i.e. paperweight and counterweight for ski-lifts, elevators and cranes). While friction force impedes the movement of a grounded weight, minimum friction is necessary for the movement of wheeled vehicles. Just as a load on a wheel is supported by a small segment of the wheel in contact with the ground, limbed animals including humans may be using gravitational force for locomotion by using their limbs like the spokes and rims of wheels, rather than fighting the force.

Wheel-like locomotion

Wheel

Although wheels are an ideal method of transportation due to (a) the proper spread of a load over a rotating circular surface with (b) minimal friction due to rolling, their use is really limited to the flat and hard surfaces of modern day pavement. Although the invention of the spoke wheel allowed for the construction of a swifter and lighter wheel, its application is still be mostly limited to the relatively flat surface. While its use is very economical on a flat plane, uphill and downhill movement can be a challenge if the wheel is not properly pushed or pulled. Furthermore, as we often experience while hiking in the mountains or crossing a small stream, wheeled vehicles do not seem to function as well in natural environments as on man-made surfaces.

When we see that the load supported by the wheel is limited to a point at which the wheel is in contact with the ground, we realize that humans may be able to use energy efficient wheel-like locomotion by using their feet and legs as part of the wheel and alternating their legs to maintain proper ground support on natural, uneven surfaces. For this dynamic and balanced alternating form of movement, the swing phase

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cannot be passive; rather, it must be active via complex motor control to achieve perfect synchronization with gravity, even possibly for "elastic restoring torques" [6]. During the joint actions for swift lifting and moving of the swing leg, generating a sufficient stiffness over the back and many joints of the stance leg will also be important.

Using legs and feet as spoke wheels

Consider a human walking with a bipedal gait. He/she may be using each leg as a spoke of the wheel rotating about the hip joint and each foot as a segment of the wheel in contact with the ground. The rigidity of the legs can function like wheel-spokes, and the feet can provide traction on the ground while supporting and distributing the weight of the body.

The center of mass (COM) located just above and in front of the sagittal axle of the hip joints will provide the rotational torque by force of gravity. Rotational torque from the COM in this position will be important in order to achieve a wheel-like locomotion. During forward and backward leg movement, the weight (mass) energy of the leg will help sustain the forward or backward momentum needed for wheel-like locomotion. Leg lifting during this swing phase is an active motion, requiring significant energy [7]. While ostriches have relatively light legs, human legs are quite heavy in comparison to their total body weight. The process of energy spending during leg movement is not well explained by the Inverted Pendulum model, the Dynamic Walking model, and the Ballistic Walking model. Instead, wheel-like locomotion considers the leg mass and requires minimal collision of the swing leg upon landing to optimize smooth forward rolling movements. Any stronger collision force would cause a loss of horizontal energy (not a redirecting force) and strain to the musculoskeletal system.

On Earth's varied terrains, bipedal gait involving wheel-like locomotion can be an efficient way of overcoming obstacles (eg, stairs)- unlike the conventional wheel. Furthermore, wheel-like locomotion requires proper friction under the foot of the stance leg for traction while torque energy from the swing leg is applied for the COM to rotate about the hip joint. The energy needed for walking during a forward movement can be reduced to the energy for lifting and moving the swing leg forward to keep the COM just above and in the front of the sagittal axle of the hip joints if the rigidity of the stance leg on the ground can be maintained by the gravitational force as passive tensile energy. While lifting and forwarding the swing leg can provide the necessary torque, the mechanism of energy-efficient leg extension of the stance leg must be examined.

In guinea fowl (*Numida meleagris*), the energetic cost of limb swinging was approximately 25% of the total energy cost, regardless of the speed achieved [8]. The energy requirement was higher when weight was applied to the legs rather than to the upper body of the birds [9]. The energy cost of human running increased linearly – not exponentially – with speed and incline [10]. Similarly, as seen in birds, different energy costs were observed by placing a load on different parts of the human body [7,11]. In ostriches, the spent energy during a range of running speed (3 m/s to 7 m/s) was the same or even slightly lower at higher ranges [12]. If the bipedal gait of birds uses wheel-like locomotion, the energy cost of swinging their light legs can be very low. From these findings, we can postulate that the needed energy for proper leg lifting is a very important factor in locomotion; conversely, it can be very costly if proper leg lifting is impeded. From this discussion, we may predict that the energy efficiency of humans in certain load-carrying situations [1,2] is made possible by wheel-like locomotion with its relatively constant energy cost of leg lifting when passive stiffness of the back and stance leg is achieved by the gravitational force by the forward-moving lifted swing leg and the carried load, as we use a counterweight for stabilization in ski-lifts, elevators and cranes. While the rigidity of the stance leg on the ground is maintained by a passive gravitational force, lifting and forwarding the swing leg can provide the necessary torque on the COM around the hip joints. Similarly, we use gravitational force by getting off the seat to push forward the bicycle pedals when we need more torque to go uphill or to accelerate to cross the street. The mechanisms of energy-efficient leg extension of the stance leg need to be examined.

Hamstring muscles as pulley ropes

It is still unknown as to why flamingos stay perched on one leg. One theory involving thermoregulation (or the maintenance of body temperature) has been suggested; it hypothesizes that the birds, in a cold environment, can capture heat by folding one leg up [13]. But this theory was not able to support the increased incidence of standing bipedally on hard concrete surfaces. However, if they use their body weight to tighten the ankle joints through eccentric contraction of their leg muscles, they will then need to put their entire weight on one leg. In a muddy environment, having their whole weight supported by one leg will cause more tension and also allow them to compact the soft wet ground for a better control of their COM like a balancing stick. As a result, they are able to achieve a very narrow range of center of pressure (COP) and energy saving by a passive tension mechanism from gravity [14].

In humans, the knee joints are major weight-bearing joints with various degrees of movement [15]. Improper tightening of the muscles surrounding the joints upon dynamic loading during locomotion can result in knee injuries. Many muscles acting on the knee joint will need to contract eccentrically to produce a higher tensile force with less energy expenditure when compared to the concentric contraction. The existence of biarticular muscles (including hamstrings and quadriceps of the knee and hip) which cross over two joints in series has been considered to provide a range of four-bar linkage properties over the joints. Even though the role of biarticular muscles is important in stabilizing joints and saving energy in human locomotion, the underlying mechanism is not well known.

The co-contraction of the quadriceps and hamstring muscles upon standing from a sitting position is known as "Lombard's Paradox". In the past, the co-contraction of these antagonistic muscle groups was thought to waste energy. However, the complicated and paradoxical movements of these bi-articular muscles upon standing can be assistive in the extension of the knee and hip joints if they can transfer the dynamic torque caused by the weight of the forward leaning upper body at the initiation of standing from sitting.

Once their feet are secured on the ground by their own weight, the extensor moment created by forwarding upper body weight through the hamstrings will be applied to the knee joint. At the same time, the gastrocnemius (another bi-articular muscle) could act as a knee extensor during extension by stabilizing the knee and ankle joints. Seemingly complicated and paradoxical, the true role of paradoxical co-contraction of these bi-articular muscles can now be viewed as a form of passive energy saving and strong eccentric contraction for the stability of joints by gravity.

Shortly after activation of the hamstrings, the action of quadriceps whose distal end is secured to the knee by the patellar bone can now extend the hip joint with assistance from extension moment of back muscles (including the erector spinae) when the head goes up from forward-leaning. These series of isometric/eccentric contractions of postural muscles will stabilize the knee and hip joints during the act of standing up while the feet get secured onto the ground by the own weight. The extension moment of the erector spinae (via the psoas) to the hip joint will be discussed later.

During wheel-like walking and running, the weight of the swing leg (if lifted and advanced properly) will help extend the knee joint through the eccentric contraction of the hamstring muscles and other calf muscles of the stance leg. If the passive energy from the lifted leg is not transferred properly to the stance leg, we may experience a heavy feeling in the front thigh of the stance leg (like when we climb up stairs and stop lifting our legs after reaching the upper floors). In one study,