Simplified biomechanical study of the propulsion of a cycle* in permanent upright position

* In this document, the word “cycle” is to be understood, not as a synonym of “bicycle”, but in a more general sense as any human powered vehicle with one or more wheels.

Warning

The reality that this document tries to analyze is complex, actually much more than what is described hereafter. We sometimes had to simplify certain statements and demonstrations which, to be perfectly correct, can only be given in mathematical form. We are aware of the limits of such an endeavour, and realizes well that some readers will see several parts as rather obscure.

What are the advantages of the upright position to propel a cycle?

If one accepts the advantage of a vehicle which would combine the advantages of the bicycle and the scooter, one must be interested in the propulsion of a cycle in upright position.

Indeed, the upright position offer many advantages :

- Sensations similar to board sports and a great freedom of movement, standing is the most natural position for the human your body during most types of exertion. Sports such as skateboarding, rollerblading, skiing and surfing are all practised in an upright position. The cycle can thus be perceived as an extension of the rider's body, like skis or rollerblades.
- Another advantage of standing is that every muscle in the rider's body can be put to work, while relieving the pressure on his back and neck.
- By applying all his weight on the pedals, the rider generates a lot of power that lets him reach a high speed, climb steep slopes, and achieve amazing acceleration.
- Improved security as the rider position gives him a better overall view of the traffic and the pedestrians. This allows him to better anticipate any hazard.
- The absence of a seat makes the cycle easy to mount, and allows to design a low frame. In turn, this makes it really easy to hop off the cycle, without even slowing down.
- Better riding precision, as the upright position makes any body mass shifting easier (for example, from front to back, to climb a kerb), as well as the ability to master new control techniques; for example, keep pedalling through a bend whilst holding the cycle straight but tilting the body to compensate for the centrifugal force. Any obstacle may be avoided by a simple undulation of the body.
- Unrivalled comfort on damaged road surfaces or on impact, because the rider's legs act as natural shock absorbers, which they are unable to do when he is sitting on a bicycle.

Why is standing pedalling so exhausting when using a classic pedalling system ?

In the rest of the document, we'll use alternatively standing pedalling or pedalling in upright position.

Empirically, it's easy to understand that standing pedalling on a traditional cycle is useful to produce a much increased engine torque during a short period.

However, when the torque produced is low or average, the standing pedalling yield is much lower than the classic pedalling (in sitting position) yield, which means that the relationship between the horsepower provided to the cycle and the power consumption by the muscles is much weaker for the standing pedalling.

Strong torque and poor yield are the main features of the standing pedalling compared to the classic pedalling. Furthermore, the lower the gear ration (and the higher the RPMs), the worse the standing pedalling yield is. This is why the traditional crankset is completely unsuited to standing pedalling.

In order to better understand the causes of these empirical observations, we will study a theoretical system, because it is obvious that reality is way too complex to be conceptualizes easily. Our model will be a cyclist upright on the pedals, the centre of gravity of his body being directly above the axis of the pedals, the totality of its weight resting on the two pedals (not the handlebar), the axis of the pedals preserving a constant direction (i.e. bicycle not leaning).

The cyclist himself will be idealized, the articulations of his hips and of its knees will be regarded as perfect pivots whose axes remain always parallel to that of the pedals, the unit ankle/foot/pedal will be assimilated as a simple pivot localized at the axis of the pedal.

We are perfectly aware that, in using these simplifications, we move away from the complex reality from the cycling movement. Indeed the informed cyclists, in order to be able to maintain the standing position, use a balancing technique in which the arms, the undulations of the body and the side leaning of the bicycle play a key role. But by removing these complex compensatory movements, one can understand the biomechanical basis for the standing pedalling and explain by the theory what the experiment shows us.

This simplified model immediately enables us to select, among the innumerable manners of standing pedalling, the two following extreme situations::

1. **Standing pedalling with extended legs** : one of the two legs is always extended while the other is more or less bent, the centre of gravity of the cyclist is moving up and down with a frequency double of the pedalling and an amplitude slightly lower than the length of the cranks.

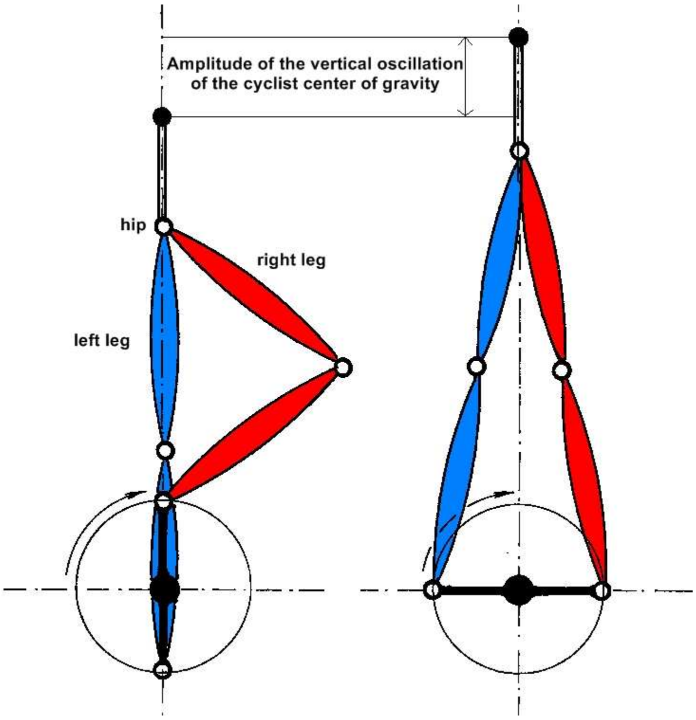


Figure 1 *above : two successive positions in the standing pedalling movement with extended legs. One notices the important amplitude of the oscillation of the centre of gravity of the cyclist. The first (left) position corresponds to the higher dead spot for the right leg and to the lower dead spot for the left leg. This is also the lowest point for the centre of gravity. The second position (right) corresponds to the equilibrium point (the two pedals are with the same height) which is also the highest point in the oscillation of the centre of gravity.*

2. **Standing pedalling with fixed centre of gravity** : the legs are both permanently more or less bent, the centre of gravity of the cyclist being fixed at a constant height. One can notice that this kind of standing pedalling is perfectly identical to the classic pedalling (in sitting position) ... except that the weight of the cyclist does not rest on the saddle.

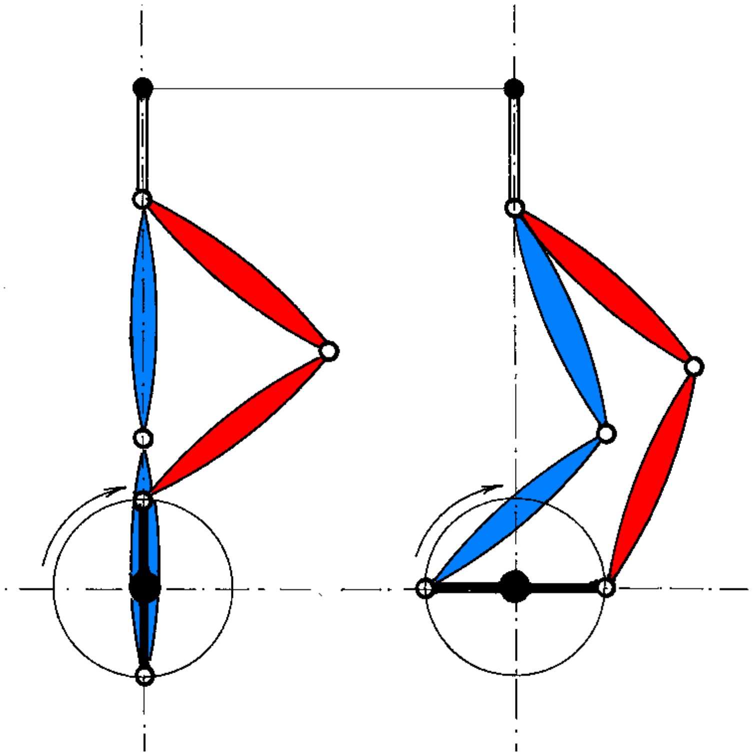


***Figure 2** above : two successive positions in t*he standing pedalling movement with fixed centre of gravity*. One notices the important (and exhausting) flexion of the legs in equilibrium position*

The standing pedalling reality is always intermediate between these two extreme cases.

Let us notice however that standing pedalling with extended legs is spontaneously adopted by the cyclist for the low RPMs while for the high RPMs, the movement approaches standing pedalling with fixed centre of gravity.

The poor yield of the standing pedalling with extended legs movement comes primarily from the fact that the kinetic energy of the body of the cyclist measured in the reference frame of the axis of the pedals, (kinetic energy which is related to the vertical speed of its centre of gravity), is almost entirely dissipated when the foot which goes down reaches its lowest position. If this speed is too high, i.e. if the cyclist does not use a high gear ratio, the energy dissipated with each half-turn of pedals is enormous.

This means that, on a classical crankset used for standing pedalling, the lower dead spot zone is not long enough if the gear ratio stays low.

The poor yield of the standing pedalling with fixed centre of gravity is due to the fact that the legs of the cyclist are almost always strongly bent. Their muscles, primarily the quadriceps, must thus permanently support the weight of the cyclist. The powering of the quadriceps without any period of relief leads to the rapid exhaustion of the cyclist who literally feels its thighs ready “to explode” because of this static effort (which does not produce any horse-power) and this, whatever the pedalling rhythm.

This means that on a classic crankset used for standing pedalling, the amplitude of the vertical oscillation of the cyclist centre of gravity is too important, which makes for too much leg bending as a compensation.

The dead spot issue

Is the dead point really a problem? In short, yes, but not for everyone, nor for every cycle usage.

It is clear that the dead spot issue is not a problem for the practice of the bicycle as a sport on the road for powerful cyclists, experts with their gear changing system.

However it is undeniable that the dead spot is often very awkward for the ordinary cyclists in urban areas where they frequently have to restart (at a red light or in traffic), or for the mountain bikers who will remain blocked, and will be unable to set out again, in a very abrupt rise.

Thus, the dead spot is precisely an issue when the cyclist stands on the pedals to produce an important torque at a low RPMs. In this case, the dead spot can even signal the end of the movement. But, well before that, it causes an increase in the cardiac rhythm, an increased tiredness in the legs, a huge torque variation on the rear wheel (and potential cause of loss of control) and frequent knee pains.

This is why any pedalling system which is geared toward standing pedalling (and designed for low or medium RPMs) will have to solve this dead spot issue as efficiently as possible..

Lastly, one need to notice that only the higher dead spot is an issue. The lower dead spot is inevitable, since the extended leg is not able to deliver power. Even more, as we saw previously, the lower dead spot on a traditional crankset is not long enough for the standing pedalling.

What have been the various answers proposed by inventors to the problem of the propulsion of a cycle in upright position?

The problem of the propulsion of a cycle in upright position, which is often compared to the self-propulsion of a child's scooter, has been a subject investigated by inventors for over a century.

Tens and tens of patents were applied to, for devices which claim to bring a solution to that particular problem. In order not to reinvent any existing solution, we spent several months to consult the various world patent databases, and assess the solutions already suggested. We concluded that some are completely whimsical, that the majority are very imperfect at a mechanical level and that none is satisfactory at a biomechanical level.

Inventors failed because they did not seek the precise reasons for the inadequacy ot the traditional crankset to the standing pedalling specificity. Most of them based their thinking and their proposals on the inaccurate intuition that it was the rotary movement of the traditional pedals which was the problem. Therefore they proposed mainly two types of solutions:

1. Devices where the feet were moving vertically as pistons (stepper type systems).
2. Devices where the original circle described by the feet was modified and transformed into an ellipse which main axis was horizontal (elliptical cycle systems)

For obvious reasons of fluidity of the movement and optimization of the use of the various muscles, the stepper type devices are biomechanically very unfavourable and can be immediately eliminated. (that's why they are used in gyms to exercise a very precise set of muscles). Some readers may remember the single pedal child's scooter of the Fifties. This system which was more a toy or a gadget, used (poorly) the power of only one leg. It has long since been abandoned.

As we saw previously, the rapid exhaustion of the cyclist pedalling in upright position on a classic crankset is due either to the excessive amplitude of the vertical oscillation of the centre of gravity or the dissipation of the kinetic energy (taken in the reference frame of the drive spindle axis).

However, the elliptic devices solve this problem only by compressing the movements in the vertical direction and consequently, by decreasing drastically the pedalling power output which is primarily produced by the vertical movements of the legs due to the contractions of the quadriceps (thighs muscles).

Currently, only a few systems, of recent design, are being marketed:

- A kind of child's scooter having a tilting platform on which the two feet exert alternatively a pressure. This system is alternative and the amplitude of the movement of the legs is very low. The power output is thus extremely limited. This toy nevertheless has had some success in the United States.
- A cycle without saddle based on a double crankset providing a deformable parallelogram, broad pedals being maintained parallel to the line formed by the axis of the two cranksets (which means the pedals remain horizontal when riding on an horizontal surface). Admittedly, the pedals are more comfortable than ordinary pedals but this system behaves exactly like a traditional pedalling system. This product is a heresy from the biomechanical point of view.
- A cycle without saddle with a pedalling system similar to the ones found un indoor training elliptical cycles. This movement is natural because close to the walking movement, but it does not optimize the output power. Moreover, the mechanism as well as the cycle is very cumbersome and heavy.

What is the solution which carries out the ideal compromise between biomechanical effectiveness and mechanical feasibility?

The classic pedalling system, associated to bicycle on which you pedal while sitting is the simplest system known to convert the human being legs movement into the rotary movement of a drive spindle.

The miracle of the bicycle, it is that it is also the best system from a biomechanical point of view to produce a high level of horse-power. This is remarkable because, usually, the systems which adapt well to the human body are of a very complex design. This circular motion of the feet is the one which makes it possible to reach the highest pedalling rhythm (80 to 120 RPM) which are essential to produce high levels of horse-power.

However, in order to produce low to medium level of horse power, the yield of the “human engine” is better at lower pedalling rhythm (30 to 60 RPM).

Based on these facts, rather than to search for a system which would produce a movement radically different from the classic pedalling, it seems more judicious to seek the simplest modification to this classic pedalling which would allow standing pedalling.

Let's look again at the specificities of our new pedalling movement. When the cycle is propelled at a constant speed, one must respect the following constraints:

- Constraint 1: the pedals must follow a circular trajectory as it is the best way to produce the necessary power and the simplest mechanical system to design.
- Constraint 2: When one pedals with extended legs, the amplitude of the vertical oscillation of the centre of gravity of the cyclist must be as low as possible (at least divided by two compared to the traditional pedals).
- Constraint 3: the speed of the pedal when it arrives in its lowest position must be low in order to avoid dissipating the kinetic energy related to the vertical movement of the centre of gravity of the cyclist when he pedals with tended leg.
- Constraint 4: the speed of the pedal when it arrives in its highest position must be as fast as possible to avoid the higher dead spot. Indeed, this would allow for the actual leverage, which is proportional to the speed of the pedal, to be maximum. It would also means that the kinetic energy of the pedal and the associated leg would help in passing the dead spot.

There is only one system which satisfies the four constraints of our specifications. We will call this system “adaptive pedalling system” in contrast with the classic pedalling system, because it adapts itself to the available strength of the user.

The adaptive pedalling system, as the classic pedalling system, is based on two cranks rotating around an axis but each crank as well as the drive spindle have different rotating speeds and, as a corollary, the angle between the cranks is not always 180°. This means t hat both cranks are independent (they move at different speeds and the angle between them varies permanently) but linked (or coupled) with each other (there are reciprocal constraints between the movement of each crank).

To follow the specifications, the coupling between the two cranks of the adaptive pedalling system, as well as between each crank and the drive spindle must obey a quite precise law. We will assume that the drive spindle rotation speed stays constant :

- To follow constraint 2, the angle between the two cranks must pass by a minimum when the two pedals are at the same height (equilibrium position).
- To follow constraint 3, the rotation speed of the downward moving crank must gradually decrease until a minimum is reached at the lower dead spot position.
- To follow constraint 4, the rotation speed of the upward moving crank must gradually increase until a maximum is reached at the upper dead spot position.

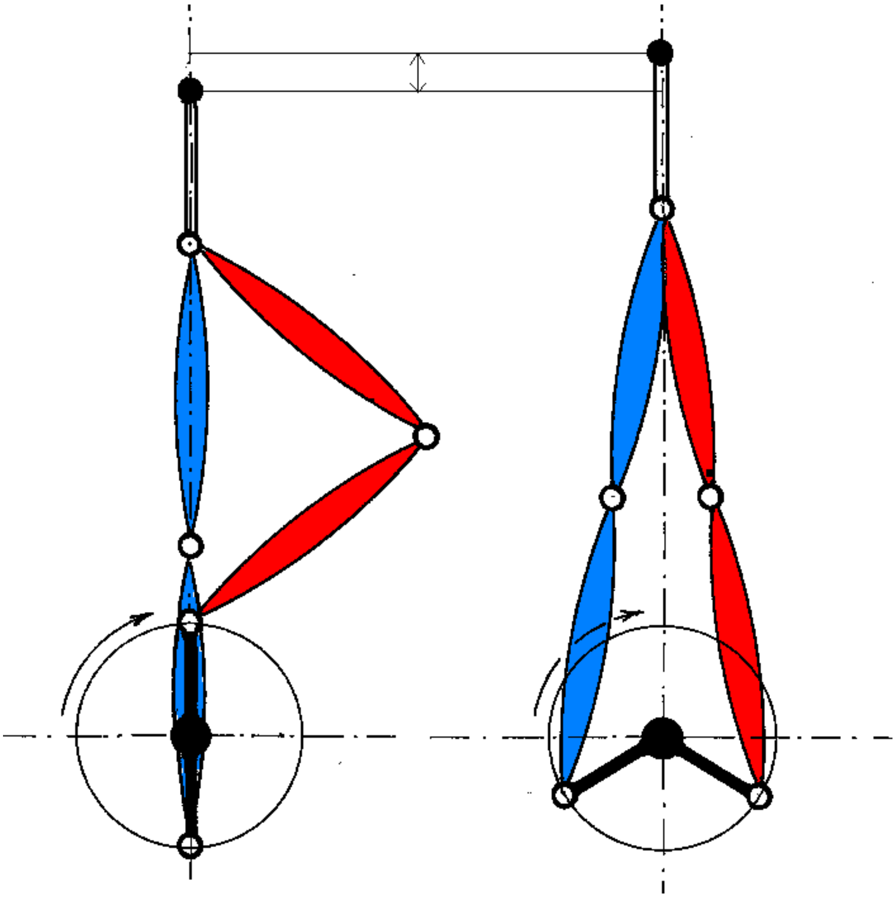


Figure 3 *above : two successive positions of the pedalling movement on an adaptive pedalling system* with extended legs. *The oscillations of the centre of gravity have been drastically reduced and the second position is the equilibrium position.*

There are three parameters that can be adjusted to perfect the adaptive pedalling system to the standing pedalling :

- the length of the cranks,
- the height of the equilibrium point (where the pedals are at the same height) compared to the height of the axis of the pedals,
- the value of the angle of the crank for which the effective leverage is the lowest.

The adaptive pedalling system correctly adjusted, provides a solution to all the problems linked to pedalling upright on a classic crankset, while preserving the amplitude of the movement of each leg, which is necessary to obtaining a satisfactory horse-power.

Compared to the classic pedalling system, the adaptive pedalling system provides the following characteristics:

- The movement is much closer to the natural running of fast walking movement. Indeed, when you walk, in the reference frame of the centre of gravity, the foot which is in contact with the ground moves less quickly, than the other foot.
- As the user can produce a strong torque and as, for a fixed pedalling rhythm, the speed of the foot which is around the upper dead spot position is higher, it is adapted to low and average pedalling rhythm.
- A constant effort will produce a constant torque due to the variation of the leverage applied to the pedals (lack of an upper dead spot).

All these specificities of the adaptive pedalling system show that its biomechanical adaptation to the human body is excellent. Its comfort (thanks to adapted pedals) and its output (for the low and average powers in particular) are comparable or even higher than those of the classic pedalling system used in sitting position.

The torque produced as well as the regularity of the torque output will be greater with the adaptive pedalling system than with the classic pedalling system used in sitting position.

With an in-depth analysis of the adaptive pedalling system, some secondary advantages appear rapidly :

- The kinetic energy of the cyclist not being dissipated at the lower dead spot, the constraints exerted on all the elements of the transmission as on the frame of the cycle will be much lower than those produced on an classic crankset when riding standing up. This will make the design of a cycle to be ridden un permanent upright position much easier and will make its mechanism more reliable.
- The rider of an adaptive pedalling system will have most of his weight pressing on the pedals, this will relieve most of the constraints on the handlebar.
- When a cyclist pedals upright on a classic crankset, the environment can sometimes appear slightly fuzzy because of the permanent movements of his head. Riding on an adaptive pedalling system, the amplitude of the vertical oscillations of the centre of gravity of the cyclist is much reduced, therefore his head and his eyes move less vertically and he benefits from a better vision of the environment and a better sense of balance.
- For the same ground clearance, the height of the centre of gravity of the cyclist, when it is in equilibrium position (two legs extended and two pedals at the same height), is roughly decreased by half the length of a crank for the adaptive pedalling system. This means that, for the same ground clearance, a cycle using the adaptive pedalling system will be more stable.

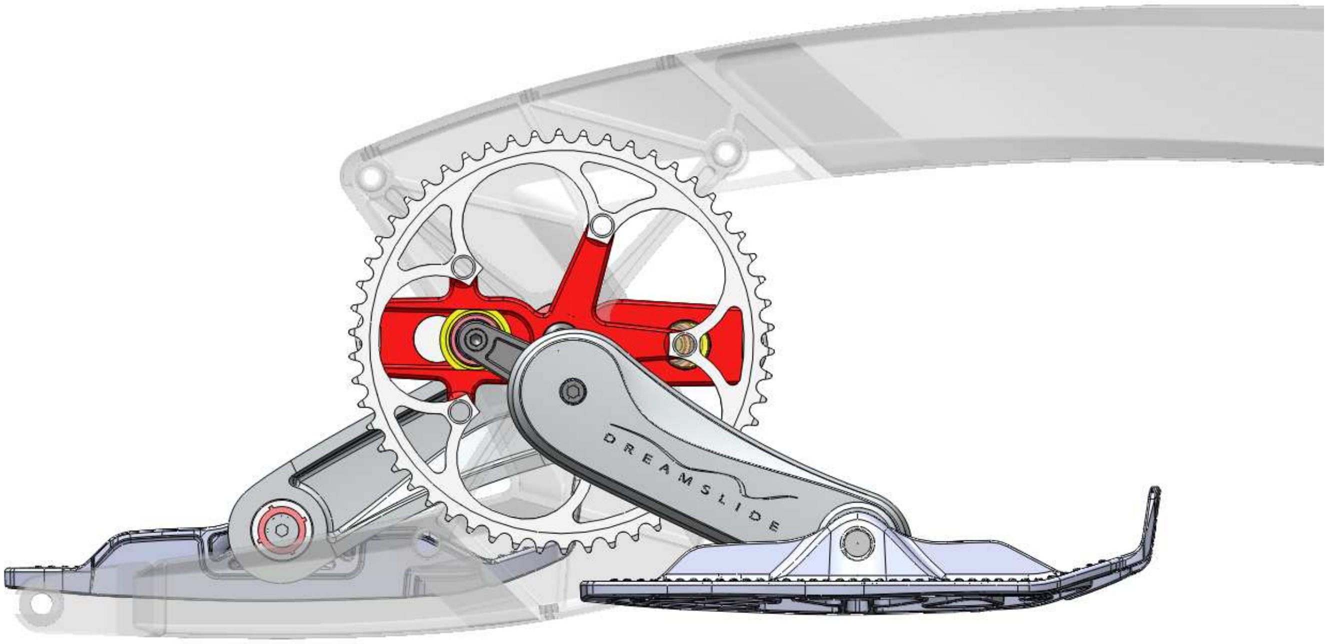
Mechanical feasibility of the adaptive pedalling system

We spent several years to search for and analyze the best mechanical solution to make the theoretical adaptive pedalling system a reality.

Among all the solutions imagined and tested over that timeframe, only two have been able to satisfy the following specifications :

- **Constraint 1** : the mechanism must tolerate the considerable efforts which are exerted on the adaptive pedalling system. For example, when the rider simply jump from a kerb, the axial load on the bearings of the axis of a classic crankset is up to 10 times the weight of the cyclist.
- **Constraint 2** : the overall dimensions and weight of the mechanism must be minimal.
- **Constraint 3** : the maintenance of the mechanism must be minimal as well as very simple.
- **Constraint 4** : the production cost of the mechanism must be minimal.
- **Constraint 5** : the mechanism must not generate more friction (output power loss) than a classic crankset.

These two solutions have been patented and the figure below shows the mechanism used to propel the dreamslide :



What kind of usage is practical for standing pedalling?

With the adaptive pedalling system, pedalling in permanent upright position may lead to a new kind of cycles made for specific usages where the rider :

- frequently need to accelerate,
- need more torque than pure horsepower,
- want to avoid changing gears too frequently,
- looks for a very precise control of his cycle.

Among these various types of cycles are in particular:

- City cycles as stop and go as well as obstacles (kerbs) are frequent. Moreover, city cyclist use gear changes very rarely.
- Folding cycles, as being saddle less makes for an easier folding experience.
- Mountain-bike/trial cycles as the availability of a strong as well as constant torque is a big advantage. The preciseness of the cycle control is also important, therefore the interest of the upright position.
- Acrobatic cycles (BMX type), as being saddle-less and having a low frame is a huge advantage when the rider loose control.
- Leisure cycle for the board sports enthusiasts. Due to its sitting position and its "massive" feeling, the classic bicycle is not seen by the young as "fun" compared to the roller-blade or the skateboard. A smaller cycle used in upright position would provide the rider with sensations very close to those of rollerblading or skiing. Such a cycle should be able to convert the many board sports enthusiasts. !
- Training cycle for runners. Most distance runners are subject to recurring articular, muscular or ligamentous pains due to training. The classic bicycle is not adapted to their training as the movement is too different from the running one. The adaptive pedalling system movement is very similar to the slow pace running one and it could provide for a cycle designed for low impact runner training.
- Static training cycles. The adaptive pedalling system could easily replace the elliptical training cycles as they provide for a movement where the quadriceps doesn't work with any amplitude.

The Dreamslide, first iteration of a cycle based on the adaptive pedalling system brings to the fore many of the advantages of these various cycles.