Chain induced stresses in bicycle and recumbent frames.
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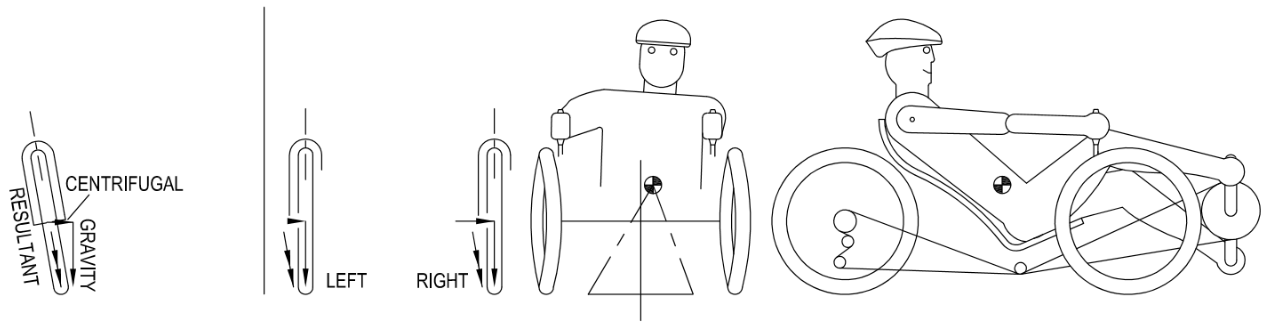
ABSTRACT

Recumbent bicycles can be more aerodynamic than standard safety bicycles, and therefor travel faster for the same effort. They also offer ergonomic alternatives by providing a large seat to support the back, buttocks and shoulders while putting little stress on the crotch, arms and hands (Gross 1983). However, more attention could be paid to recumbent cycle configurations. With careful design, chain forces stressing the frame can be confined to small areas, permitting lighter and alternative frame constructions. While forces caused by rider weight dominate recumbent frame forces and chain forces are smaller, chain forces can be the dominant force in particular directions and flex the frame. When frames flex, energy is lost, so a frame that does not flex can improve pedalling efficiency. In general, frame flex is undesirable (Wilson 2004, p. 381,382).

Recumbents such as the Bevo, Cruzbike, Kervelo and Flevobike confine chain forces in different ways and this article explains and compares the differences. The author's front wheel drive cycles and their timber and aluminium frames are discussed. Although they use untreated aluminium RHS or structural plywood monobeams as frames and are homemade, they have endured for thousands of kilometres. Management of chain forces contributes to their rideability and longevity.

This is a qualitative guide to chain induced forces in recumbent cycles. Confining chain forces in recumbents to small frame regions can result in lighter, simpler, less energy absorbing frames and extra possibilities for frame joins and materials.

1.0 Introduction.



a) *b)*

Figure 1: Leaning dynamics of a) Bicycle / Leaning Trike Wheel which absorbs axial force and b) Standard recumbent trike wheel which must cope with axial force.

Forces on cycle frames and parts determine their need for rigidity and strength. In the absence of high forces, they can be less strong, use less material and therefore be lighter and less expensive. One of the forces on cycles is the cornering axial force on trikes, which is avoided through leaning on bicycles and leaning trikes (Figure 1). Special tyres such as the Schwalbe Tryker trike tyre and specially spoked wheels are sometimes specified to cope with trike axial forces.

Chain forces are another force on cycle frames. In the same way that axial forces on cycles are avoided by leaning, some chain forces can be avoided by careful drivetrain layout.

2.0 Cycle configurations and chain forces.
On safety bicycles, tensile chain forces usually act between a secure bottom bracket and a rear wheel supported by seat- and chain- stays, while compressive leg forces act between the seat, seatpost and bottom bracket. However chain and leg forces in recumbent cycles vary with frame configurations. As shown in Fig 2 , the ratio between peak leg force and peak chain force is the chainring radius divided by the pedal length.

Most cycles have the chain mounted outboard on the right hand side with their chainstays compressed because the chain forces act on the sprocket sited between them. In recumbents, the chain can also run beside the frame compressing the frame right hand side and creating tension in the frame left hand side.

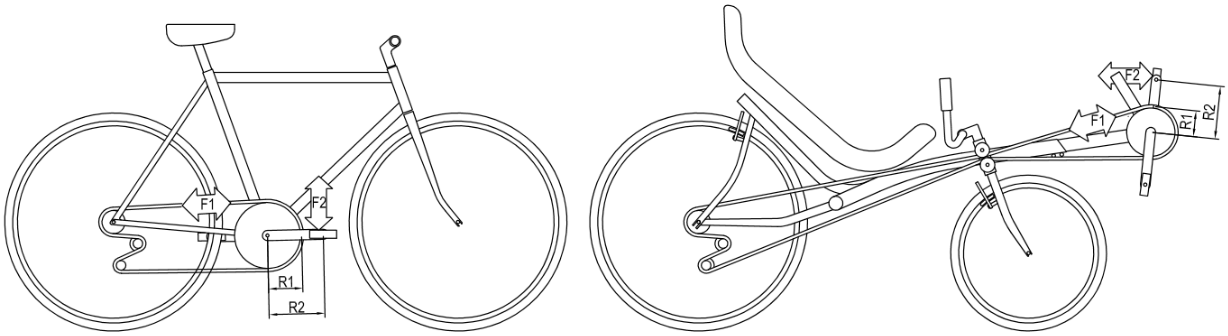


Figure 2: Chain and leg forces in safety and rear wheel drive recumbent bicycles. In each case, the crank torque is F2 * R2 (Leg) which is the same as F1*R1 (Chain), so F2 = F1* (R1/R2)

Pedalling forces are the sum of chain and leg forces. Left and right legs produce cyclic forces with a frequency called the cadence and induce oscillating chain forces at twice the cadence frequency. Leg forces are of most concern when they act on the same area of the cycle as chain forces, exacerbating chain forces and producing extra periodic frame movement and stress. This occurs on cycles such as the rear wheel drive recumbent cycle (fig 2) where the left leg and chain forces combine to stress the boom supporting the bottom bracket.

Diagrams and descriptions of chain forces on various cycle frames follow. As per Figure 3, the red section shows the frame which moves when the bike is steered, the dotted line is the steering axis and the hatched area is the frame area affected by chain forces. An arrow indicates which parts of the cycle move to adjust leg length.

2.1 Rear wheel drive safety bike.

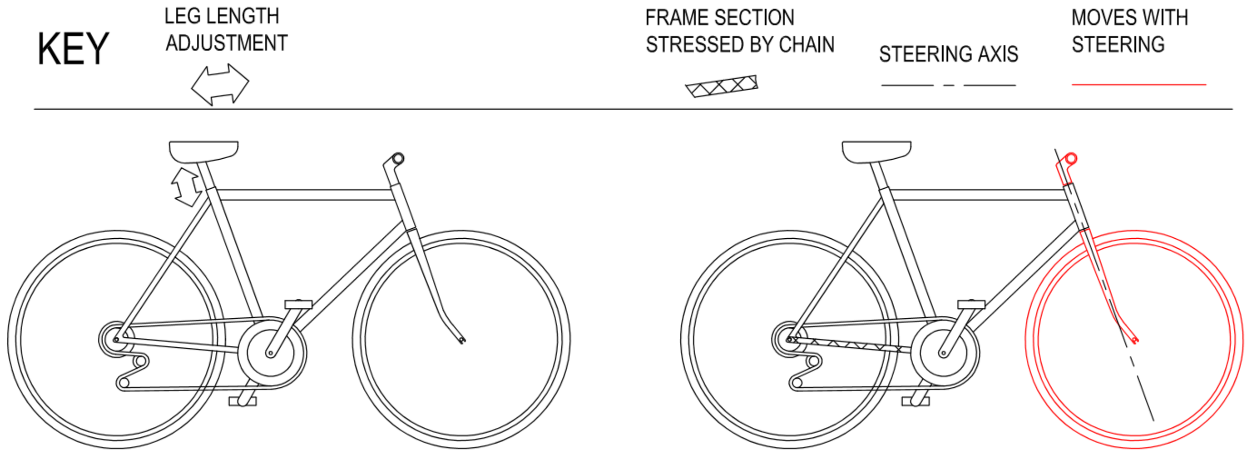
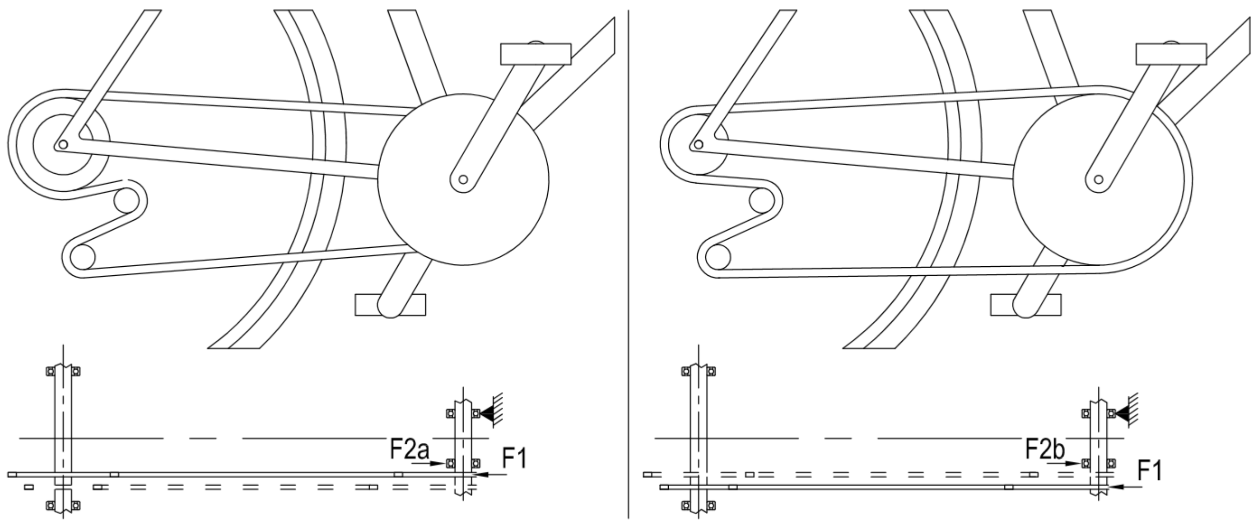


Figure 3: Safety bike and key to diagrams.

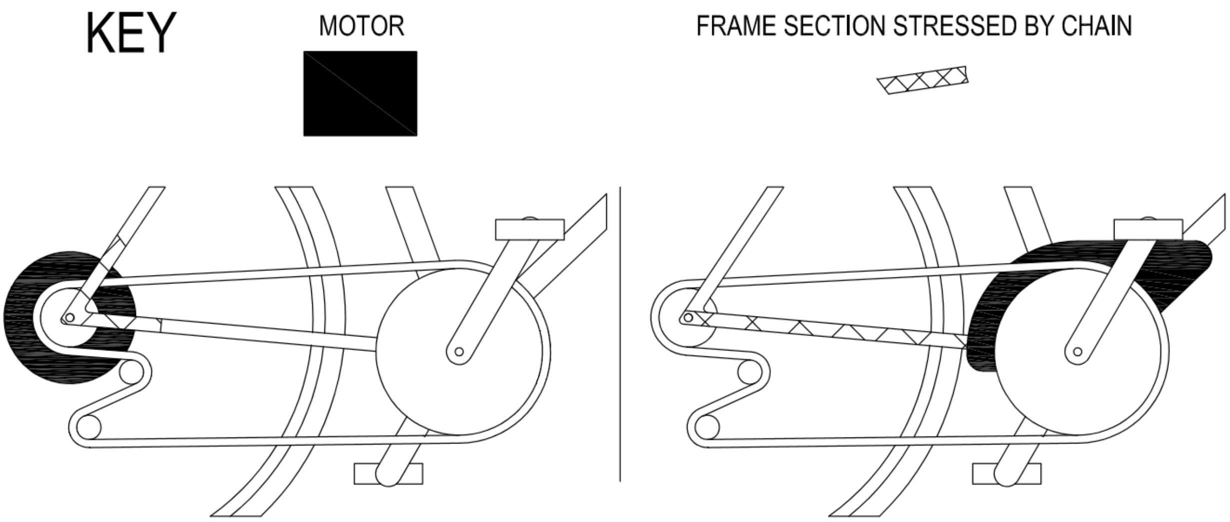
Chain forces are restricted to a small frame region and the chain is short (Figure 3). These bikes usually include derailleur gearing. On these derailleur cycles with multiple front chainrings, the chain force on the bottom bracket bearings is higher per unit of chain force (Newton) on the large chainring because the chain is further away from the frame and exerts more leverage (Figure 4). The large chainring can be associated with high cycle and chain speeds, and low chain tensions. The small chainring can be associated with low cycle and chain speeds, and high chain tensions.



a) ***b)***

Figure 4: Chain induced stress on bottom bracket a) Low gear and b) High gear. For the same chain tension F1, F2a<F2b.

This is a *productive* or *synergetic* arrangement which is good engineering – an adjustable mechanism arranged to have high forces when the mechanism can best cope, and low forces when the mechanism can least cope. A common example of an *unproductive* design is the seatpost on a safety bicycle. When raised for taller, possibly heavier riders, less of the seatpost is present in the frame as reinforcement. There is more reinforcement when it is *not* needed, that is when the cycle is adjusted to suit smaller riders.



a) *b)*

Figure 5: Motors on bicycle a) Hub and b) Crank and how they induce chain stress in cycle frames.

Two types of safety bicycle electric assist are motors which drive the cranks, and motors which drive a wheel directly through the hub. Motors which drive cranks increase the chain induced stresses in the chainstays. Motors which drive wheels directly generate torque on the wheel and an equal and opposite torque is absorbed by the frame. This torque and its effects have been documented for front hub motors by Hicks (2012): motor reaction forces are dissipated into the frame by a short lever (like hub brakes) attached to one of the stays, by keying the motor shaft into dropouts, or by axle nuts tightened so torque is transferred directly to the dropouts.

Hicks' article concerns front hub motors applying torque to forks (two small stays fixed rigidly at one end), however the same forces and need for dissipation into the frame occur with rear hub motors. Compared to front hub motors, stresses from rear hub motors can cause fewer issues because they are usually surrounded by four stays fixed rigidly at each end or two large-diameter tubes.

Similar forces apply to motorised recumbents. Chain stresses on the frame due to a drive motor add to the pedalling forces but are not cyclical with cadence.

2.2 Rear Wheel Drive Recumbent Bike. (Actionbent)

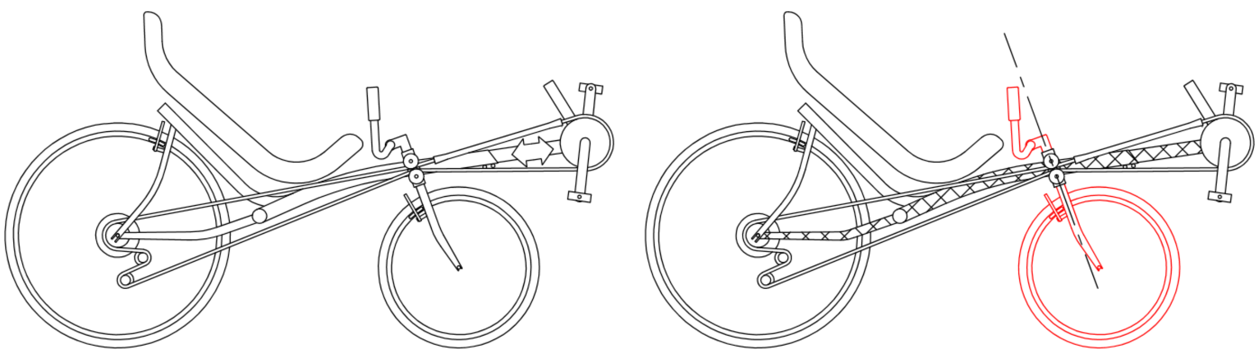


Figure 6: Actionbent rear wheel drive bicycle.

Chain forces run down the length of the frame, which must cope with the worst case of a tall (possibly strong and heavy) rider with the boom fully extended and little overlap between boom and frame (Figure 6). The chain is managed by pulleys and runs through a hose tube. These stop the long chain from swaying, staining trousers and fouling with the front wheel. The rear derailleur copes with small frame adjustments for a given chain length, however the chain length must be altered for larger variations. This style of leg length adjustment keeps weight distribution on the wheels relatively constant. No matter what size rider, the torso is in the same position relative to the back wheel, and the front wheel / back wheel weight distribution remains as the designer intended.

The top of the chain is the tension side which stresses the frame. It subtends an angle close to 180 degrees as it runs past the top pulley, so does not exert large forces on the pulley or pulley mount.

The Schlitter Encore (Maccraw 2016) is a rear drive recumbent with a simplified frame custom sized for the rider and a fixed boom. The movable seat allows for some leg length adjustment and the Schlitter avoids some of the strength and chain compromises of the Actionbent.

2.3 Front Wheel Drive Fixed Bottom Bracket (Toxy ZR with adjustable boom).

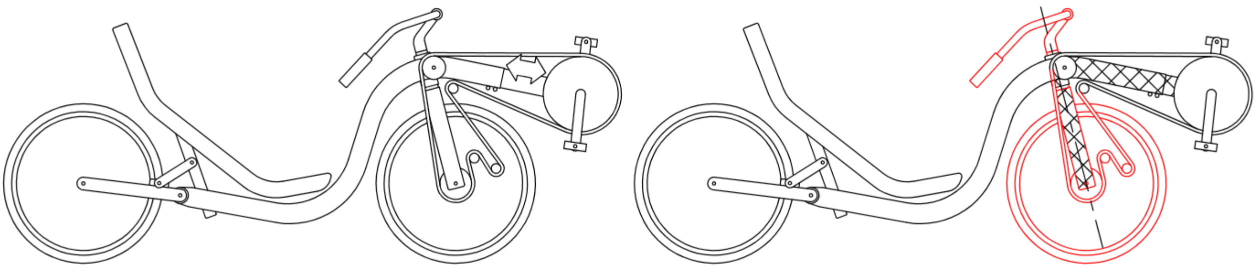


Figure 7: Toxy front wheel drive bicycle.

This cycle has a *fixed bottom bracket* (fbb) arrangement where in normal use the pedal axis is fixed relative to the rider but moves relative to the front wheel. The chain undergoes steering-related twisting which adds to twisting and displacement from derailleur mechanisms, however the interactions between pedalling and steering are small and limited to chain induced pedal steer.

Chain forces are present in the front of the frame and front fork (Figure 7). The small angle of the chain as it passes the drive side pulley creates high forces in the pulley mount. Leg length adjustment is in the boom, so as with the rear wheel drive recumbent, chain length must be adjusted to suit the boom position and weight distribution on the wheels stays fairly constant.

2.4 Front Wheel Drive Fixed Bottom Bracket (Zox 20 Z frame with adjustable seat).

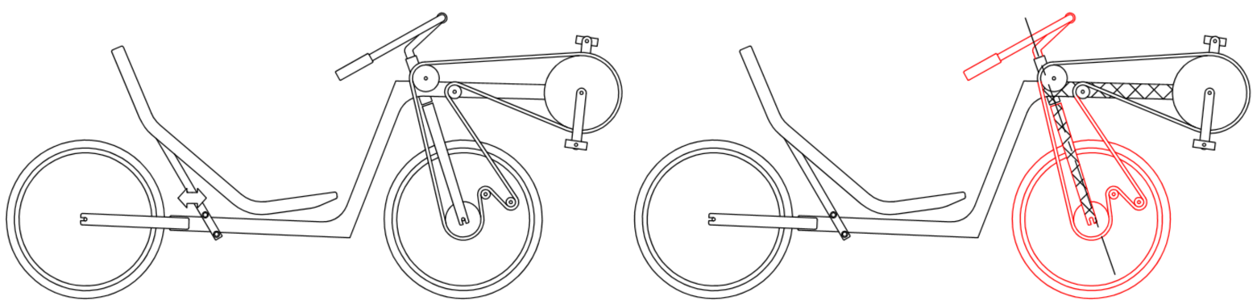


Figure 8: Zox front wheel drive bicycle

Chain forces are present in the front of the frame and front fork (Figure 8). The small angle of chain as it passes the drive side pulley creates high forces in the pulley mount. There is no adjustment for leg length in the boom position, but 7cm of adjustment in the seat position. There are no additional forces on the frame due to the boom position, and no need to adjust chain lengths for different riders. However the rider's torso position changes with leg length adjustment, affecting the weight distribution on the wheels.

2.5 Moving Bottom Bracket Front Wheel Drive (Cruzbike).

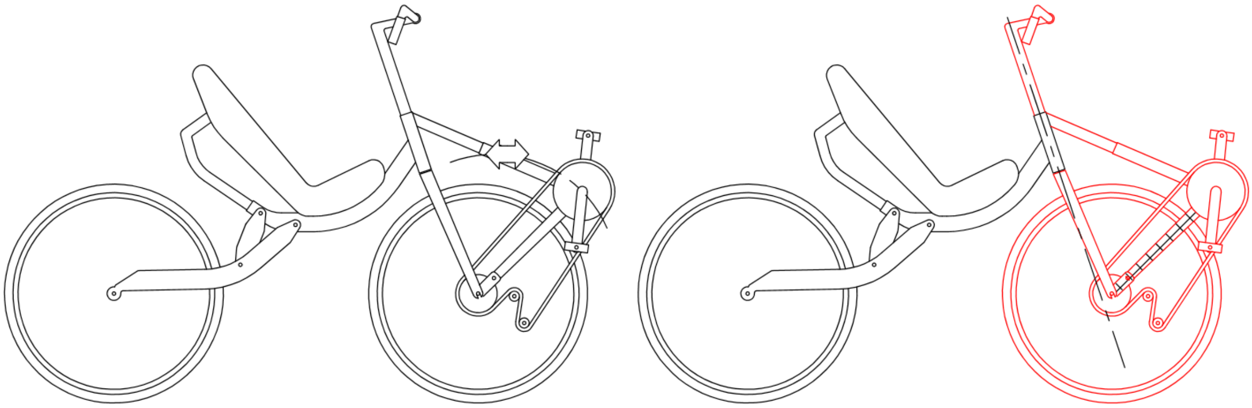


Figure 9: Cruzbike front wheel drive bicycle

This cycle has a *moving bottom bracket* (mbb) arrangement where the pedal axis moves relative to the rider but is fixed relative to the front wheel. The chain has no steering-related twisting adding to twisting and displacement from derailleur mechanisms.

Like the rear drive safety bike, chain forces are restricted to a small frame area (Figure 9). Leg forces influence steering and must be compensated for by arm forces or a highly developed pedalling action which allows “no-hands / hands free” riding, pedalling and steering. The front triangle of the bike includes joins for leg length adjustment which can make the front triangle less rigid than the equivalent safety bike rear triangle. The position of this adjustment leaves the weight distribution on the wheels fairly constant and independent of the rider's height, however like the safety bike seatpost arrangement it is weakest when set up for the largest rider.

2.6 Moving bottom bracket front wheel drive with in-hub gearbox (Kervelo / Velotegra)

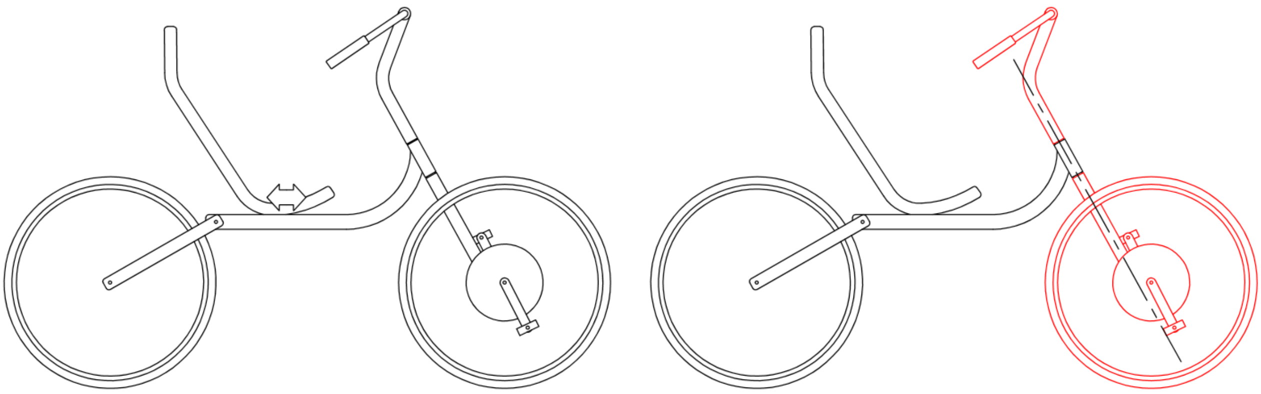


Figure 10: Kervelo front wheel drive bicycle

There is no chain in this bike design (Figure 10) which includes a multi-speed hub in the front wheel. Chains and associated forces are eliminated, however leg forces influence steering and must be compensated for by arm forces or a highly developed pedalling action. There is more likelihood of significant frame flex when the frame is adjusted for a large rider because more of the frame is exposed to leg forces, but in general eliminating chain forces leads to a productive frame arrangement.

2.7 Bevo style Fixed Bottom Bracket Front Wheel Drive.

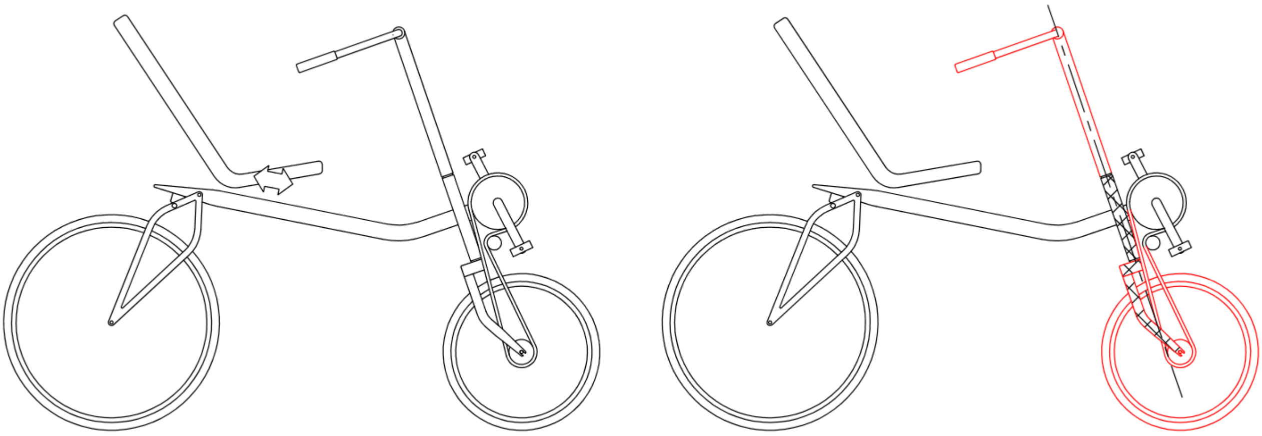


Figure 11: Bevo front wheel drive bicycle.

In this bike style, chain forces are restricted to a small frame region (Figure 11). The fixed bottom bracket front wheel drive does not need a drive side chain pulley because chain tension acts close to the steering axis and does not unduly influence steering. Adjusting the seat for larger riders places more weight on the back wheel, something that can affect traction as the front wheel is lightly loaded. A small slack chain side pulley lets the steering sweep through a wide angle without tyre scrub or chain derailment. (Davidson 1996, p. 34).

2.8 Flevobike Greenmachine

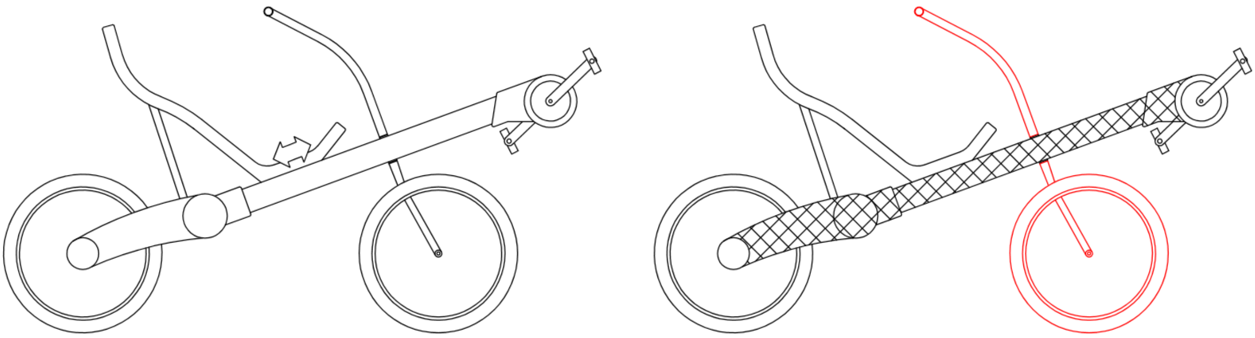


Figure 12: Greenmachine enclosed chain bicycle.

The Flevobike Greenmachine is rear wheel drive and has a hollow frame in front and rear sections which fully enclose and protect the chain. This makes the chain forces on the frame wholly compressive, minimising chain induced distortion. It comes in 3 frame sizes to suit riders from 150 to 205cm high, and adjustments for leg length are made by sliding the seat (Lepisto, 2009).

3.0 Experimental front wheel drive bikes and trikes.

Since 2008, I have experimented with bikes and leaning trikes using drive configurations close to that of the Bevo bike, that is direct front wheel drive with the fixed bottom bracket located near the steering bearings. The first cycles I built in this style had a 50.8 x 1.2mm round chromoly steel frame whose resistance to bending was the same in vertical and horizontal direction. There is no hardware used to guide the chain except for plates preventing derailment each side of the chainring,. Steering while pedalling is restricted to a small angle because the rider's knees must stay inside the handlebars while pedalling and this helps stop chain derailment.

3.1 Murray aluminium frame front wheel drive bicycle

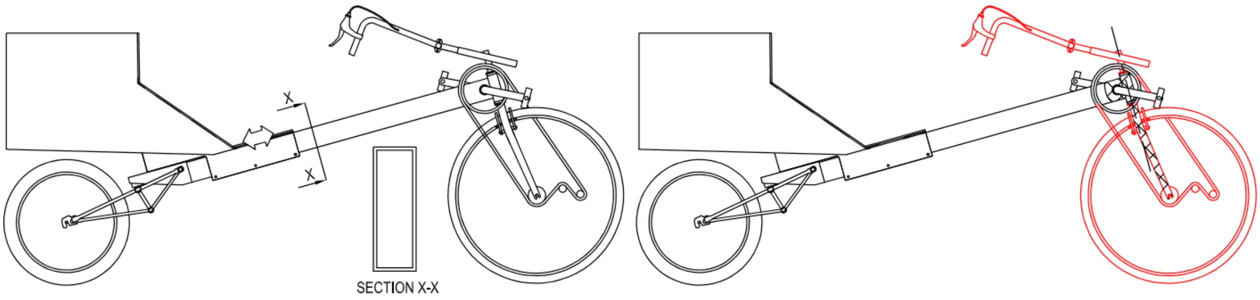
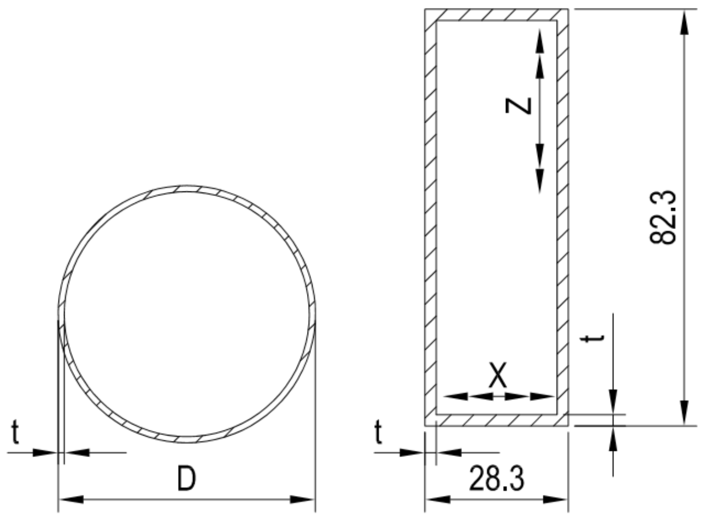


Figure 13: "Murray" front wheel drive bicycle.

In 2009, I developed the "Murray" bike with rear suspension (Figure 13). The frame was welded and used aluminium rectangular hollow section (RHS) whose resistance to bending was similar to the steel frame material in the vertical direction but six times weaker in the horizontal direction. This section was chosen because it is a lightweight rectangular beam to which an adjustable seat frame and tailbox storage area could be clamped. The relative strengths of the round steel and rectangular aluminium frames are shown in figure 14.



Measurement	direction	D	t	A	B	i (section dependant)	e (material dependant)	ei	density	mass / metre
Unit		mm				(mm)^4	n/(m^2)	nm^2	kg/(dm^3)	kg/m
Steel Tube Cro Moly	X, Z	50.8	1.2	-		57502	700	**4.03E+07**	7.9	1.48
Aluminium 6060 Rectangular Hollow Section (RHS)	Z	-	2.2	82.28	28.28	386279	150	**5.79E+07**	2.7	1.31
	X	-	2.2	28.28	82.28	68883	150	**1.03E+07**		

Figure 14: Material Strength Calculations.

This bike was ridden successfully in a flat 1200k Audax ride along the Murray River. Later bikes sharing this rectangular frame configuration were made using solid and chambered timber frames. The chambered timber frame was made structural by hollowing out in areas not subject to stress while keeping stressed areas solid.

3.2 Separating frame front wheel drive leaning Trike

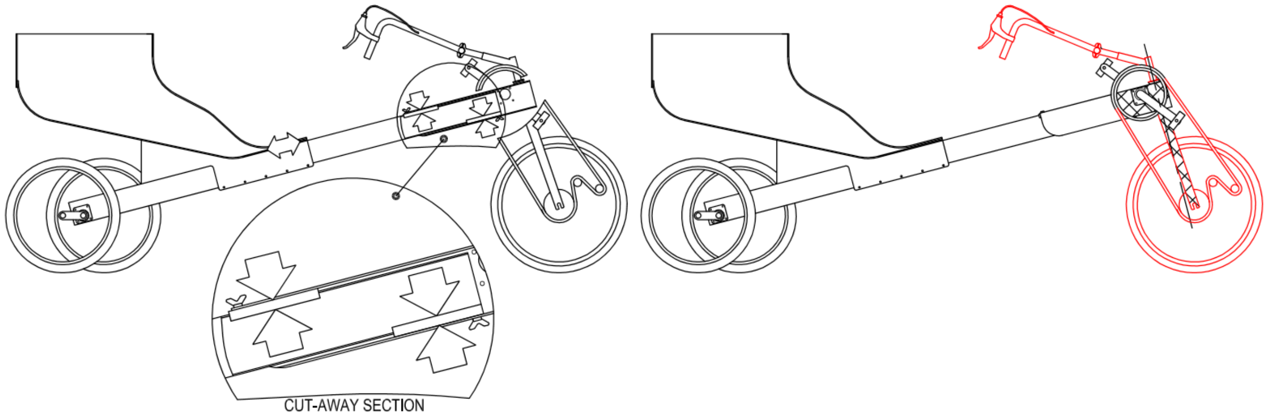


Figure 15: Leaning trike with separating aluminium frame.

A variation on these bikes was a tilting solid frame timber trike completed in 2013. It used a rear wheel setup invented by Vi Vuong (Nurse 2017) and can be seen on video in Nurse (2013). Further frame configurations with same layout as this trike were made between 2015 and 2017.

A trike sharing frame geometry with the Murray Bike was made during 2016 (Figure 15). The frame is assembled rather than welded together, and the rear frame tube RHS matches that used in the Murray Bike. At the front, a larger section aluminium RHS caps the rear frame tube RHS. This larger section is wide enough to accommodate bicycle head tube (steering) bearing housings. The two frame sections are kept apart by two 3d printed spacers and held in place by two bolts with wing-nut style heads. The dominant force across this join is the rider’s weight which acts to keep the join in place and dimensionally stable. This force is reduced when braking, and chain forces would act to confound the stability of the join (Nurse 2017, p.46).

The trike and its frame split mechanism have worked well. The join is snug and does not move perceptibly when riding. Disassembly for transporting in cars and trains takes only a few minutes.

3.3 Plywood Trike

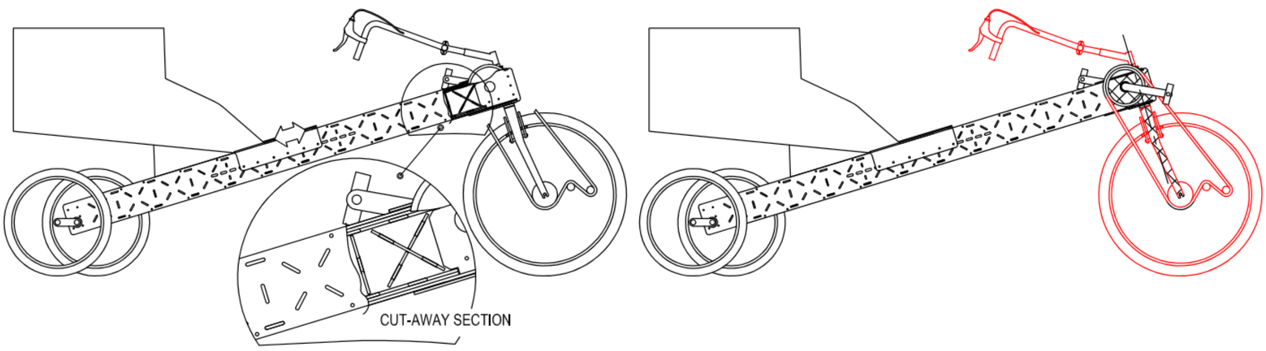


Figure 16: Leaning trike with plywood frame.

Another trike completed in 2016 uses structural plywood for the frame (Figure 16). Layers of plywood combine to make thick solid timber where the frame is stressed by the chain and rear wheels, and reinforced hollow sections are used in other areas. By limiting the frame regions required to resist oscillating chain forces and using a rear wheel assembly mounted on pedal bearings, the heavy solid sections of the frame are reduced in size making the trike lighter.

4.0 Summary

Safety cycles have one dominant configuration which confines chain stresses to a small area of the frame. Their derailleur gearing often has two front chainrings, and this setup is empathetic, placing higher chain forces on the bottom bracket when the chain is close in. Electric motors are sometimes fitted to safety cycles, and motors included in the hub of the wheel are best for confining additional chain induced forces on the frame.

Rear wheel drive recumbents have chain stresses present in the whole length of the frame, while front wheel drive configurations confine chain stresses more. In the front wheel drive Kervelo, the chain and its attendant forces are eliminated altogether.

Designing recumbents with small frame areas subject to chain forces has allowed alternate frame materials such as aluminium RHS and plywood and enabled a novel frame joining system.

Understanding chain forces acting on recumbent cycle frames is an important factor in their design.

REFERENCES

DAVIDSON, A. 1996. Encycleopedia 96, Rotherham, UK, Open Road.

HICKS, E, 2012, Torque Arms on Hub Motor Bikes https://www.electricbike.com/torque-arm/ [Accessed 2018]

GROSS, A. C. & KYLE, C. R. 1983. The aerodynamics of human-powered land vehicles, Scientific American

LEPISTO, C. 2009. Green Machine by Flevobike is the ultimate commuter bike. https://www.treehugger.com/bikes/green-machine-by-flevobike-is-the-ultimate-commuter-bicycle.html [Accessed 2018]

MACRAW, D. 2015. Schlitter recumbent review available online, http://mccraw.co.uk/schlitter-encore-review/ [Accessed 2018]

NURSE, S., LIVINGSTON, S. 2013. Steve's Leaning Wooden Recumbent Trike [Online]. Available: https://www.youtube.com/watch?v=bIijLujoA2c [Accessed 2017].

NURSE, S. 2017. A Simple Leaning Trike, Monash University Master’s Degree Exigesis available from https://figshare.com/articles/A_Simple_Leaning_Trike/5373910 [Accessed 2017].

WILSON, D. G. & PAPADOPOULOS, J. 2004. Bicycling science 3rd Edition, Cambridge, MA, MIT Press.