First Look at Rider Biomechanics while Controlling a Bicycle

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&
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The Holy Grail

- What are we seeking?

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  - To be able to predict the handling qualities of a bicycle.

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- What is a handling quality?

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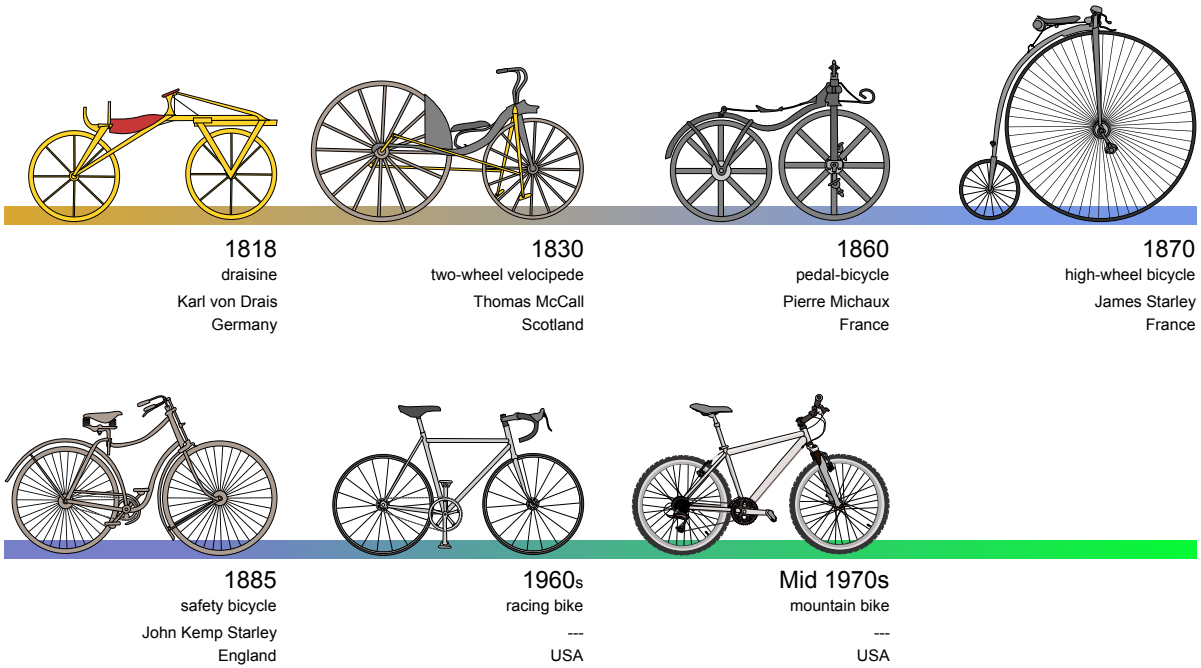
- What are we seeking?
  - To be able to predict the handling qualities of a bicycle.
- What is a handling quality?
  - A measure that determines the ease and precision with which a rider may complete a given task

But why?

Isn't the bicycle perfect the way it is?



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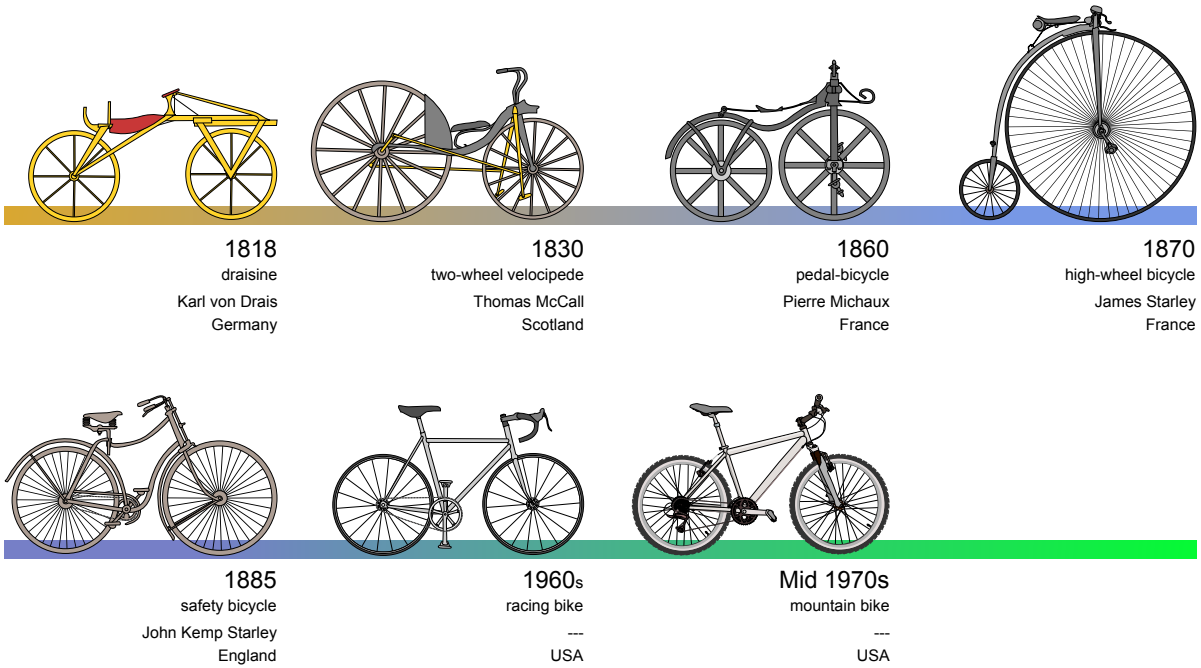

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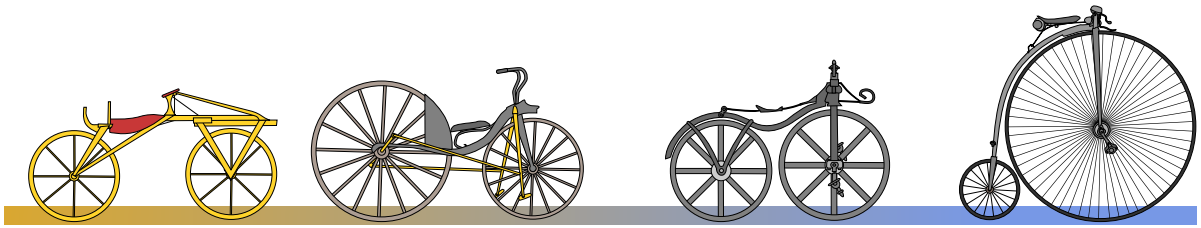
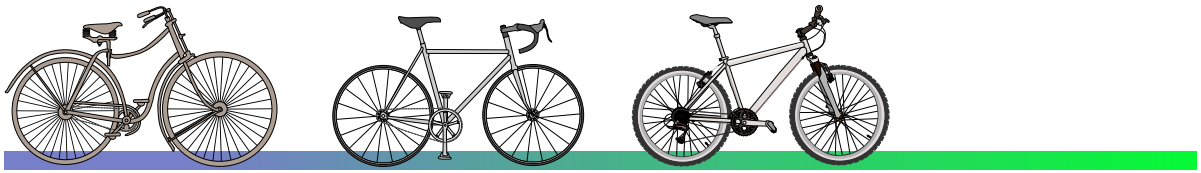


1818
draisine
Karl von Drais
Germany

1830
two-wheel velocipede
Thomas McCall
Scotland

1860
pedal-bicycle
Pierre Michaux
France

1870
high-wheel bicycle
James Starley
France



1885
safety bicycle
John Kemp Starley
England

1960s
racing bike

USA

Mid 1970s
mountain bike

USA

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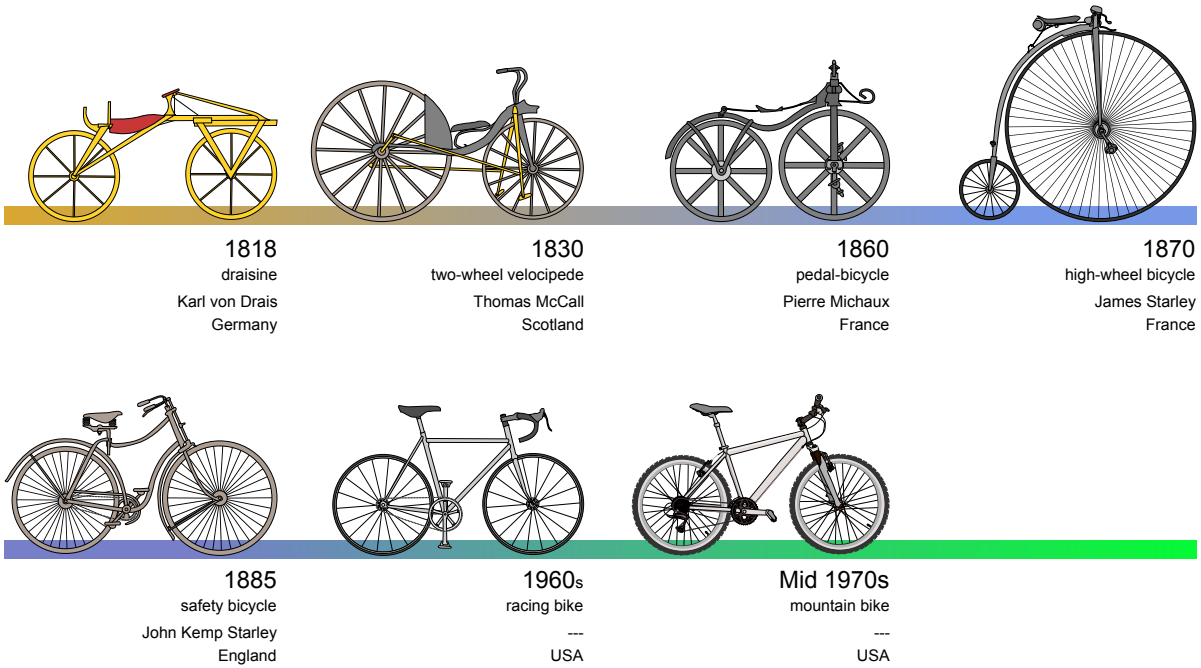
- Alternative designs do not have this luxury.
- Help shed light on many other human/machine interactions.



Handling qualities road map

Vehicle Dynamics

↓

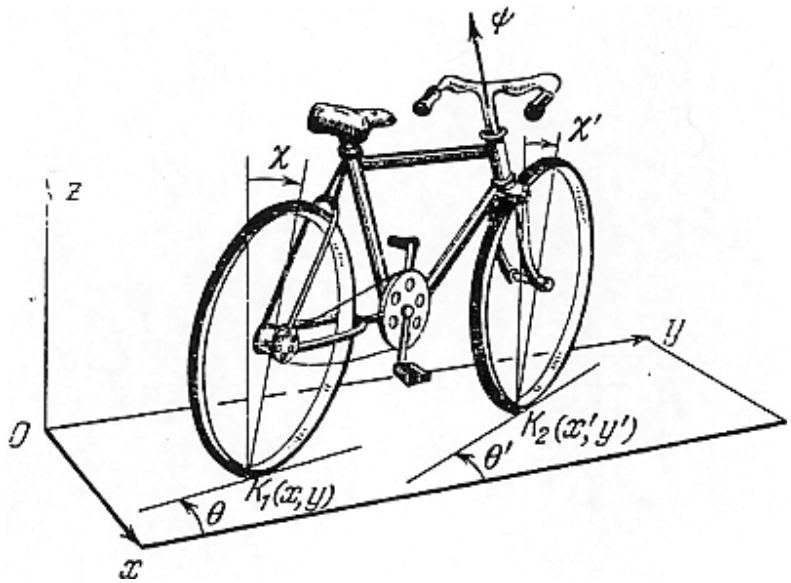
Human Biomechanics

↓

Manual Control

↓

Handling qualities



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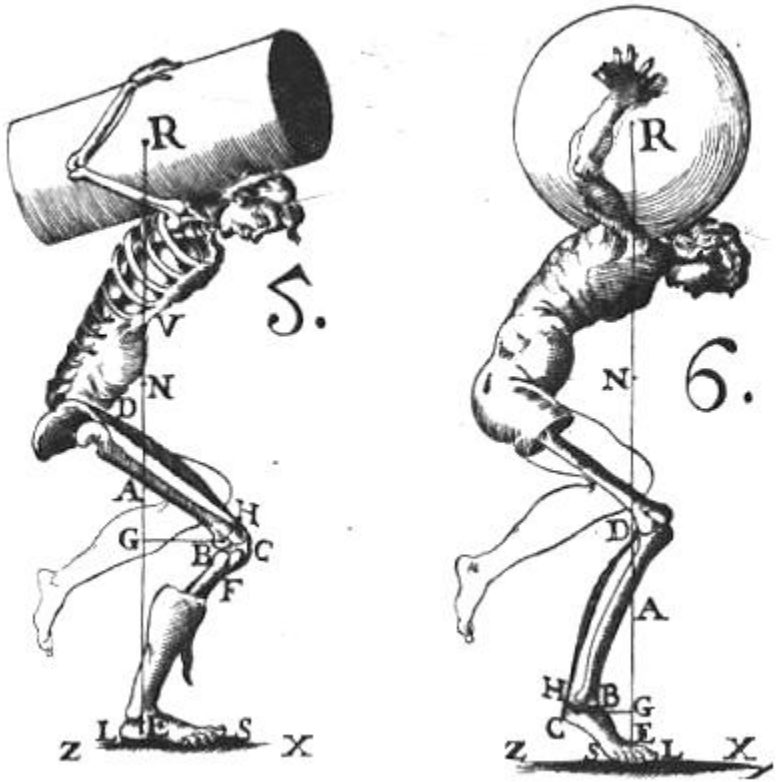

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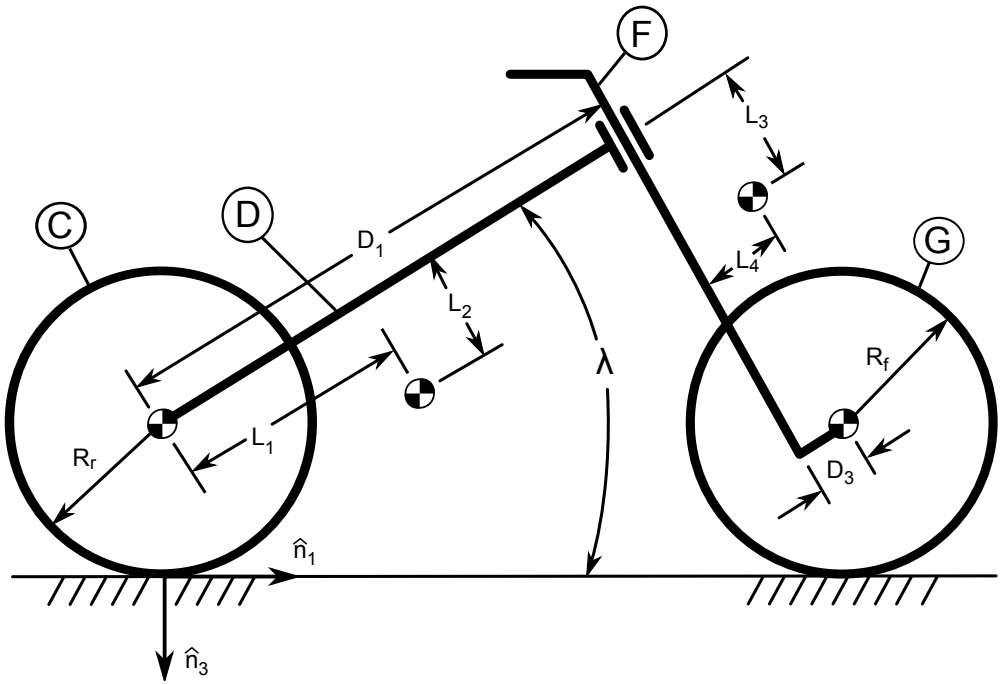
- Fact # 2: Steering into the lean will stabilize the bicycle.
- Fact # 3: To initiate a right turn (rightward lean) you have to first steer to the left!

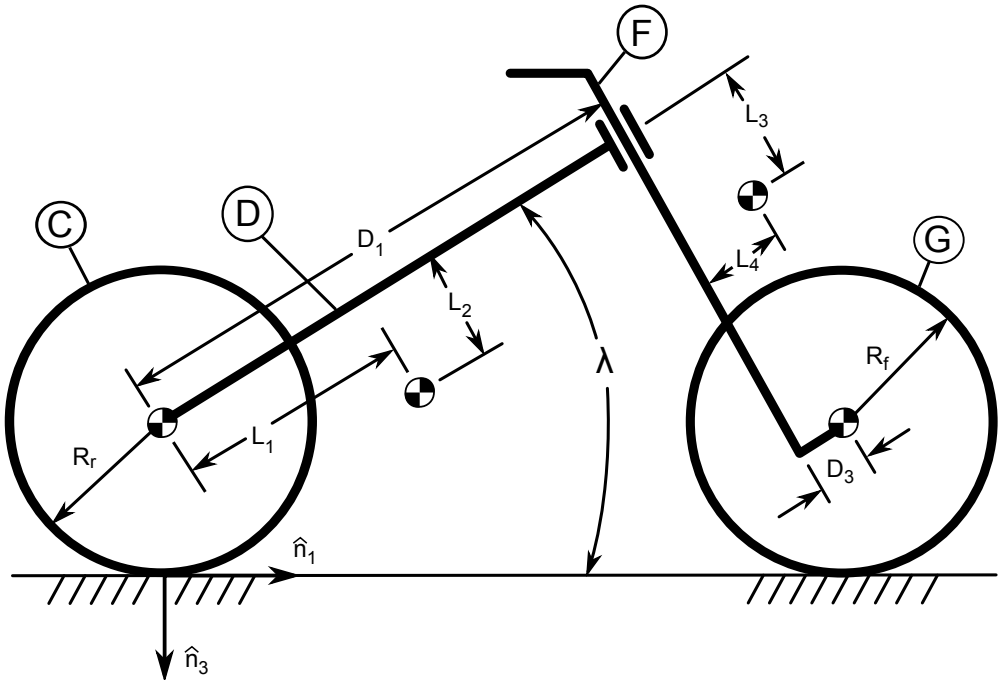
Whipple Model Description

- Four rigid bodies



Whipple Model Description

- Four rigid bodies
- Frictionless revolute joints



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- Four rigid bodies
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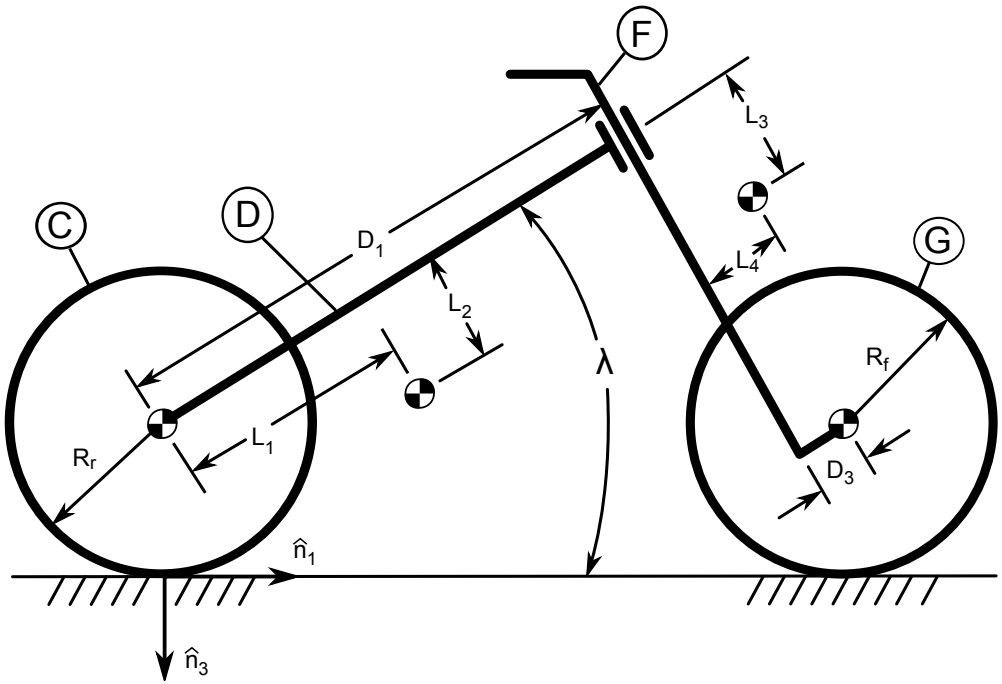

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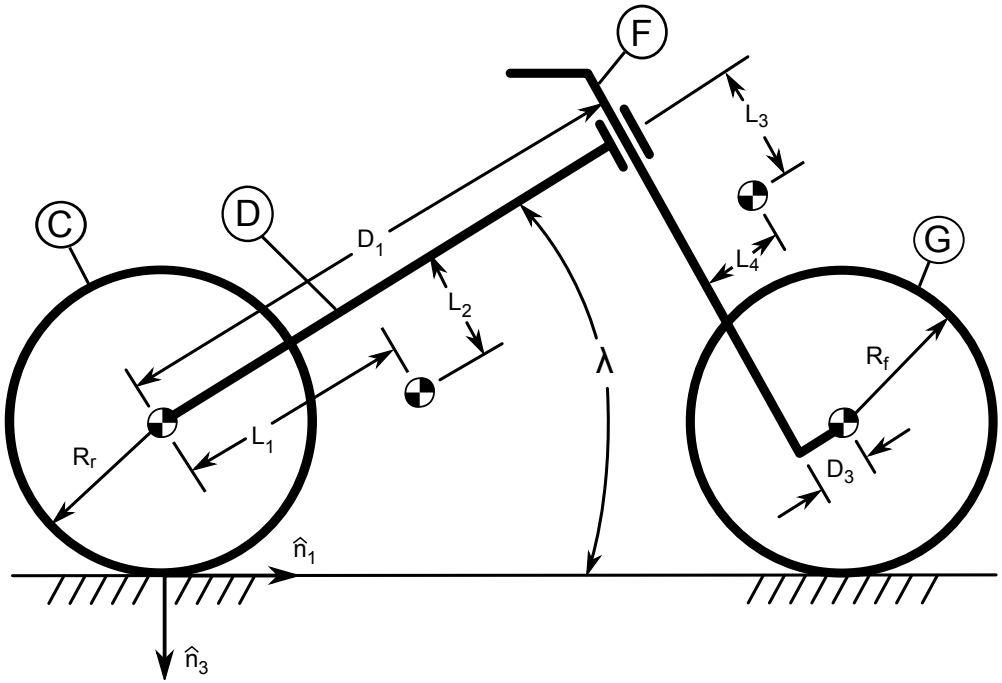

Whipple Model Description

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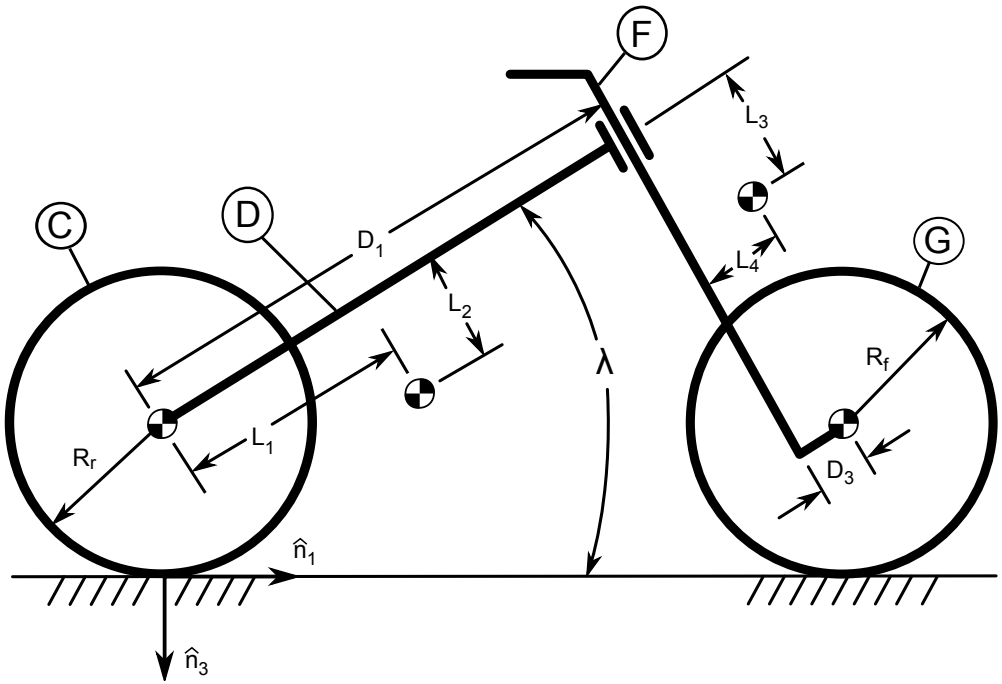
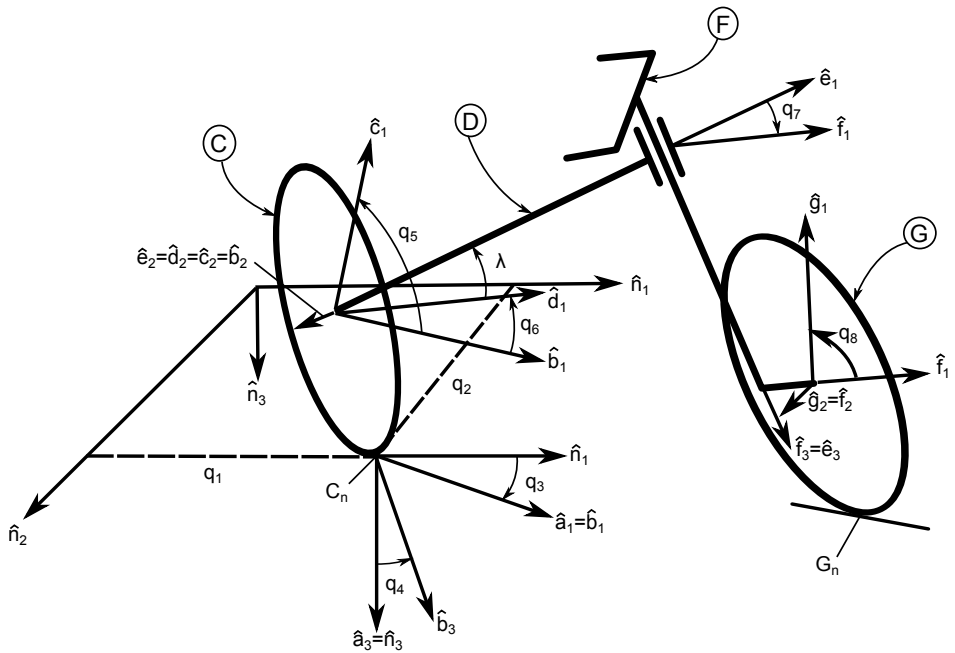


Degrees of Freedom

8 GCs - 1 HC - 4 NHCs = 3 DoF

8 generalized coordinates



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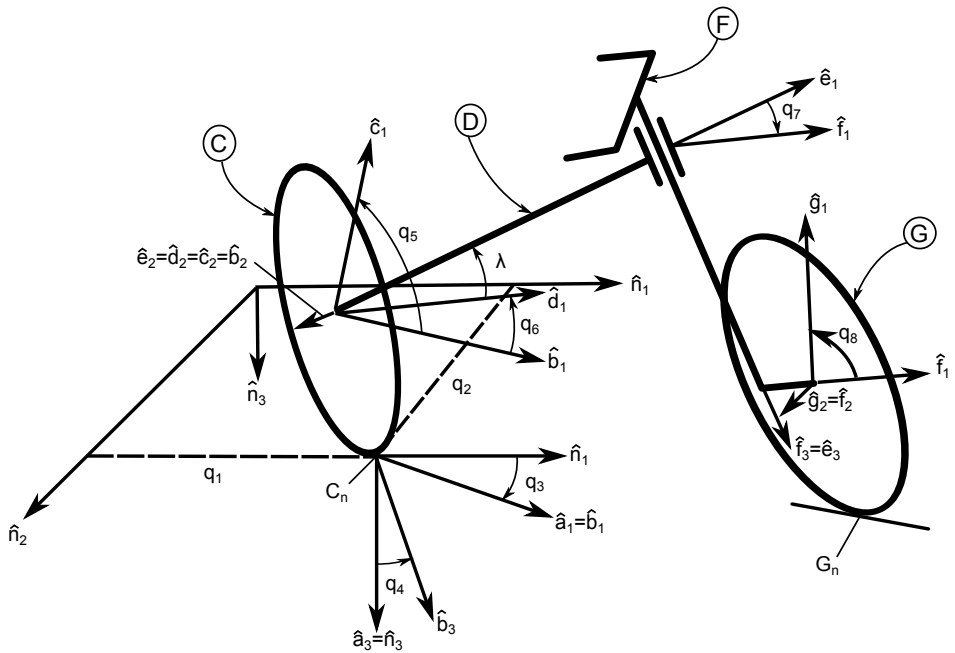
1 holonomic constraint



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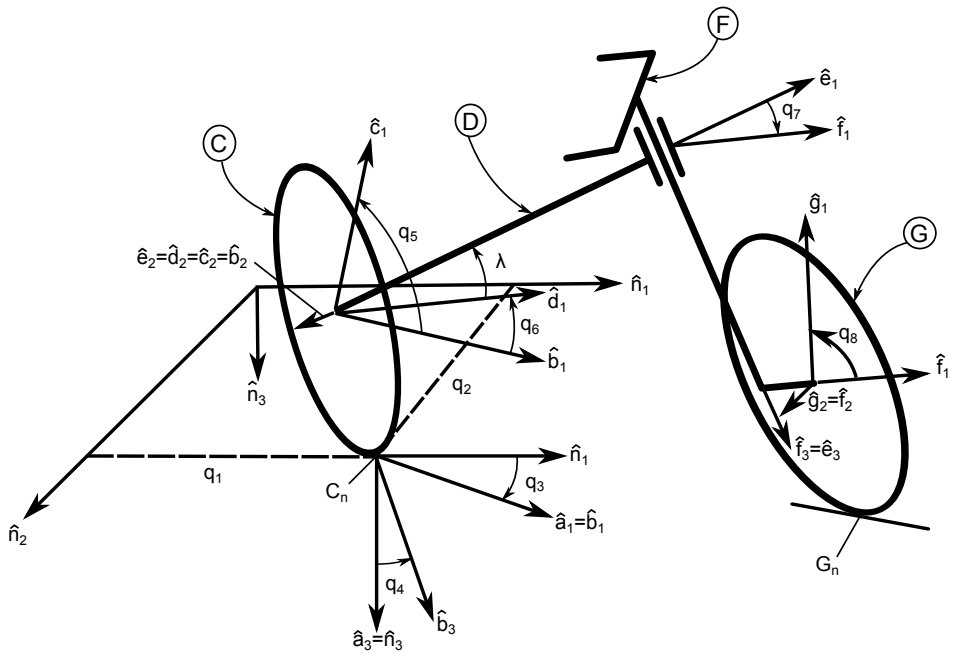
4 nonholonomic constraints



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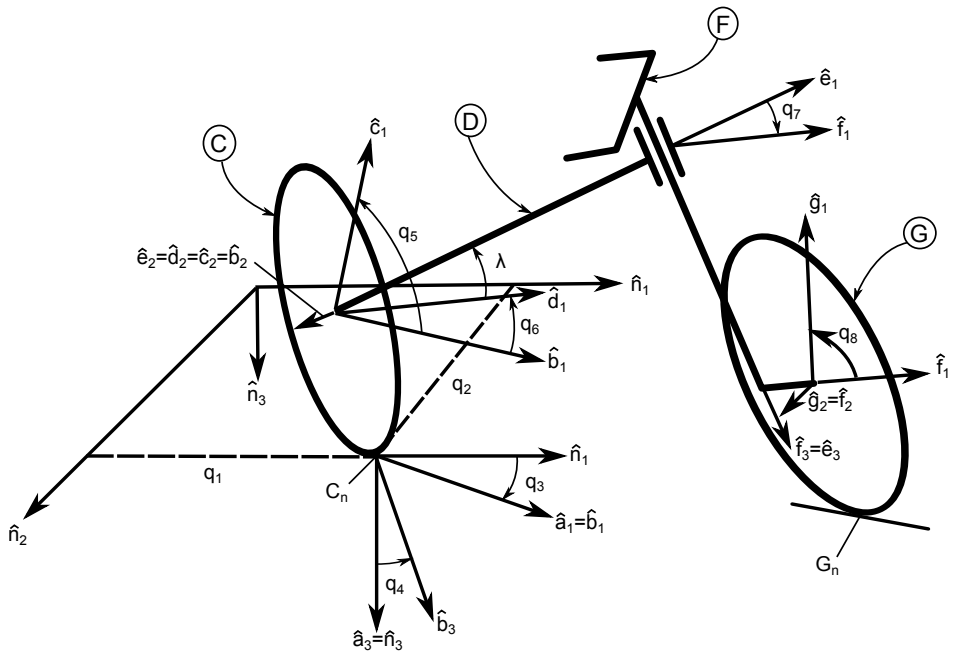
3 degrees of freedom: steer, lean, rear wheel rates



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  - Capsize: Stable at lower speeds.
  - Caster: Always stable.

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- Three modes of motion:
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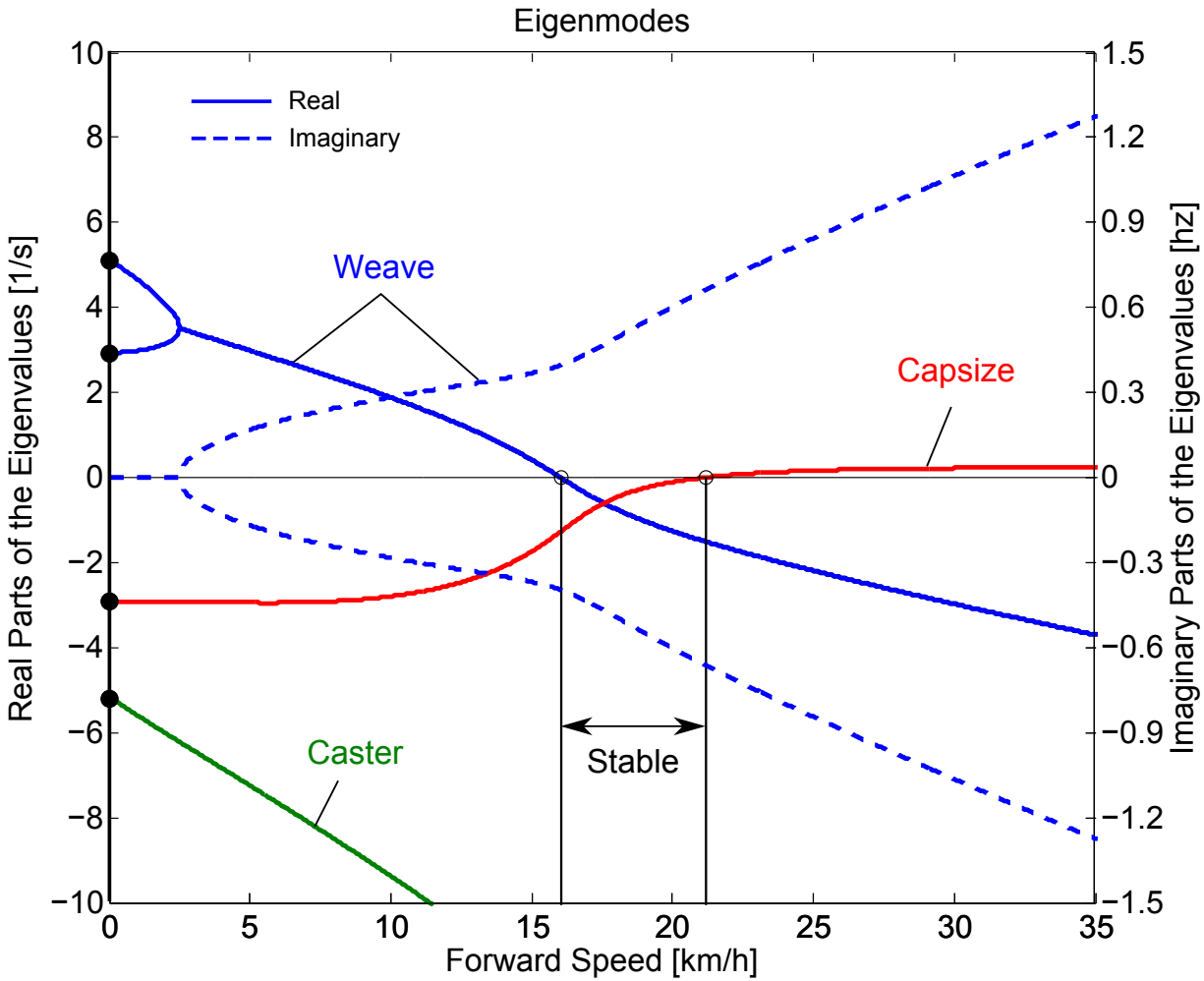
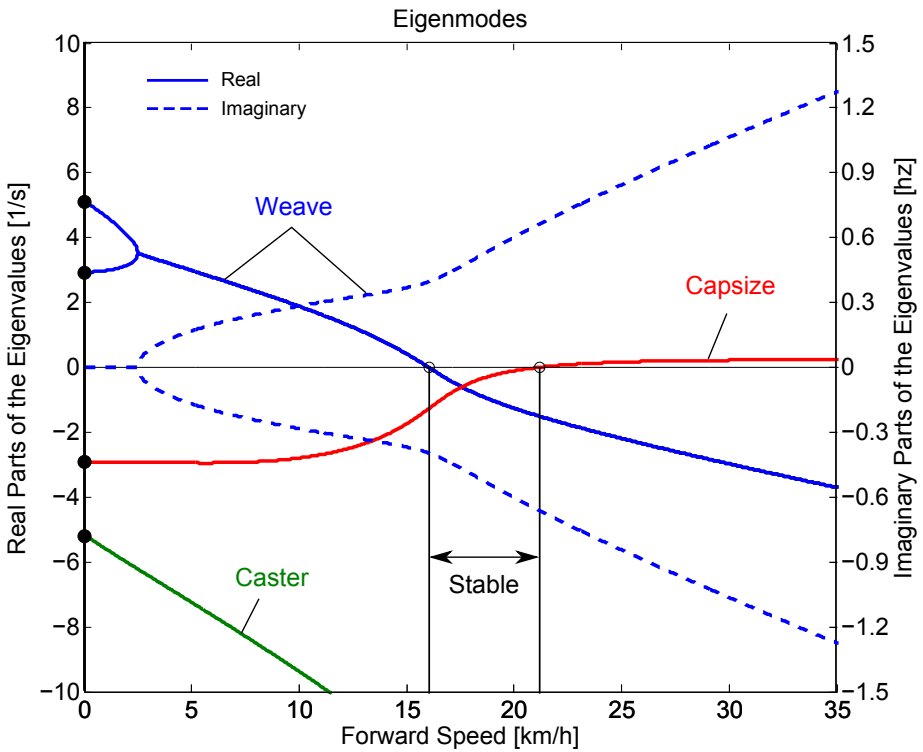
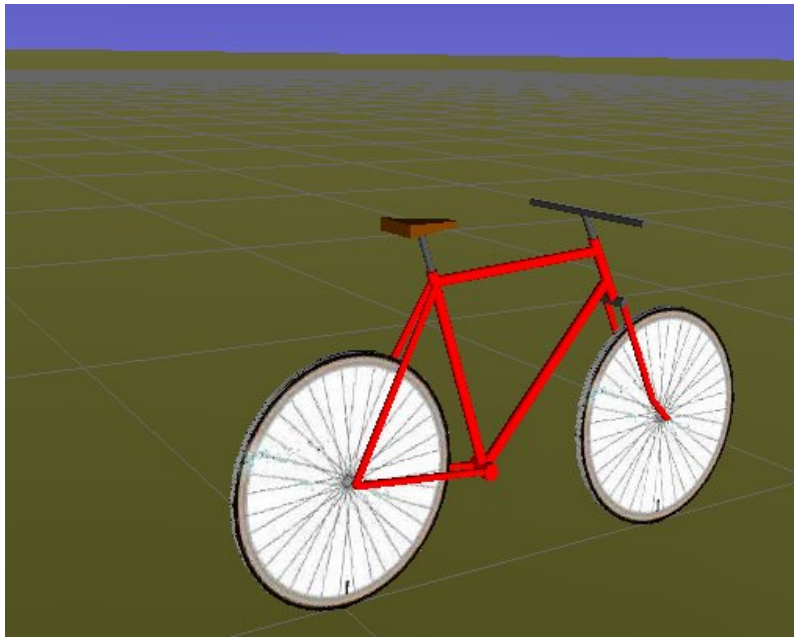
- Average bicycle stable speed range: 11 to 18 $\frac{km}{h}$ (7 to 11 mph).

Eigenvalues vs. Speed

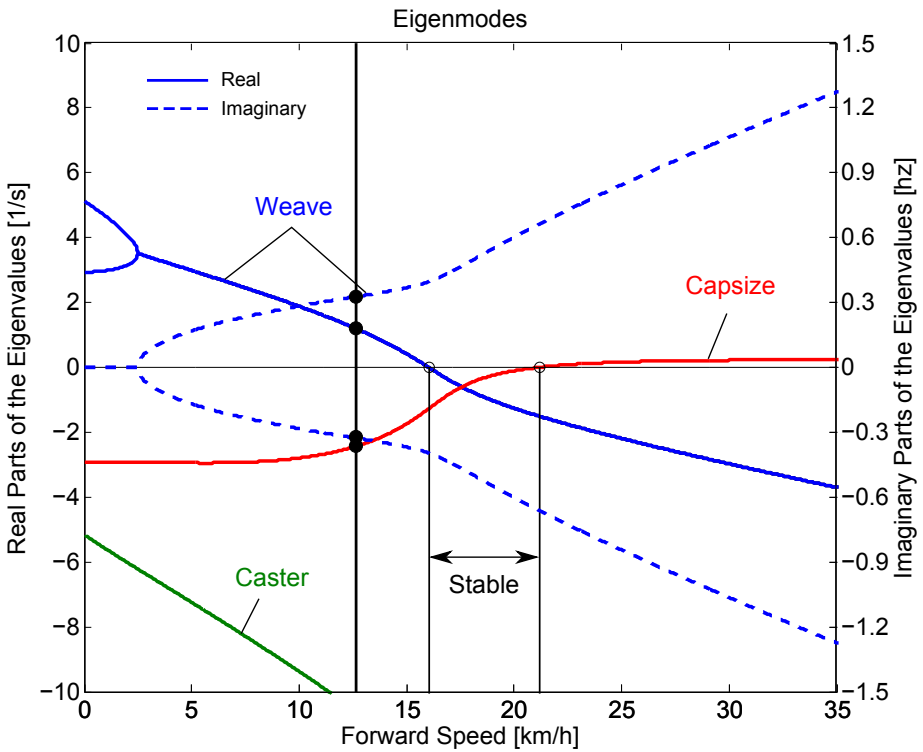


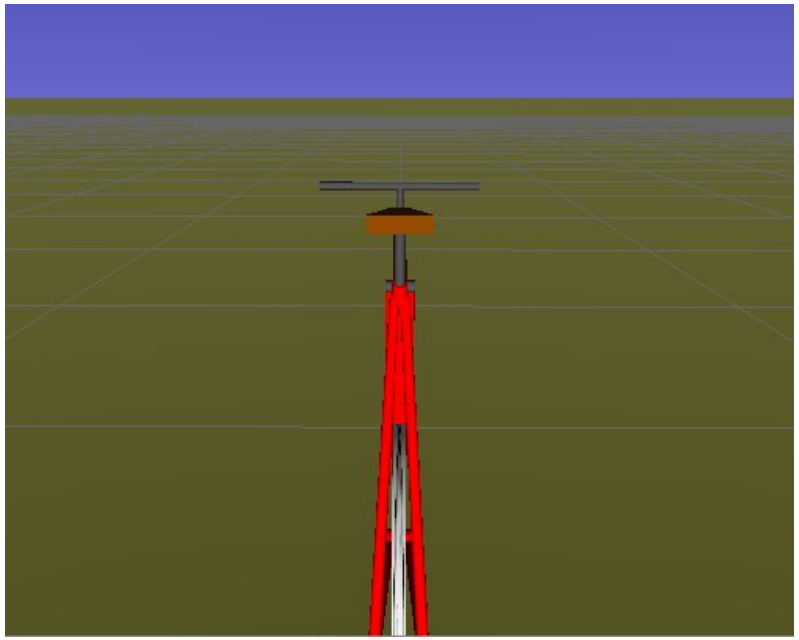
Unstable at 0 km/h (0 mph)



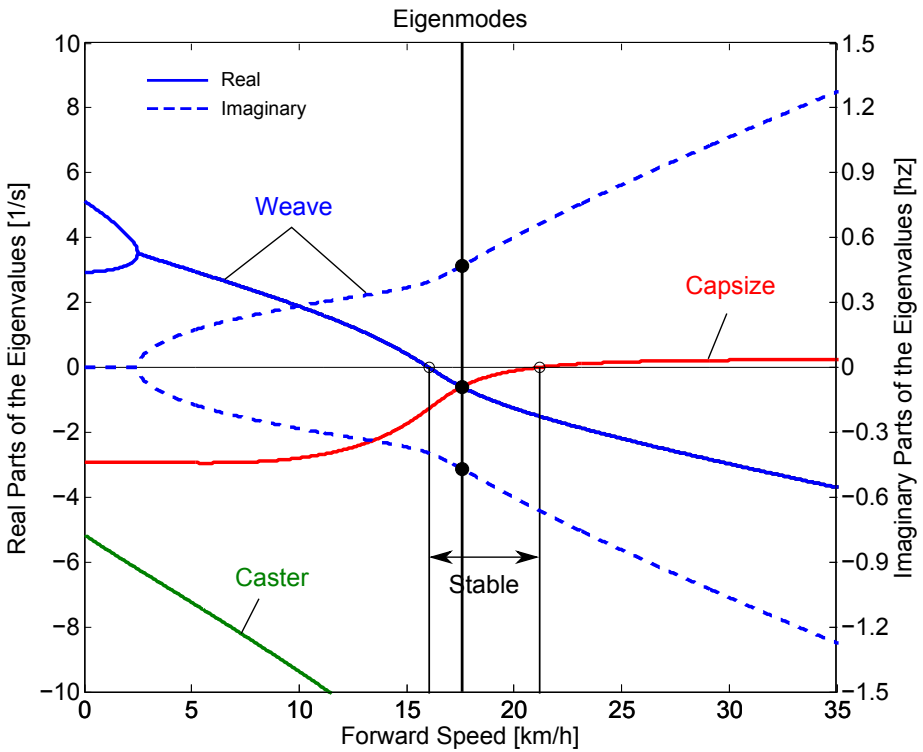


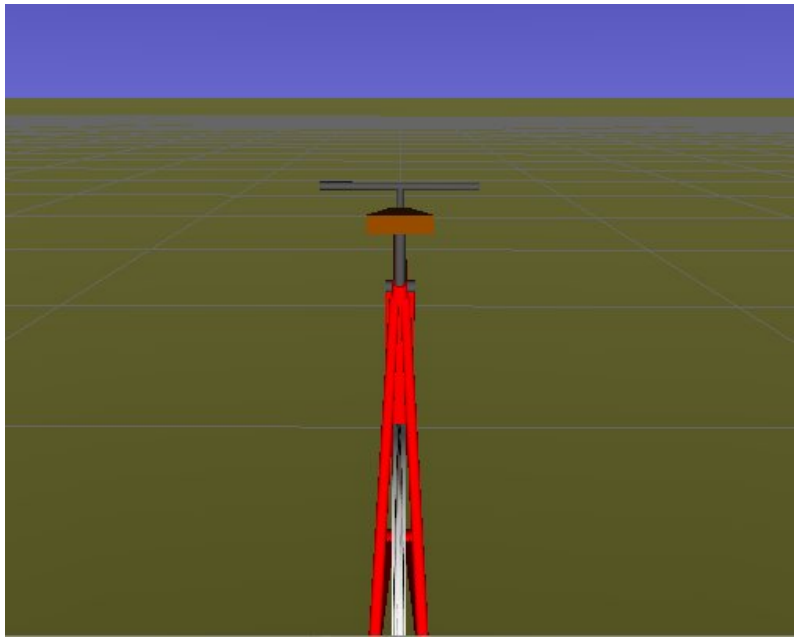
Unstable 12.6 km/h (7.9 mph)



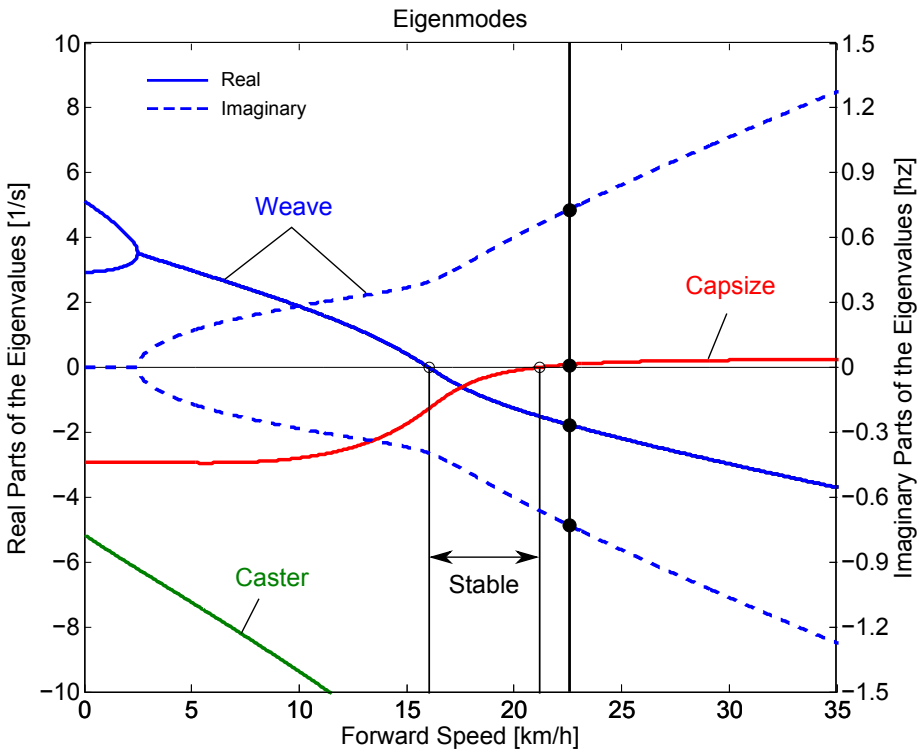


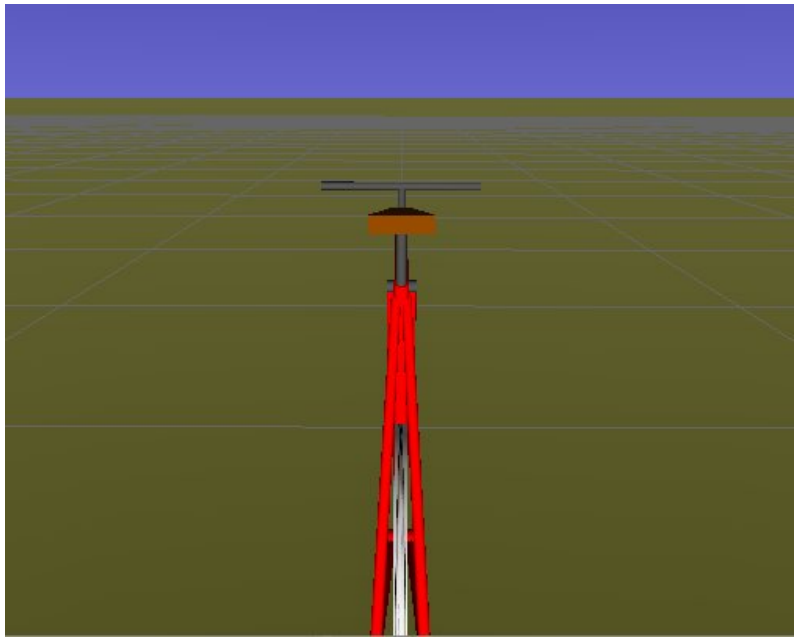
Stable at 17.6 km/h (11.0 mph)





Unstable at 22.7 km/h (14.2 mph)





Yellow Bicycle

Gyrobike

Countersteering

Vehicle dynamics and handling

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- Are the uncontrolled dynamics and indicator of handling?
  - For aircraft, connections have been found
  - Unlike a bicycle, the pilot's motion does not affect the aircraft's dynamics
  - Pilot and manual control theory have provided more insight

How do we control the bicycle?

Danny MacAskill, Pro Trials Rider

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Obvious control input candidates:

Not so obvious candidates:

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- Steering

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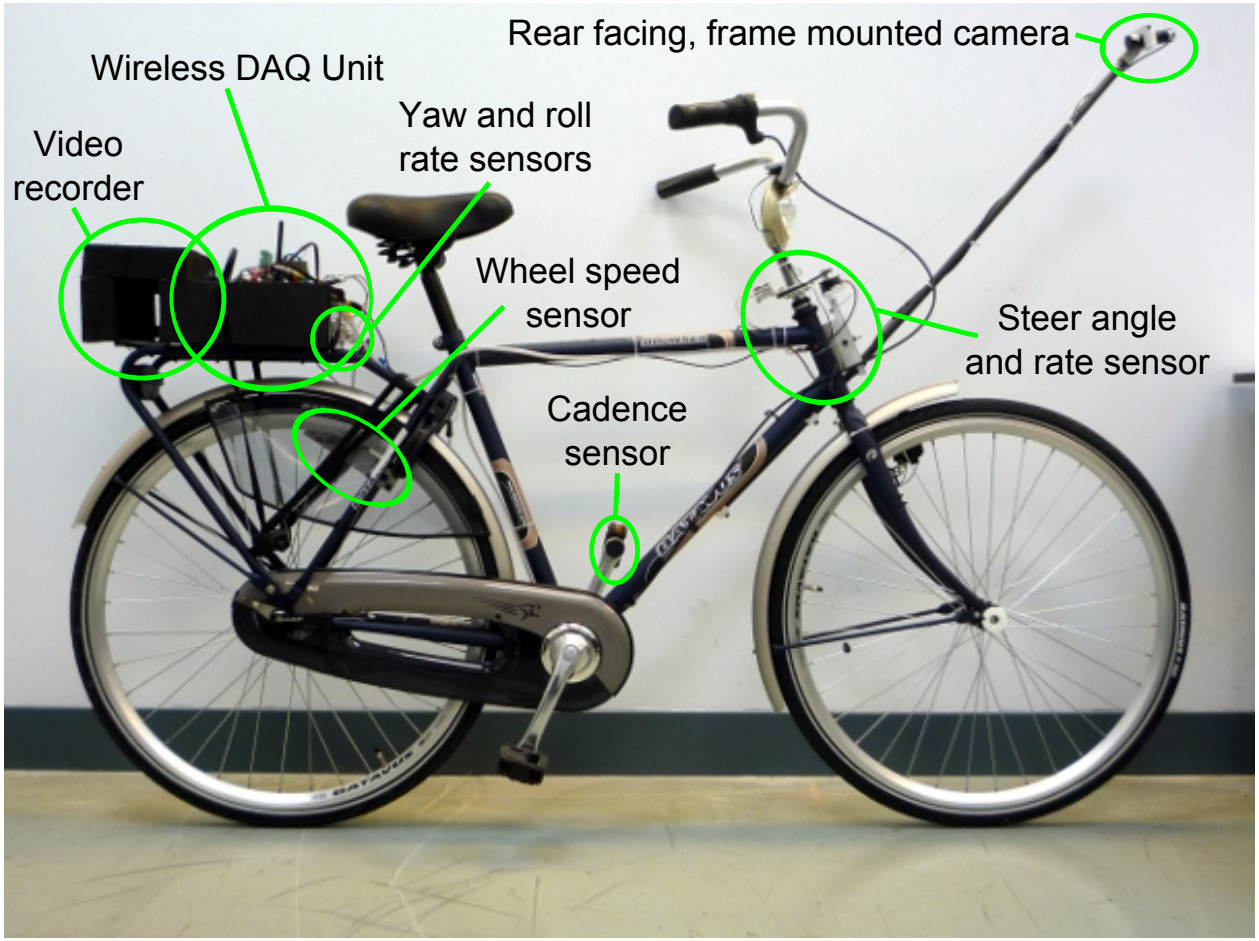
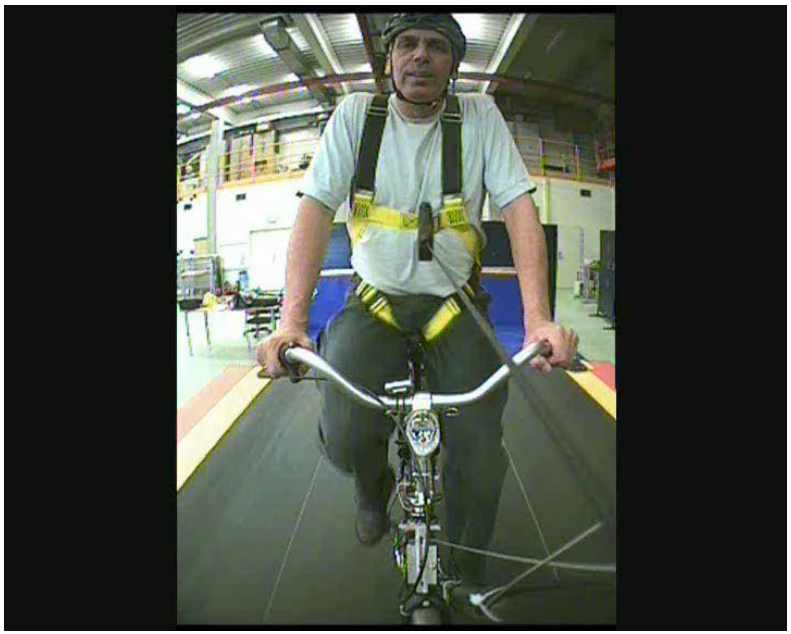
First step: objectively observe and measure what the rider does

The bicycle


Rear facing, frame mounted camera
Wireless DAQ Unit
Yaw and roll
rate sensors
Video
recorder
Wheel speed
sensor
Steer angle
and rate sensor
Cadence
sensor

Experiments

- Around the town ride



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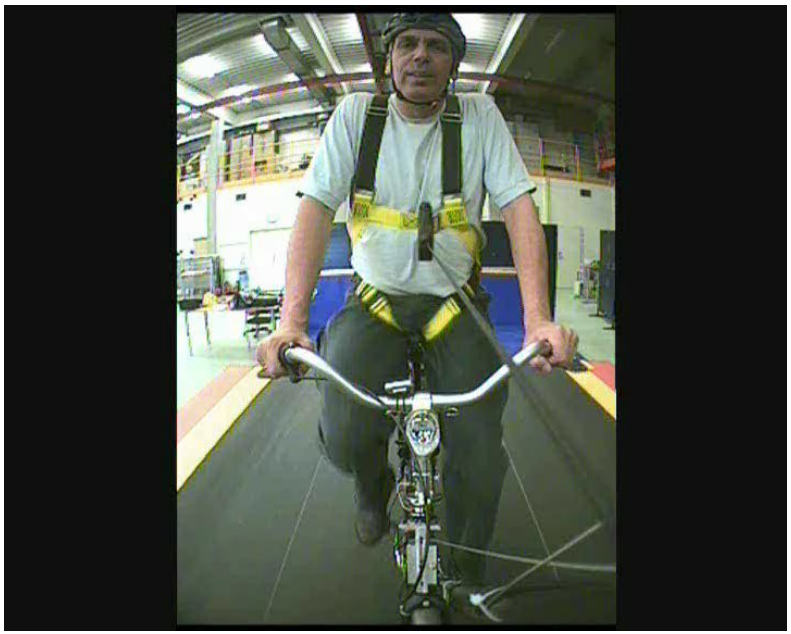

Experiments

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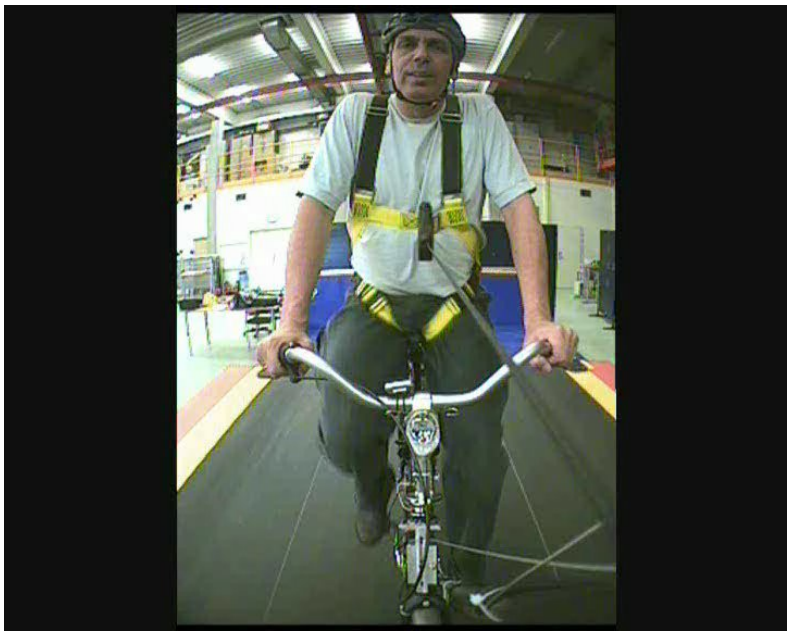
- Measured bicycle dynamics and observed rider



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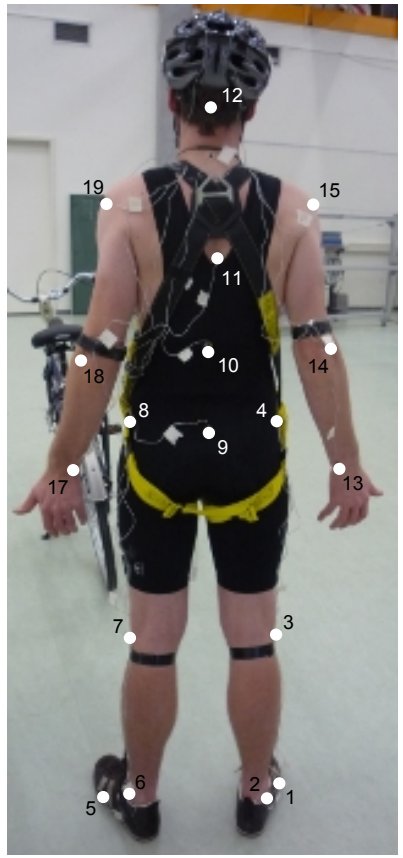
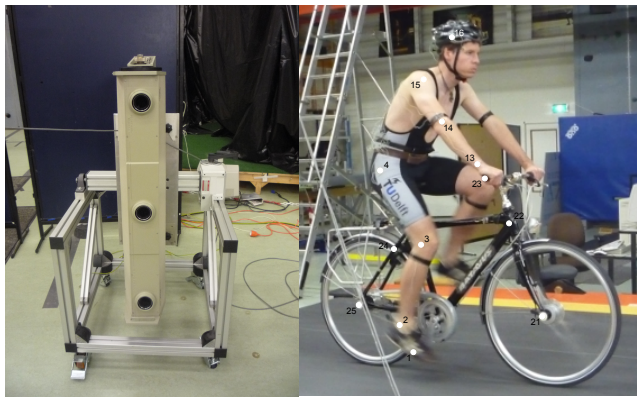
But, no easy way to quantify the rider's movements.

Experimental Setup

- Full body motion capture with active markers
- Two different bicycles and three adult male riders
- Treadmill tests (pedaling, no pedaling, no-hands, tracking) at different speeds





Principal component analysis

$$3 \text{ riders} \times 90 \frac{\text{runs}}{\text{rider}} \times 560,000 \frac{\text{data points}}{\text{run}} = 150 \cdot 10^6 \text{ data points}$$

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Principal Component Analysis!

- Statistical data reduction technique based on an eigenanalysis of data variance
- Used for face recognition, data compression, characterizing human walking
- Largest eigenvalue corresponds to largest variance in motion

PCA in a nutshell

$$\mathbf{P} = \begin{bmatrix} x_1 & \cdots & x_j & \cdots & x_n \\ y_1 & \cdots & y_j & \cdots & y_n \end{bmatrix}$$

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$$\mathbf{C} = \frac{1}{1-n}(\mathbf{P} - \overline{\mathbf{P}})(\mathbf{P} - \overline{\mathbf{P}})^T$$

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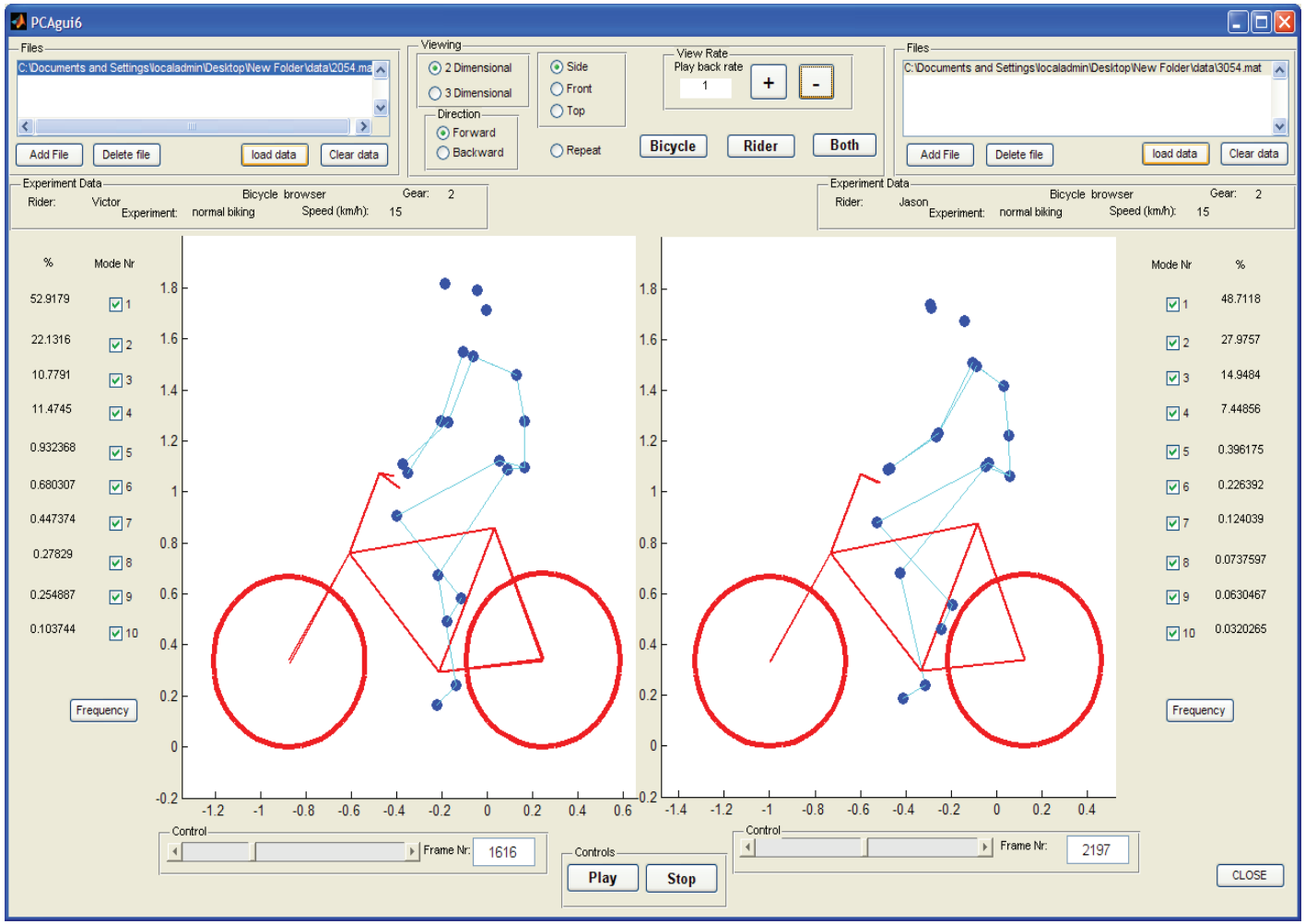
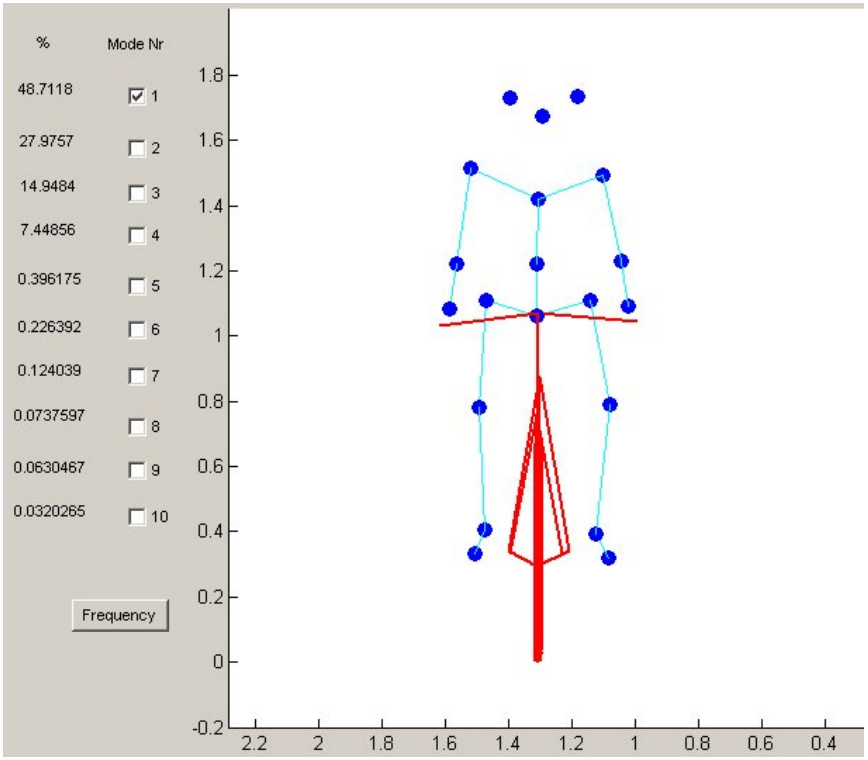
$$\begin{bmatrix} x_j \\ y_j \end{bmatrix} = \overline{\mathbf{u}} + a_{1j}\mathbf{v}_1 + a_{2j}\mathbf{v}_2$$

$\mathbf{v}_1$ and $\mathbf{v}_2$ are the eigenvectors of the covariance matrix, $\mathbf{C}$

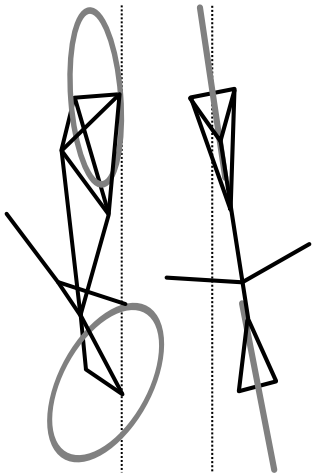
Graphical User Interface



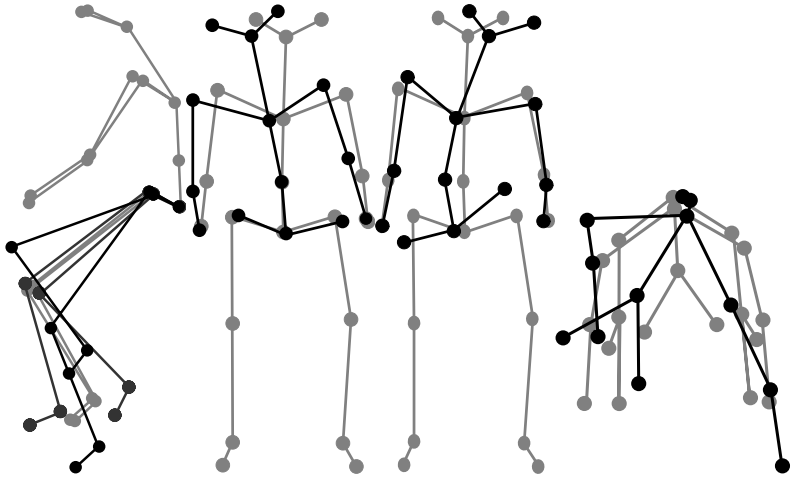
Normal bicycling at 15 km/h



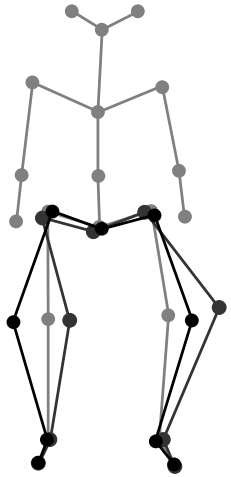
Motions and Groups



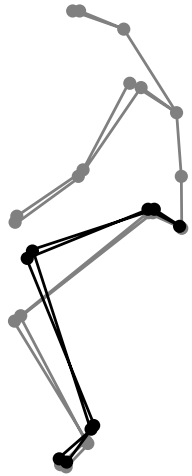
Steer-Roll-Yaw Group



Pedaling Group

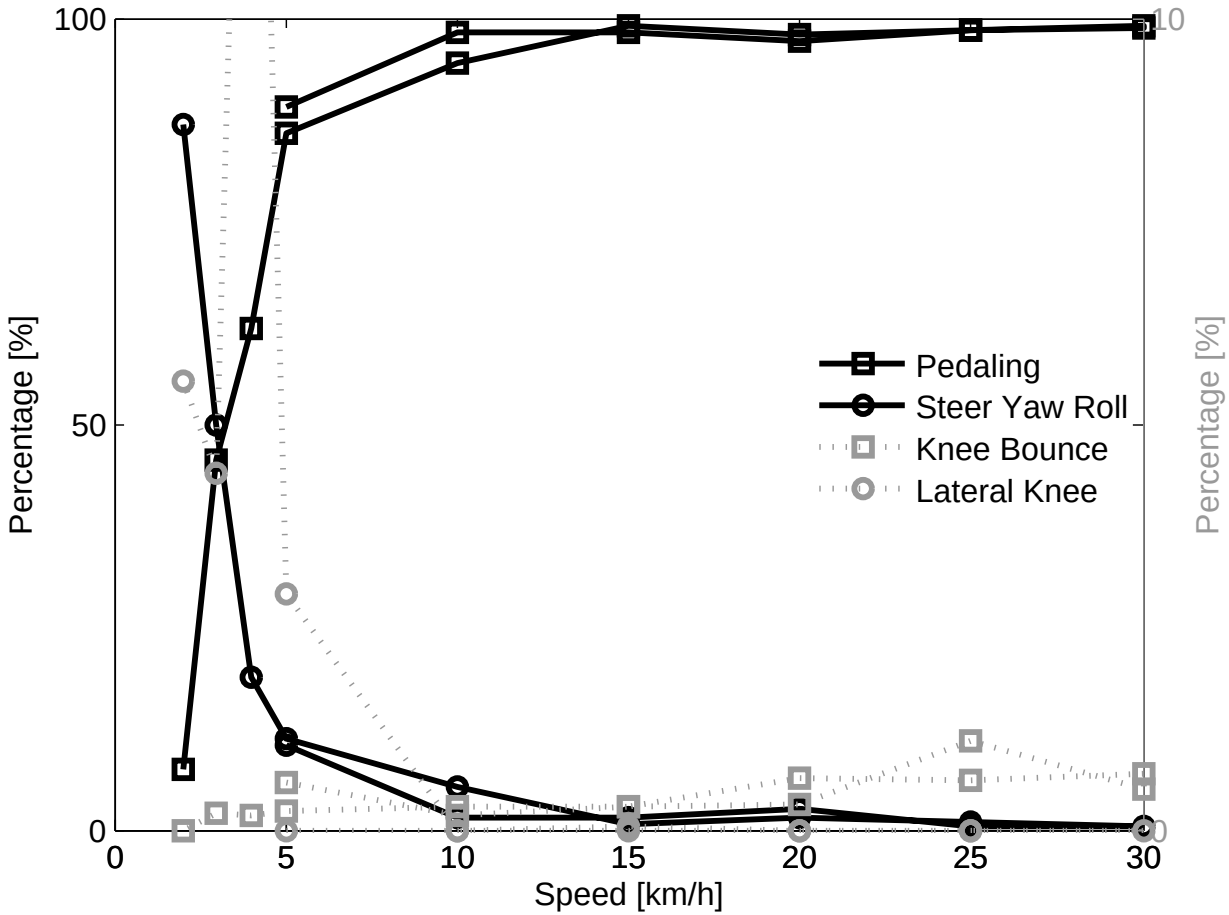


Lateral Knee Group

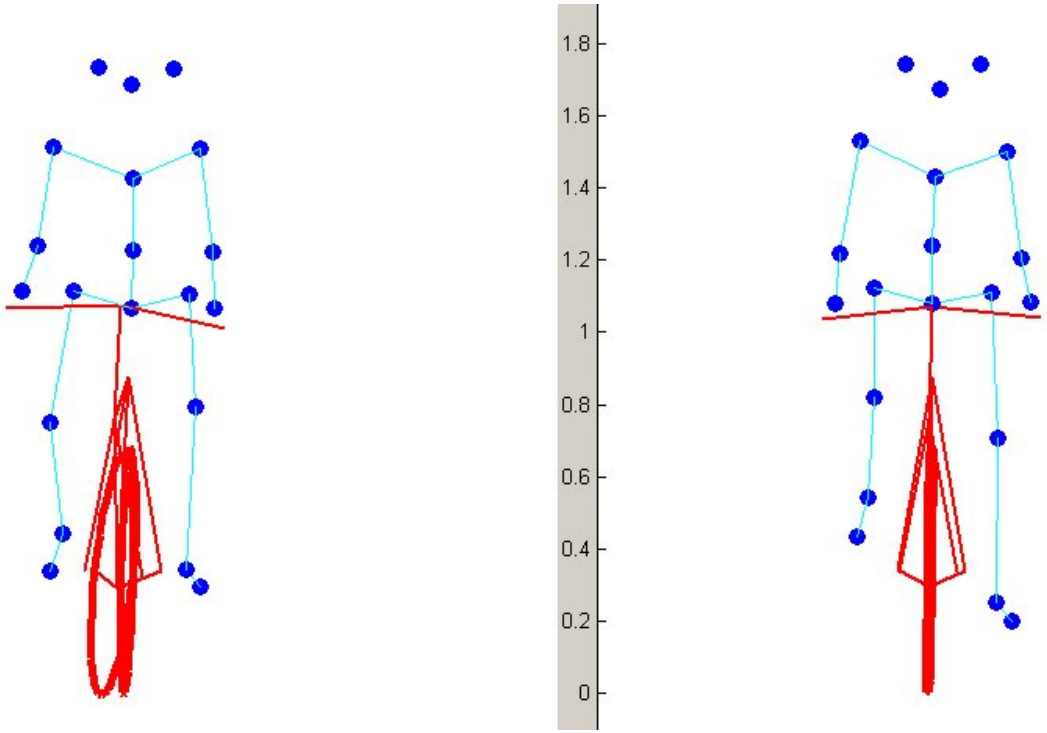


Knee Bounce Group

Group variance vs speed

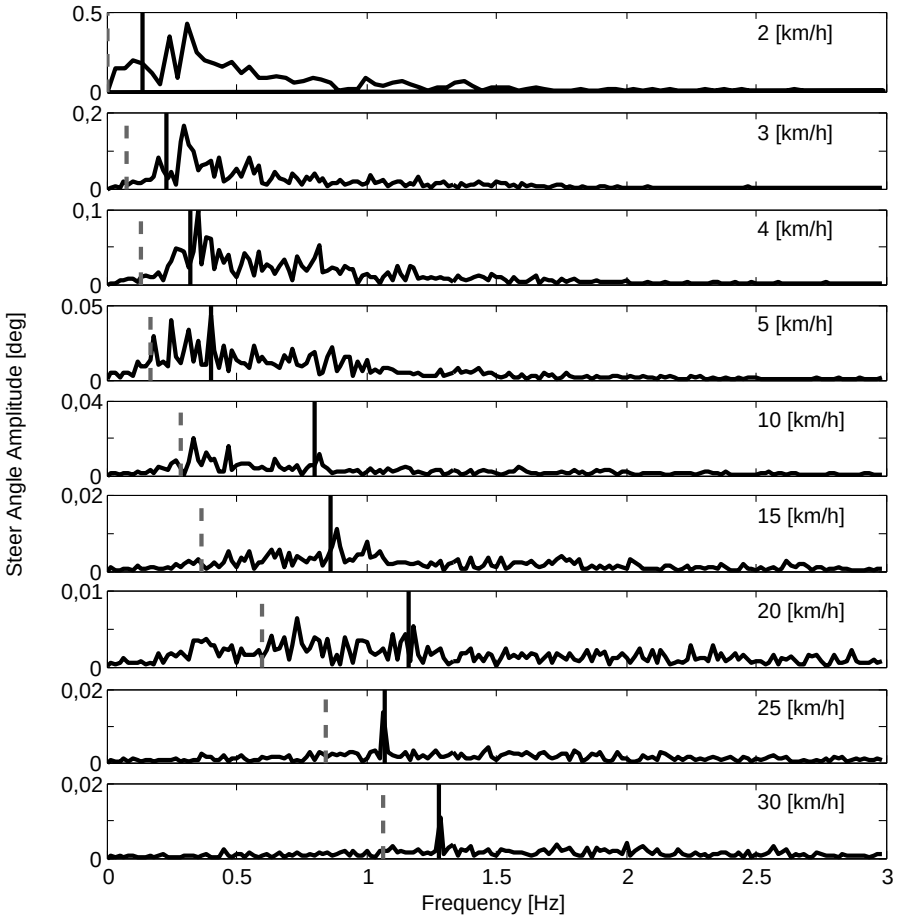


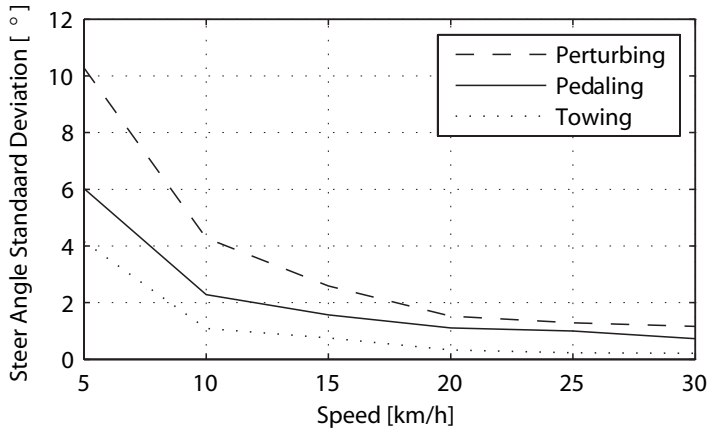
Normal bicycling at 5 km/h and 25 km/h



5 km/h and 25 km/h

Steer angle comparisons





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- We hypothesize that lateral control is mainly done by steering since we observed only upper body motion in the pedaling frequency.
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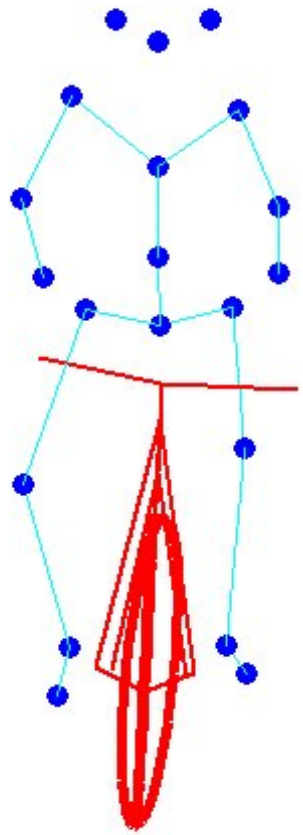
- When pedaling at low speed we observe lateral knee motions which are probably also used for control.

Conclusions

Bicycles present a rich complex and robust system to study

- vehicle dynamics (rolling contacts, variable stability)



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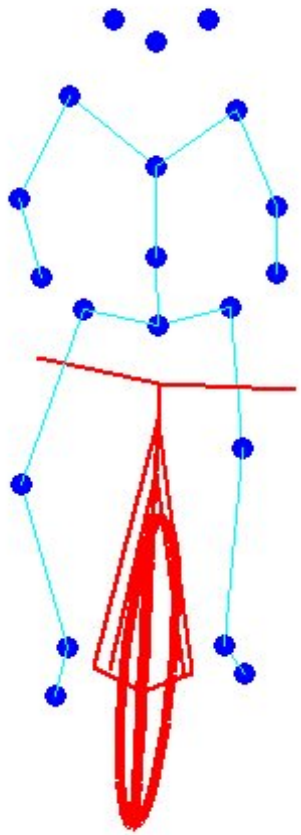

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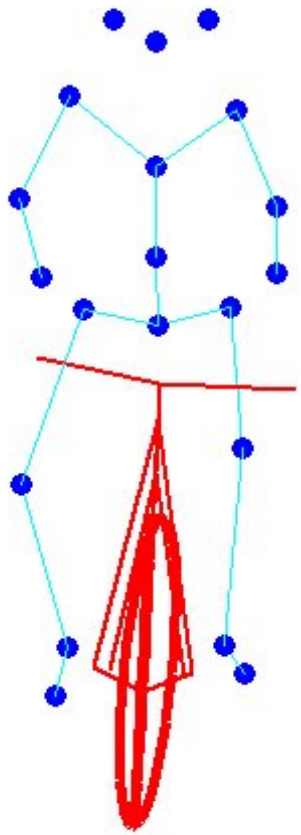

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- human control (stabilization + manuveuring)
- handling qualities (perception, psychology)