# RiSE Power Analysis

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March 23nd 2007

# Outline

Note: Some of the *Matlab* scripts that I used are courtesy of **G. Clark Haynes**.

1. Objective
2. Notations and models
3. Data Validation
4. Problems
5. Test Conditions
6. Results and Analysis
7. Results Summary
8. Future work

# 1. Question I

- Why can't RiSE climb faster?
  1. We have reached the limit of capability of the motors (torque, speed or power)
  2. Something else (for example, attachment at high climbing velocity not well understood)

Since the second point is hard to answer, let us make the hypothesis that RiSE motors reach their limits with the present operating conditions: gaits, gains and body.

# Question II

In which case/s, among the three possible regions in the figure to the right, are RiSE motors limited and, if they are, in which stride phase* does this occur?

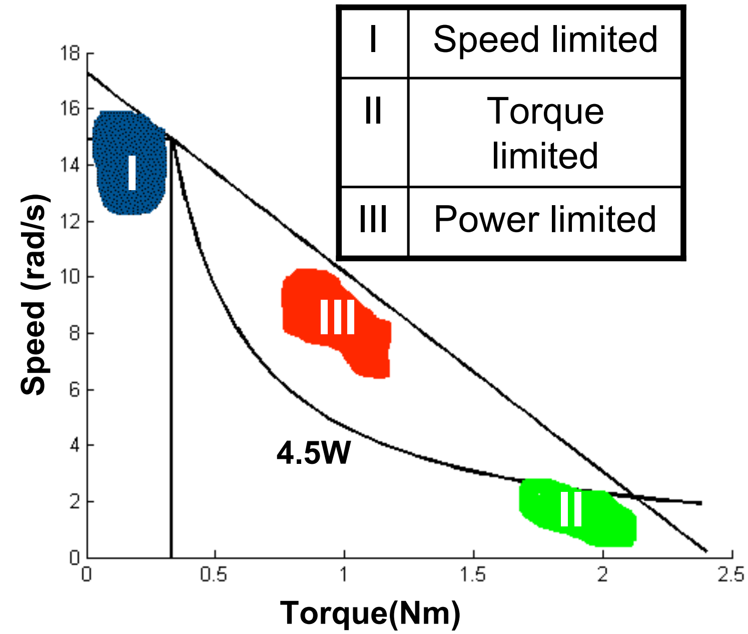



*Figure 1.* **Torque-Speed plot for RiSE DC Motor (Order #: 118730)**

- **A stride under analysis is divided into four phases: stance, detach, attach and flight. This notion will be explained in detail later.**

# Possible Motor Limitations

## I. Speed Limitation

If speed limitation happens, most likely it will occur in the flight retraction because of quick recovery motion of the leg to the initial stance position and because there is no load during this phase.

## II. Torque Limitation

Torque limitation will occur when the legs are on the ground, if it really happens,

## III. Power Limitation

Theoretically it could be in any phase (For example, large tracking error during flight)

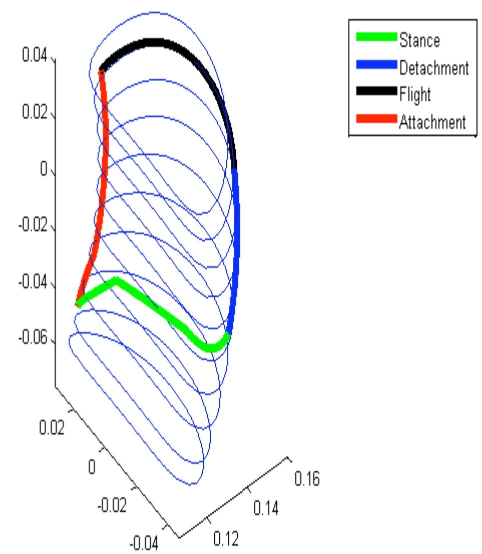
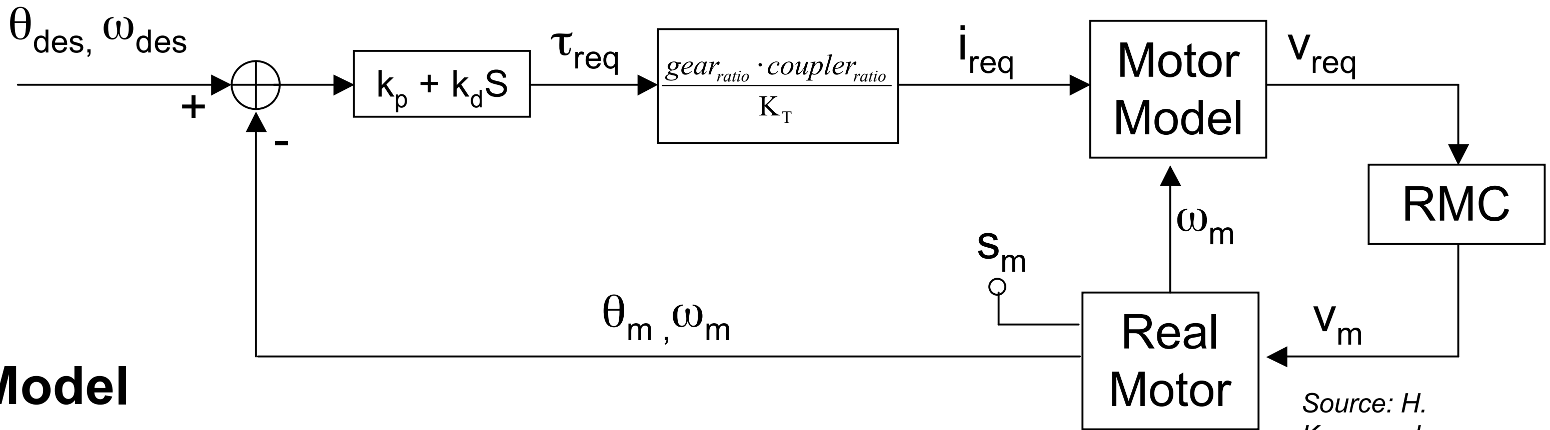



***Figure 2.*** **A 2-D leg trajectory of RiSE. The color black indicates when the leg is in the air, green, when it is on the ground, and blue and red when the leg is between them.**

# 2. Notation and model: *PD Controller and Motor Model*

## PD Controller




Source: H. Komsuoglu

## Motor Model

$$v_{req} = \frac{\omega_m}{K_\omega \cdot gear_{ratio} \cdot coupler_{ratio}} + i_{req} \cdot R_{term}$$

where

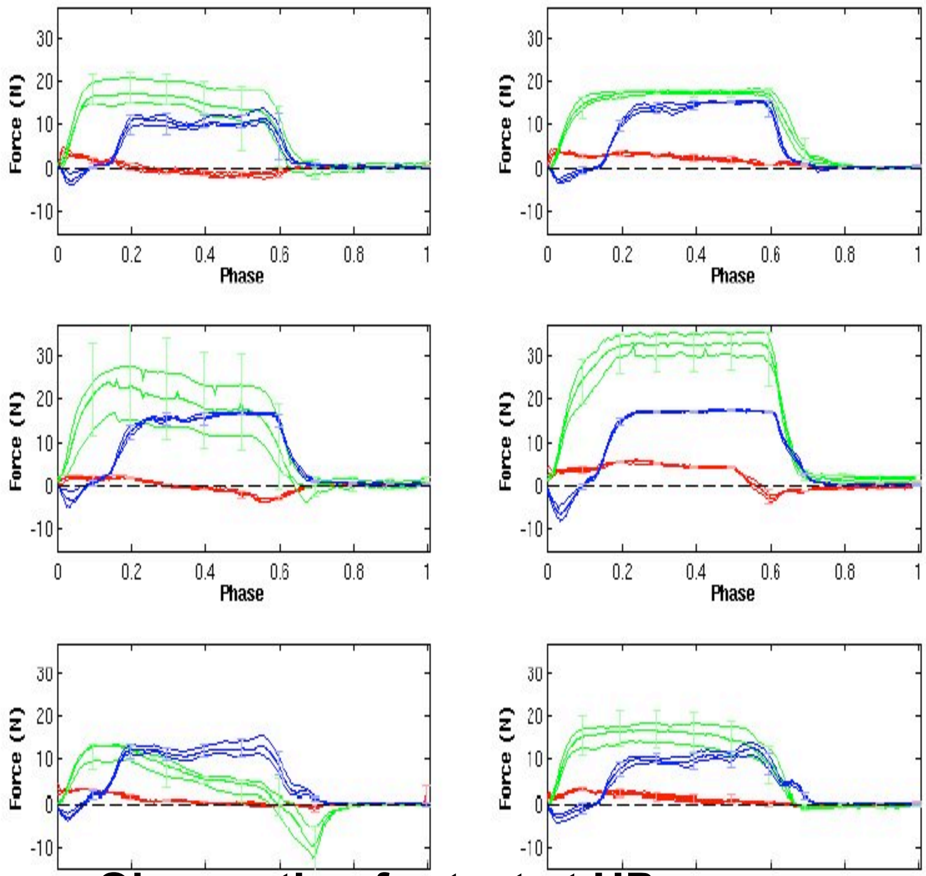
$$\omega_m = \pm 2\pi \cdot \frac{gear_{ratio} \cdot coupler_{ratio}}{encoder_{ratio}} \cdot \frac{\Delta encoder}{\Delta t}$$

| Nomenclature | Meaning |
|---|---|
| $\theta_{des}, \omega_{des}$ | Desired motor position and velocity |
| $k_p, k_d$ | Proportional and derivative gains |
| $\tau_{req}$ | Required torque |
| $i_{req}$ | Required motor current |
| $v_{req}$ | Required motor voltage |
| $v_m$ | Measured terminal voltage |
| $s_m$ | Measured (sensed) motor current |
| $\theta_m, \omega_m$ | Measured motor position and velocity |
| $K_T, K_\omega$ | Torque and speed constant |
| $R_{term}$ | Terminal Resistance |

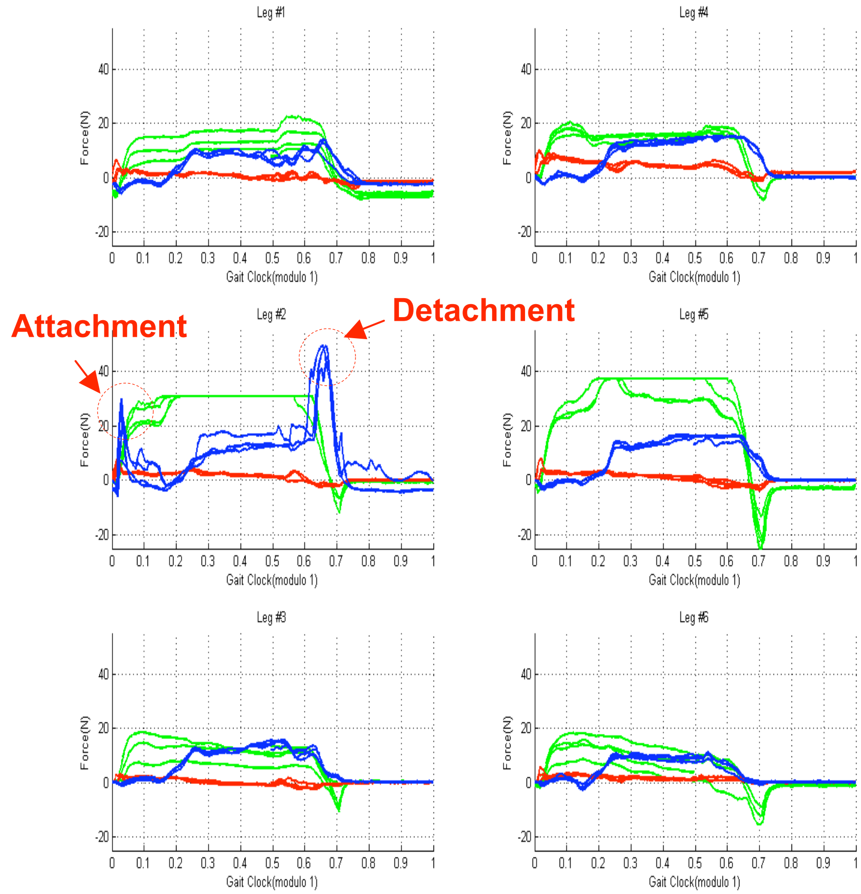
# 3. Data Validation: *Lateral*, *Normal*, *Traction* *Force Data* *(1/2)*

## "GOOD" RUN

**From SwRI tests (April 2006) at 0.97Hz (stride speed)**
**(robotA_carpet_90_run_1_sow_1_060405_040505.mat)**




**Test at UPenn (March 2007) with April 2006 .rc files**
**(Experiment id: exp_070312_174035) at 0.5hz**




**time interval: 0-7sec**

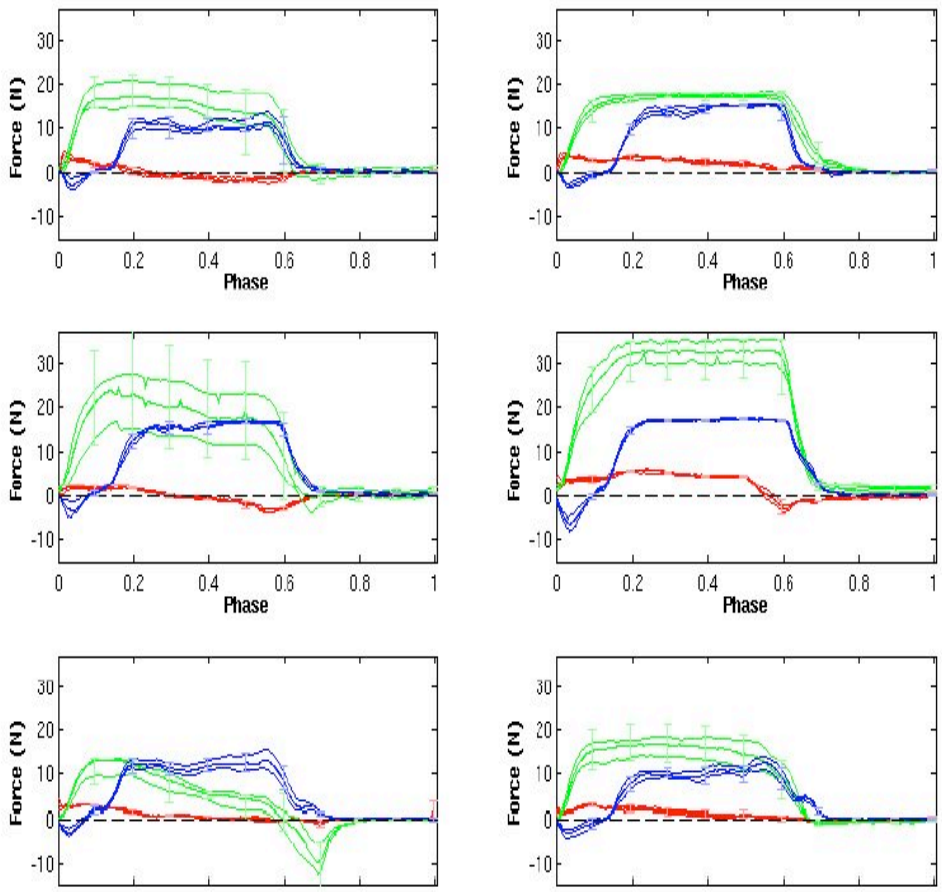
**Observation for test at UPenn:**

- **Overall force data is smooth for all 6 legs**
- **Attachment and detachment problem with leg #2**
- **Significant negative lateral force at leg #5**

# Data Validation: *Lateral*, *Normal*, *Traction* *Force Data* *(2/2)*

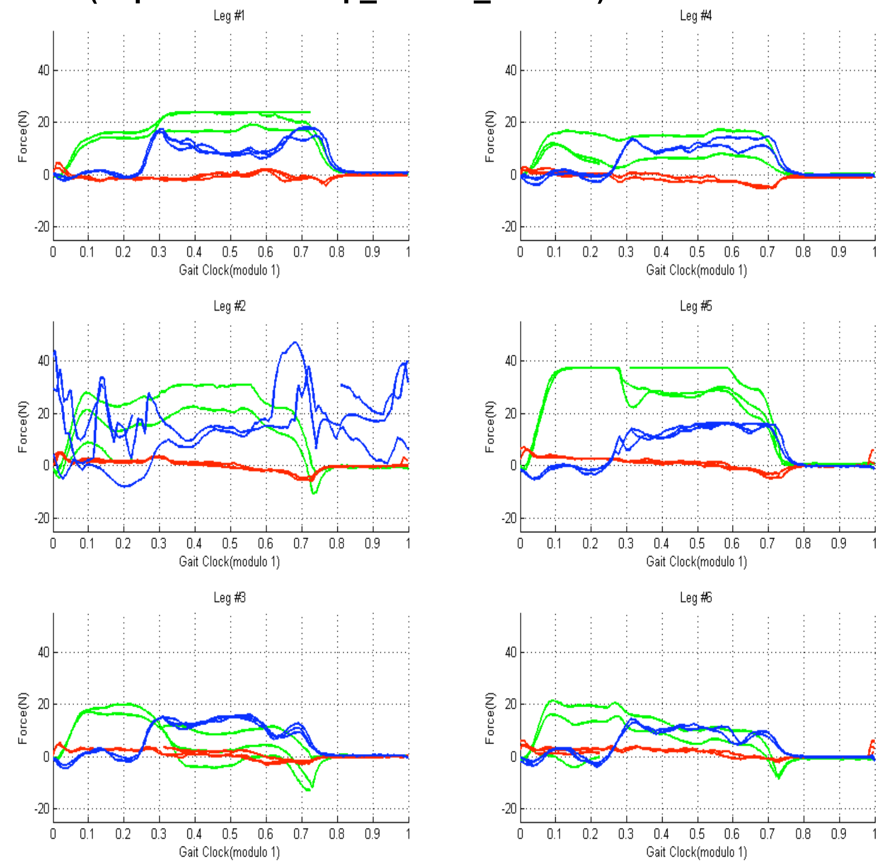
**“GOOD” RUN**

**From SwRI tests (April 2006) at 0.97Hz (stride speed)**
**(robotA_carpet_90_run_1_sow_1_060405_040505.mat)**




**Test at UPenn (March 2007) with September 2006 .rc files**

**(Experiment id: exp_070314_074931 ) at 0.8hz**



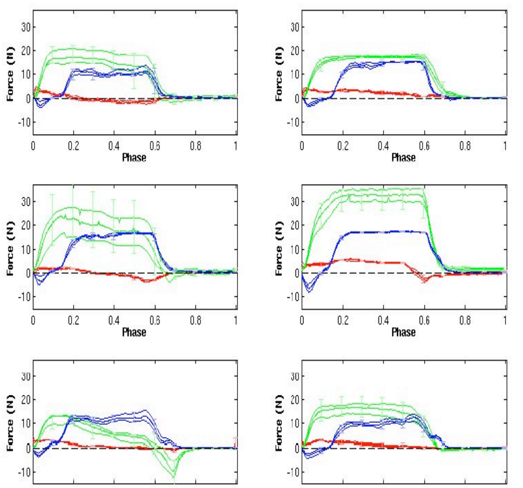

**time interval: 1.4-4.4sec**

**Observation for test at UPenn:**

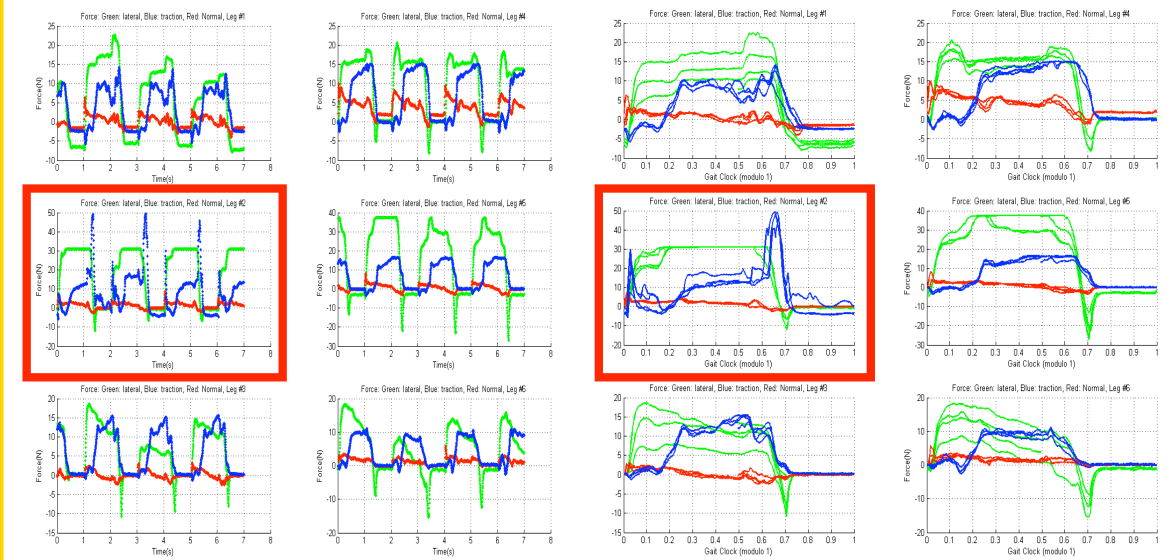
- **Overall force data is smooth for all 6 legs**
- **Bad performance of leg #2**

# 4. Problem : *Bad force data from the leg #2*

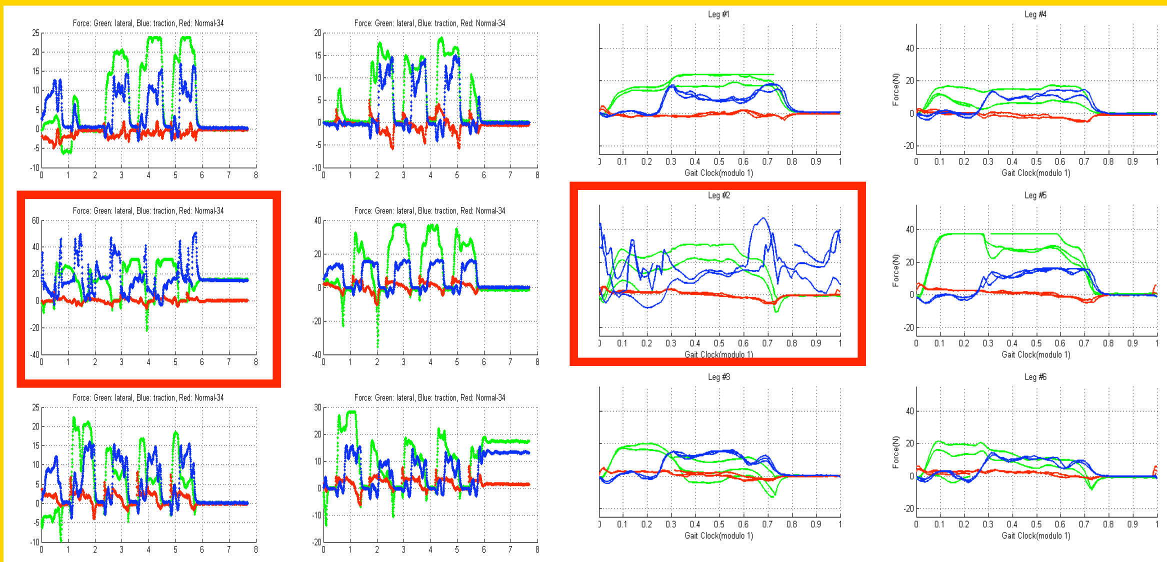
**SwRI Test**




**Stride Speed: 0.5hz**




**Stride Speed: 0.8hz**




**Problem:**

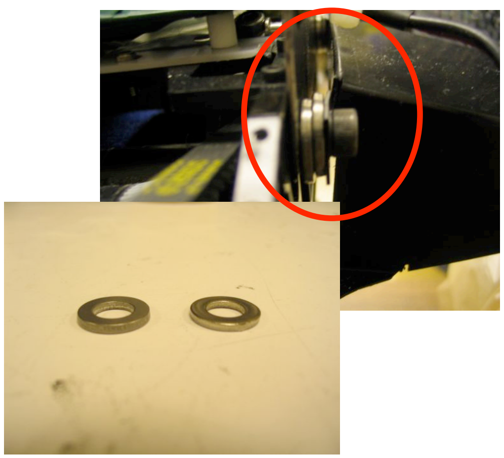
Bad attachment and detachment of leg #2.

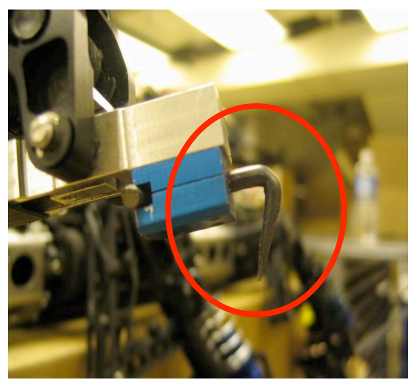
**Tested:**

Changed dactyls, carpet and wing offset but, the problem is still not solved.

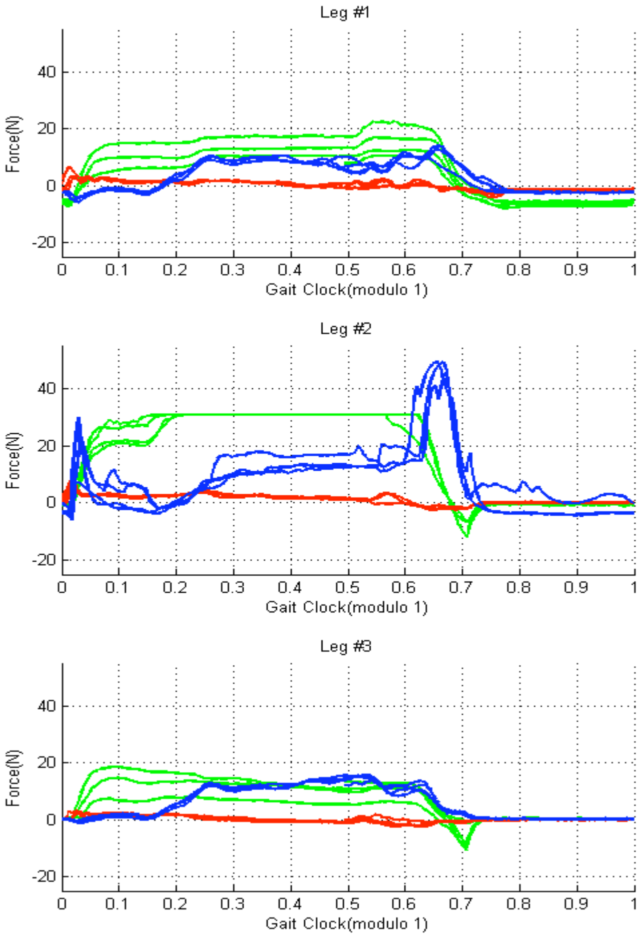
# 5. Test Conditions

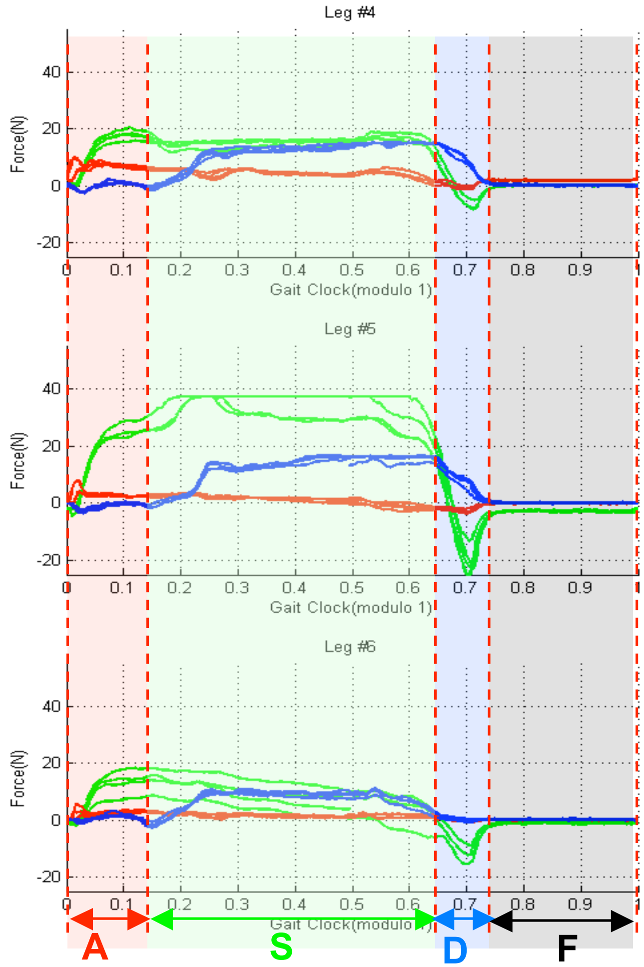
- Test bed: **Carpet with small loops**
- Behavior & gait: **Carpet Mode Tripod gait**
- Leg trajectories & clock maps: **April 2006 & Sept.2006**
- Stride speeds: **0.5Hz & 0.8Hz**
- Other considerations: **two washers in the tail joint, short dactyls suitable for carpet climbing**

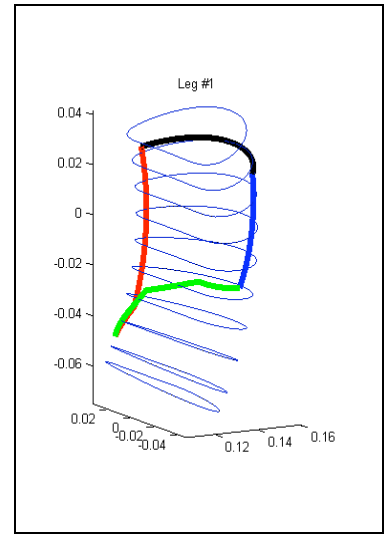




# Assumption I: *Gait Section Labeling for 0.5Hz*




| Gait Sections |
|---|
| Stance |
| Detach |
| Flight |
| Attach |

From ***carpet_tripod1_90.rc(old*)***,

- Stance: 0.00 - 0.68
- Detach: 0.68 – 0.77
- Flight: 0.77 – 0.96
- Attach: 0.96 – 1.00

***From several force data plots,***

- Stance: 0.15 - 0.65
- Detach: 0.65 – 0.74
- Flight: 0.74 – 1.00
- Attach: 0.00 – 0.15

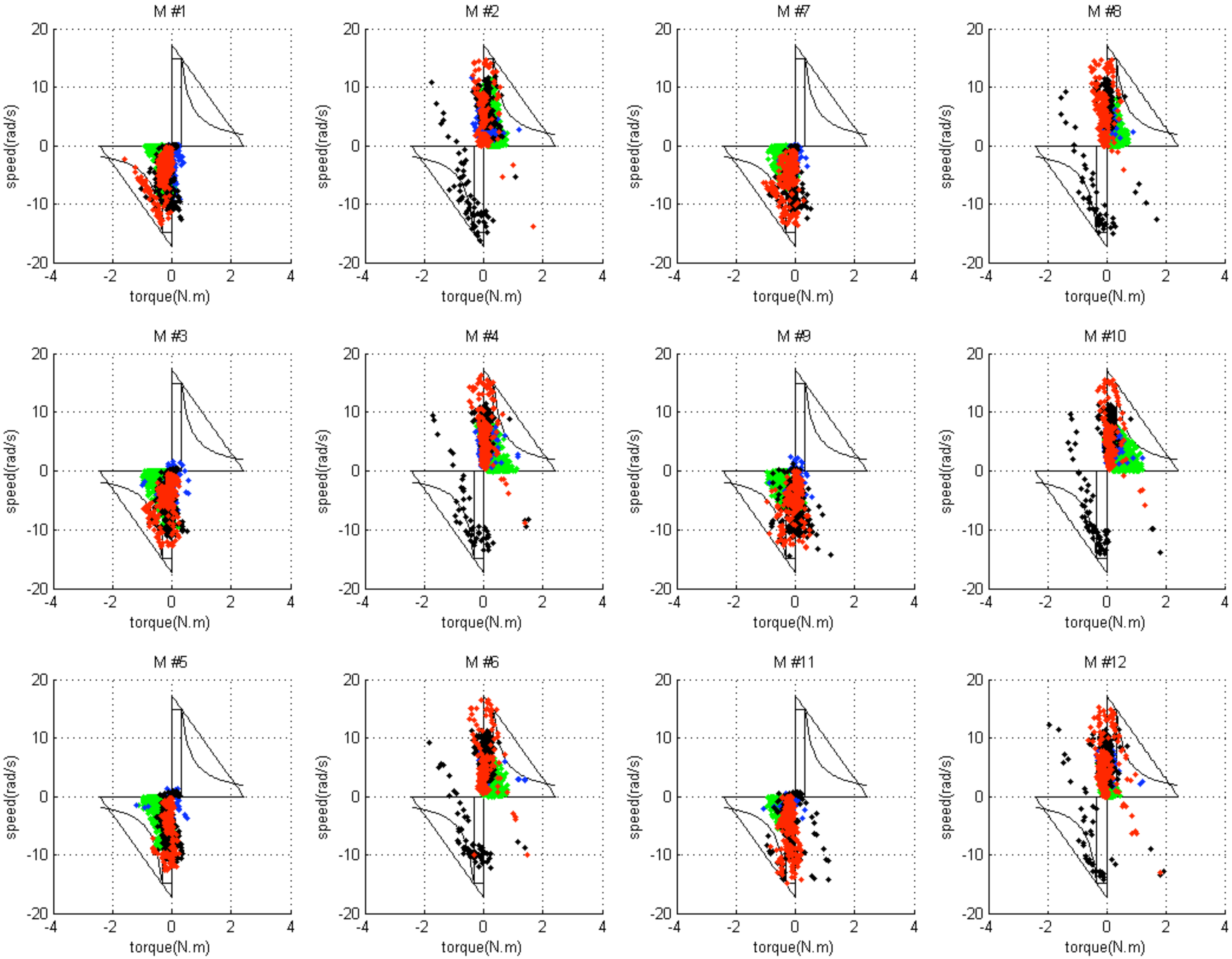
*. April 2006 .rc files

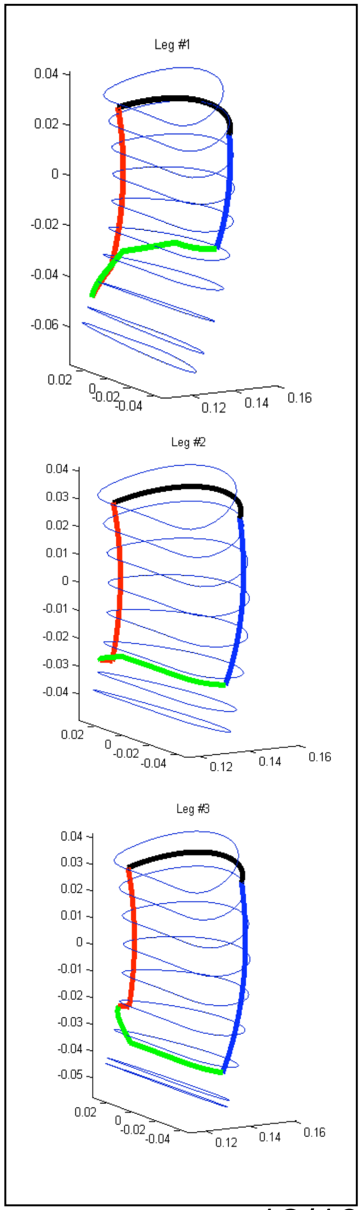
# 6. Results I: *Raw Torque-Speed Samples*

0.5Hz

| Gait Sections | Stance | Detach | Flight | Attach |
|---|---|---|---|---|

**Experiment id: exp_070312_174035 at 0.5hz**

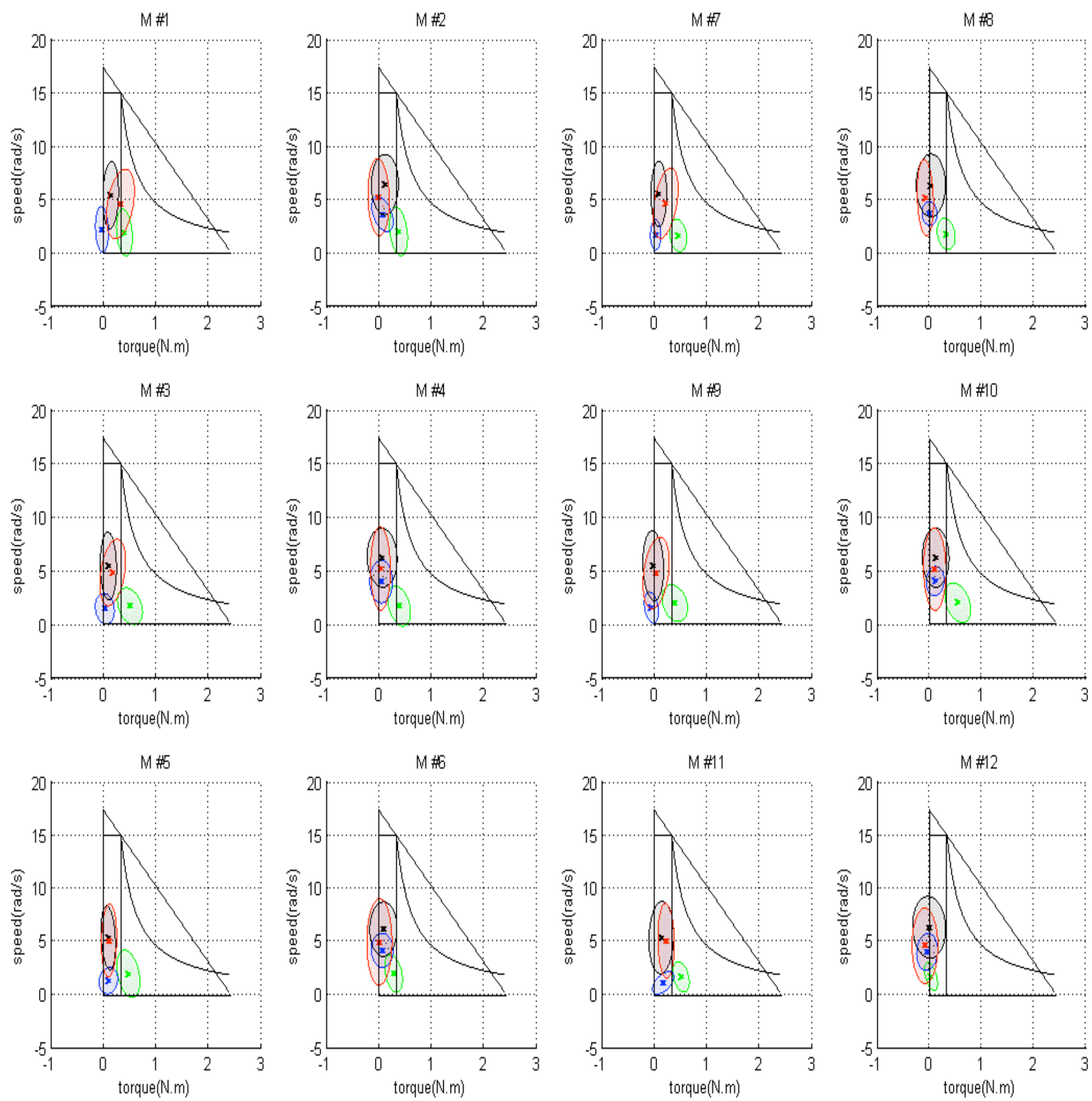


# Results II: *Torque-Speed Ellipses*

0.5Hz

| Gait Sections | Stanc e | Detac h | Flight | Attac h |
|---|---|---|---|---|




**Experiment id: exp_070312_174035 at 0.5hz**

## Specification for RiSE motors

| | |
|---|---|
| No Load Speed (rad/s) | 17.268 |
| Nominal Speed (rad/s) | 14.9 |
| Stall Torque (Nm) | 2.4277 |
| Nominal Torque (Nm) | 0.33296 |

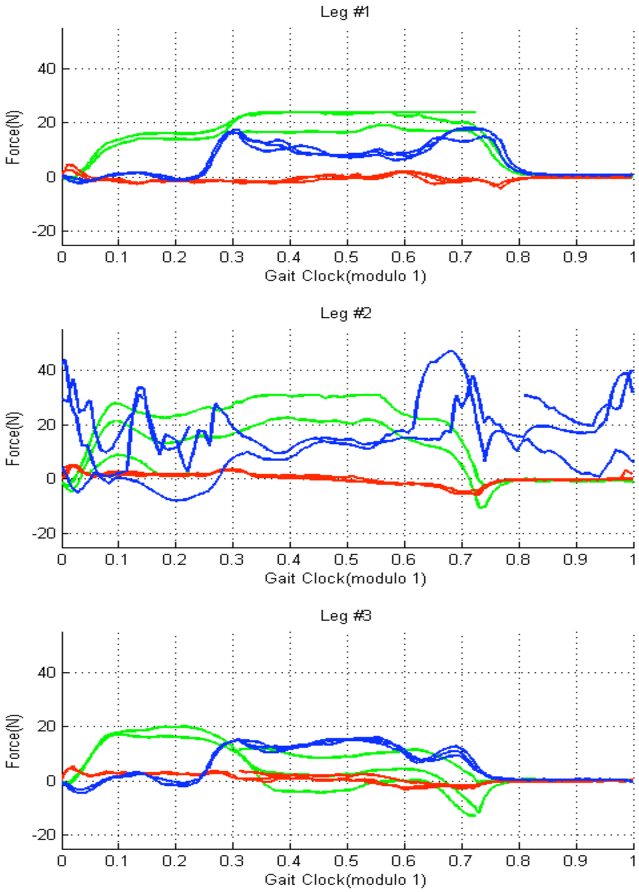
(after gearbox)

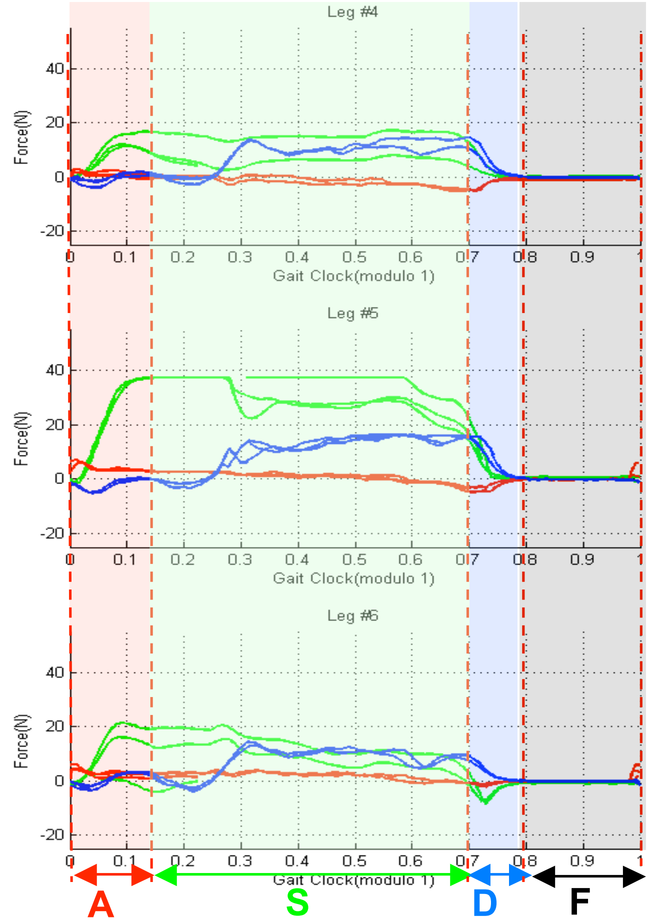
## Results: Average of means

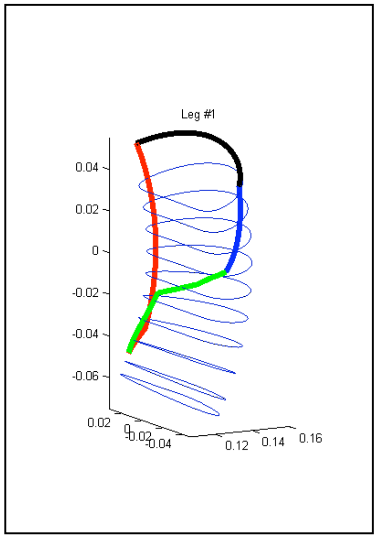
| | Mean Torque (Nm) | Mean Speed (rad/s) |
|---|---|---|
| Attach | 0.0887 | 4.9312 |
| Stance | **0.3892** | 1.8449 |
| Detach | 0.0409 | 2.7391 |
| Flight | 0.0785 | **5.8348** |

# **Assumption II:** *Gait Section Labeling*

0.8Hz




| Gait Sections |
|---|
| Stance |
| Detach |
| Flight |
| Attach |

From ***carpet_tripod1_90.rc(new*),***

- Stance: 0.00 – 0.68
- Detach: 0.68 – 0.77
- Flight: 0.77 – 0.90
- Attach: 0.90 – 1.00

***From several force data plots,***

- Stance: 0.15 – 0.70
- Detach: 0.70 – 0.80
- Flight: 0.80 – 1.00
- Attach: 0.00 – 0.15

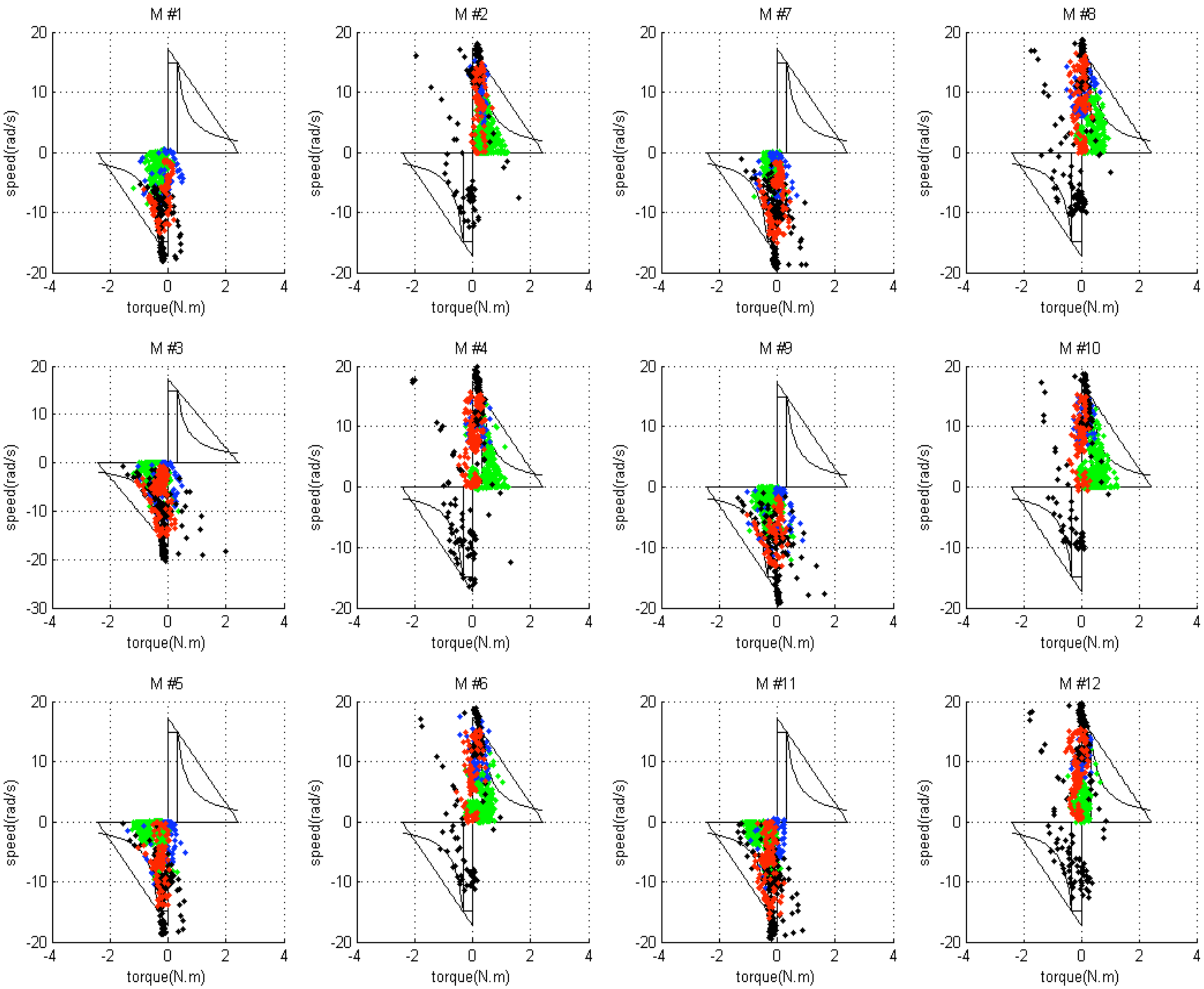
*. September 2006 .rc files

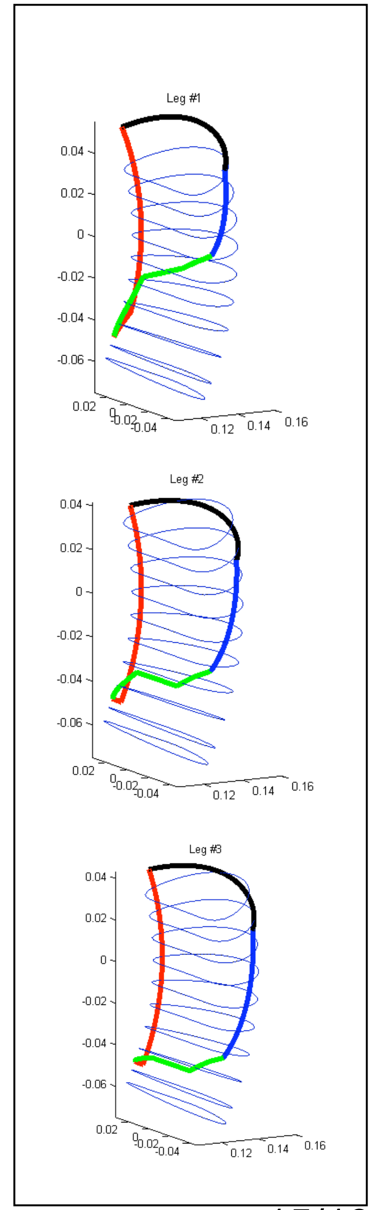
# **Results III:** *Raw Torque-Speed Samples*

0.8Hz

| Gait Sections | Stanc<br>e | Detac<br>h | Flight | Attac<br>h |
|---|---|---|---|---|

**Experiment id: exp_070314_074808 at 0.8hz**

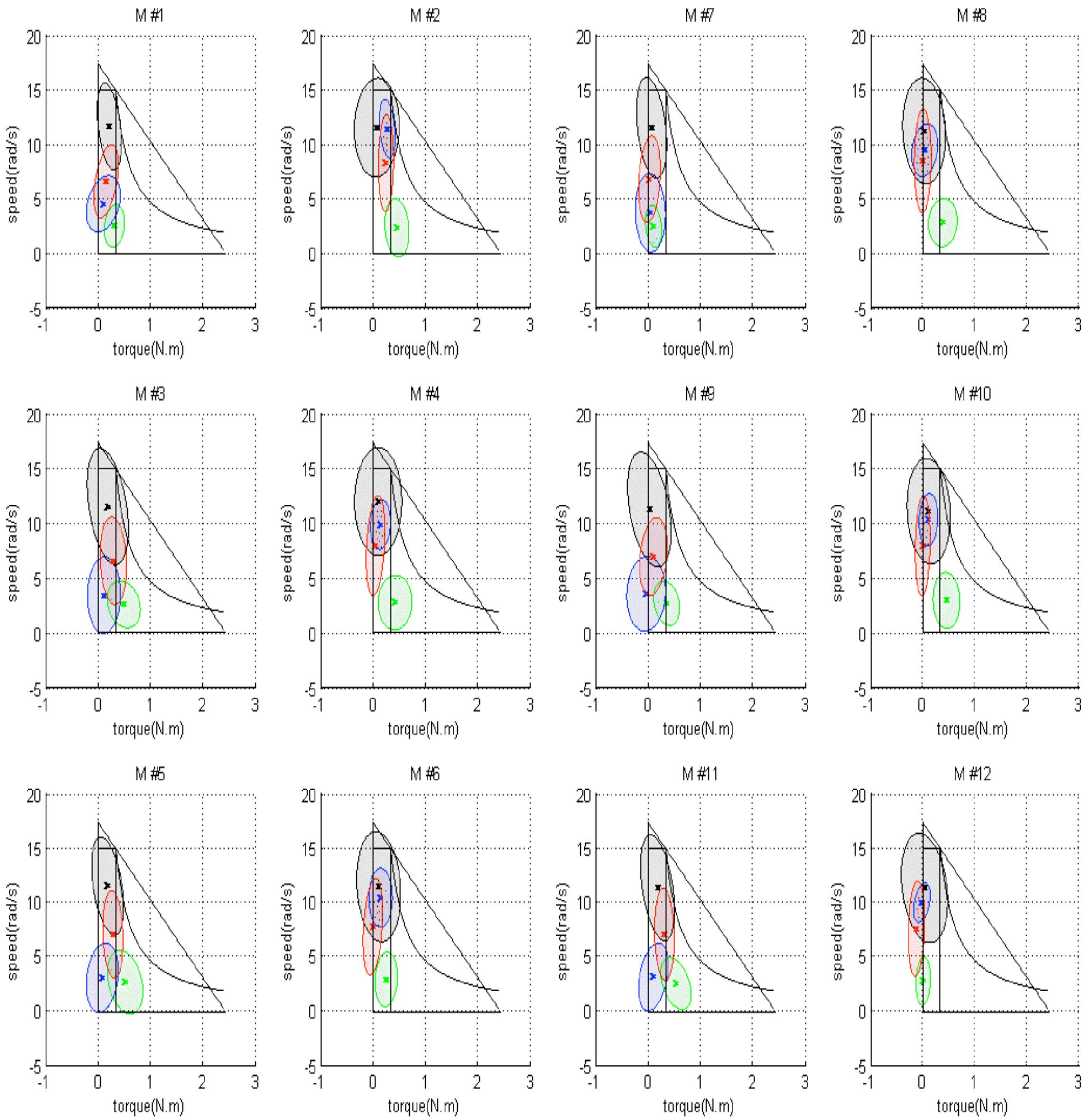


# **Results IV:** *Torque-Speed Ellipses*

0.8Hz

| Gait Sections | Stance | Detach | Flight | Attach |
|---|---|---|---|---|




**Experiment id: exp_070314_074808 at 0.8hz**

## Specification for RiSE motors

| | |
|---|---|
| No Load Speed (rad/s) | 17.268 |
| Nominal Speed (rad/s) | 14.9 |
| Stall Torque (Nm) | 2.4277 |
| Nominal Torque (Nm) | 0.33296 |

(after gearbox)

## Results: Average of means

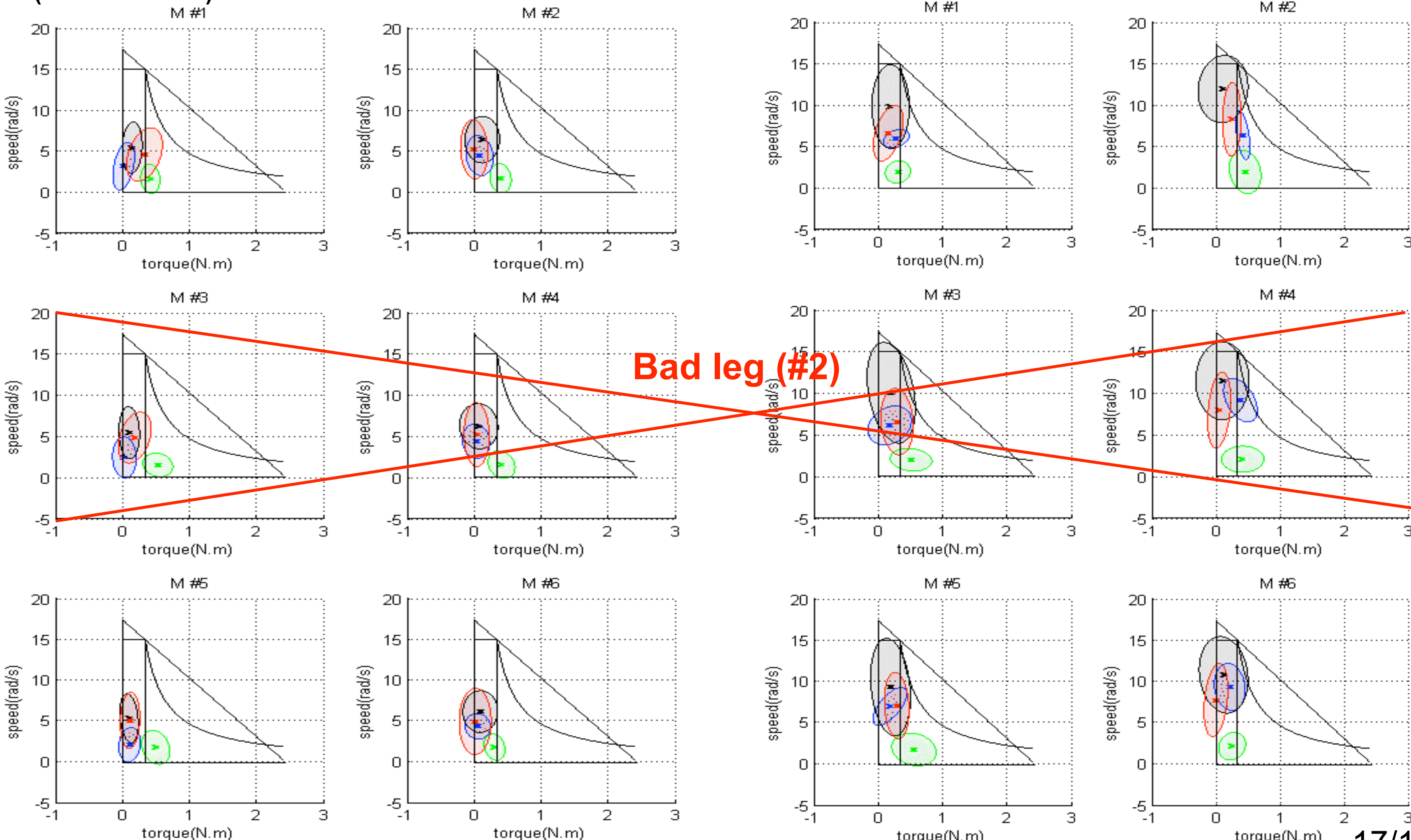
| | Mean Torque (Nm) | Mean Speed (rad/s) |
|---|---|---|
| Attach | 0.1092 | 7.4092 |
| Stance | **0.3541** | 2.6882 |
| Detach | 0.0881 | 6.9021 |
| Flight | 0.1064 | **11.4080** |

# Results V: *Comparison 0.5Hz & 0.8Hz (I)*

| Gait Sections | Stance | Detach | Flight | Attach |
|---|---|---|---|---|

**Experiment id: exp_070312_174035 at 0.5hz (First 6 motors)**

**Experiment id: exp_070314_074808 at 0.8hz (First 6 motors)**



# **Results V:** *Comparison 0.5Hz & 0.8Hz (II)*

**Specification for RiSE motors**

| | |
|---|---|
| No Load Speed (rad/s) | 17.268 |
| Nominal Speed (rad/s) | 14.9 |
| Stall Torque (Nm) | 2.4277 |
| Nominal Torque(Nm) | 0.33296 |

**Results: Average of means**

| | Mean Torque (Nm) | Mean Speed (rad/s) |
|---|---|---|
| Attach | 0.0887 | 4.9312 |
| Stance | **0.3892** | 1.8449 |
| Detach | 0.0409 | 2.7391 |
| Flight | 0.0785 | **5.8348** |

**0.5Hz**

| | Mean Torque (Nm) | Mean Speed (rad/s) |
|---|---|---|
| Attach | 0.1092 | 7.4092 |
| Stance | **0.3541** | 2.6882 |
| Detach | 0.0881 | 6.9021 |
| Flight | 0.1064 | **11.4080** |

**0.8Hz**

# 7. Results Summary

1. For both stride speeds 0.5Hz and 0.8Hz, the largest value of torque is achieved during stance.
2. For both stride speeds 0.5Hz and 0.8Hz, the largest value of speed is achieved during flight.
3. Increasing stride speed from 0.5Hz to 0.8Hz, the motor speed during flight phase is approximately doubled from its initial mean value.
4. This increment of stride speed does not seem to increase stance torque in general.
5. Among the three possible motor limitations, so far, we only could see the motor speed limitation case.

# 8. Future work

1. Verify the obtained results increasing the stride speed.
2. Find out a way, if there is any, to provoke all three possible motor limitations.

Questions ?

# Back up

# Knowledge II: *Current measurement calibration*

**Model:** $i_m = s_m - o_m$

**$i_m$**: calibrated measured current
**$s_m$**: measured current
**$o_m$**: current offset

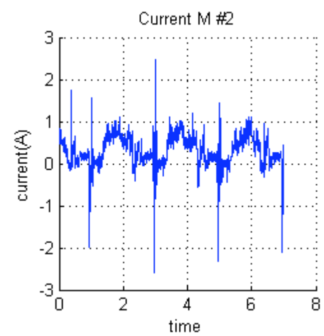
## Calibration Procedure

- Before **each run**, for **each of the twelve motors**, measure current with all motors disabled ($s_m$).
- Using the model on the right, compensate the current offset ($o_m = s_m$, under this condition)

| | Before | After | Avg. |
|---|---|---|---|
| M #1 | 0.2130 | 0.2074 | 0.2102 |
| M #2 | 0.2406 | 0.2363 | 0.2384 |
| M #3 | -0.0346 | -0.0409 | -0.0377 |
| M #4 | 0.1422 | 0.1370 | 0.1396 |
| M #5 | -0.0149 | -0.0209 | -0.0179 |
| M #6 | 0.1333 | 0.1248 | 0.1290 |
| M #7 | 0.1700 | 0.1641 | 0.1670 |
| M #8 | 0.2261 | 0.2202 | 0.2231 |
| M #9 | 0.0564 | 0.0514 | 0.0539 |
| M #10 | 0.1867 | 0.1814 | 0.1841 |
| M #11 | 0.0069 | 0.0025 | 0.0047 |
| M #12 | 0.1513 | 0.1439 | 0.1476 |

## Importance of calibration

1. Current offset ~10% of peak current

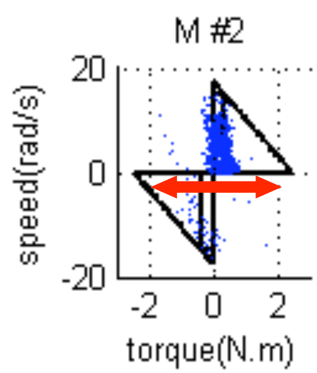


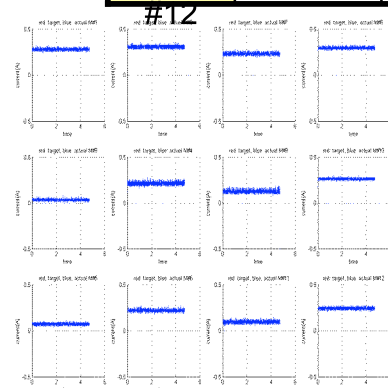

**Typical current data when RiSE climbs carpet wall**

2. Calibration affects torque values

$$\tau_m = \frac{K_T}{gear_{ratio}}\left[s_m + o_m\right]$$

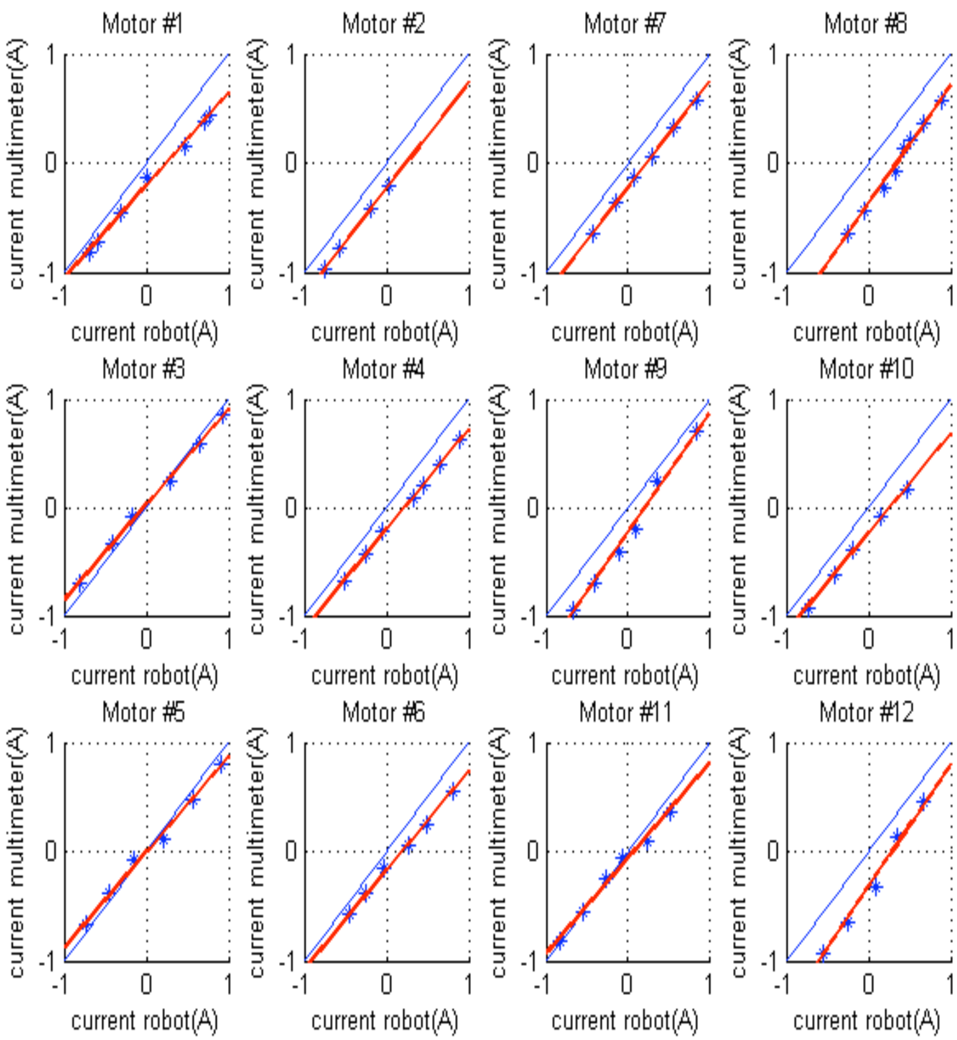
where $\tau_m$ is measured (computed) torque, $K_T$ is torque constant.



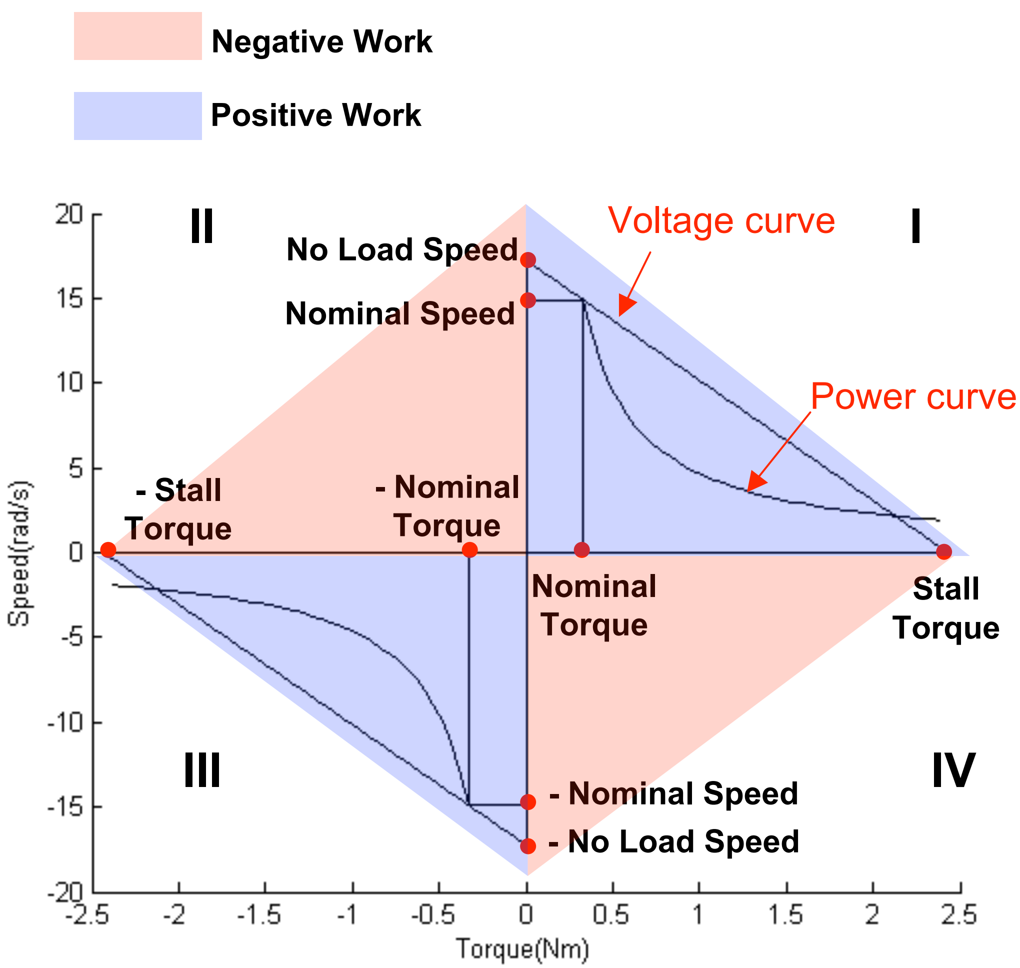
**Typical current offsets when the motors are disabled**

# Comparison between a multimeter reading and built-in current sensor




| | scaling | offset |
|---|---|---|
| Motor #1 | 0.8452 | -0.2089 |
| Motor #2 | 0.9765 | -0.2412 |
| Motor #3 | 0.8775 | 0.0202 |
| Motor #4 | 0.9222 | -0.2071 |
| Motor #5 | 0.8705 | -0.0104 |
| Motor #6 | 0.9069 | -0.1744 |
| Motor #7 | 0.9705 | -0.2290 |
| Motor #8 | 1.0930 | -0.3789 |
| Motor #9 | 1.0937 | -0.2350 |
| Motor #10 | 0.9151 | -0.2407 |
| Motor #11 | 0.8691 | -0.0642 |
| Motor #12 | 1.1229 | -0.3272 |

# Introduction to torque – speed analysis



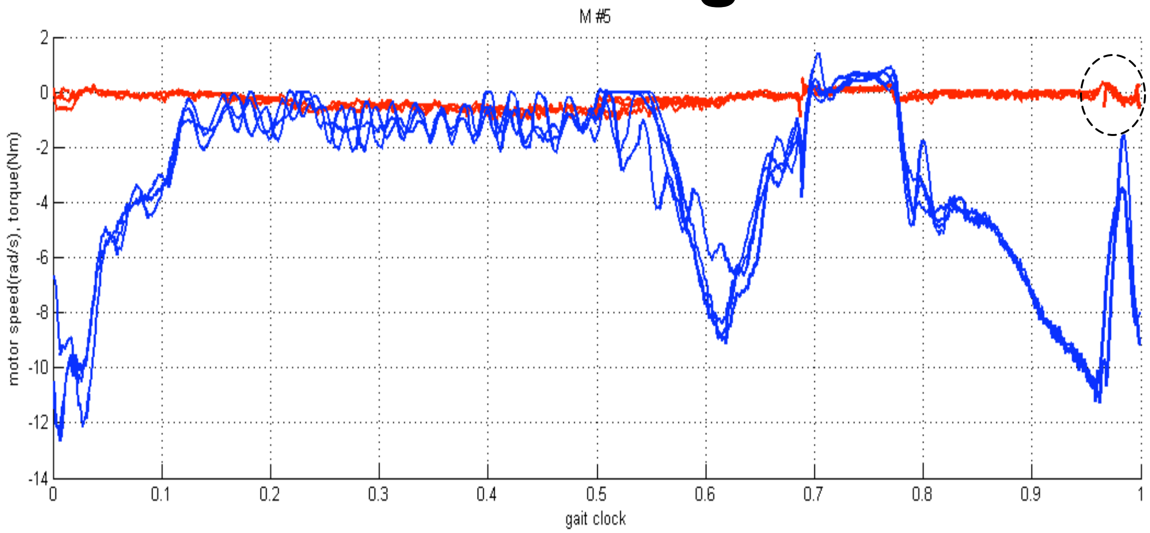

*Source: J. Amory*

| Parts | Part # |
|---|---|
| RiSE motor | Maxon RE-16, 4.5Watt (Part #: 118730) |
| Gearbox | 110323X |
| Encoder | 201937 |

| Data | Values |
|---|---|
| No Load Speed (rad/s) | 17.268 |
| Nominal Speed (rad/s) | 14.9 |
| Stall Torque (Nm) | 2.4277 |
| Nominal Torque (Nm) | 0.33296 |
| Speed Constant ((rad/s)/Nm) | 128.511 |
| Torque Constant (Nm/A) | 0.00811 |
| Terminal Resistance (Ω) | 4.0 |
| Nominal Voltage (V) | 12.0 |
| Power (W) | 4.5 |
| Gear Ratio | 2197/185193 |
| Coupler Ratio | 1 |
| Encoder Ratio | 2048 |

# Justification for negative work

0.5Hz

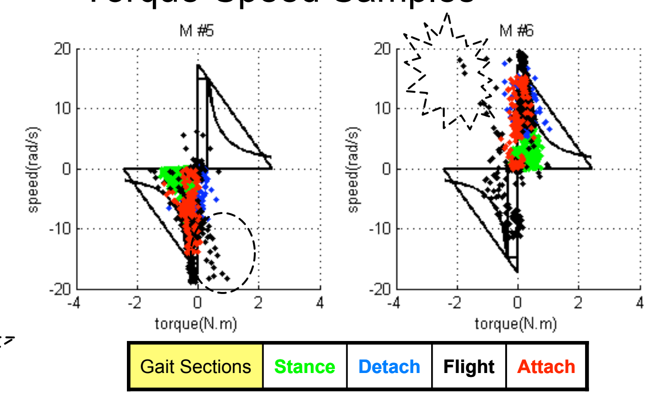


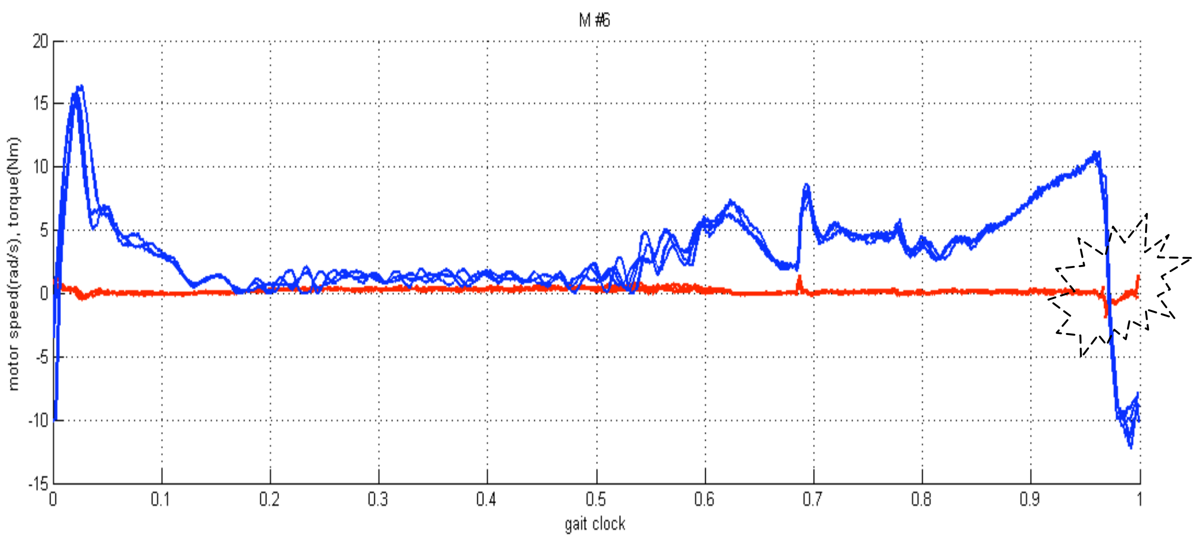

**Experiment id: exp_070312_174035 at 0.5hz**

Legend

| | |
|---|---|
| **Red** | **Torque (Nm)** |
| **Blue** | **Motor Speed (rad/s)** |
| (dashed circle) | **Negative Work (flight)** |

Torque-Speed Samples




**Gait Clock definition**

- Stance: 0.15 - 0.65
- Detach: 0.65 – 0.74
- Flight: 0.74 – 1.00
- Attach: 0.00 – 0.15

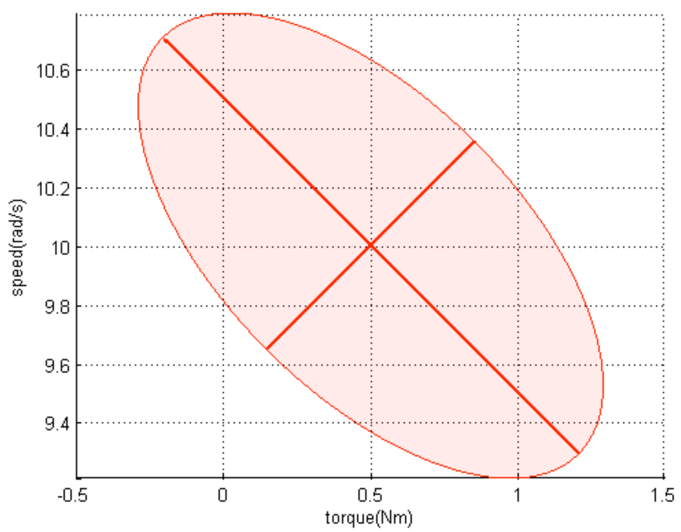
Negative work during flight due to deceleration of motors

# How do I get ellipses for statistical analysis?

## Procedures

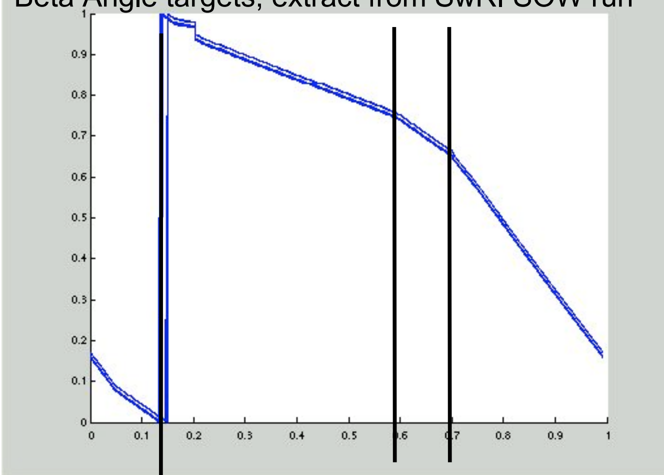
Given motor torque and motor speed,

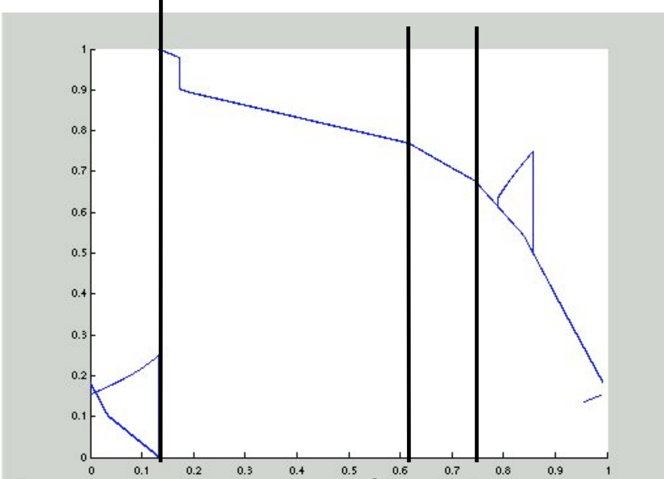
1. Compute the means of torque and speed
2. Compute the covariance matrix
3. Compute eigenvectors and eigenvalues
4. Find angle between the positive x-axis (torque) and the direction of the eigenvector of the largest eigenvalue counter-clockwisely.
5. Draw ellipses with largest and smallest eigenvectors (we have only two) as semi-major and semi-minor axes, respectively with radii as the square root of corresponding eigenvalues.



# Differences between 0.5Hz & 0.8Hz gaits

Beta Angle targets, extract from SwRI SOW run





Beta Angle targets, extract from U-Penn tests
(spurious curves are gait start-up)

SwRI carpet remains different from any carpet used at our institutions

Minor tweaks made to gait (according to CVS, during BDI/CMU transition box work in Sept 2006, but only minor tweaks ... probably worth reverting, however)

To be fair, U-Penn data was extracted from runs with extensive pitch-back data, but is still mostly representative of recent force data.

**This slide is from *G.C. Haynes* comments on the leg trajectories differences**

# Consideration II: *Noisy Required Torque*

**Model:** $$\tau_{req} = k_p(\theta_{des} - \theta_m) + k_d(\omega_{des} - \omega_m)$$

where $\tau_{req}$ is the required torque, $k_p$ and $k_d$ are proportional and derivative gain, respectively, $\theta_{des}$ and $\theta_m$ are desired and actual motor positions, respectively, and, finally, $\omega_{des}$ and $\omega_m$ are desired and actual motor speed, respectively.

**Notion:** The required torque is noisy because of the actual motor speed.

$$\omega_{act} = \pm 2\pi \cdot \frac{gear_{ratio} \cdot coupler_{ratio}}{encoder_{ratio}} \cdot \frac{\Delta encoder}{\Delta t}$$

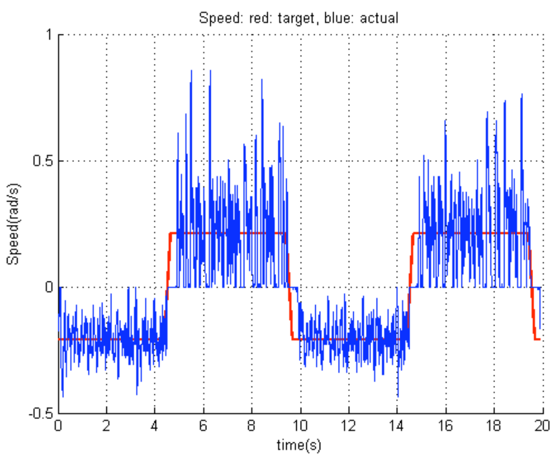



***Figure.*** **Target and Actual Motor Speed of Pure Wing Motion (90°-30°-90°) at 0.1hz**

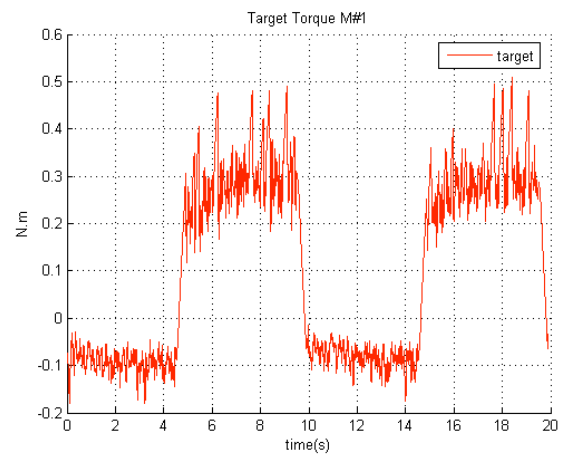
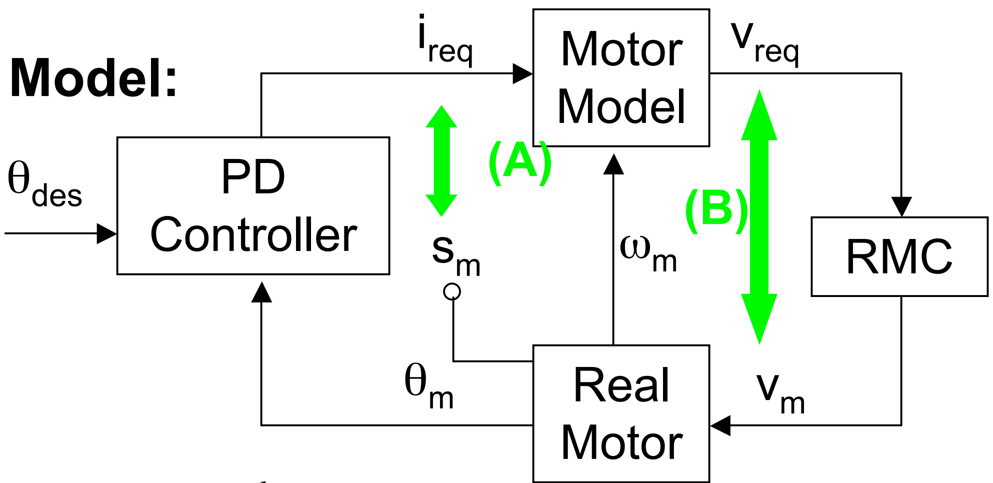



***Figure.*** **Target torque of the same experiment**

# **Consideration III:** *Large error between required current and measured current*

**Model:**




$$i_{req} = \frac{gear_{ratio} \cdot coupler_{ratio}}{K_T} \tau_{req}$$

$$v_{req} = \frac{\omega_m}{K_\omega \cdot gear_{ratio} \cdot coupler_{ratio}} + i_{req} \cdot R_{term}$$

***$K_\omega$*:** Speed constant  ***$R_{term}$*:** Terminal Resistance

***$\omega_m$*:** actual speed

**Problem:** Motor model does not predict the real motor well.

(A)

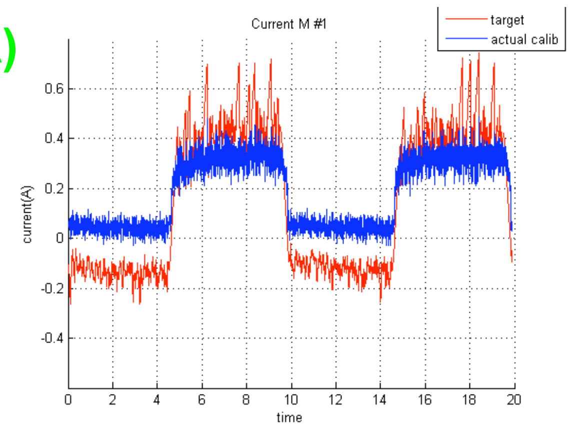



***Figure.*** **Required current ($i_{req}$) and measured current ($s_m$)**

(B)

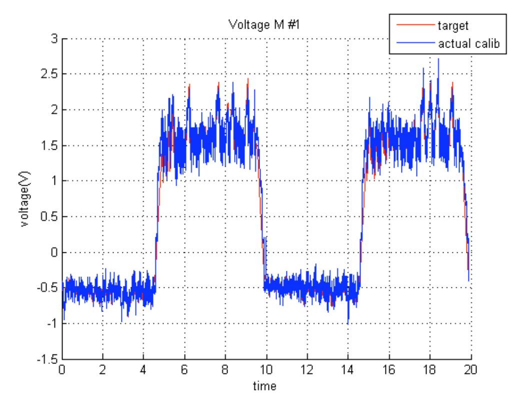
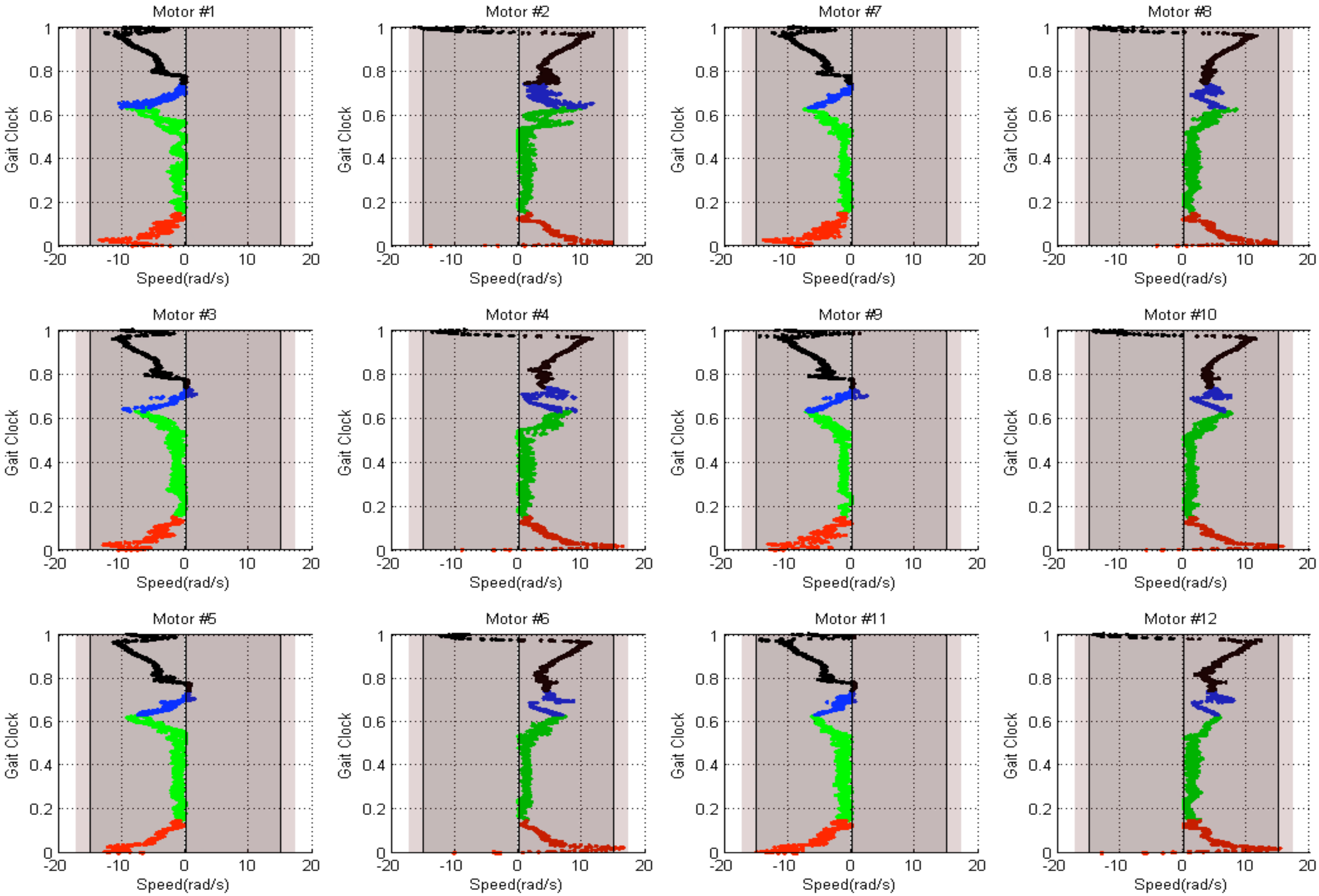



***Figure.*** **Required voltage ($v_{req}$) and measured voltage ($V_m$)**

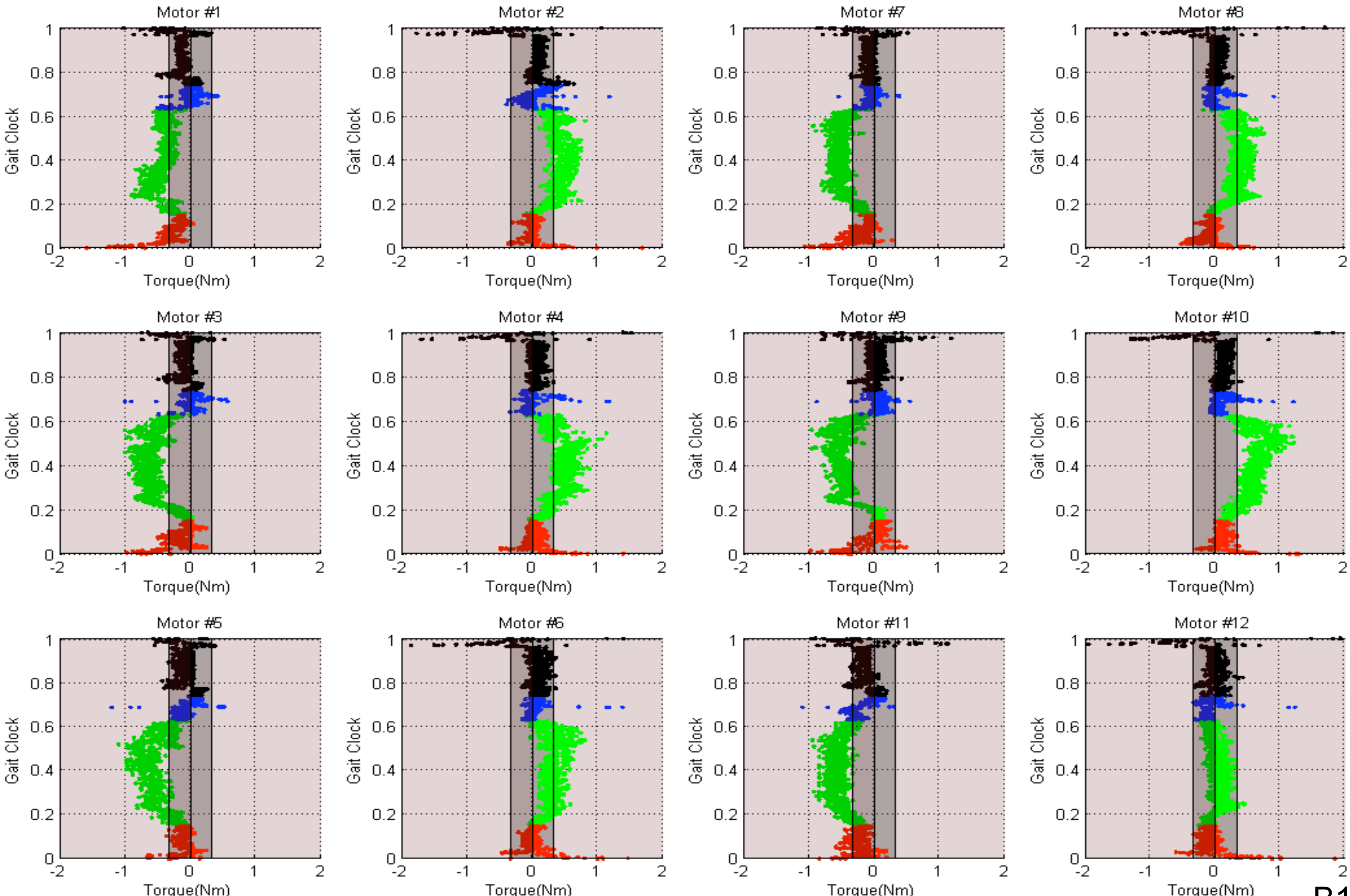
# Results III: Raw Speed-Gait_Clock Samples

| Gait Sections | Stance | Detach | Flight | Attach |
|---|---|---|---|---|

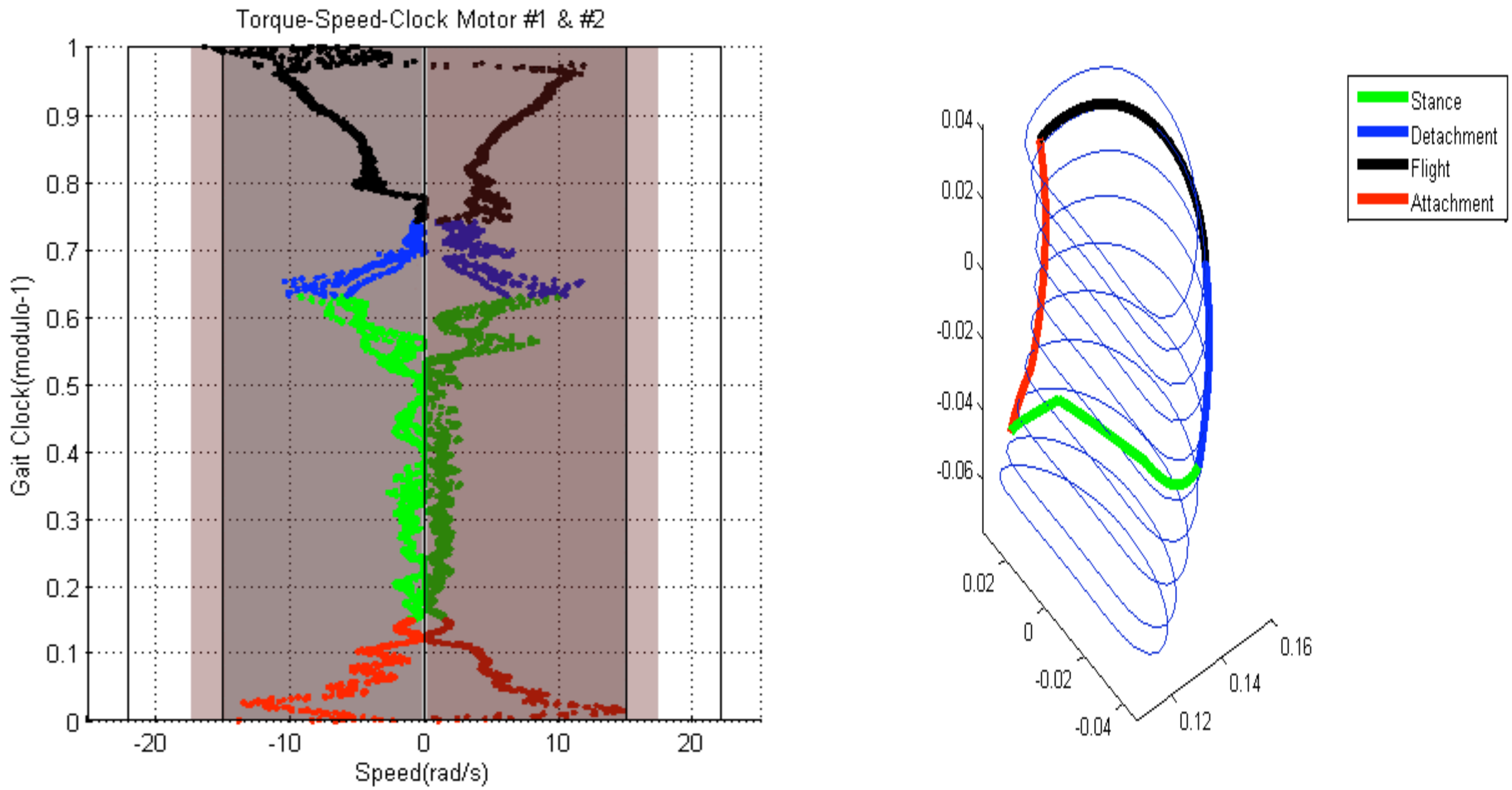


# Results IV: Raw Torque-Gait_Clock Samples

| Gait Sections | Stanc e | Detac h | Flight | Attac h |
| --- | --- | --- | --- | --- |



# Motor speed and Legtrajectory




motor(1) = hip(1) + hip(2)

motor(2) = hip(1) – hip(2)

hip(1) = 0.5(motor(1) + motor(2))

hip(2) = 0.5(motor(1) - motor(2))