MODELING AND SIMULATION OF PASSIVE AND SEMI-ACTIVE SUSPENSION SYSTEMS FOR RIDE COMFORT

2015. 06. 22

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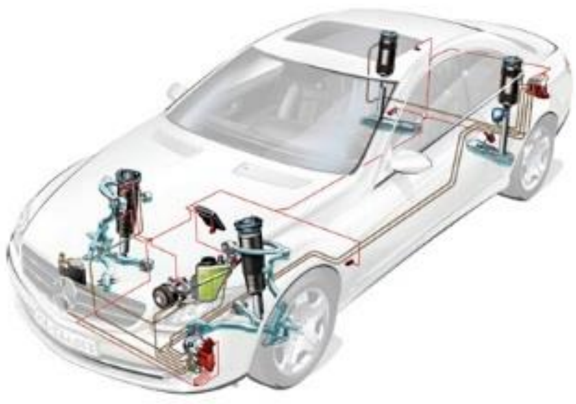
Computational Design Lab.

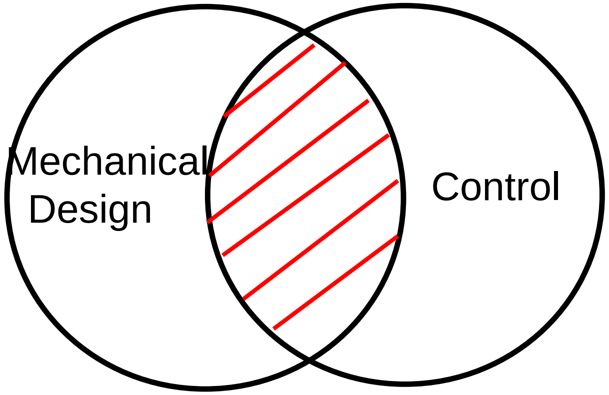
Outline

1. Research objective
2. Suspension design theory
3. Passive & Semi-active suspension design
4. Simulation & Comparison

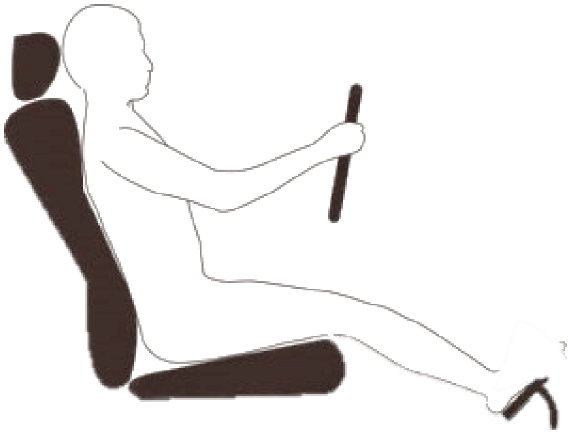
Introduction



Passive & Semi-active suspension



Modeling & Simulation



Estimating ride comfort

Design objective

① Two typical passive suspension design

- Macpherson strut, Double wishbone

② Semi-active suspension design

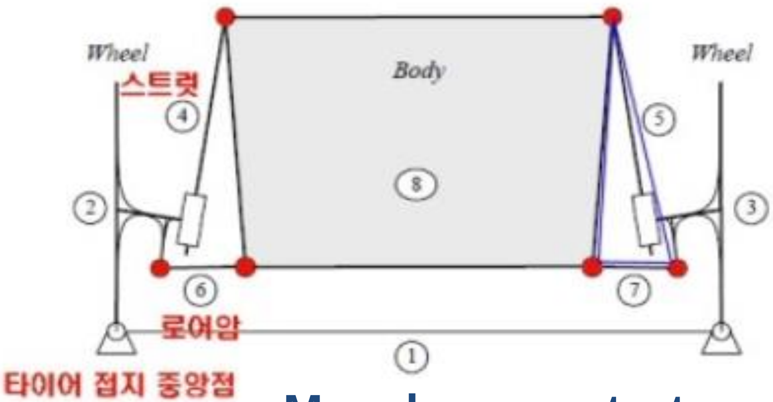
- Sky-hook (On-off / Continuous)
- Balance control (On-off / Continuous)

③ Time-domain / Frequency domain comparison

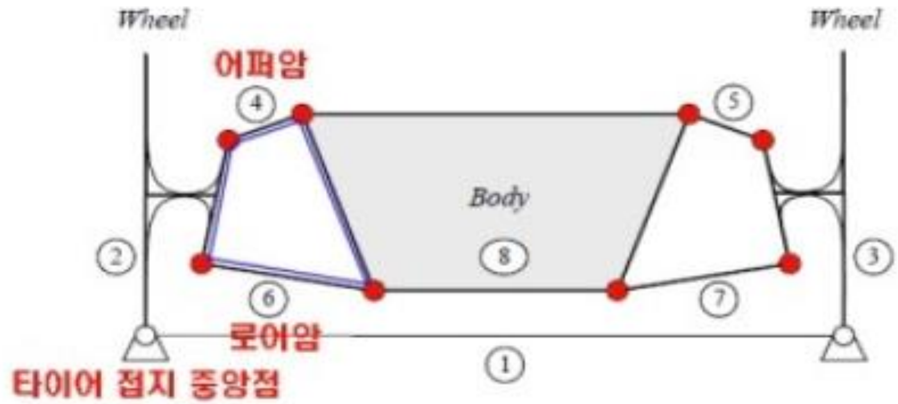
- Vertical acceleration for ride comfort

④ Comparison

Macpherson vs Double wishbone



Macpherson strut

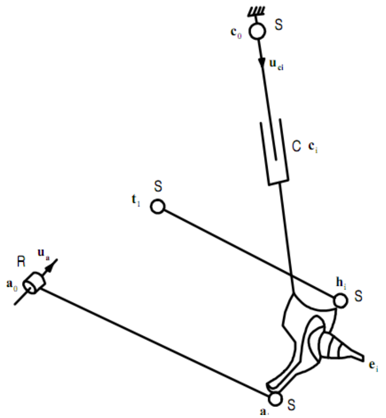


Double wishbone

	Macpherson strut	Double wishbone
장점	생산 원가 낮음	운동학적으로 컨트롤이 용이
	Upper arm 이 없어 Compact	Geometry 설계가 자유로움
	얼라인먼트 조절장치 없어 구조 단순	승차감이 좋고 핸들링이 뛰어남
단점	운동 특성이 더블위시본에 비해 떨어짐	생산 원가 비쌈
	횡력에 대한 저항력이 약해 조향 안정성 저하	공간 많이 차지
	노면의 진동이 바디에 직접 전달	구성부품이 많아 구조가 복잡

Suspension design

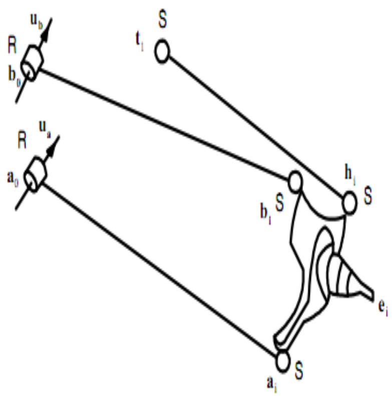
Macpherson strut



Macpherson strut

l = 5, j=6, w= 6, $\sum_{i=1}^{j} f_i$ =15

M=3



Double wishbone

l = 5, j=6, w=6, $\sum_{i=1}^{j} f_i$ =16

M = 4

Design Freedom

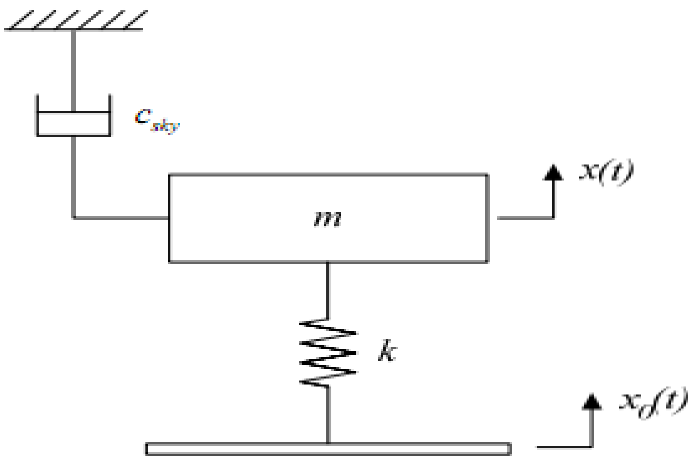
Double wishbone > Macpherson

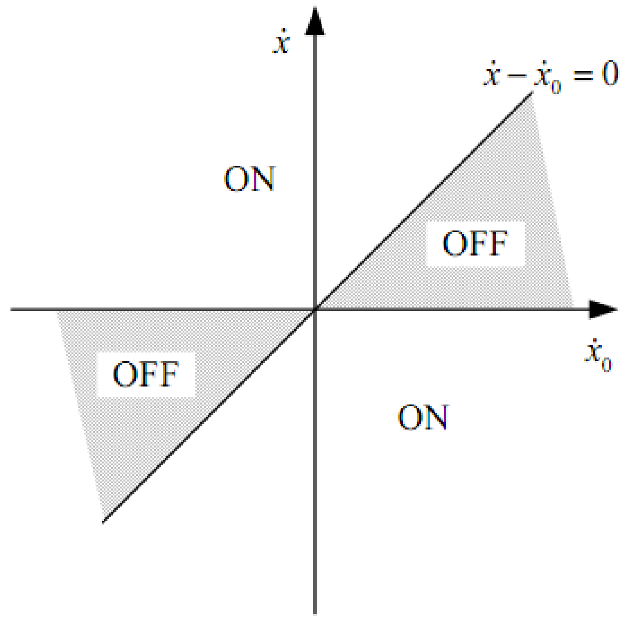
Free Geometry design

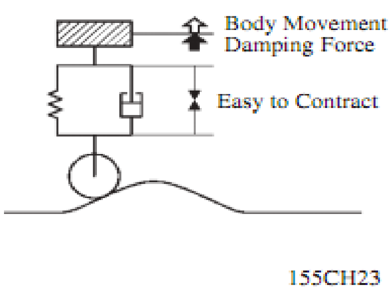
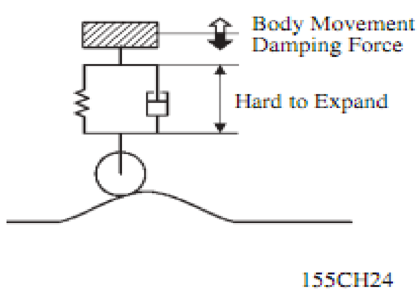
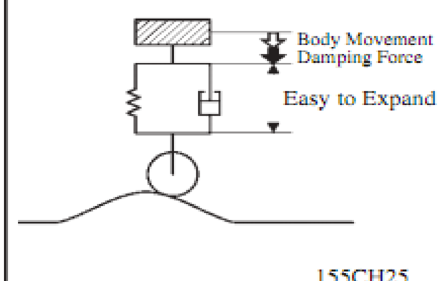
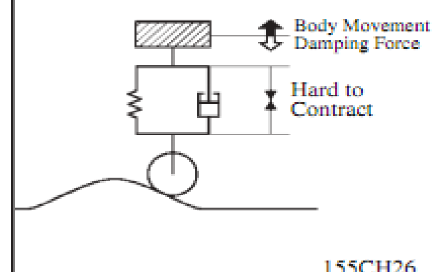
Easy to control

Gruebler's formula	
$M = \omega(l - j - 1) + \sum_{i=1}^{j} f_i$	M : mobility l : the number of link j : the number of joint f_i : degree of freedom of 'i' th joint w : Mobility number (space :6)

- Sky-hook control

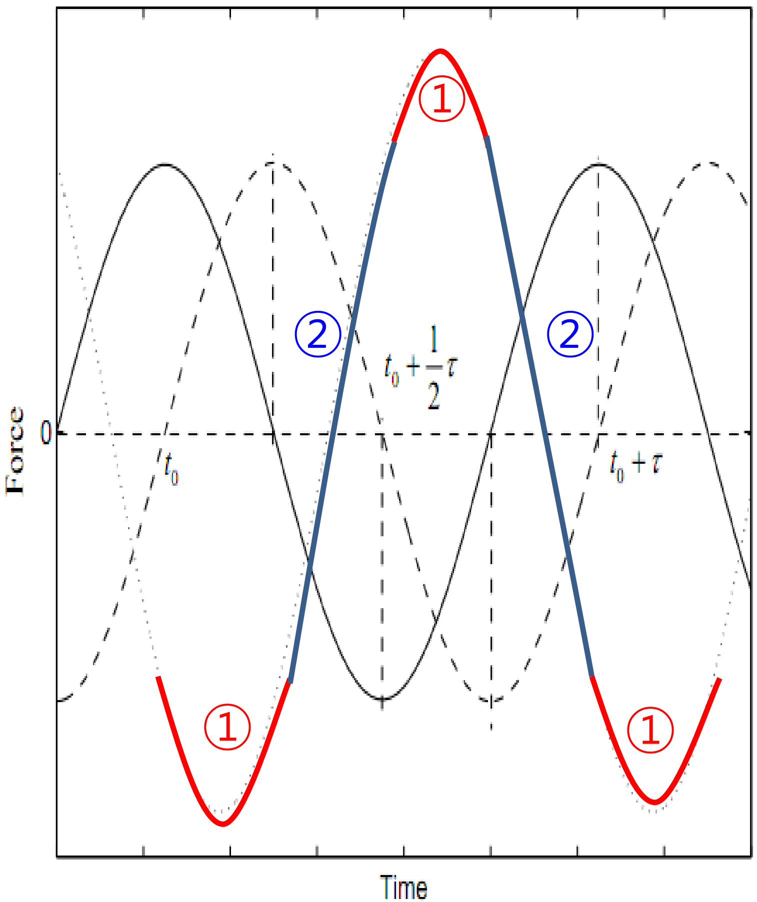




Stage ①	Stage ②	Stage ③	Stage ④
			
Assisting the Vibrations	Suppressing the Vibrations	Assisting the Vibrations	Suppressing the Vibrations

Semi-active control

- Balance control



— damping force (F_d); ---- spring force (F_k); inertial force ($m\ddot{x}$)

To reduce the magnitude of $\ddot{x}$

$$F_k = k(x - x_0)$$
$$F_d = c(\dot{x} - \dot{x}_0)$$

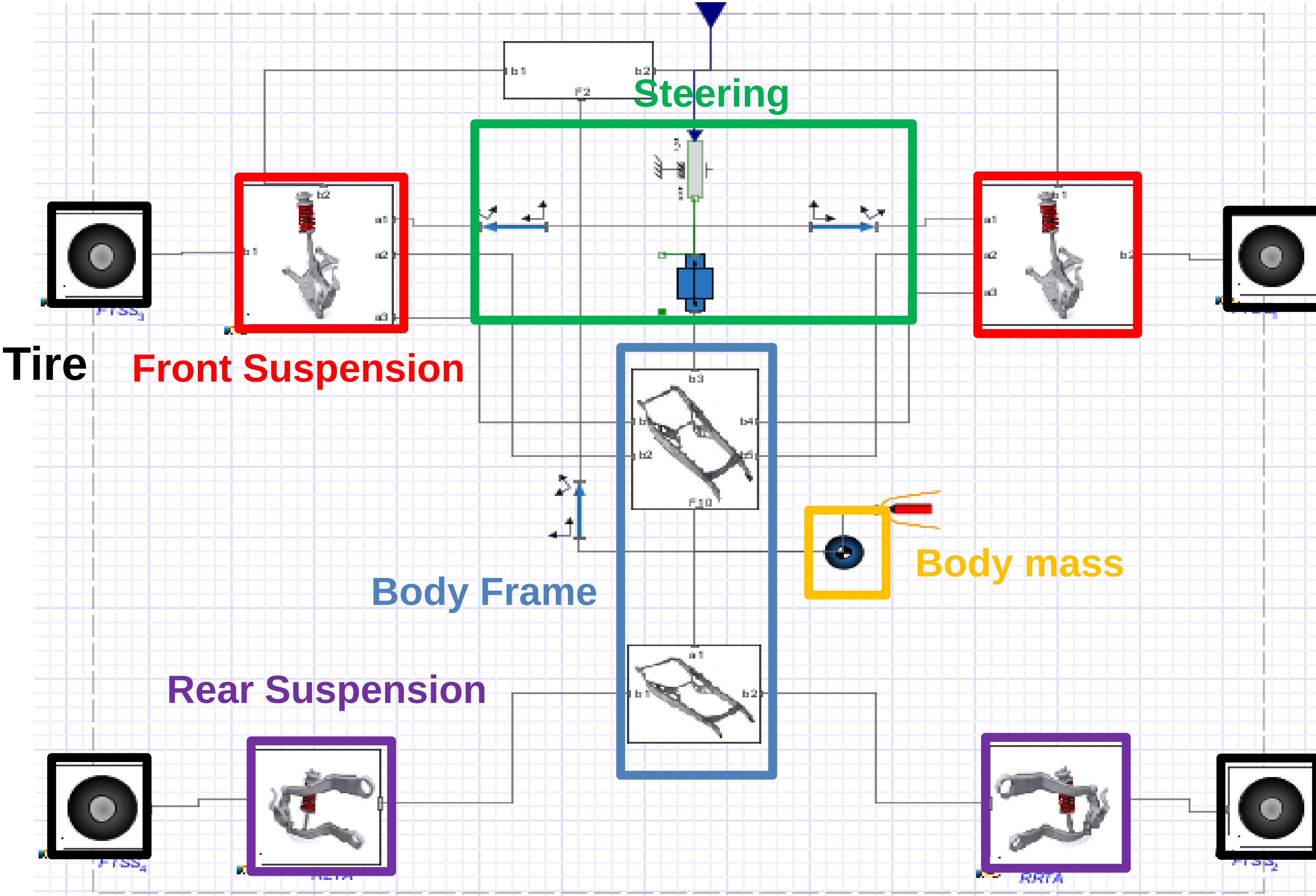
① $(x - x_0)(\dot{x} - \dot{x}_0) > 0$

$$|\ddot{x}| = \frac{|F_k| + |F_d|}{m} \Rightarrow |F_d| = 0$$

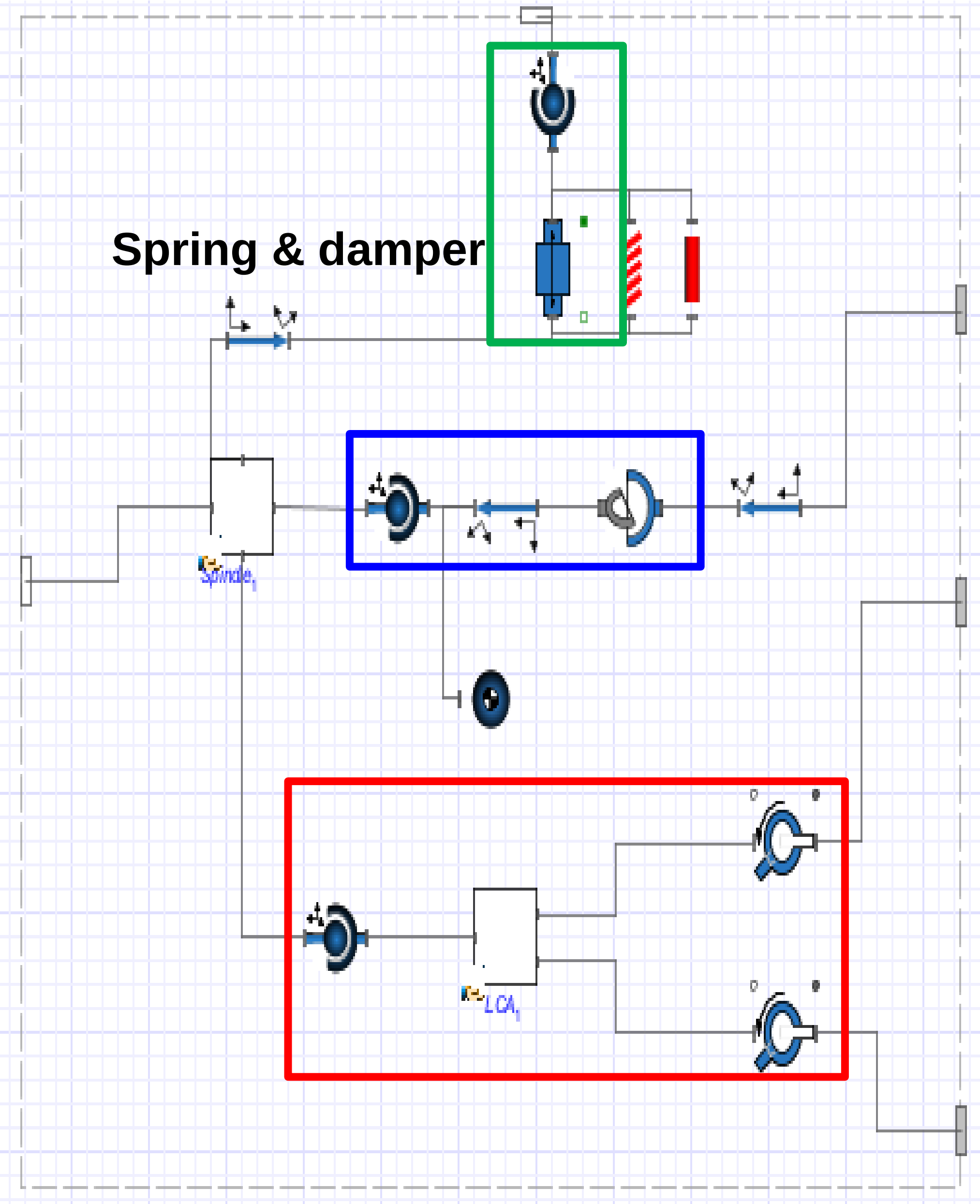
② $(x - x_0)(\dot{x} - \dot{x}_0) \leq 0$

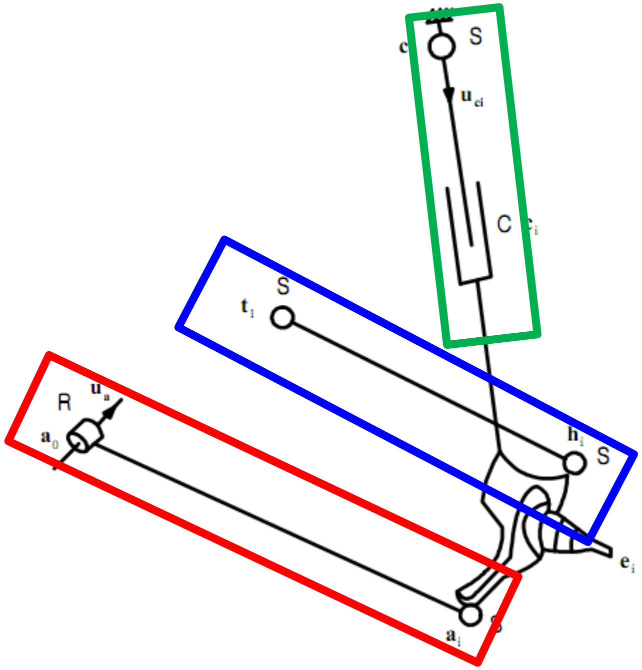
$$|\ddot{x}| = \frac{|F_k| - |F_d|}{m} \Rightarrow |F_d| = |F_k|$$

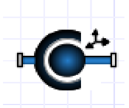
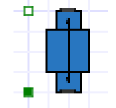
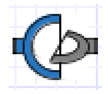
Vehicle modeling



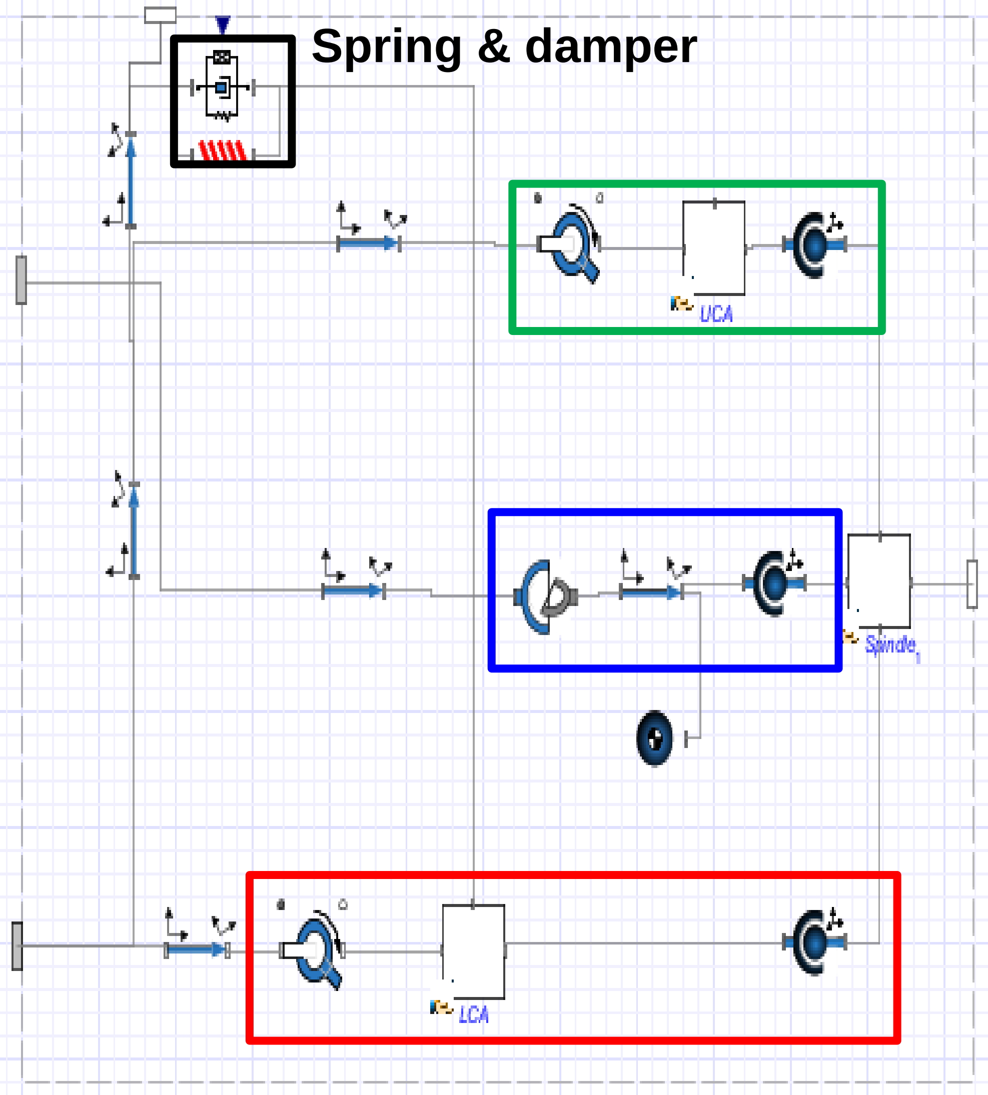
Macpherson Design

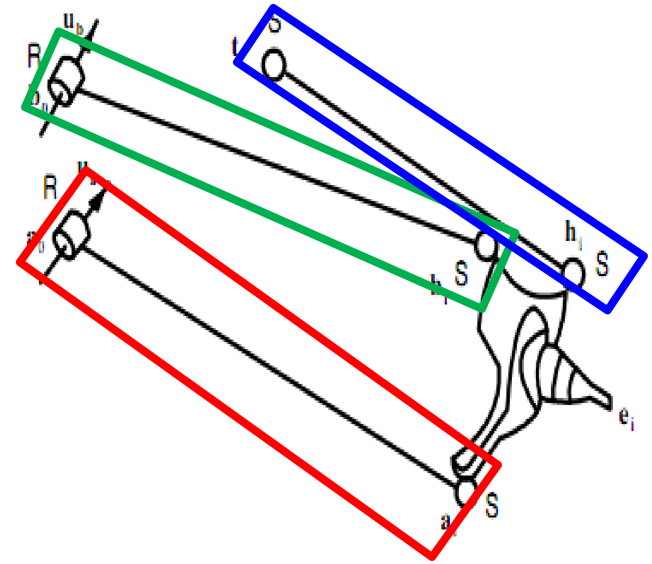


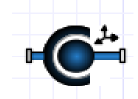
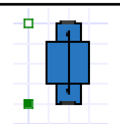
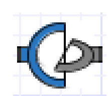


	S	Spherical (Ball) joint
	R	Revolute joint
	C	Prismatic (spring & damper)
	S	Universal joint

Double wishbone Design

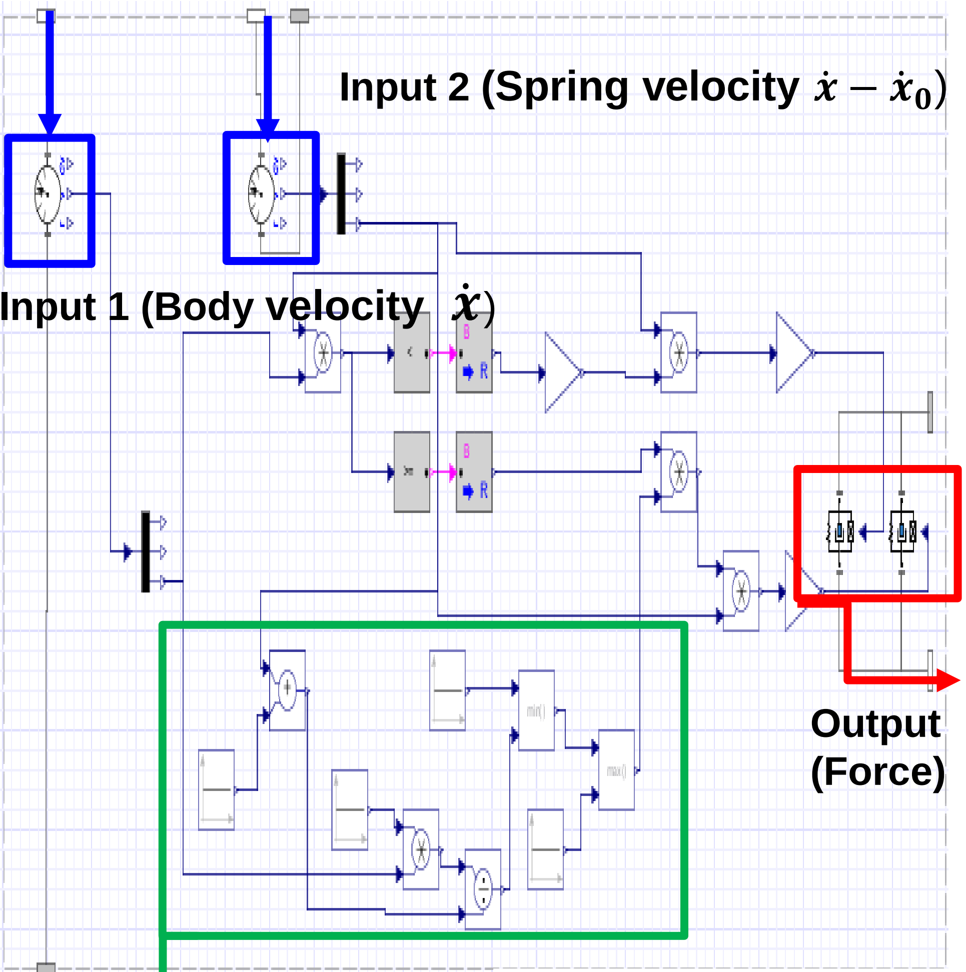




	S	Spherical (Ball) joint
	R	Revolute joint
	C	Prismatic (spring & damper)
	S	Universal joint

Controller Design

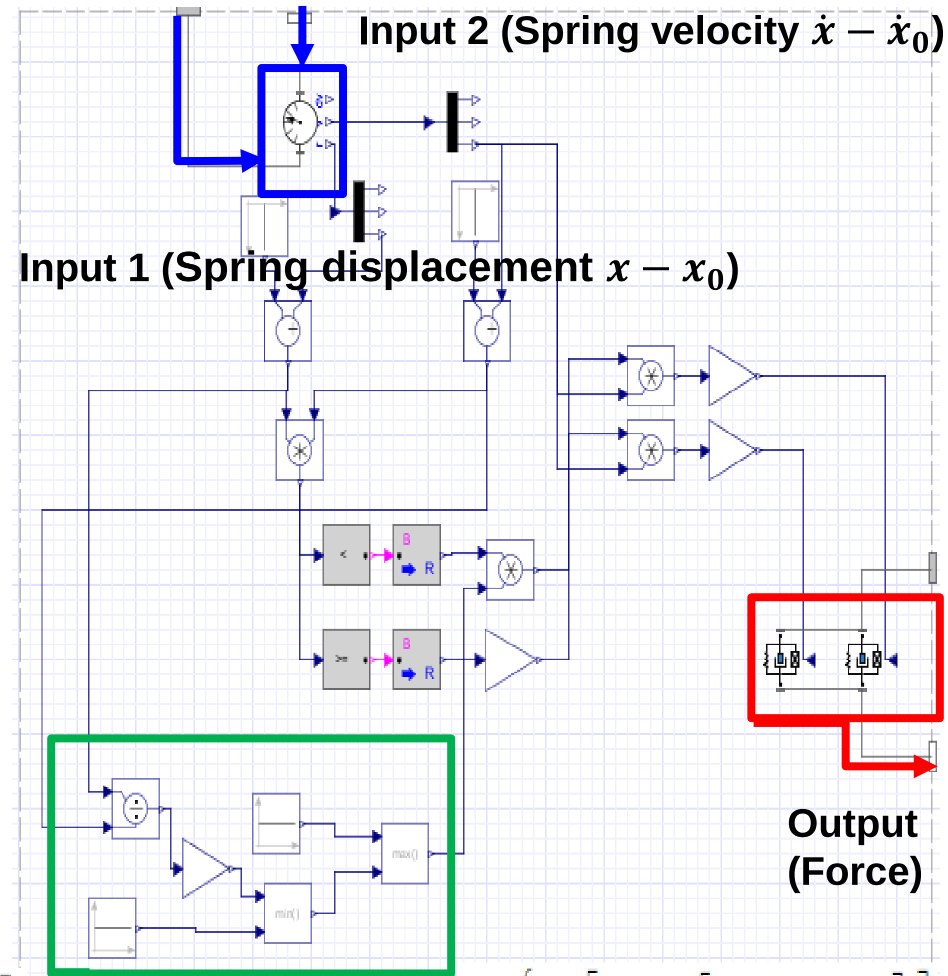
Skyhook Control



C value (Damping coefficient)

$$c_{sa} = \begin{cases} \max\left[c_{\min}, \min\left[\frac{c_{sky}\dot{x}}{\dot{x}-\dot{x}_0}, c_{\max}\right]\right] \\ c_{\min} \end{cases}$$

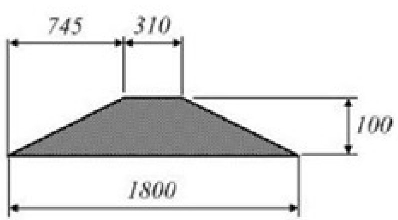
Balance control



C value (Damping coefficient)

$$c_{sa} = \begin{cases} \max\left[c_{\min}, \min\left[\frac{-k(x-x_0)}{\dot{x}-\dot{x}_0}, c_{\max}\right]\right] \\ c_{\min} \end{cases}$$

Example

Driving Condition	
Front	Macpherson / Double wishbone
Rear	Semi-trailing arm
Tire	Fiala tire
Velocity	10 m/s
Bump	180 cm / 10 cm 

Parameter	Description	Value
M	Sprung mass	1500 kg
m	Unsprung mass	40 kg
K_f	Front spring stiffness	35000 N/m
K_r	Rear spring stiffness	31400 N/m
$C_{passive}$	Passive damping coefficient	2000 N*s/m
C_{max}	Maximum damping coefficient	3000 N*s/m
C_{min}	Minimum damping coefficient	300 N*s/m
K_t	Tire stiffness	180000 N/m
C_t	Tire damping coefficient	500 N*s/m

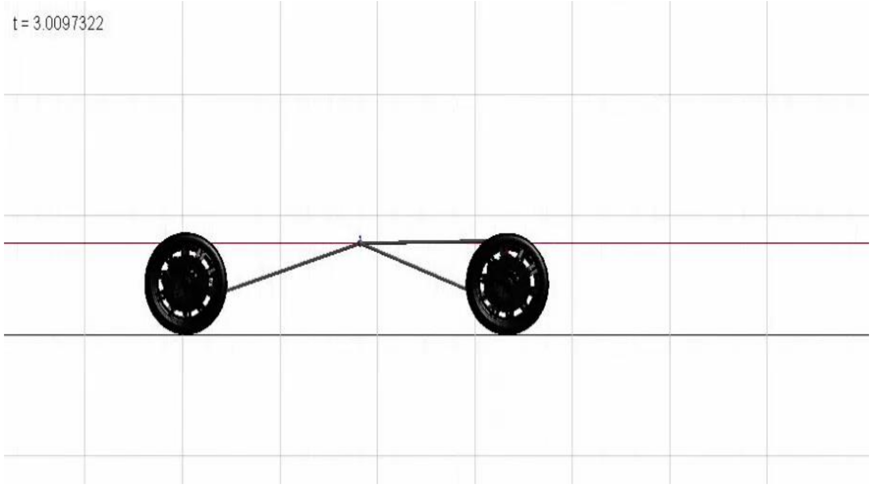
***Mohamed M. ElMadany*. (2011)**

Control and Evaluation of Slow-Active Suspensions with Preview for a Full Car , 10

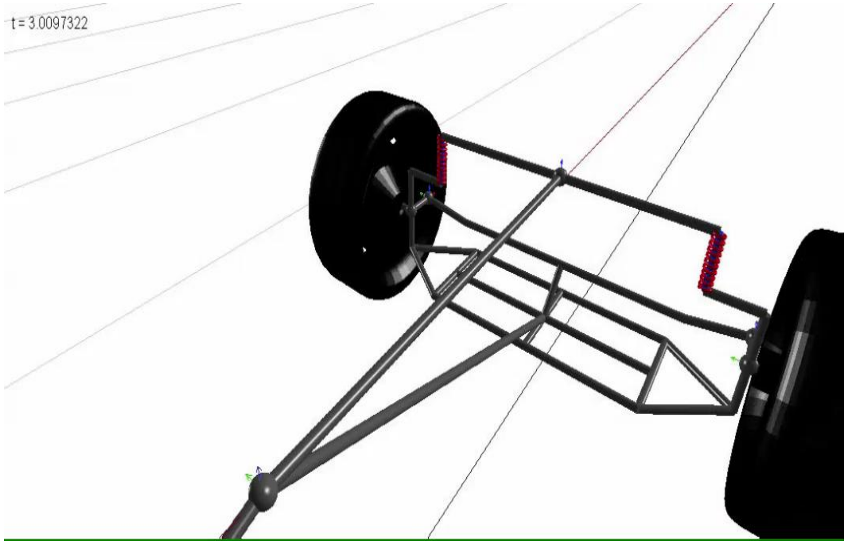
Simulation

① Driving Condition

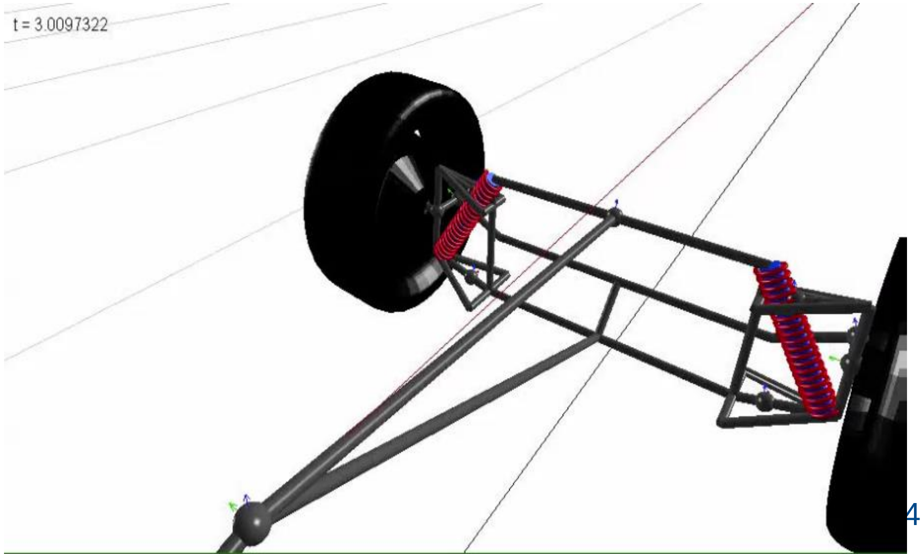
: Passing Bump



② Macpherson strut



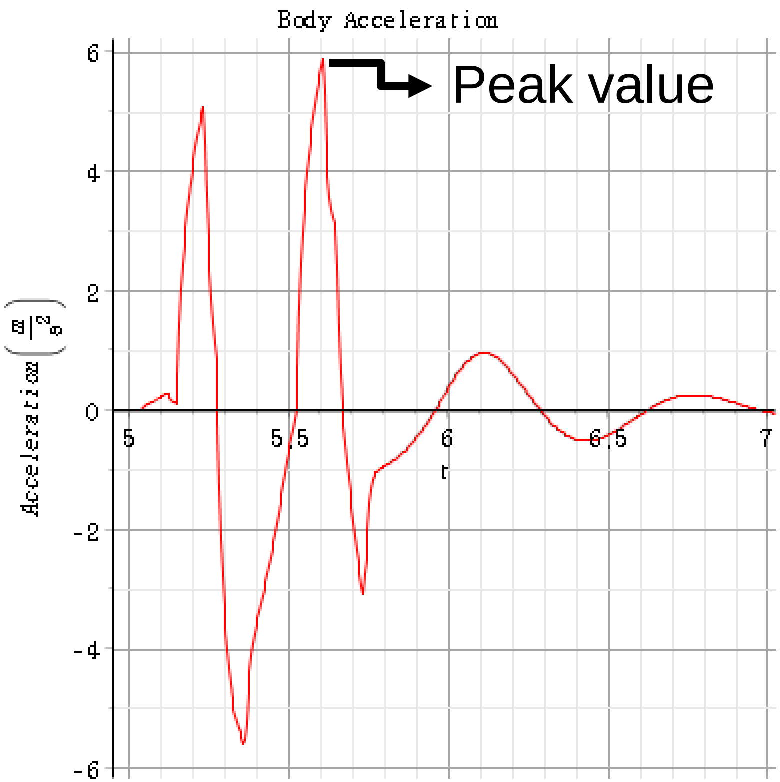
③ Double wishbone

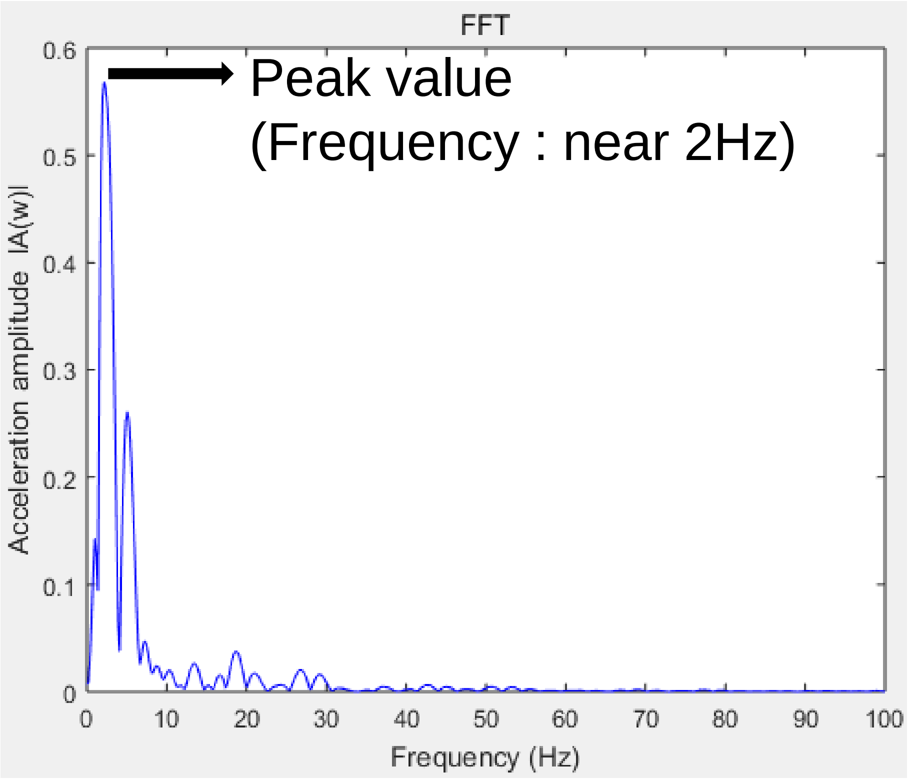


Evaluation criterion

RMS Acceleration
(n = 1000 for 5sec)

$$a_{rms} = \sqrt{\frac{{a_1}^2 + {a_2}^2 + \cdots + {a_n}^2}{n}}$$



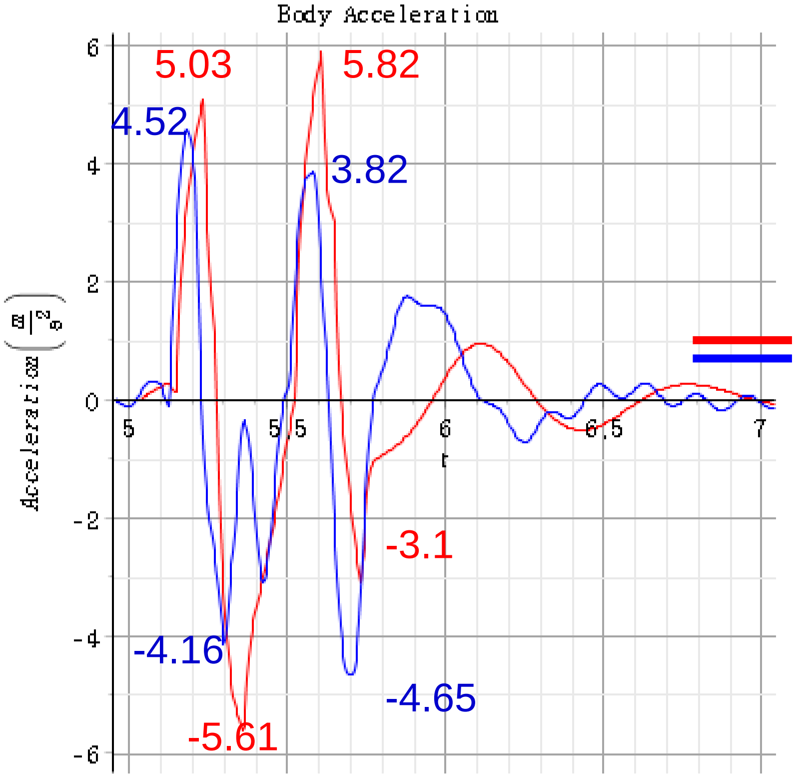


Time domain

Frequency domain

Simulation Result (Time)

① Passive



RMS

1.21

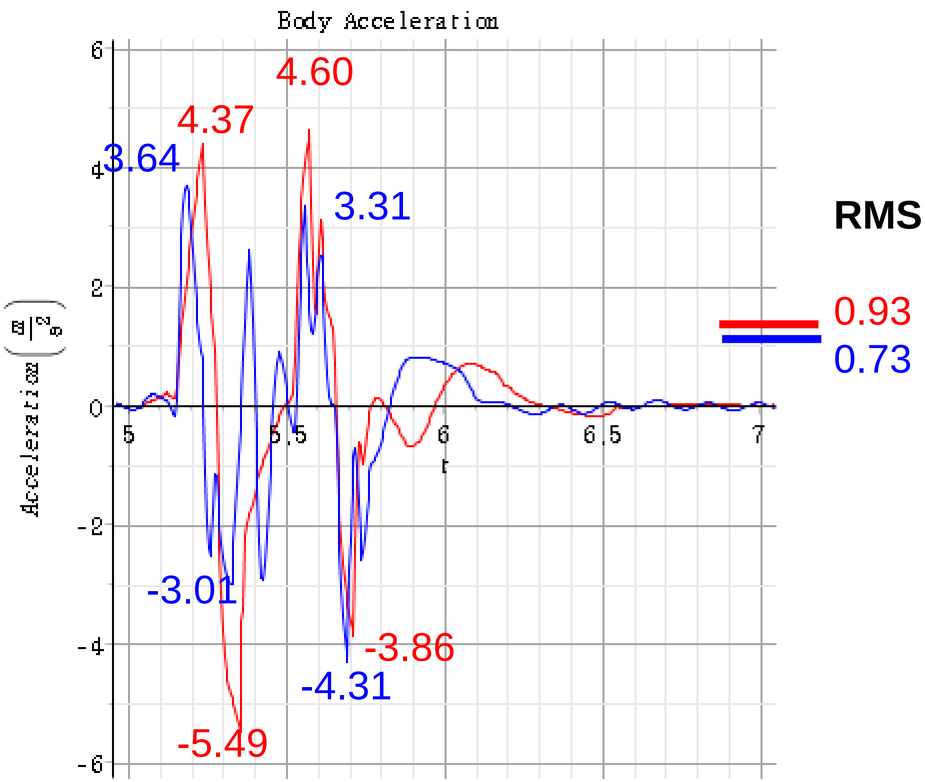
1.07

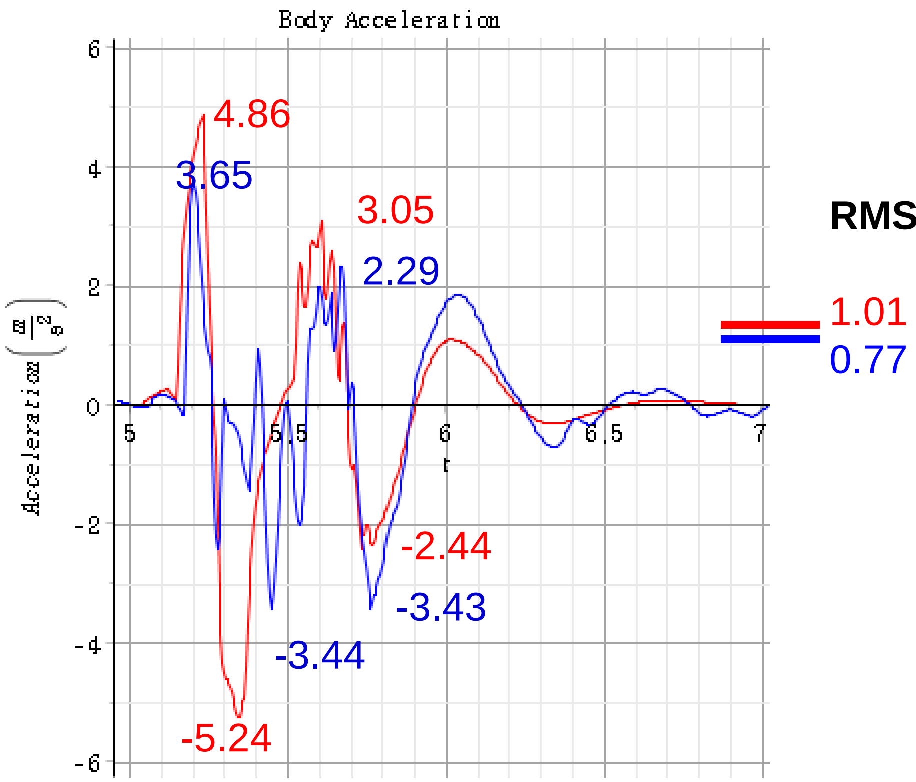
Macpherson

Double wishbone

Simulation Result (Time)

② Skyhook On-Off | Skyhook Continuous

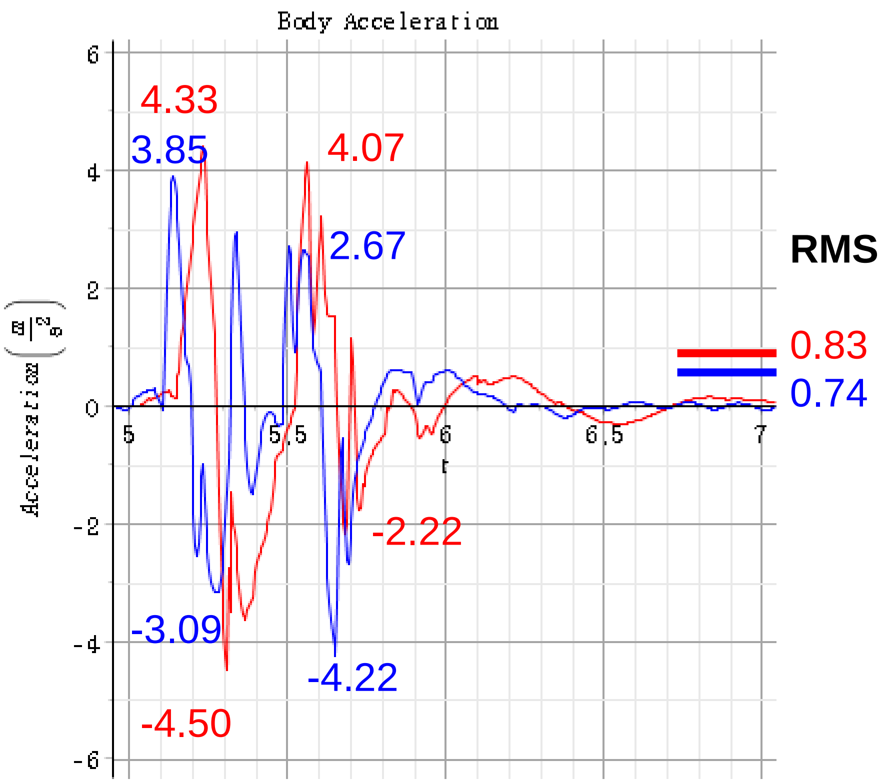




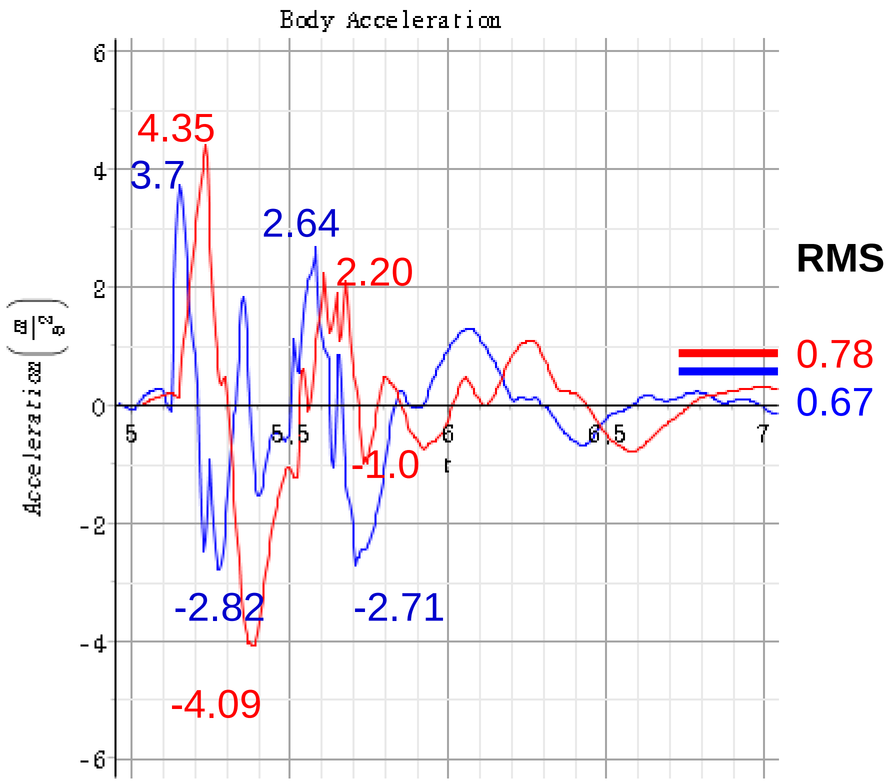
Macpherson   Double wishbone

Simulation Result (Time)

③ Balance On-Off



Balance Continuous

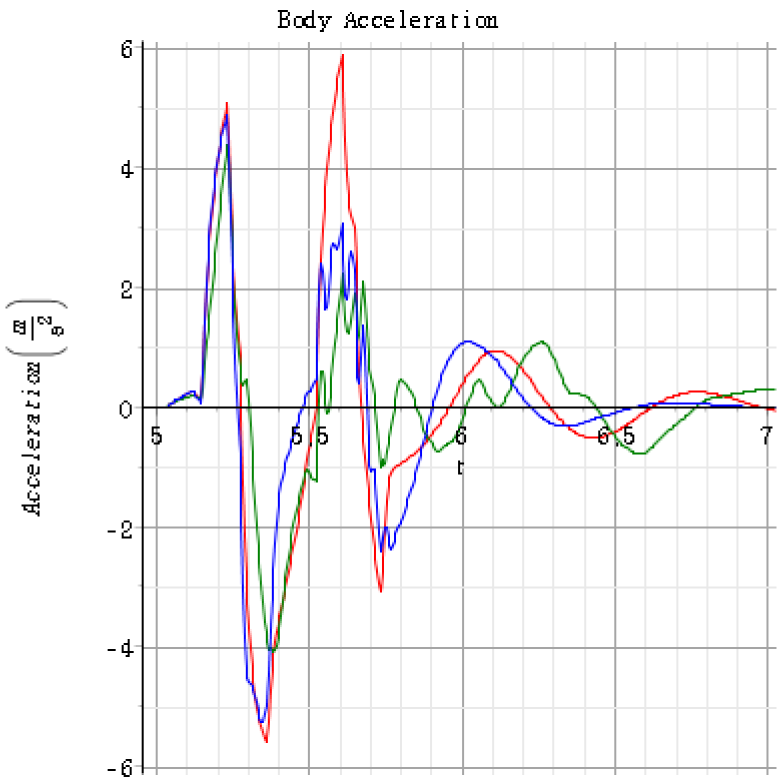


Macpherson

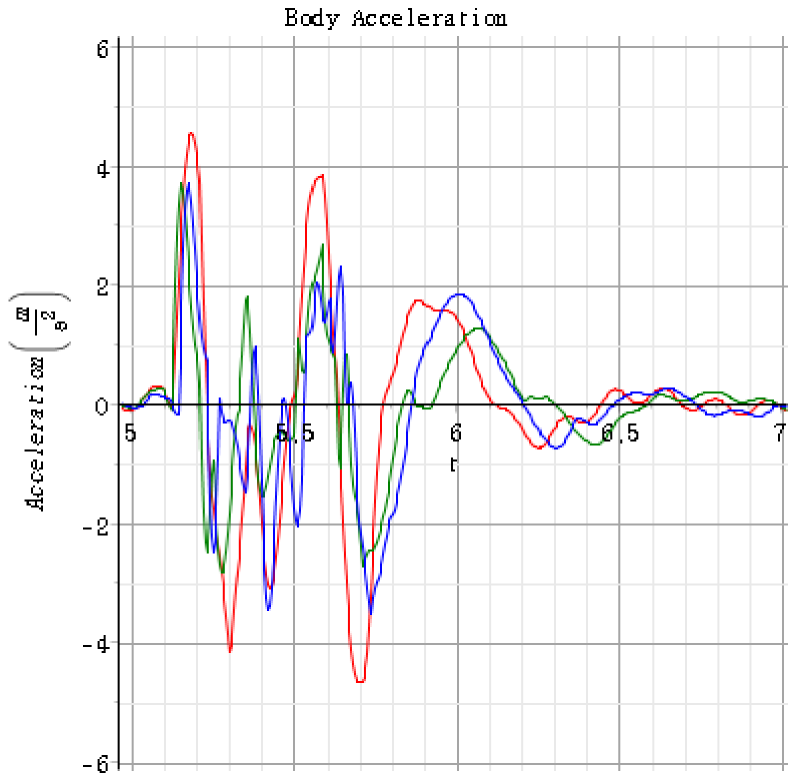
Double wishbone

Simulation Result (Time)

Macpherson type



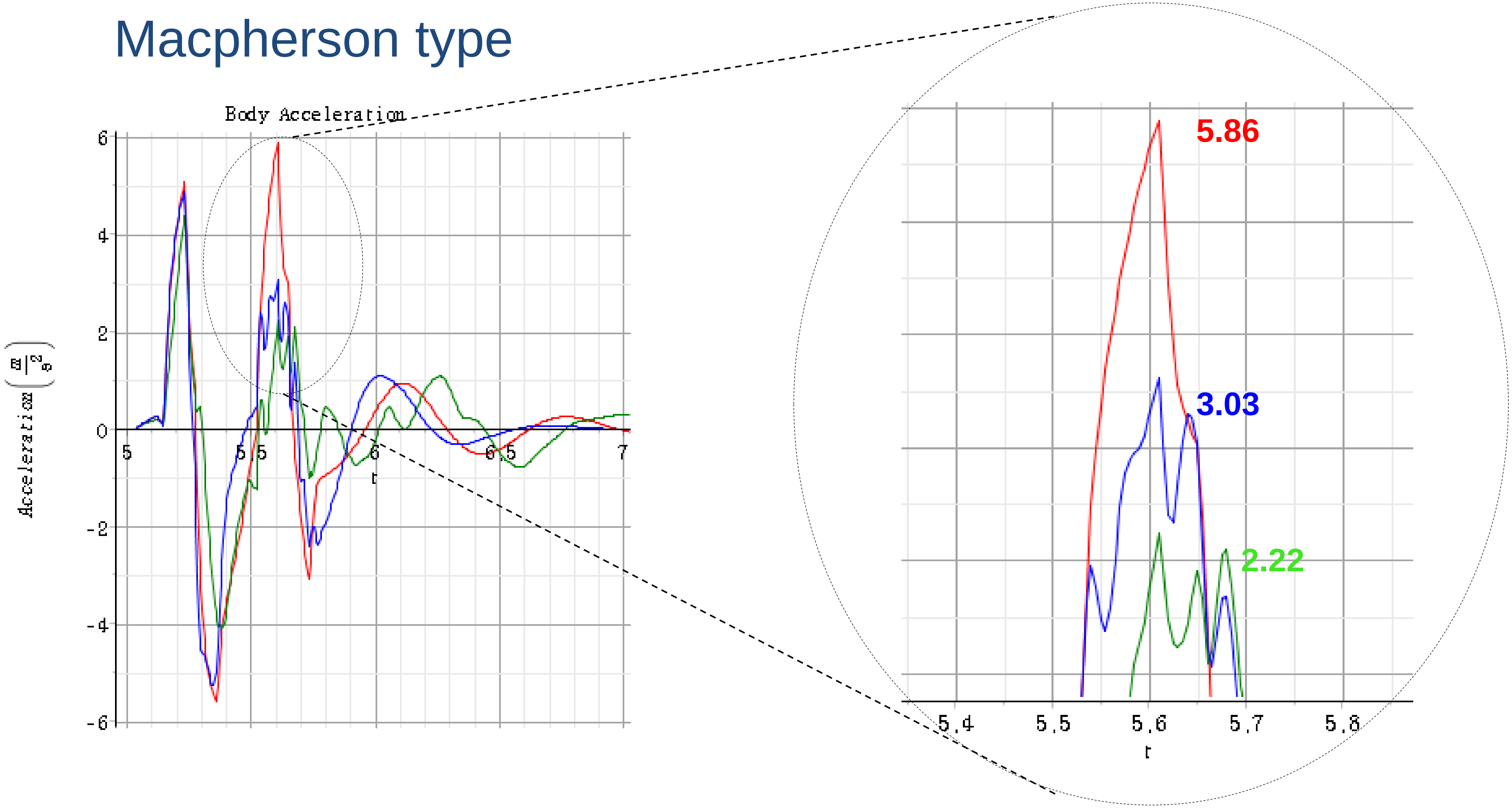
Double wishbone type



Passive Skyhook Balance

Simulation Result (Time)

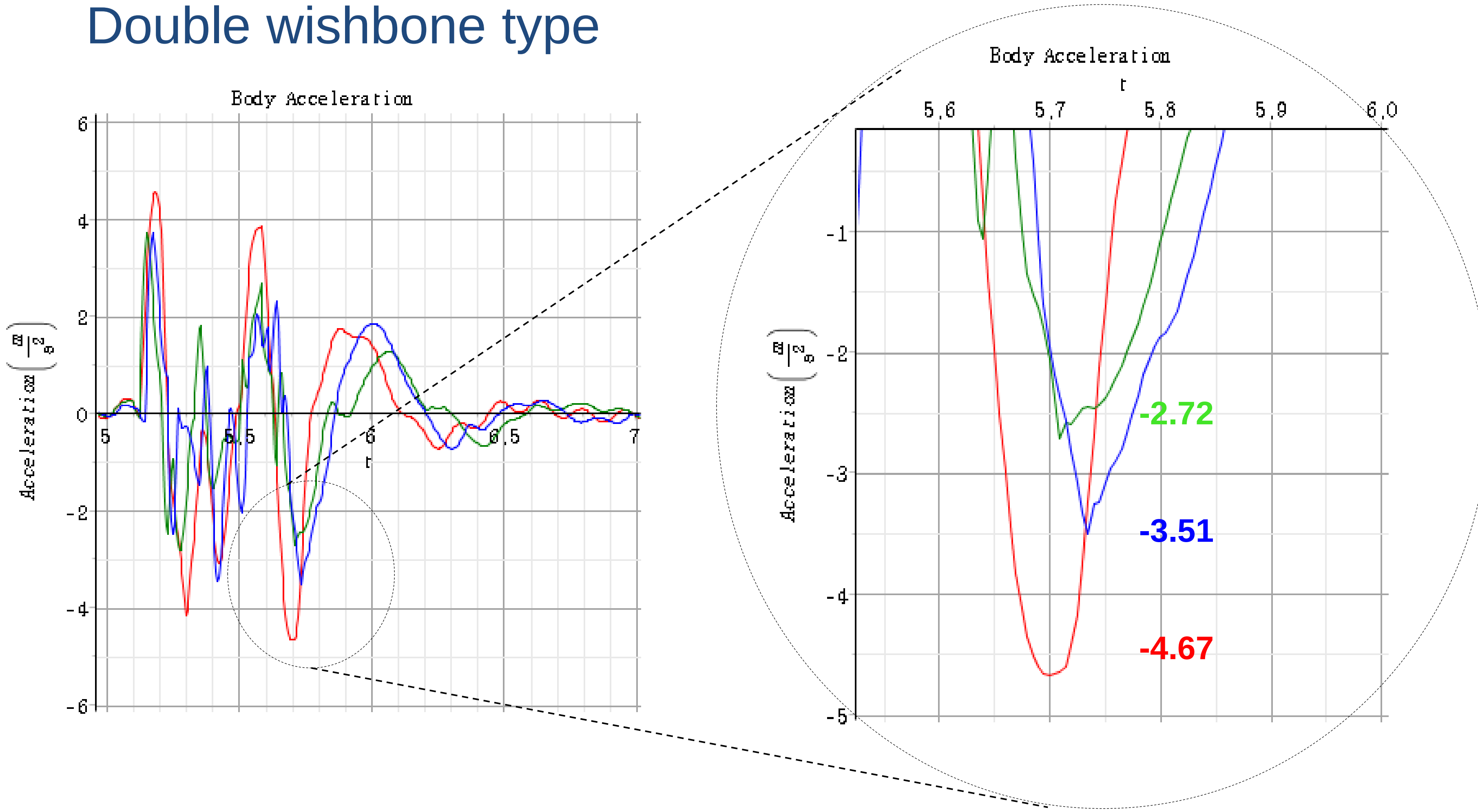
Macpherson type



Passive   Skyhook   Balance

Simulation Result (Time)

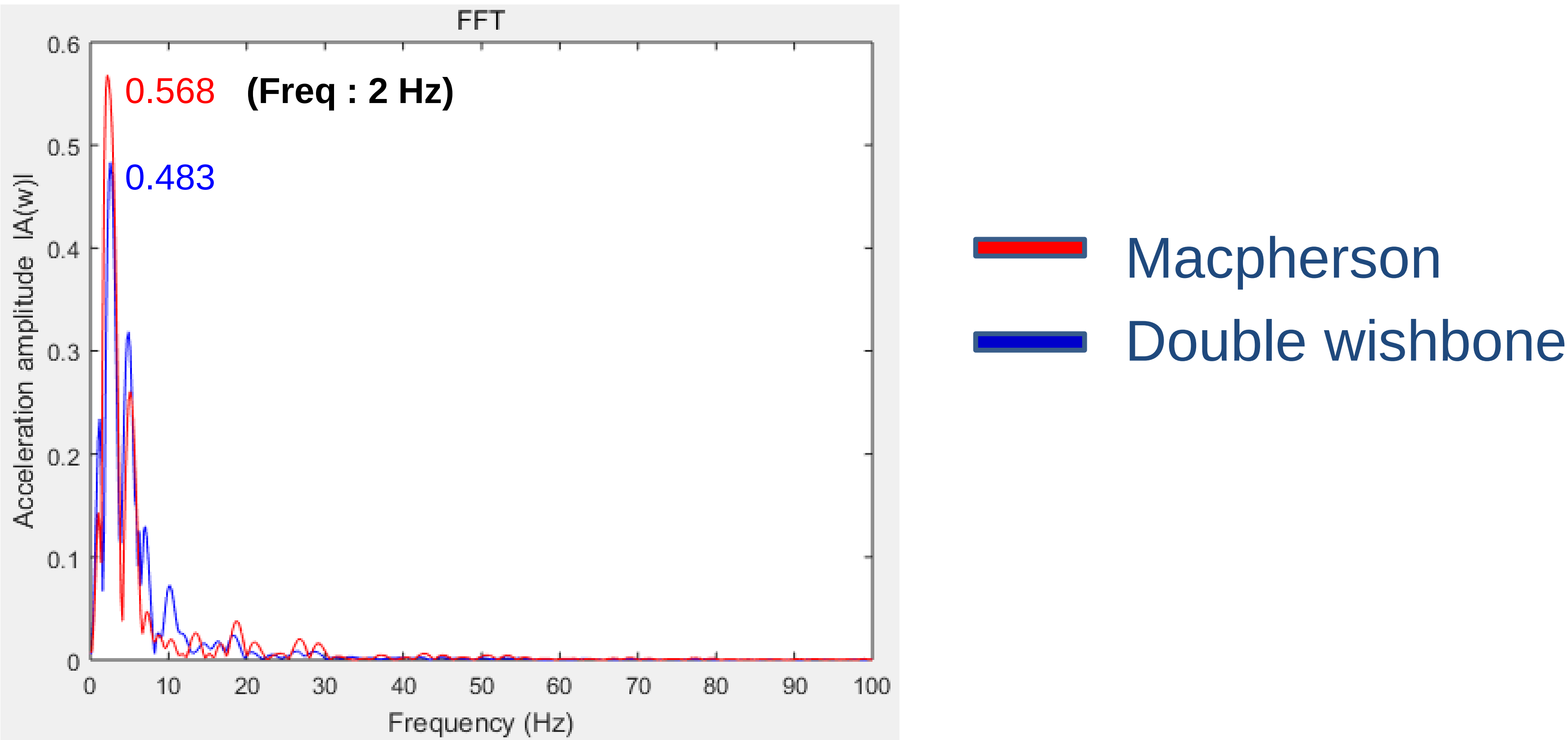
Double wishbone type



Passive Skyhook Balance

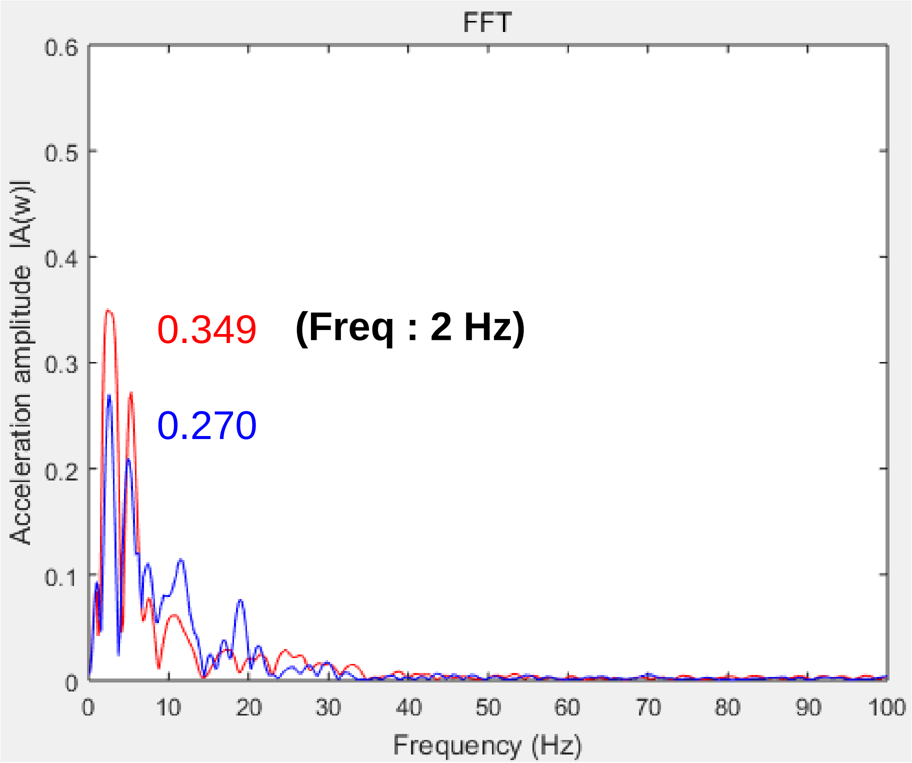
Simulation Result (Frequency)

① Passive

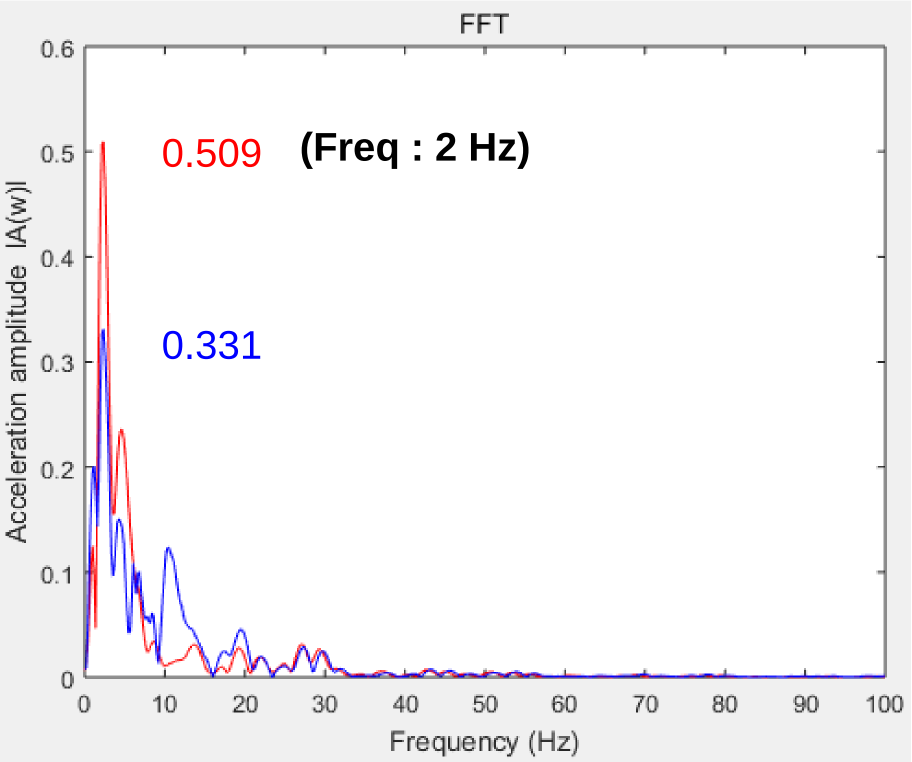


Simulation Result (Frequency)

② Skyhook On-Off



Skyhook Continuous

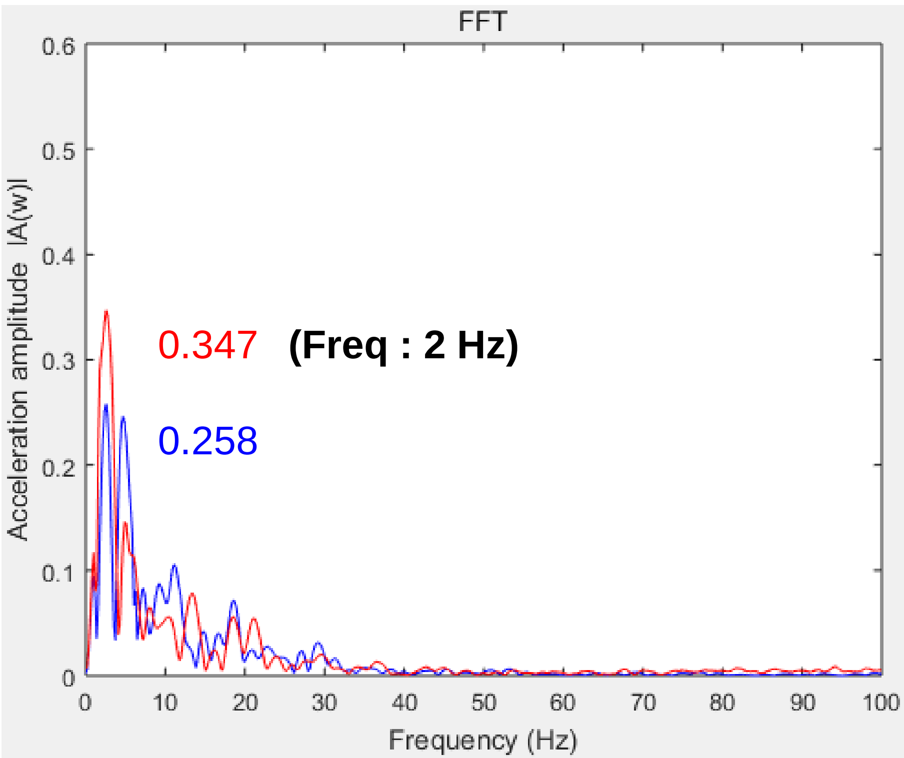


Macpherson

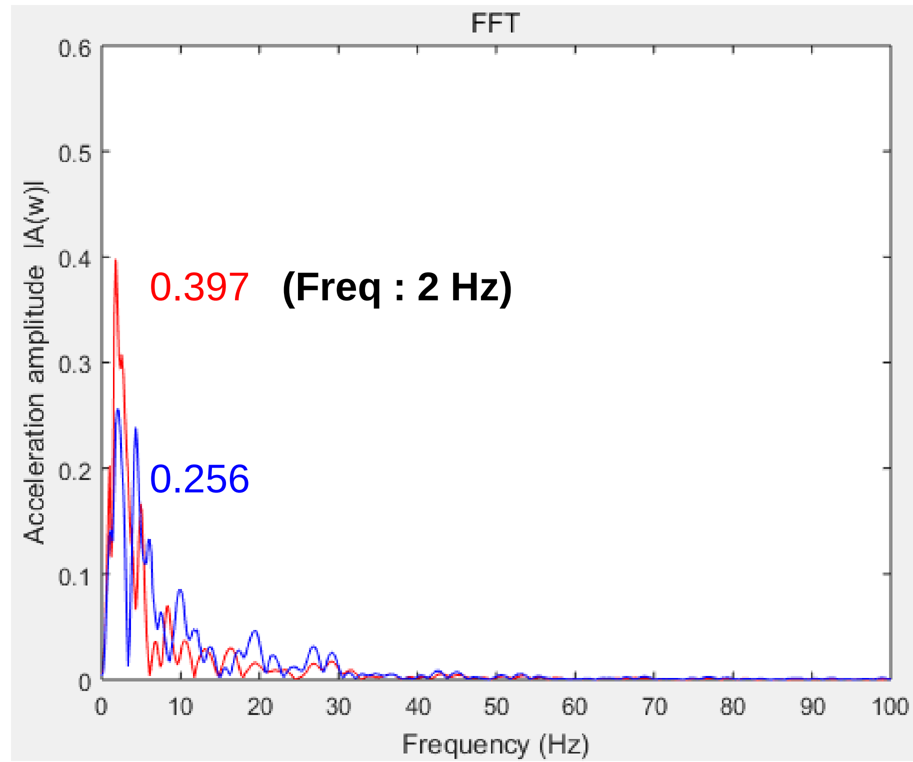
Double wishbone

Simulation Result (Frequency)

③ Balance On-Off



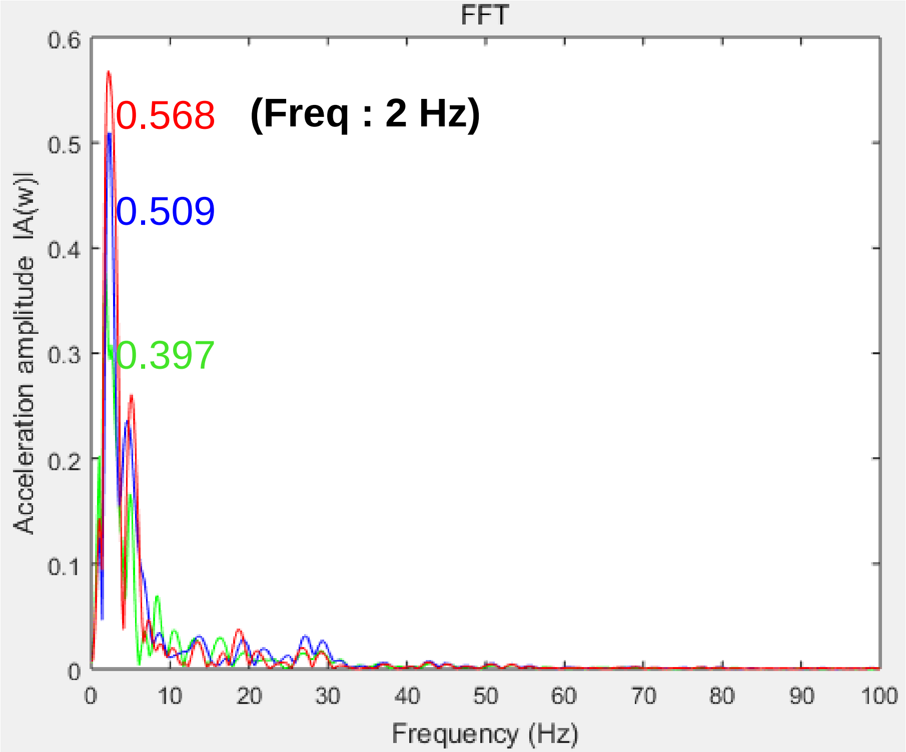
Balance Continuous



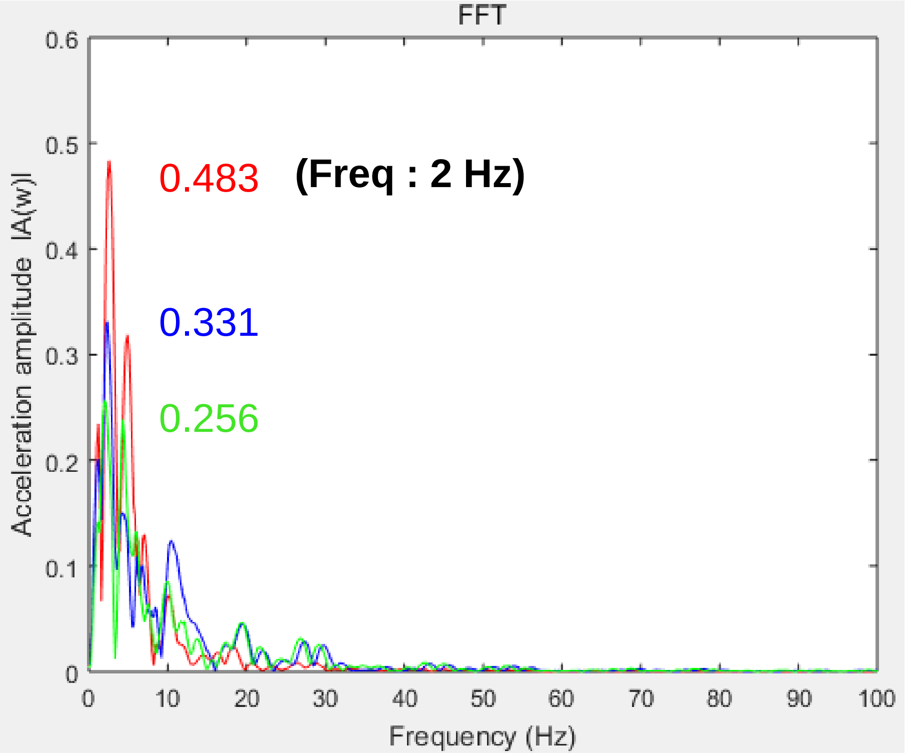
Macpherson Double wishbone

Simulation Result (Frequency)

Macpherson type



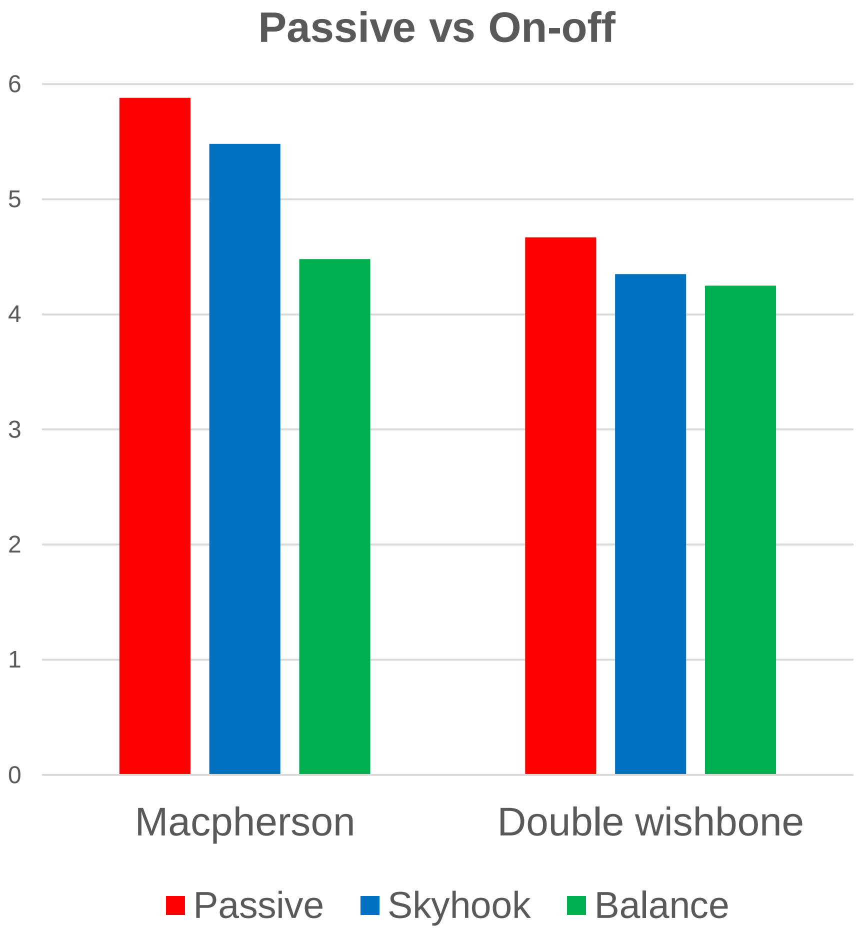
Double wishbone type

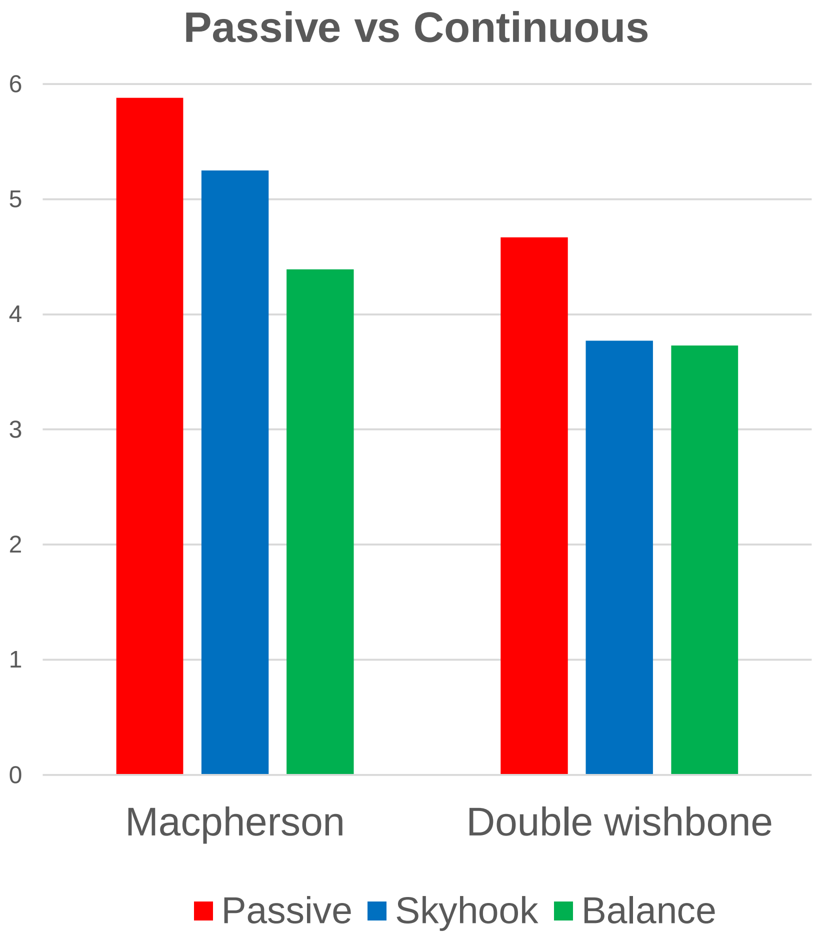


Passive Skyhook Balance

Comparison

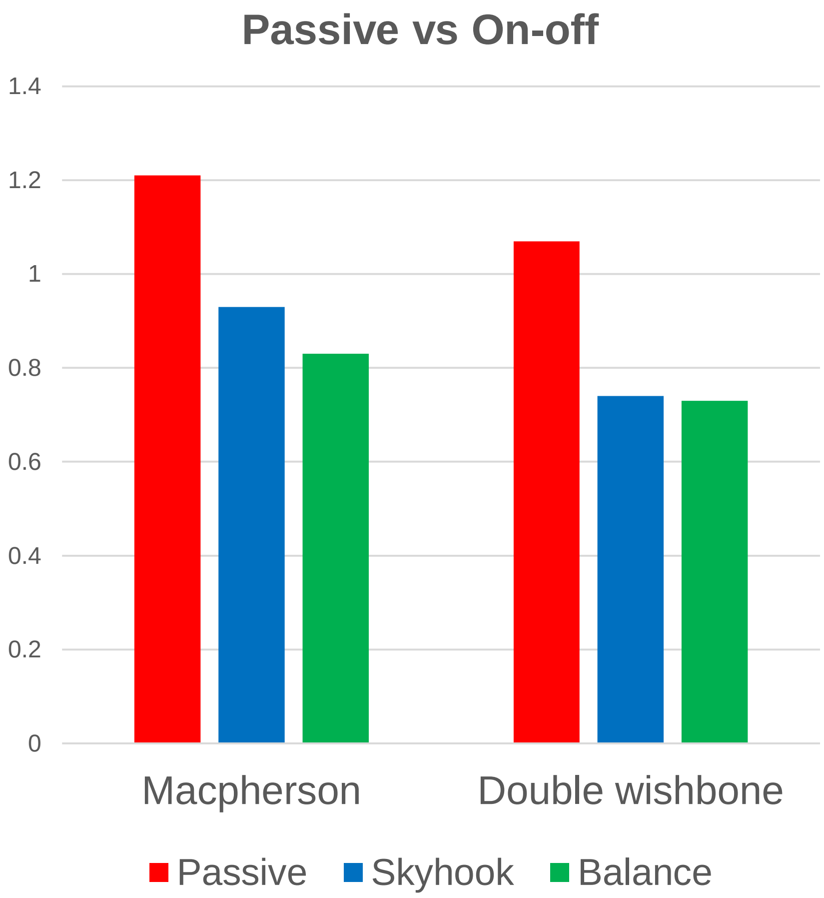
- *Maximum acceleration* (Time domain)

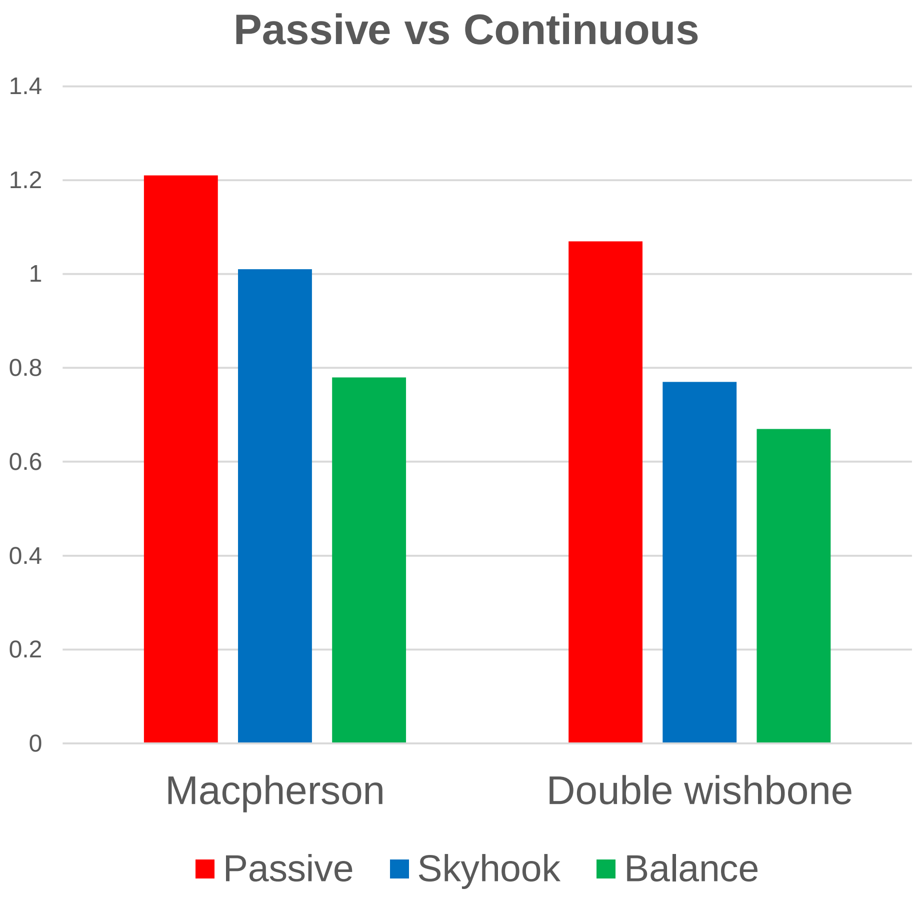




Comparison

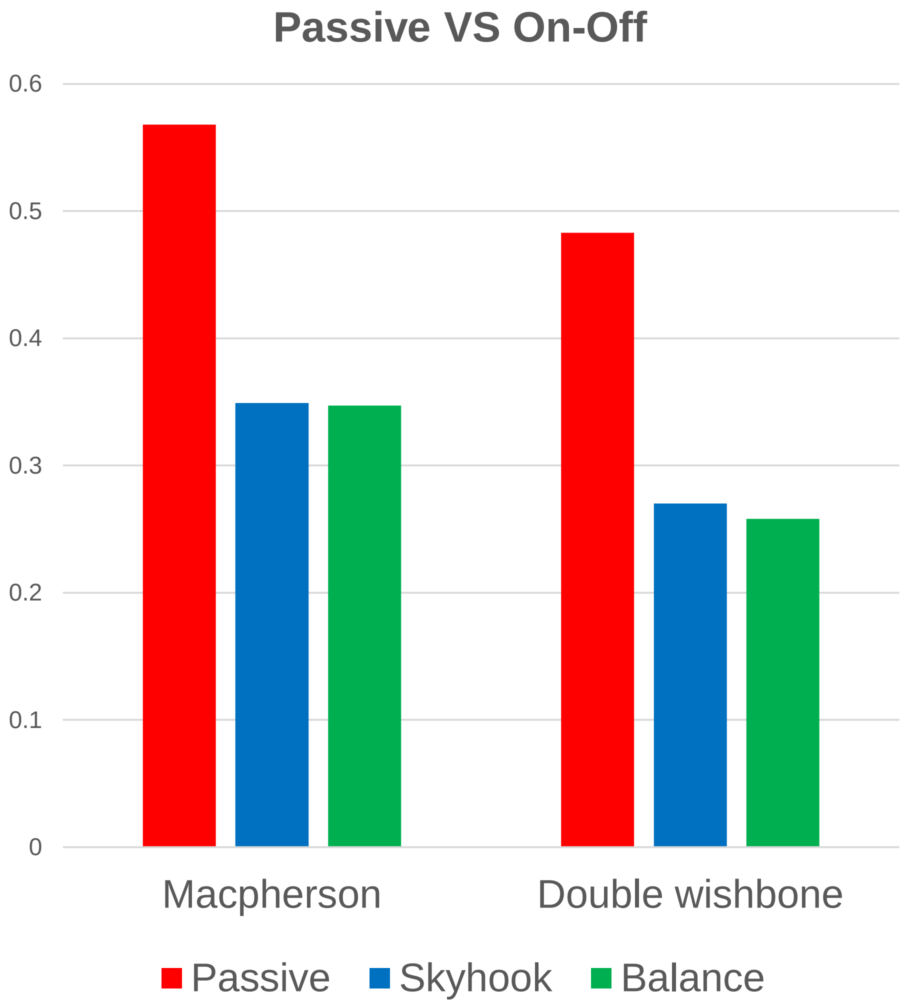
- *RMS value of acceleration* (Time domain)

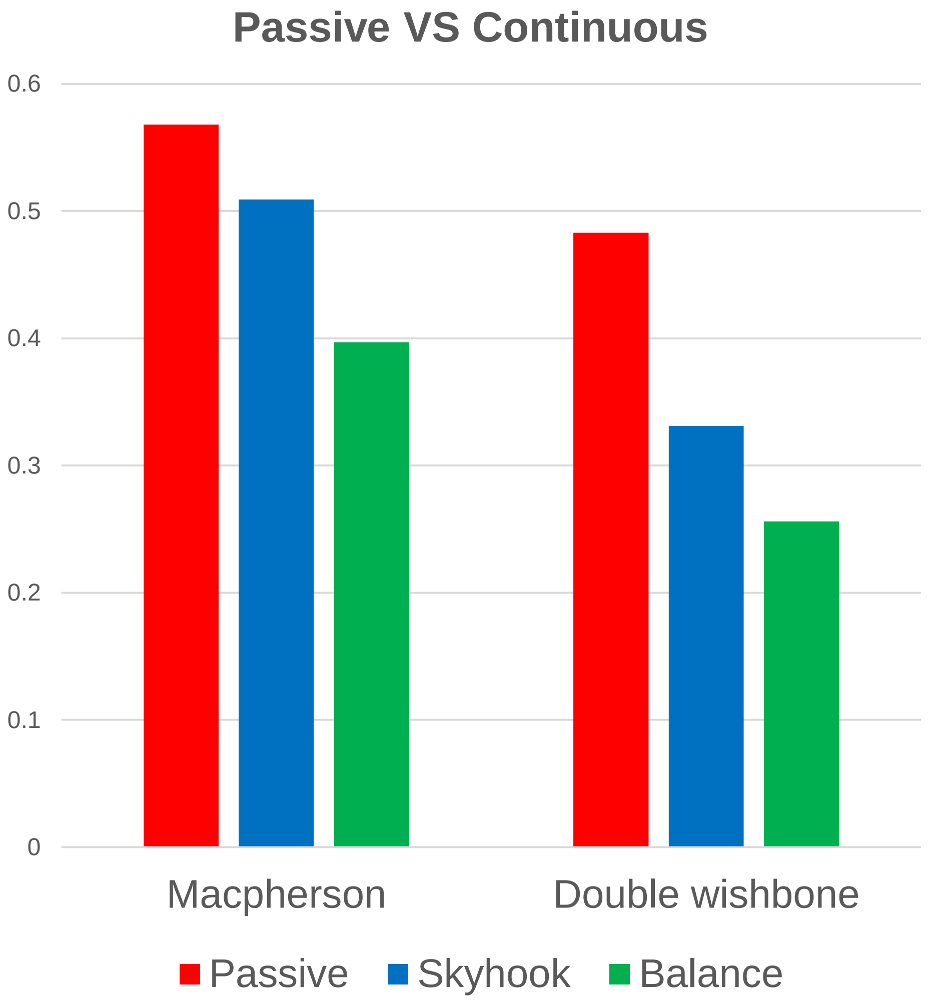




Comparison

- *Peak value near 2Hz* (Frequency domain)





Conclusion

- Ride comfort comparison using body acceleration

- (Time domain) Low maximum acceleration & low RMS mean that it has good ride comfort
- (Frequency domain) Near 2Hz, low peak value means it has good ride comfort

- Ride comfort

- Macpherson < Double wishbone

- Passive < Sky-hook control < Balance control

- Near fundamental frequency of car (2Hz) : Passive << Semi - active

Future work

- **Changing Parameter**

→ Spring stiffness, damping coefficient , mass

- **Changing Driving condition**

→ Bump size, velocity, random road input

- **Optimization**

→ Tuning for optimal damping coefficient

References

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Comparison

- *Comparative study* (Time domain)

Input	Controller		Maximum				RMS			
			Macpherson		Double wishbone		Macpherson		Double Wishbone	
			Acc. [m/s^2]	Diff. (%)	Acc. [m/s^2]	Diff. (%)	Acc. [m/s^2]	Diff. (%)	Acc. [m/s^2]	Diff. (%)
Bump	Passive		5.88	0	4.67	0	1.21	0	1.07	0
	Sky-hook	On-Off	5.48	-6.80	4.35	-6.85	0.93	-23.14	0.74	-30.84
		Continuous	5.25	-10.71	3.77	-19.27	1.01	-16.53	0.77	-28.03
	Balance	On-Off	4.48	-23.81	4.25	-8.99	0.83	-31.41	0.73	-31.77
		Continuous	4.39	-25.34	3.73	-20.12	0.78	-35.53	0.67	-37.38

Comparison

- *Comparative study* (Frequency domain)

Input	Controller		Peak value (Freq : 2Hz)			
			Macpherson		Double wishbone	
			Acc. Magnitude	Diff. (%)	Acc. Magnitude	Diff. (%)
Bump	Passive		0.568	0	0.483	0
	Sky-hook	On-Off	0.349	-38.55	0.270	-44.09
		Continuous	0.509	-10.38	0.331	-31.47
	Balance	On-Off	0.347	-38.9	0.258	-46.58
		Continuous	0.397	-30.1	0.256	-46.99