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Review of Wearable Human Extremity Exoskeleton and Research on Crucial Technologies

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February，2019

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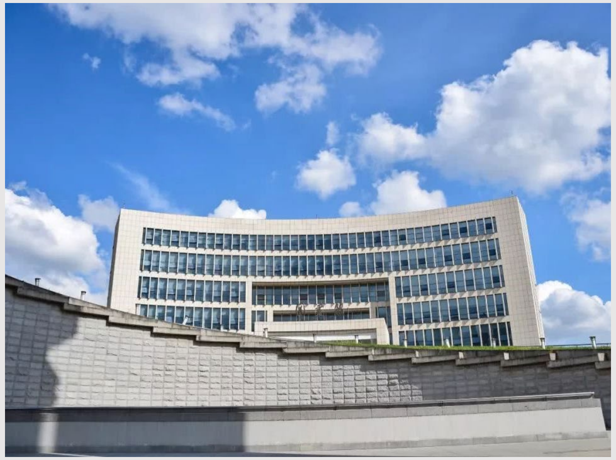
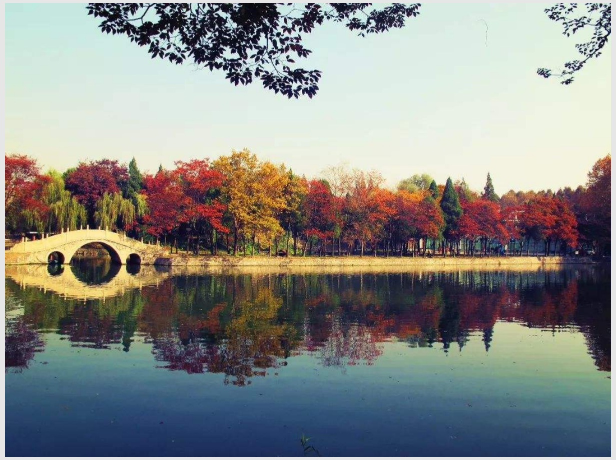
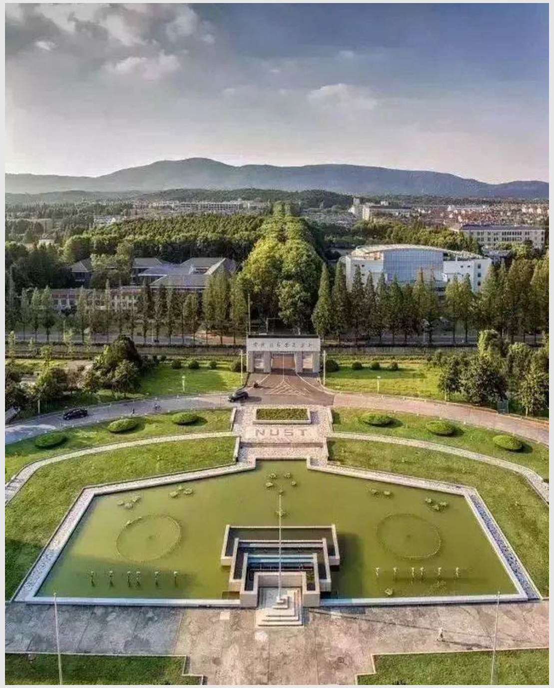






Welcome to Nanjing & NUST

CONTENTS

PART ONE

Review of Research Activities on WHEE

Part 01 → Preface

An exoskeleton is the external skeleton that supports and protects an animal's body, in contrast to the internal skeleton "endoskeleton"

Exoskeletons contain rigid and resistant components that fulfill a set of functional roles in many animals including protection, excretion, sensing, support, feeding and acting as a barrier against desiccation in terrestrial organisms

Wearable Human Extremity Exoskeleton (WHEE) is a wearable mobile machine that is powered by a system of electric motors, pneumatics, levers, hydraulics, or a combination of technologies that allow for limb movement with increased strength & endurance

Part 01 → Background

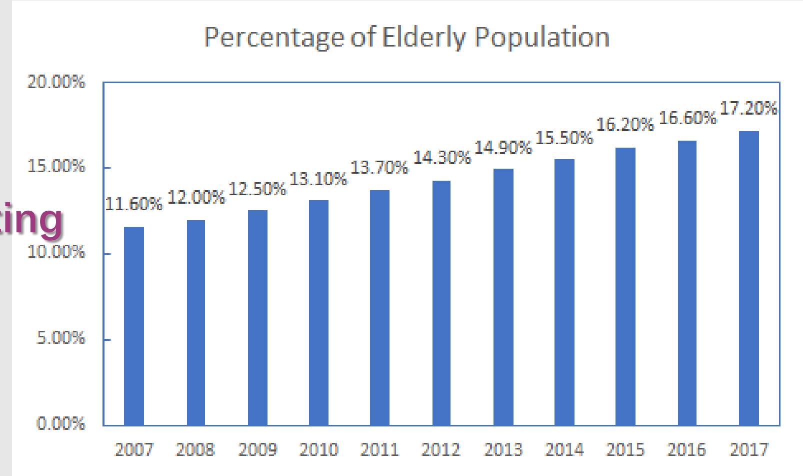

Wheeled Transport,
Impossible

Air Transport,
High Cost

Firefighting Load
Costing much

?

Aging Aggravating



The Disabled & Ailing
Population Increasing

Industrial Work Load
Being Enhanced

Part 01 → Achievements of WHEE

Before 2000

Leslie, USA, 1917
“Pedomotor”
Assist Walking
With Steam Power

Nicolas, Russia, 1890
Helping to Run & Jump
With Spring Steel Plate

GE, USA, 1960
“Hardiman”
First Active WHEE
SW 680kg, 30 DOF
Strengthening Human
Power 25 Times

Dick & Edwards, 1990
“Spring Walker”
Helping to Run & Jump
MV 50km/h
With Leverage Principle

Part 01 → Achievements of WHEE

«« After 2000 »» Classification

Strengthening Power & Motion	1	Military	BLEEX, HULC Soft Exosuit
	2	Aerospace	NASA X-1
	3	Industry	Fortis, DSME Honda Walking Assist
	4	Firefighting & Rescue	HERCULE, WAS PAS
Assisting Disabled & Ailing	1	Paralysis & Spinal Injury	Rewalk, eLEGs HAL-5, Indego, Rex
	2	Stroke & Sports Injury	LOPES EXPOS

Part 01 → Key Technologies

01 Biomimetic Structure Design

02 Motion Prediction

03 Control Scheme

04 Drive Mode

05 Power Source

06 Effectiveness Assessment

?

Part 01→Key Technologies

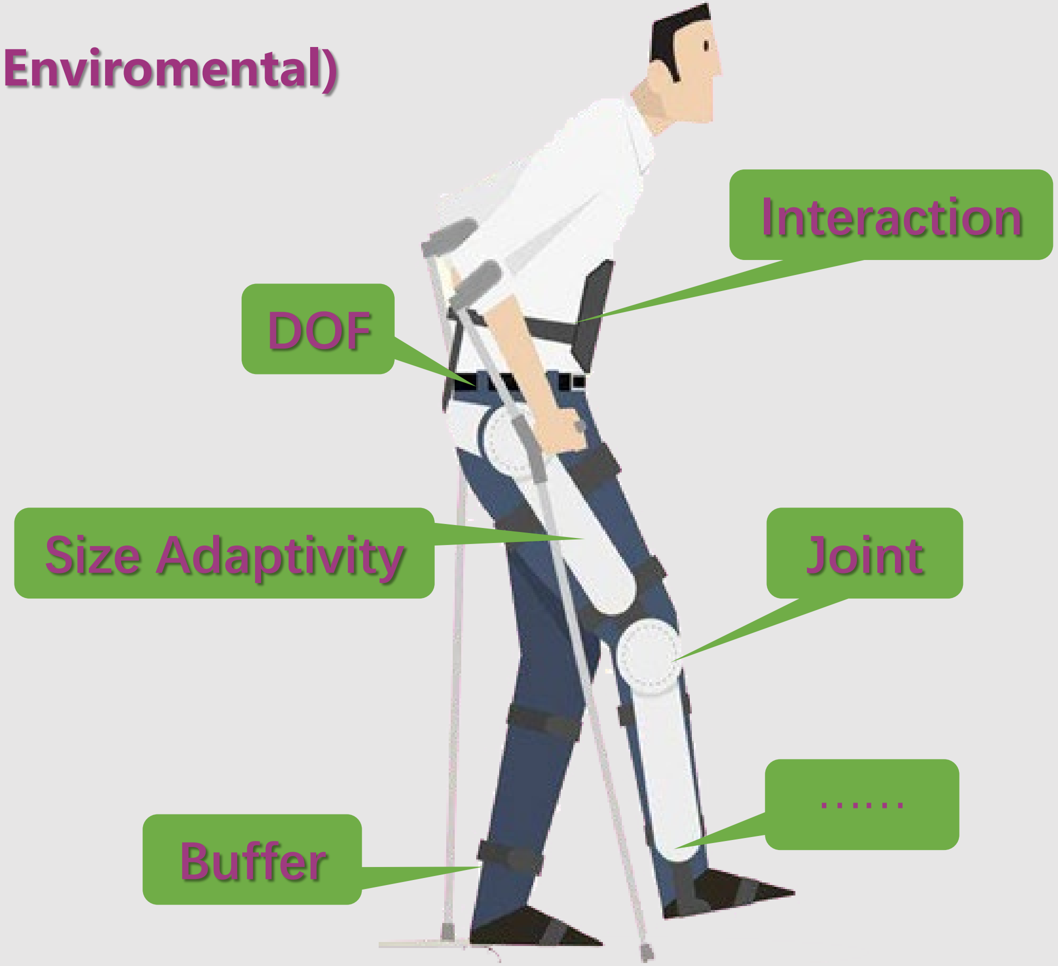
Biomimetic Structure Design

Materials

Requirements

- Adaptivity (Wearer & Enviromental)
- Interference
- Bionics
- Comfort
- Lightweight
- Strength
- Flexibility
- Safety

Design Contents



Part 01 → Key Technologies

Motion Prediction

Requirements

- Accuracy
- Response Speed
- Reliability
- Adaptivity

Sensor
- Force Sensor
- Posture Sensor
- Bioelectricity Sensor
- ……

Algorithm
- Multi-sensor Fusion
- Combined with Motion Control
- ……

Part 01 → Key Technologies

Control Scheme

- Harmony
- Accuracy
- Self Learning
- Real Time
- Adaptivity

	Pre-programming	Direct Force Feedback	Ground Force Feedback	ZMP	EMG	Operator	Master-Slave	Sensitivity Amplification
Operator Adaptivity	2	3	2	1	1	5	1	1
Motion Adaptivity	1	5	5	5	2	1	5	3
Motion Stability	2	5	2	5	1	1	5	1
Ergonomics	5	2	4	2	5	5	2	4
Sensors on Wearer	5	2	3	1	1	3	2	1
Sensors on Machine	4	3	1	1	3	3	4	1
Hardware Requirement	5	2	2	3	5	5	1	2
Computational Load	3	3	1	4	2	5	4	5

Part 01 → Key Technologies

Drive Mode

Requirements

- Power Density (weight & size)
- Flexibility (Variable Stiffness)
- Accuracy
- Safety

	Advantages	Disadvantages
Hydraulic Drive	• High Reliability • Smooth Work • Small Inertia • Overload Protection • Stepless Speed Regulation	• High Sensitivity to Load & Oil Temperature • Easy Leakage of Oil
Motor Drive	• High Response • High Standardization • High Automation • Simple Construction • Low Pollution	• Low Motion Balance • High Sensitivity to Load • High Inertia • Slow Reversal • Large Volume
Pneumatic Drive	• Simple Construction • Low Cost • Stepless Speed Regulation • Low Pollution • Low Resistance Loss	• Easy Compressibility and Leakage of Air • High Sensitivity to Load • Low Accuracy • Difficult Sealing • Fit Low Power Drive

Part 01 → Key Technologies

Power Source

Requirements

- High Energy Density
- Long Charge Life
- Safety
- Light Weight

	Energy Density (Wh/kg)	Charge Life (Times)
Lead-Acid Battery	25	1000 - 2000
Ni-Cd Battery	45 - 80	3000
Zinc Bromide Battery	70	-
Sodium-Sulfur Battery	100	2500
Lithium Battery	90 - 190	3000
Gasoline	11963	-

Effectiveness Assessment

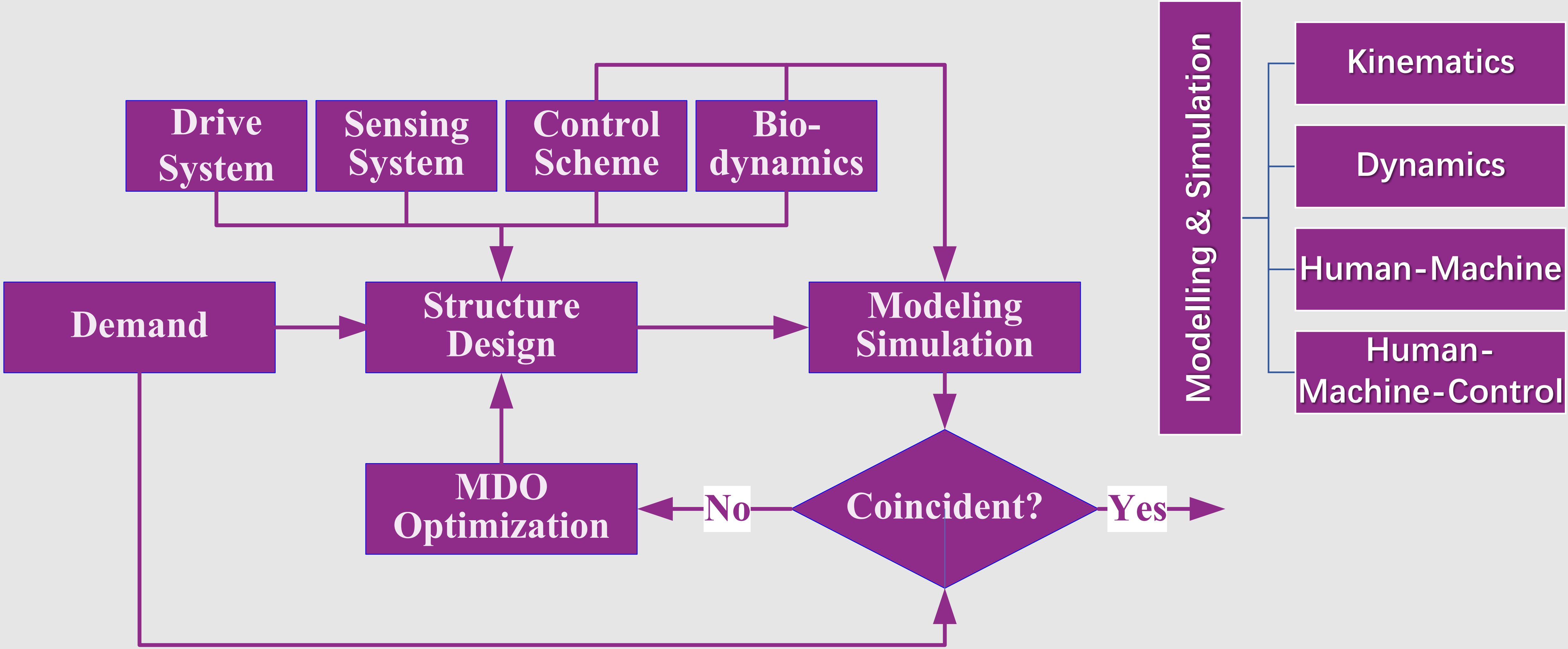
Problems

- Obvious Differences from Subjective & Qualitative Assessments
- No Standards
- Difficulty in Obtaining Human Indices

PART TWO

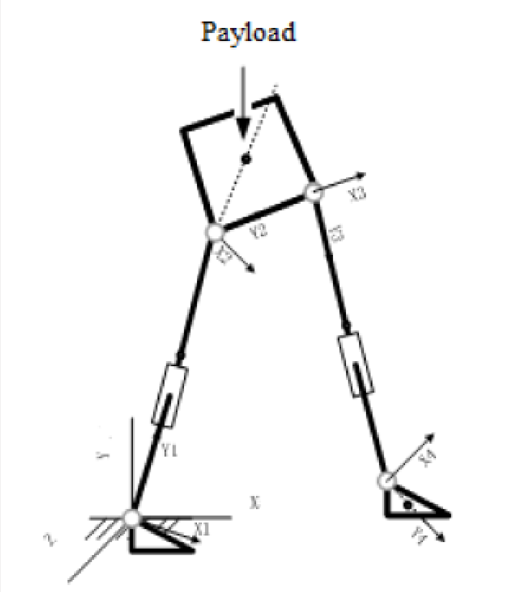
Work Related to WHEE Performed by NUST Team

Part 02 → Way to Design Biomimetic Structure



Kinematics, Dynamics & Human-Machine Coupled Simulation

Lagrange Mechanics Theory Adopted Here



Angular Velocity of Mass Center

$$[\omega_{i0}]=[\Delta_{i0}]/dt=\begin{bmatrix}0 & -\omega_{i0z} & \omega_{i0y}\\ \omega_{i0z} & 0 & -\omega_{i0x}\\ -\omega_{i0y} & \omega_{i0x} & 0\end{bmatrix}=\begin{bmatrix}0 & -\omega_{i0z} & 0\\ \omega_{i0z} & 0 & -\omega_{i0x}\\ 0 & \omega_{i0x} & 0\end{bmatrix}$$

Velocity of Mass Center

$$[v_{i0}]=\left[\dot{P}_{i0}\right]=[\dot{S}_{i0}]+[R_{i0}]\left[\dot{P}_{ii}\right]+[\omega_{i0}][R_{i0}][P_{ii}]$$

Space Coordinate Transformation

$$\begin{bmatrix}P_a\\1\end{bmatrix}=[T_{ab}]\begin{bmatrix}P_b\\1\end{bmatrix}=\begin{bmatrix}R_{ab} & S_{ab}\\0 & 1\end{bmatrix}\begin{bmatrix}P_b\\1\end{bmatrix}$$

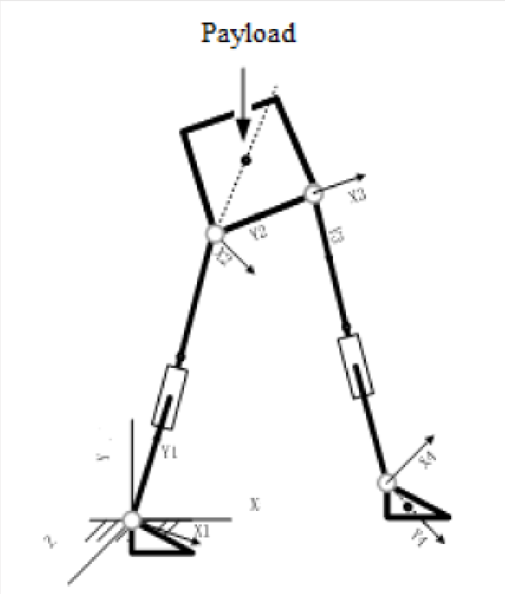
Gravitational Potential Energy

$$N_i=m_i g y_{Gi0}$$

Part 02 → Way to Design Biomimetic Structure

Kinematics, Dynamics & Human-Machine Coupled Simulation

Lagrange Mechanics Theory Adopted Here



Translational Kinetic Energy

$$K_{Gi0}^{v} = \frac{1}{2} m_{Gi} [v_{i0}]^{T} [v_{i0}]$$

Rotational Kinetic Energy

$$K_{Gii}^{\omega} = \frac{1}{2} I^{ii} \left[\omega_{i0x}{}^{2} \quad \omega_{i0y}{}^{2} \quad \omega_{i0z}{}^{2} \right]^{T}$$

Lagrange Equations

$$\begin{cases} T_{\alpha_i} = \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{\alpha}_i} - \dfrac{\partial L}{\partial \alpha_i} \ldots\ldots\ldots\ldots\ldots (\text{Rotational joint}) \\ F_{l_i} = \dfrac{d}{dt}\dfrac{\partial L}{\partial \dot{l}_i} - \dfrac{\partial L}{\partial l_i} \ldots\ldots\ldots\ldots\ldots (\text{Translational joint}) \end{cases}$$

Space Coordinate Transformation

$$\begin{bmatrix} P_a \\ 1 \end{bmatrix} = [T_{ab}] \begin{bmatrix} P_b \\ 1 \end{bmatrix} = \begin{bmatrix} R_{ab} & S_{ab} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} P_b \\ 1 \end{bmatrix}$$

Establish the 3d model of every part

Obtain the angle curve of Clinical Gait Analysis （CGA） by measuring or based on the gait database

Import the 3d models and the angle curve of Clinical Gait Analysis into the Adams

Drive the human body model by the angle curve of Clinical Gait Analysis to calculate out the angle curve （curve of angle changing with time） of every DOF of the lower extremity exoskeleton in Adams.

Get rid of the human body model， driving every DOF of the lower extremity exoskeleton model by the angle curve to calculate out the pressure curve of the four hydraulic cylinders of the lower extremity exoskeleton in Adams

Simulate the coupled model of human body, lower limb exoskeleton and payload to calculate out the torque curves and power curves of every DOF of human body in Adams

Simulate the model of human body directly bearing load to calculate out the torque curves and power curves of DOF of human body in Adams

Simulate the model of human body without bearing load to calculate out the torque curves and power curves of every DOF of human body in Adams

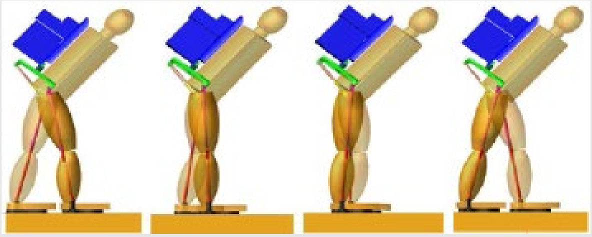
Get the energy consumption of every DOF of human body by integrating the power curves. In order To analysis the auxiliary effect of the lower extremity exoskeleton by comparing the torque and the energy consumption of the three models.

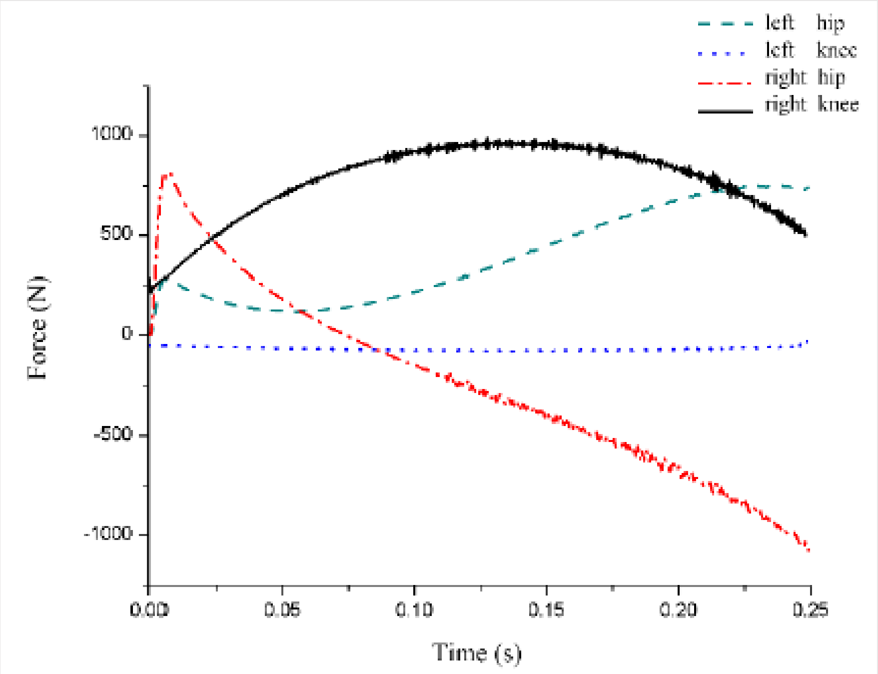
Simulation Flow

Part 02 → Way to Design Biomimetic Structure

Kinematics, Dynamics & Human-Machine Coupled Simulation

Parameters	Value
Part	22
Translational Joint	4
Spherical Joint	5
Hook Joint	2
Revolute Joint	2
Fixed Joint	9
Rotational Motion	2
General Motion	4
Force Motion	4
Spline	14
Payload	100 Kg
Process Time	0.25 s
Half Stride	377.75 mm
Walk Speed	1.511 m/s





Pressure of Hydraulic Cylinder

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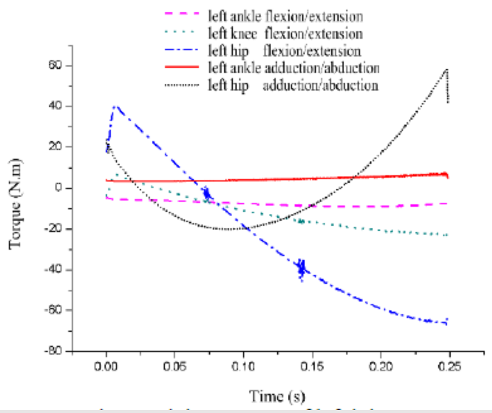
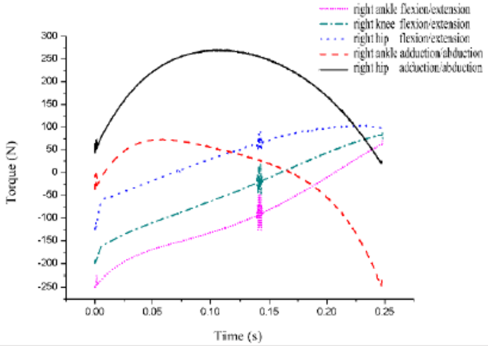
Part 02 → Way to Design Biomimetic Structure

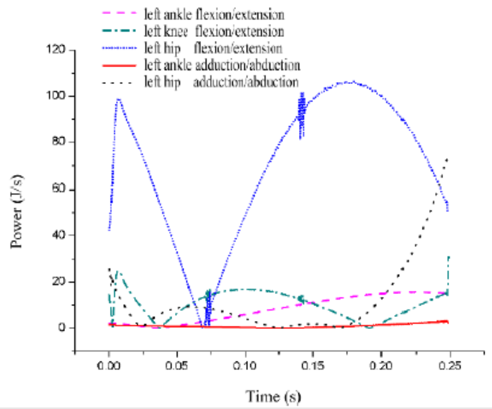
Kinematics, Dynamics & Human-Machine Coupled Simulation



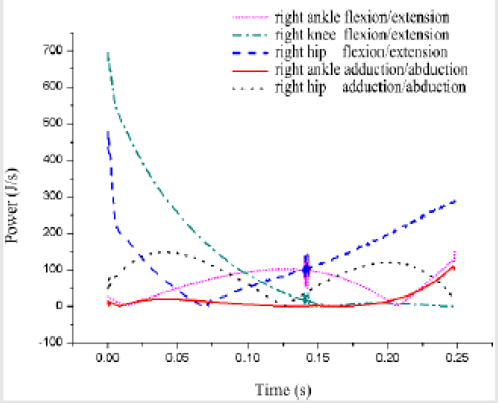
Drive Torques of Left Joints



Drive Torques of Right Joints



Drive Power of Left Joints



Drive Power of Right Joints

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Part 02 → Way to Design Biomimetic Structure

Kinematics, Dynamics & Human-Machine Coupled Simulation

Drive Torques of Different Models

Case	I		II		III	
DOF	fle/ext	add/abd	fle/ext	add/abd	fle/ext	add/abd
Torque of right ankle, Nm	-58~-33	-84~26	-249~60	-249~72	-249~89	-264~36
Torque of right knee, Nm	-55~26		-198~82		-208~139	
Torque of right hip, Nm	-44~109	-3~122	-124~99	20~269	-118~177	0.2~217
Torque of left ankle, Nm	-9~-5	0~4	-9~-5	3~7	-9~5	0~4
Torque of left knee, Nm	-37.9~-3		-17~7		-37.9~-3	
Torque of left hip, Nm	-107~21	-20~58	-66~41	-20~58	-107~17	-20~58

Case I: Human Body: Case II: Human Body + WHEE; Case III: Human Body + Payload
fle/ext: flexion/abduction; add/abd: adduction/abduction

The power support effect of WHEE can not be reflected directedly by the range of drive torques

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Part 02 → Way to Design Biomimetic Structure

Kinematics, Dynamics & Human-Machine Coupled Simulation

Energy Consumption of Different Models

Case	I		II		III	
DOF	fle/ext	add/abd	fle/ext	add/abd	fle/ext	add/abd
Energy of right ankle, J	11.9	1.7	15.6	4.0	18.1	4.4
Energy of right knee, J	11.8		31.2		34.7	
Energy of right hip, J	28.3	10.0	32.3	22.3	50.5	36.5
Total energy of right leg, J	63.7		105.4		144.2	
Energy of left ankle, J	2.0	0.1	2.1	0.3	2.0	0.1
Energy of left knee, J	3.6		2.6		3.6	
Energy of left hip, J	25.0	3.0	17.4	2.9	25.0	3.0
Total energy of left leg, J	33.7		25.3		33.7	
Total energy, J	97.4		130.7		177.9	

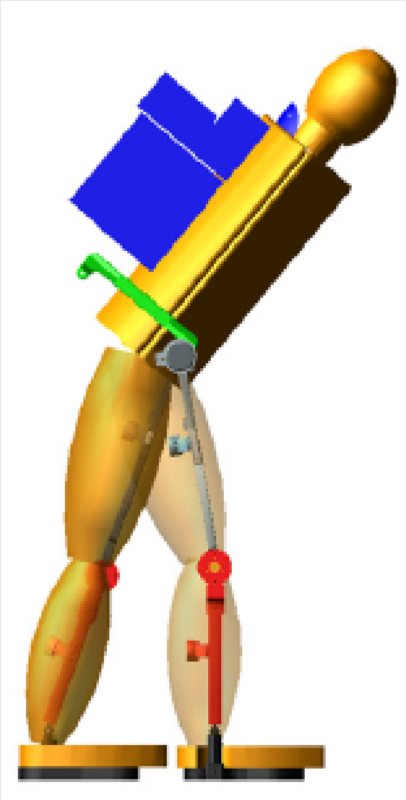
Case I: Human Body: Case II: Human Body+WHEE; Case III: Human Body+Payload
fle/ext: flexion/abduction; add/abd: adduction/abduction

The WHEE can obviously reduce the energy consumption of human body

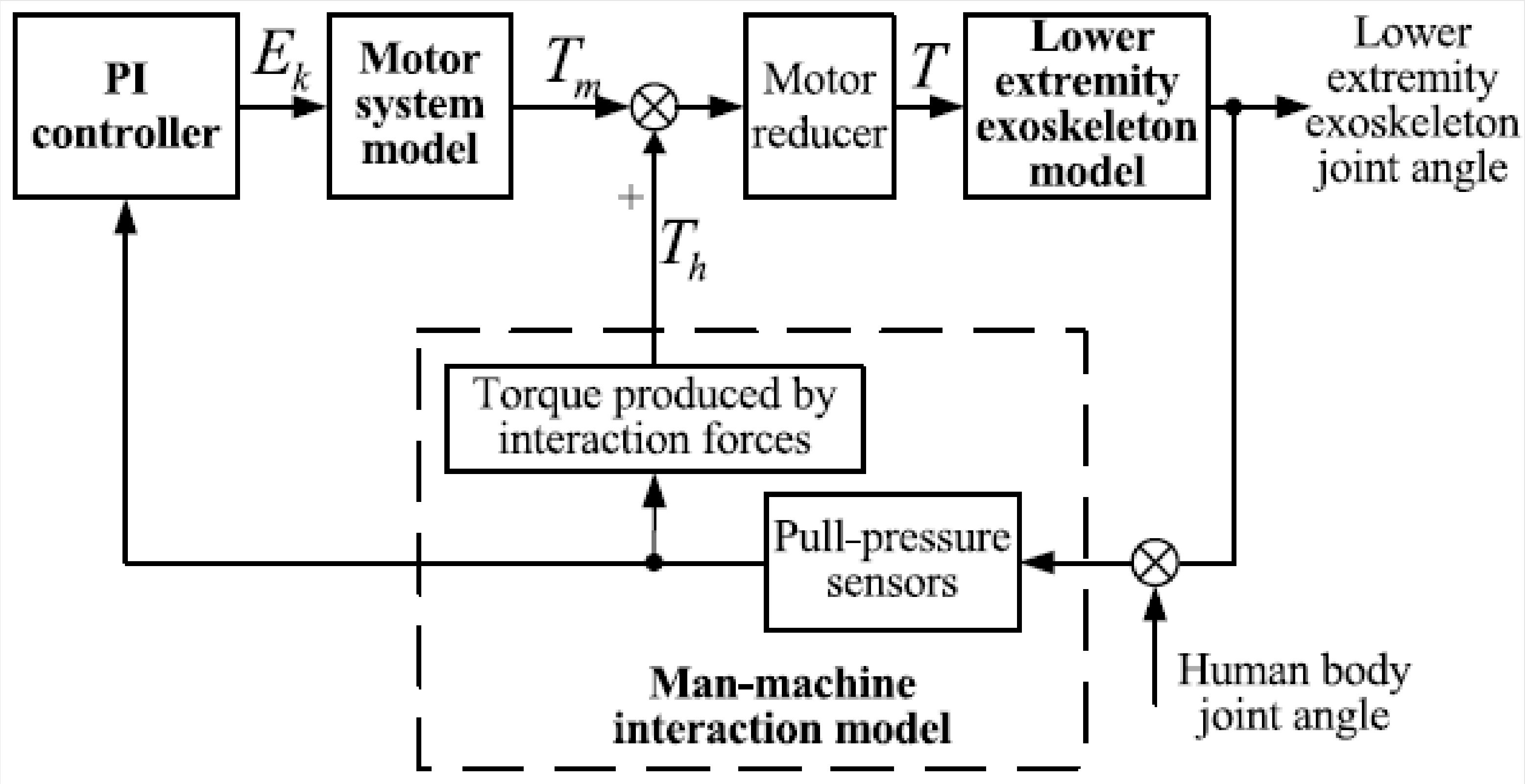
Part 02 → Control Schemes

The Force Control Method is adopted here, and this idea is to minimize the interaction force between human body and machine for reducing energy consumption of human

- **Traditional PI Controller**

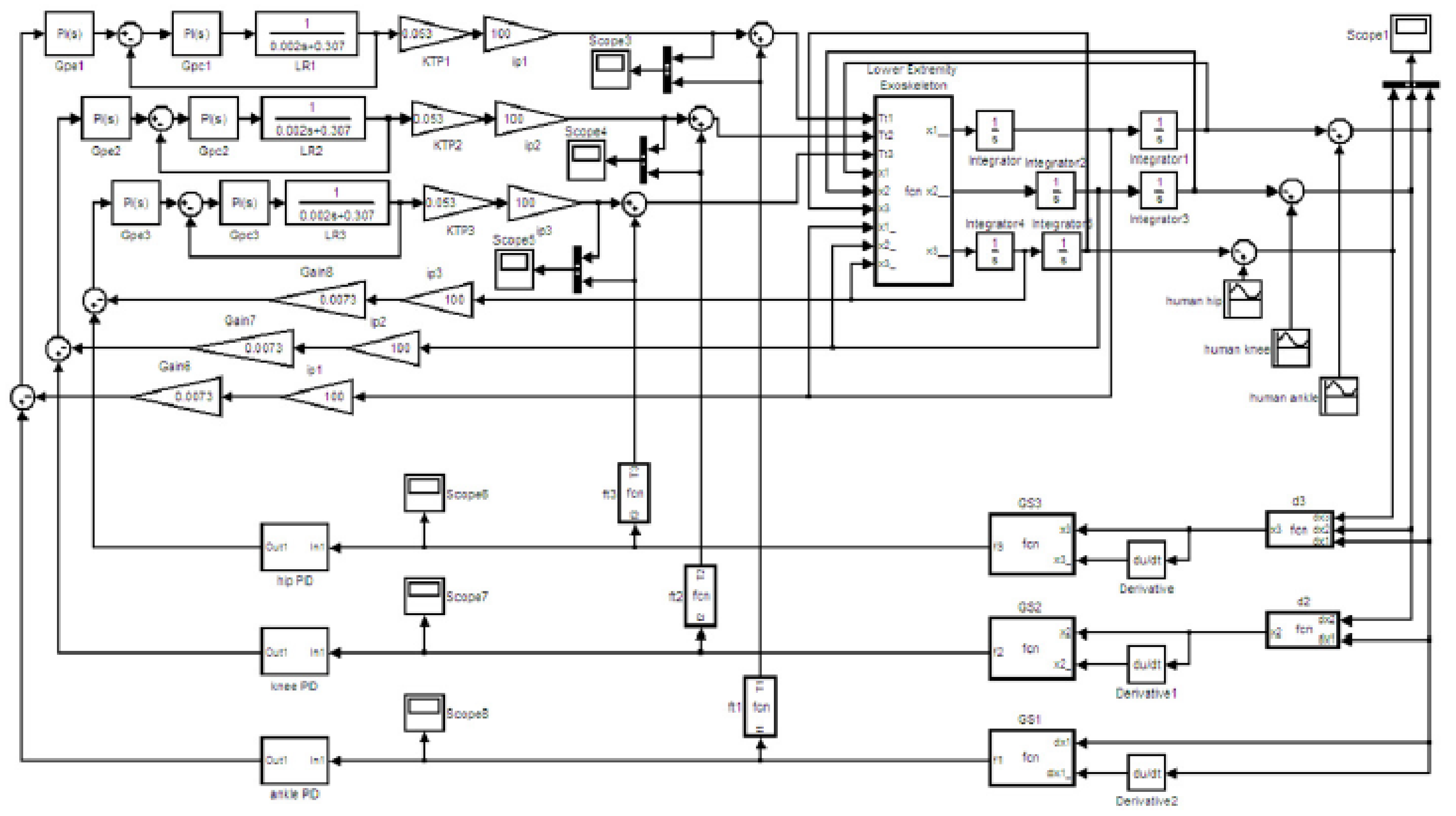


Structure Model

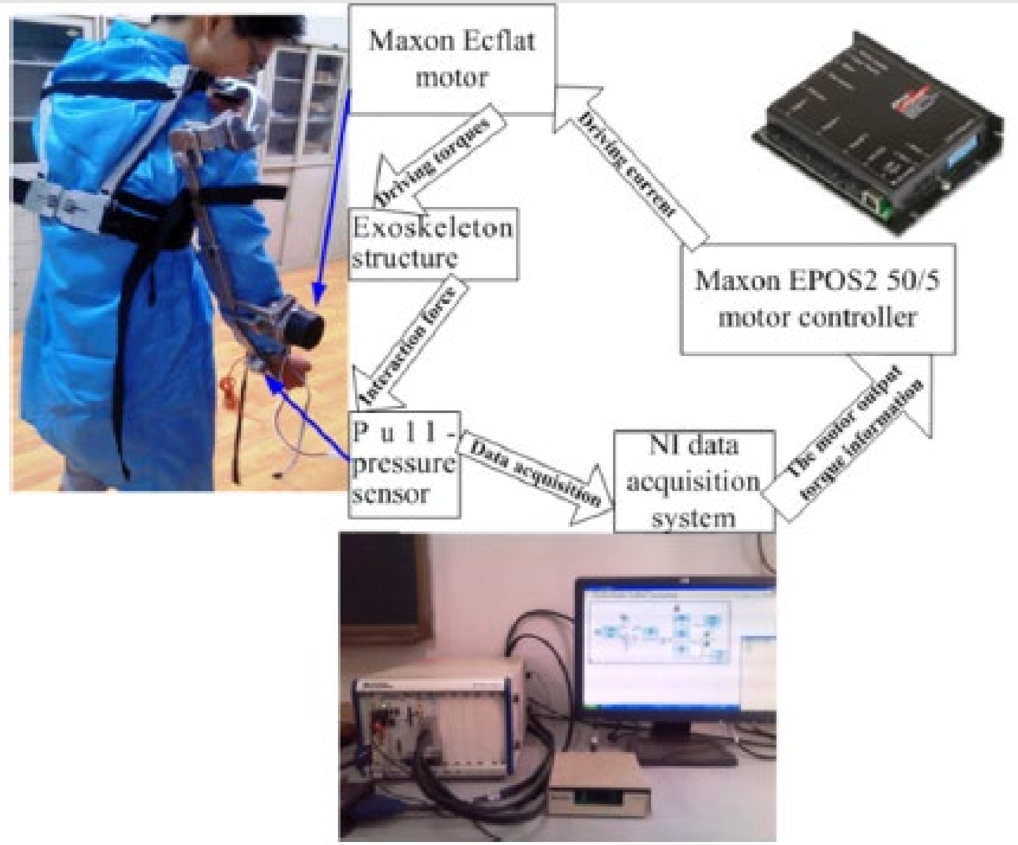


Control Model

Part 02 → Control Schemes



Simulation Model



Experimental Scheme

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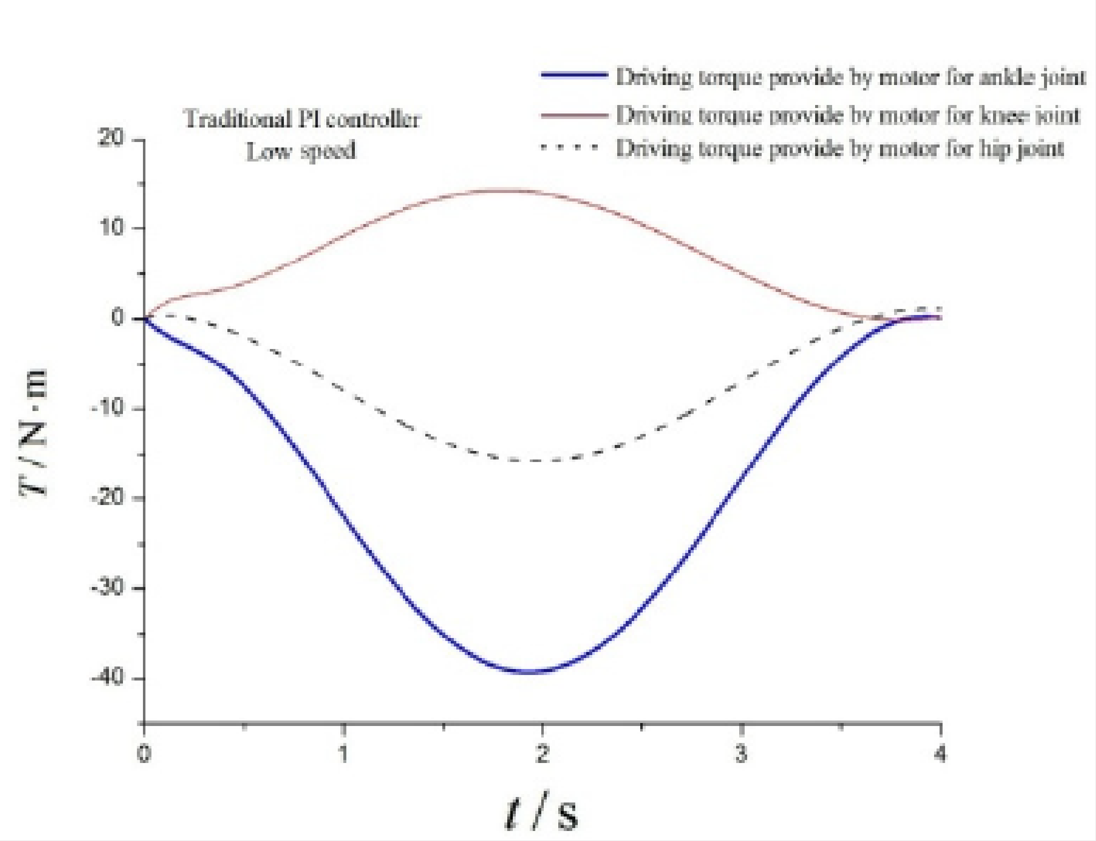
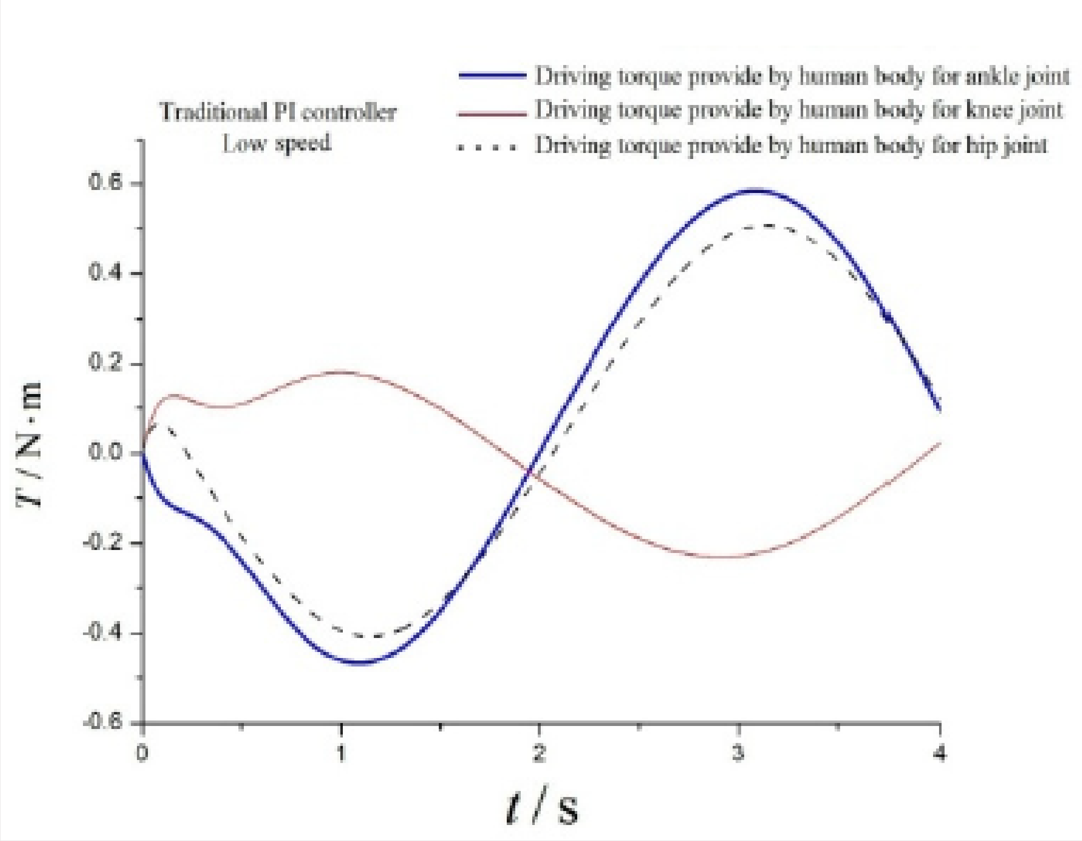
Part 02 → Control Schemes

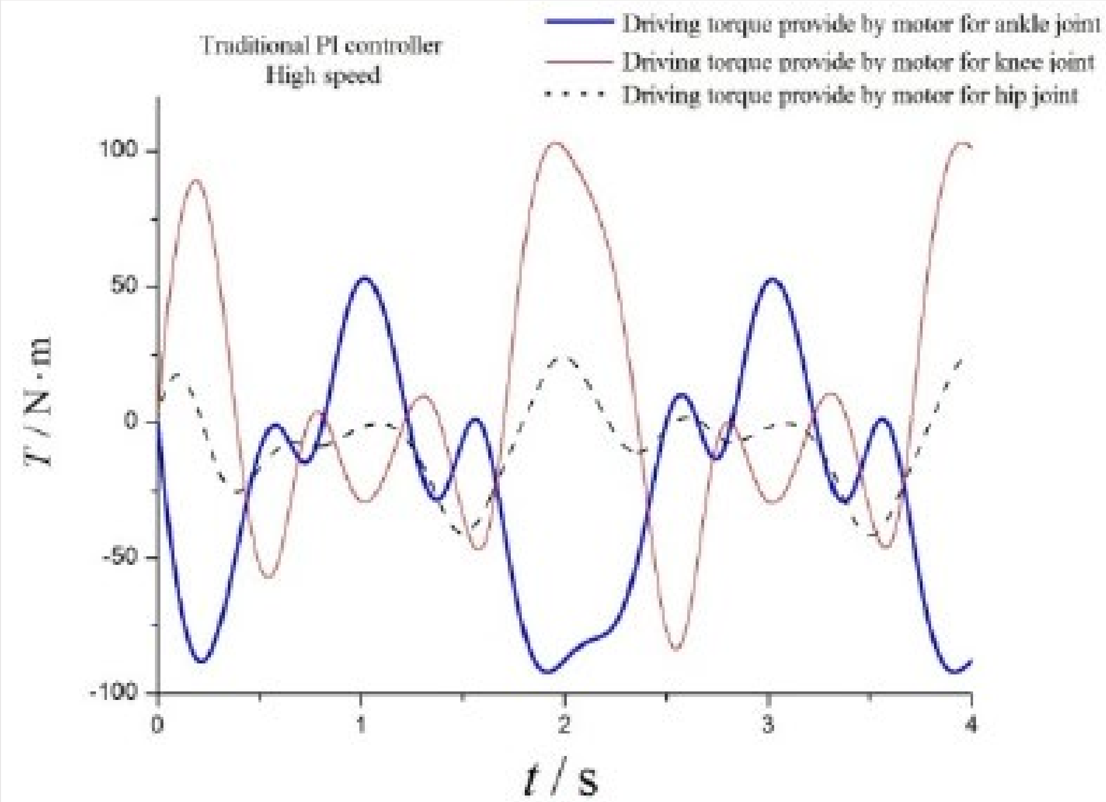


Drive Torque at Low Speed by Motor

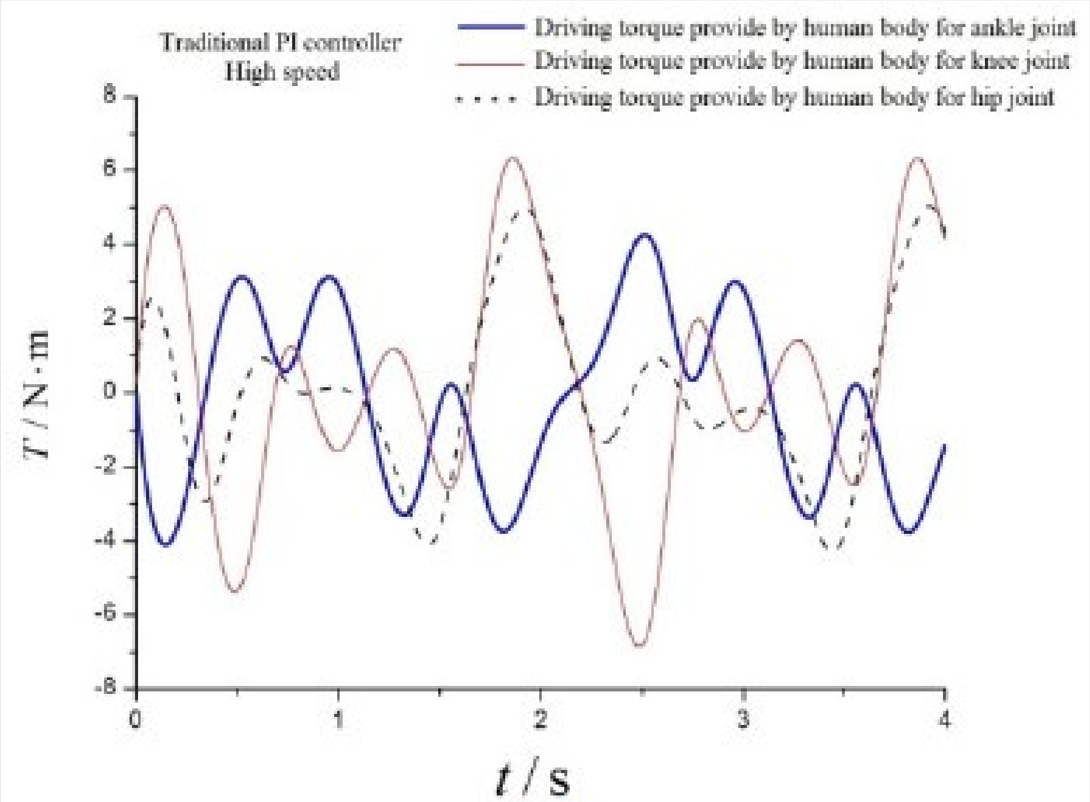


Drive Torque at Low Speed by Human Body

Part 02 → Control Schemes



Drive Torque at High Speed by Motor



Drive Torque at High Speed by Human Body

Human body should provide larger drive torque at high speed than at low speed, and thus the traditional PI controller can not obtain nice effect at high speed

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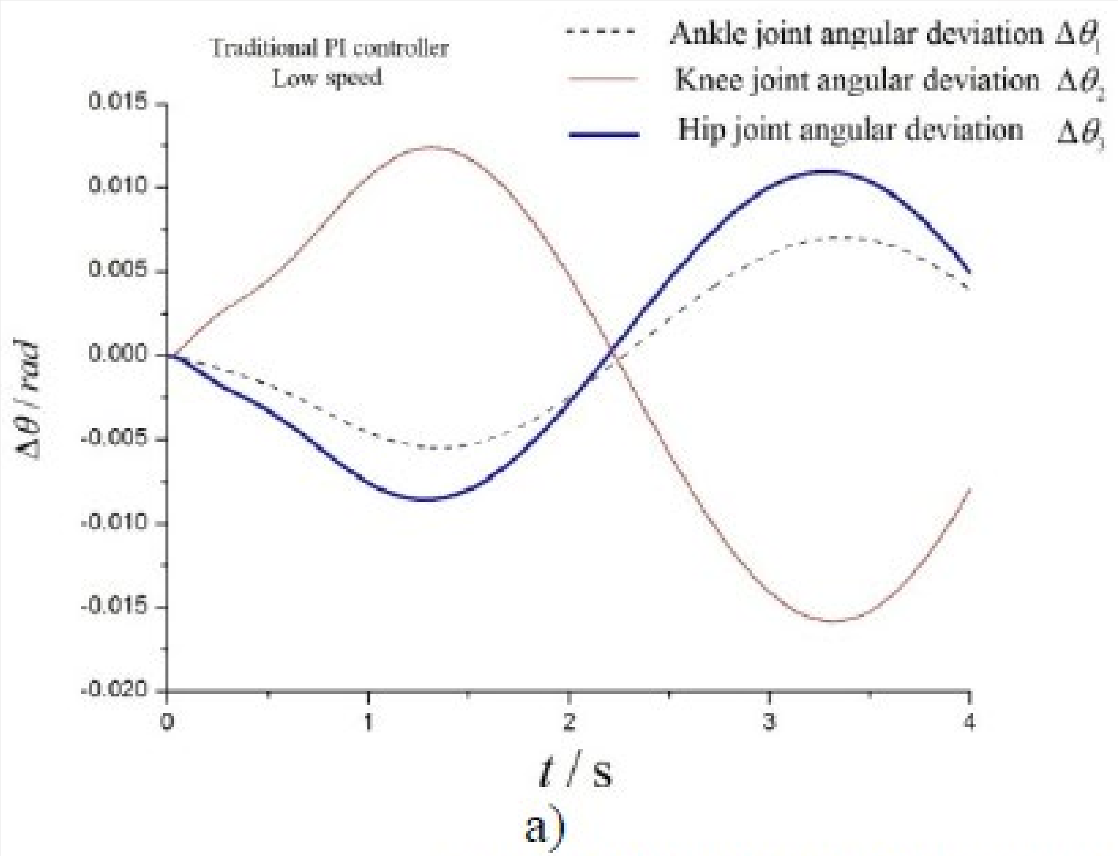
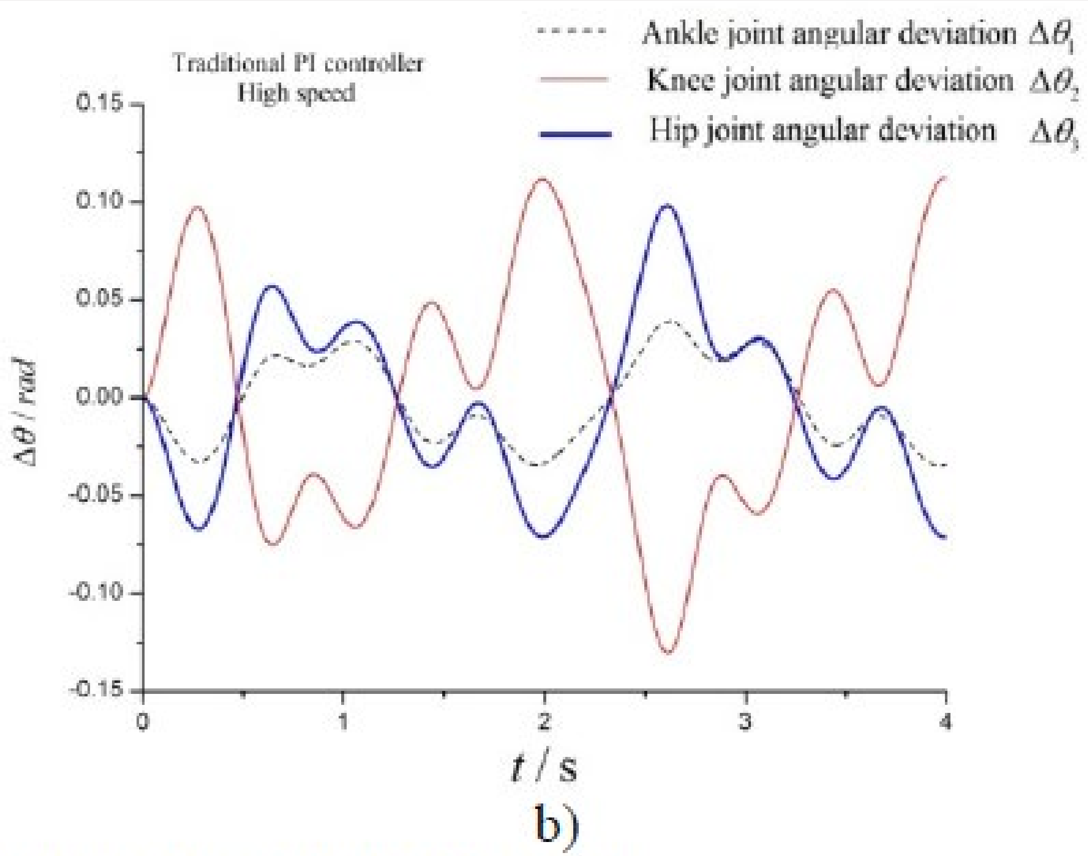
Part 02 → Control Schemes



Angular Deviation at Low Speed



Angular Deviation at High Speed

The angular deviation at high speed becomes bigger, and thus it's unfavorable for the WHEE performance as well as system safety

For the Interaction Force Control Method of WHEE, the traditional PI controller is not efficient, especially at high speed

Thus, the Fuzzy Self-Adaptive PI Controller is advanced

Part 02 → Control Schemes

➢ Fuzzy Self-Adaptive PI Controller

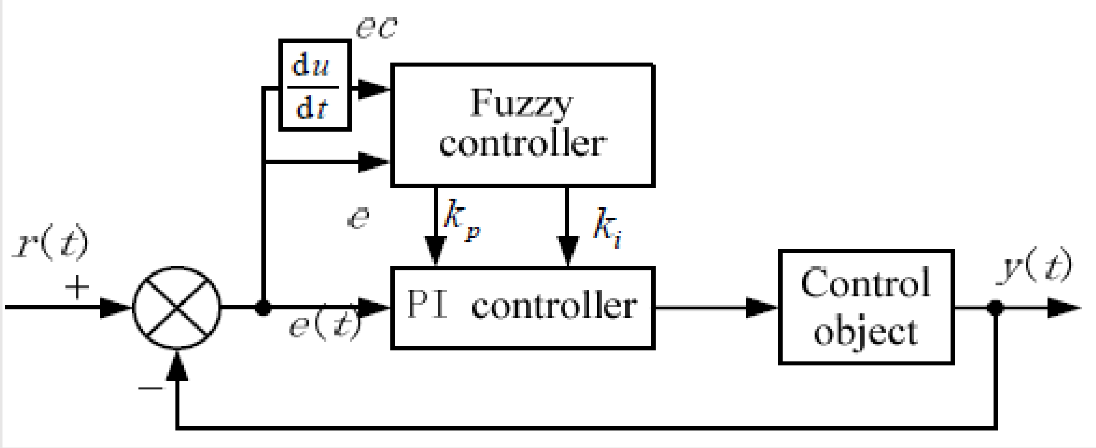
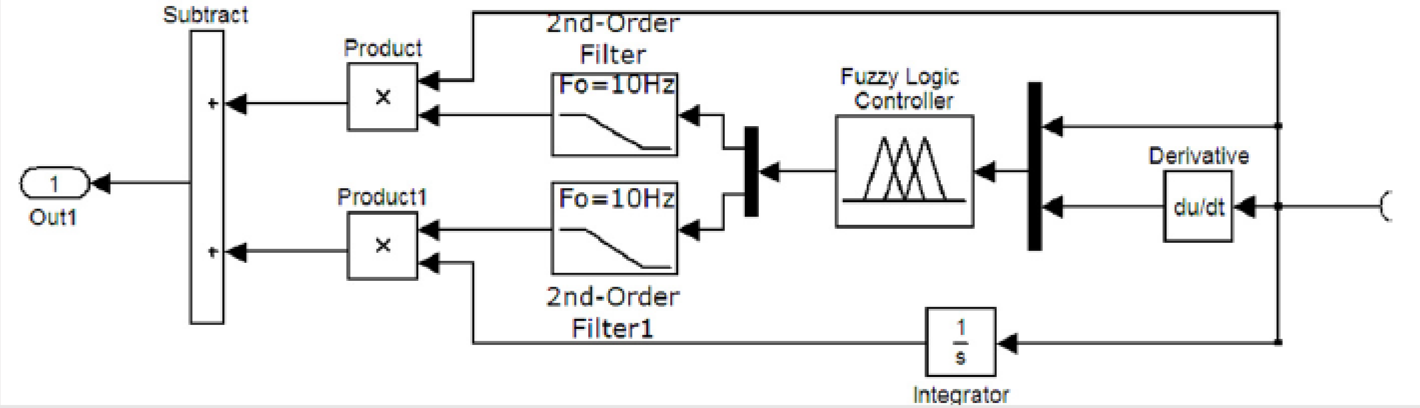


Diagram of Fuzzy Self-Adaptive PI Controller

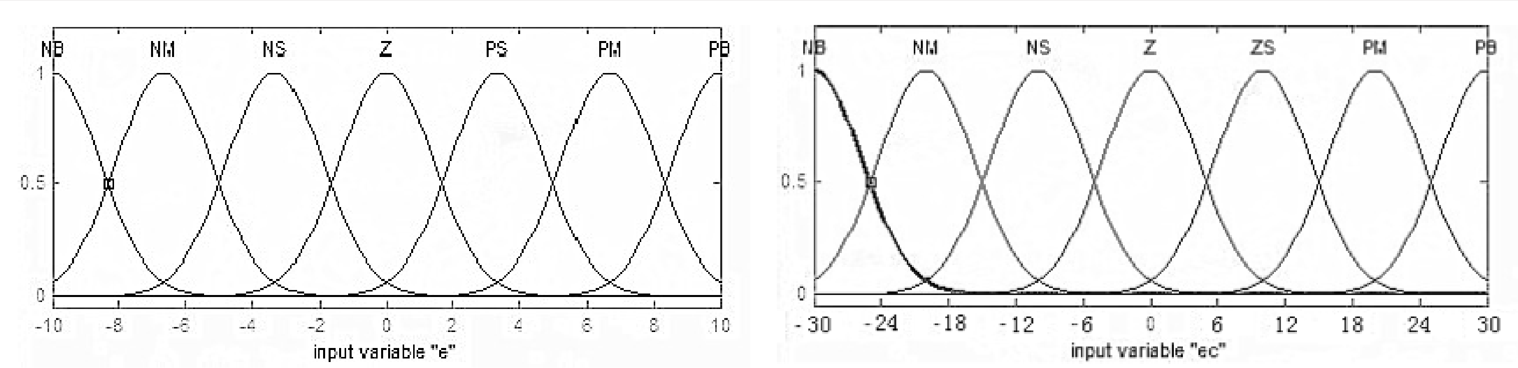
Proportional-action coefficient k_p and integral-action coefficient k_i is adjusted by the controller based on the input signal *e* and the input differential signal *ec*. After low-pass filtering, the outputs of Fuzzy Logic Controller is changed to k_p and k_i, and PI signal can be obtained by multiplying the input signal, k_p and k_i.



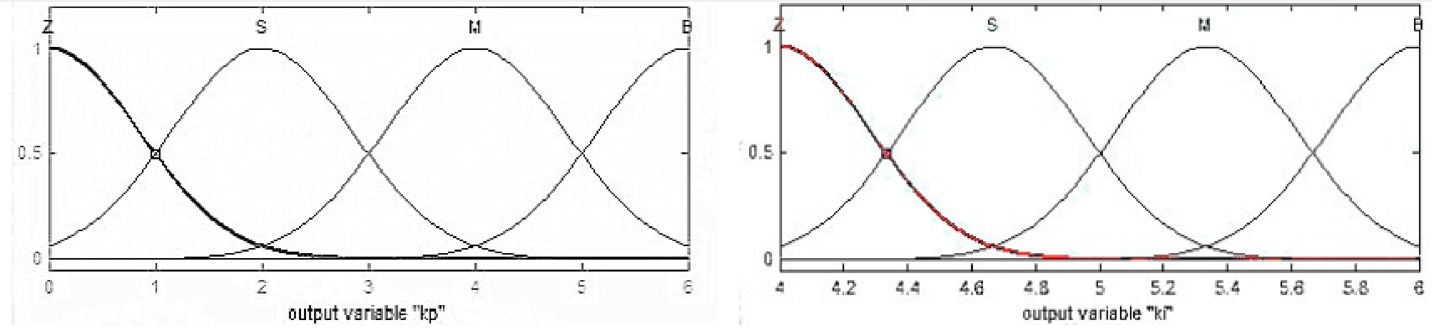
Simulation Model of Self-Adaptive PI Controller

Part 02→Control Schemes

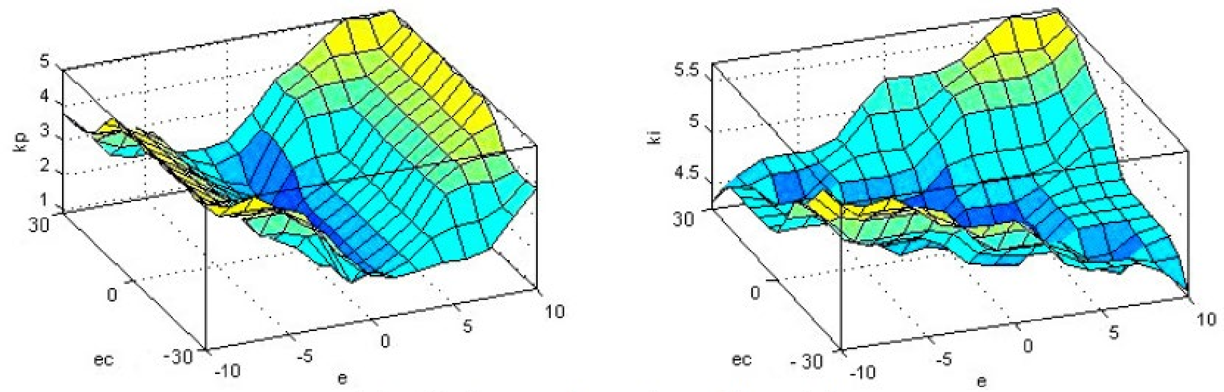
➢ Parameters Settings for Fuzzy Self-Adaptive PI Controller



Membership Function of *e* and *ec*

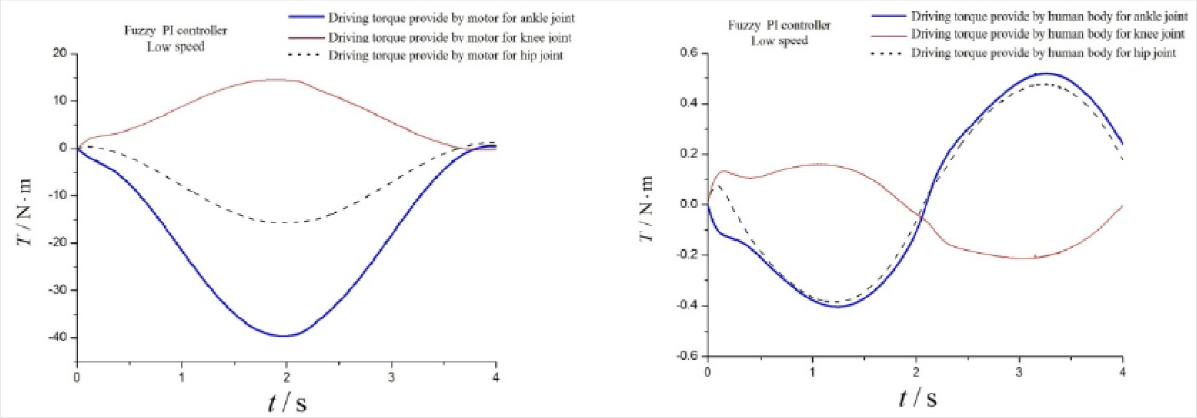


Membership Function of k_p and k_i

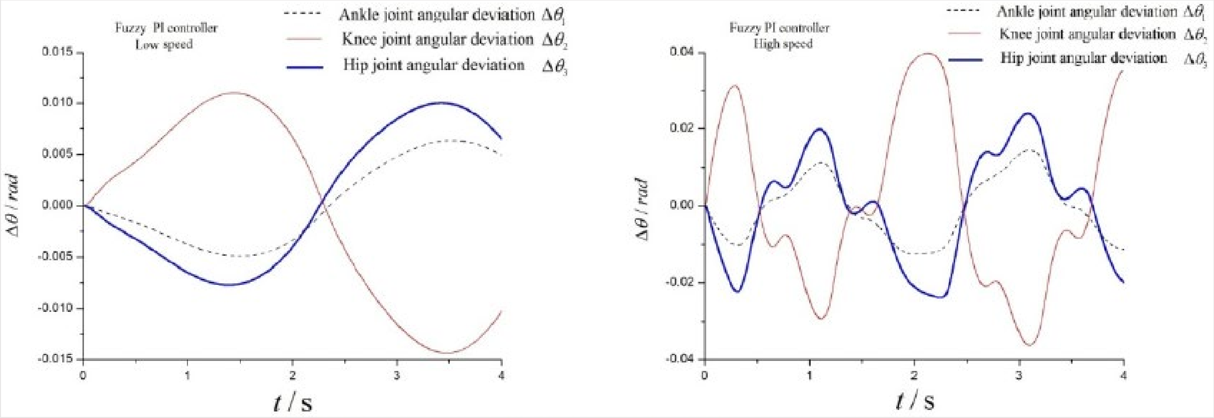


Fuzzy Rules Surface of k_p and k_i

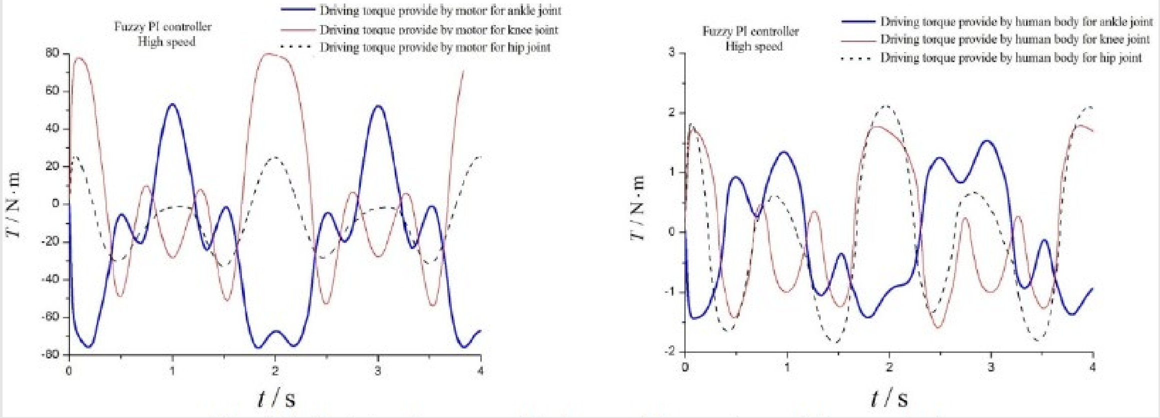
Part 02→Control Schemes



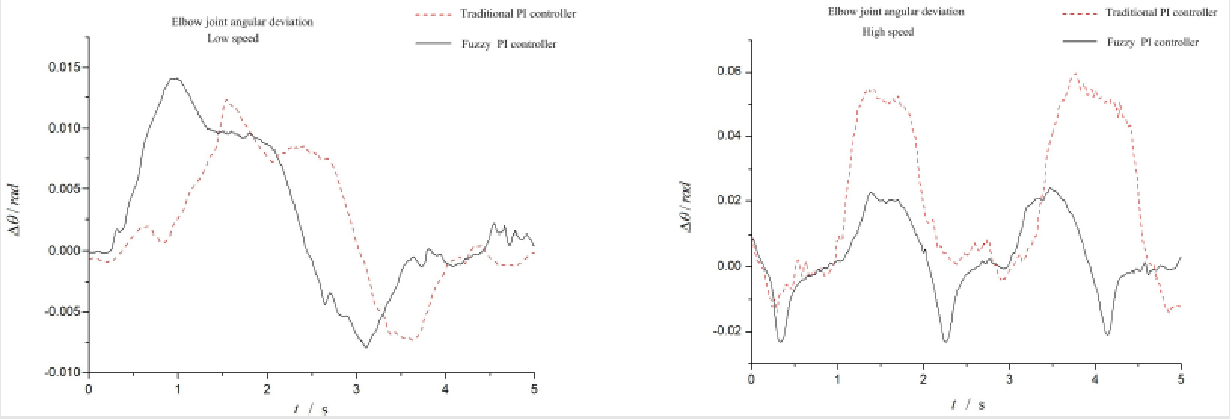
Drive Torque at Low Speed



Angular Deviation at Both Low & High Speed



Drive Torque at High Speed



Elbow Joint Angular Deviation at Both Low and High Speed

Part 02 → Control Schemes

The Fuzzy Self-Adaptive PI Controller can insure that the motor’s drive torques are much larger than those provided by human body, and the angular deviations at both low and high speed are all acceptable.

So the Fuzzy Self-Adaptive PI Controller can work well for WHEE.

Part 02 → WHEE Prototypes

	HULC USA	HERCULE France	Warrior-21 Russia	HAL-5 Japan	NUST P.R. China
Self Weight	24 kg	30 kg	—	21 kg	18.5 kg
Weight Bearing	90 kg	100 kg	—	40 kg	65 kg
Max Velocity	4.8 km/h	4 km/h	16 km/h	4 km/h	5 km/h
Efficiency	—	—	—	—	75.1%

THANK YOU FOR WATCHING