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The Technical Trend of the Exoskeleton Robot System for Human Power Assistance

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The exoskeleton robot system is a brand new type of human-robot cooperation system. It fully combines human intelligence and robot power so that robot intelligence and human operator's power are both enhanced. Therefore, it achieves a high-level performance that neither robots nor humans could achieve separately. This paper describes the basic exoskeleton concepts from biological systems to human-robot intelligent systems. It is followed by an overview of the development history of exoskeleton systems and their two main applications: human power assistance and human power augmentation. Besides the key technologies in exoskeleton systems, the research is presented from several viewpoints of the biomechanical design, system structure modeling, human-robot interaction, and control strategy.

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1. Introduction

The exoskeleton robot system is a human-robot cooperation system that enhances the power of the wearer in various environments while the human operator is in charge of the position control, contextual perception, and motion signal generation through the robot's artificial intelligence.[1,5] This system is in the form of a mechanical structure that is combined to the exterior of a human body to improve the muscular power of the wearer.[2] Exoskeleton robots have been actively studied in the USA, Japan, and Europe since the 1990s and are now researched for applications in various industries including military, medicine, and rehabilitation.

Exoskeleton robots can be classified according to muscle strength supporting parts: upper limb systems,[1,3,4,31] lower limb systems,[5-10,17,18] upper and lower limbs integrated systems,[11,12] and specific joint muscle strength support system.[13,14] They can also be categorized by the purpose of muscle strength support: power assistance and power augmentation systems.

Power assistance systems are exoskeleton robots that directly assist power exerted by the human body, thereby giving the wearer greater strength. EKSO and HAL are notable exoskeleton robots currently under development. EKSO is a bionic exoskeleton that allows wheelchair users to stand and walk. HAL is also capable of enabling the user, whose own muscles are not capable of supplying the power required,[8,18] to walk. These exoskeleton robots are mainly developed for persons who are aged, feeble, or disabled to assist them in their daily lives.[3,4,8,9,11,13,18]

Meanwhile, power augmentation systems to amplify the power of wearers, enabling them to perform tasks that they otherwise cannot easily perform by themselves. A major impetus for recent work in power augmenting exoskeletons has come from a program sponsored by DARPA (Defense Advanced Research Projects Research Agency), called the Exoskeleton for Human Performance Augmentation in USA. The HULC and XOS are being designed for DARPA with a goal of offloading the weight carried by soldiers onto the exoskeleton.[12,17] For the same purpose, an exoskeleton called HEXAR[1,5] was developed in South Korea. Power augmentation exoskeleton robots are developed for military applications, and industrial fields that require moving or manipulating heavy objects.[1,5-7,10,12,15,17]

Elementary technologies for the development of exoskeleton robots include mechanism design technology, human intent measurement technology, and human-robot cooperation control technology. For successful development of exoskeleton robot systems, consideration of the application field, purpose of power support and which part the robot would give support is needed.

To understand the technical trends, this paper classifies and comparatively analyzes the characteristics of the elementary technologies, including the mechanism design, human intent measurement, and human-robot cooperation control areas of representative research cases.

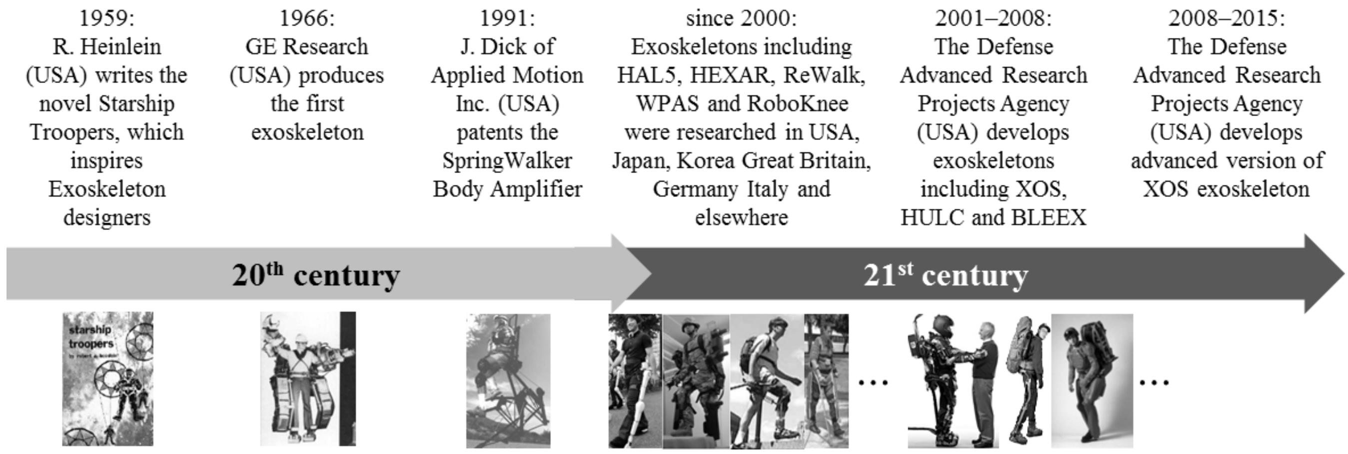


Fig. 1 History of exoskeleton robot system

Table 1 Classification of exoskeleton robot systems by mechanism architecture and joint mechanism type

Purpose	Augment						Assist				
Exoskeleton name	BLEEX [6,15]	HULC [17]	HEXAR [5]	XOS [12]	LTU-LEE [10]	WAD [16]	MIT [14]	EKSO [18]	HAL [8]	ALEX [9]	HARO [11]
Mechanism architecture	Quasi-anthropomorphic	Quasi-anthropomorphic	Quasi-anthropomorphic	Quasi-anthropomorphic	Anthropomorphic	Non-anthropomorphic	Anthropomorphic	Quasi-anthropomorphic	Anthropomorphic	Anthropomorphic	Anthropomorphic
Joint type	Active/ Passive	Active/ Passive	Active/ Quasi-passive	Active	Active	Active/ Passive	Quasi-Passive	Active/ Passive	Active/ Passive	Active/ Passive	Active

2. Exoskeleton mechanism

The exoskeleton is attached to the exterior of a human body. Thus, the design of an exoskeleton robot requires sufficient understanding and analysis of the body mechanism of the wearer as well as the purpose of robot development, and the motion environment. Table 1 classifies the representative research cases by exoskeleton mechanism structures and joint mechanism types.

2.1 Exoskeleton mechanism structures

The exoskeleton robot mechanism structures can be classified into the anthropomorphic type, which is designed so that the rotation axis of the robot joint in alignment with the rotation axis of the human joint; the quasi-anthropomorphic type, which has a robot joint functionally similar to the human joint; and the non-anthropomorphic type, which the robot joint is in misalignment with the human joint.[15]

The anthropomorphic type enables the exoskeleton robot to make the same motions as the wearer since the robot is designed to mechanically align with the human body. This can simplify the exoskeleton robot's design elements that determine the robot's motion range and prevent collision between the human and robot. However, it is mechanically difficult to design in such a way that the rotation axis of the robot joint is in alignment with that of the human and provide all degrees of freedom when the exoskeleton robot is attached to the exterior of the human body.

The quasi-anthropomorphic type is an exoskeleton robot designed to allow similar motions, although the rotation axis of the robot joint is not in alignment with that of the human. To design the joints and links of such mechanism, human motions must be analyzed. For this purpose, the permission range of relative motions and the connection position between the exoskeleton robot and its wearer must be established.

The non-anthropomorphic type allows more diverse possibilities in the functional aspects of the exoskeleton robot, although it is not a general type. This type of exoskeleton mechanism can be designed to have an optimized structure for performing tasks intended by the wearer. This allows more convenient motions in performing tasks and more effective energy consumption than the exoskeleton robots that have the similar shape as the human body.

In general, exoskeleton robots developed for the purpose of assisting have the form of the anthropomorphic type. This is because the power generated by exoskeletons can be fully delivered to the human by conforming the exoskeleton with the joint rotation axes of the human body. Meanwhile, exoskeleton robots developed for the purpose of augmentation are quasi-anthropomorphic or non-anthropomorphic types. These types play a role in reducing the impact of external loads on the wearer when the wearer performs a specific task with the exoskeleton robot.

2.2 Joint mechanism of exoskeleton robot

The exoskeleton is generally composed of active, passive, and/or quasi-passive joints. For power assistance or power augmentation, the power of the robot joints must be generated with active joints such as electric motors or hydraulic cylinders. However, it is difficult to implement all degrees of freedom in the anthropomorphic and quasi-anthropomorphic type exoskeleton robots because of the space limitation due to the structural characteristics since they are attached to the exterior of the human body. Thus, passive or quasi-passive joints are used in certain joints through the analysis of human motions and tasks to implement the degrees of freedom of the human body.

Quasi-passive joints refer to passive joints that contain energy-storing devices with elasticity or viscosity such as springs or dampers. This mechanism is to accumulate energy in specific sections of motion and discharge it when needed to enable power assistance.[7] To design such quasi-passive joints, the task for which the exoskeleton robot is to be used needs to be clearly defined. Also, the motions that can accumulate energy and the motions that require energy discharge must be analyzed through the motions of the wearer performing the task.

The quasi-passive leg exoskeleton developed by MIT is a key research case using the quasi-passive joint mechanism. This system was developed to augment the lower limb muscle strength of the wearer when moving heavy objects. It has no actuators, but only the ankle and hip springs and a knee variable-damper. Without a payload, the exoskeleton weighs 11.7 kg and requires only 2 Watts of electrical power during loaded walking. For a 36 kg payload, we can demonstrate that the quasi-passive exoskeleton transfers average 80% of the load to the ground during single support phase of walking.[7,14]

3. Acquisition of human intent

It is essential to acquire human intent to control exoskeleton robots. The intent of the wearer can be identified by measuring interactions between the human and robot. These days, many studies are being conducted on sensors to measure of human-robot interactions.

3.1 Human-robot interaction

Humans perform cognitive processes such as inference, planning, and actions to move their body based on information about the surrounding environment acquired through various senses such as visual, tactile, and auditory senses.

Human-robot cooperation systems such as exoskeleton robots that are combined with humans can influence human cognitive processes; in turn, the changing human cognitive processes can influence the motions of the robots performing cooperative tasks. This is referred to as human-robot interaction. The device and method to measure the human-robot interaction is called the human-robot interface. Human-robot interactions can be divided into cHRI (cognitive human-robot interaction) and pHRI (physical human-robot interaction). cHRI refers to the interaction that occurs by the influence of the robot during human cognitive processes. pHRI refers to the physical interaction with a robot that occurs by human motions as a result of an action during cognitive processes.[20,21] Fig. 2 illustrates the human-robot interaction on an exoskeleton robot with forces and signals.

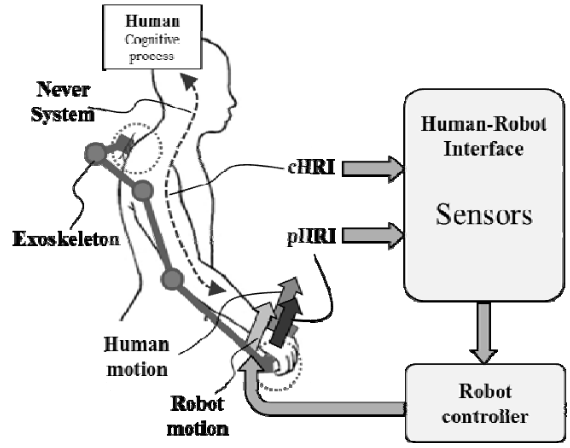
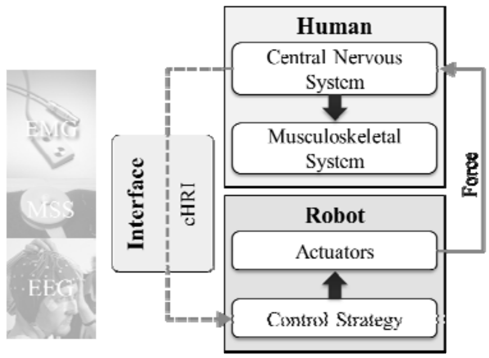
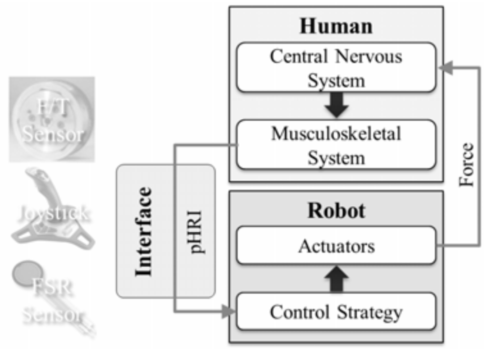


Fig. 2 Concepts of human-robot interaction and human-robot interface



(a) cHRI-based system



(b) pHRI-based system

Fig. 3 Classification of exoskeleton robot systems by HRI used as control input

The wearer and the exoskeleton robot as a human-robot cooperation system form a closed loop from the control aspect. As illustrated in Fig. 3, the system can be divided into cHRI-based system and pHRI-based system, depending on the measurement method of the human-robot interaction that is used as control input for exoskeleton robots.

The cHRI-based system measures the electric signals from the central nervous system to the musculoskeletal system of humans and use them as inputs to the robot controller. Thus, since it can identify the human intent before the occurrence of actual motion of the wearer and predict the required torque for the motion of human joints, it is mainly used in exoskeleton robots for power assistance.

Table 2 Sensors that can be used to measure human intent

Physical Human-Robot Interaction	Position and Motion Sensors	Encoder, LVDT (Linear Variable Differential Transformer), Potentiometer, Accelerator, Inclinometer, Magnetic Sensor, Electro-goniometer, MEMS Inertial Sensor Device
	Force and Pressure Sensors	Strain Gauge, Force/Torque Sensor, Pressure Sensor, Piezoelectric Sensor, Piezoresistive Polymer, Capacitive Force Sensor
Cognitive Human-Robot Interaction	Muscle Activity Sensors	EMG (Electromyography), MSS (Muscle Stiffness Sensor), Muscle Tenseness Sensor, Ultrasonic Muscle Activity Sensor, Mechano-myography
	Brain Activation Sensor	EEG (Electroencephalogram)
	Etc.	Humidity sensor, Temperature sensor

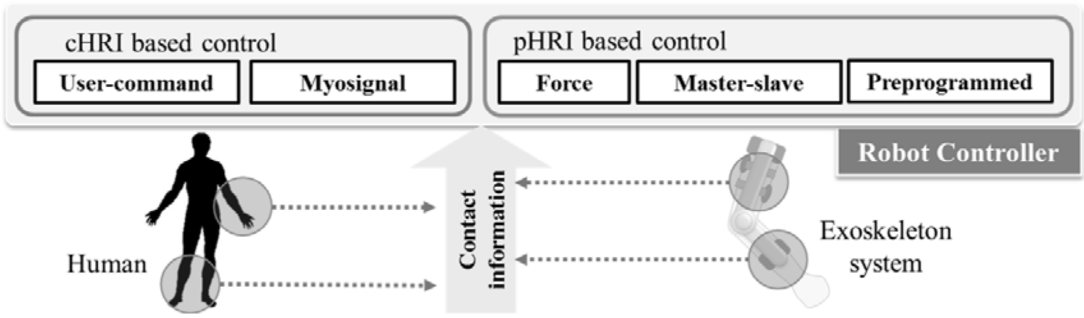


Fig. 4 Classification of representative control methods by HRI type

On the other hand, the pHRI-based system measures the force or position changes that are the results of the motions by the human musculoskeletal system and use them as inputs to the robot controller. Thus, as the robot can be controlled to augment the current power of the wearer, it is mainly used in exoskeleton robots for power augmentation.

3.2 Human intent measurement sensor

Identification of human intent in exoskeleton robot systems is essential for generation of input signals to the controller. For this purpose, various studies on sensors that measure cHRI and pHRI are being conducted. Table 2 shows the sensors that can be used to measure cHRI and pHRI.

Since cHRI measurement can directly measure human cognitive processes, many researchers use it to conduct studies on the techniques to identify human intent.[20] cHRI signals can be measured with biomedical signal sensors such as brain activity measurement using EEG (electroencephalogram) and muscular activity measurement using EMG (electromyograph). For cHRI-based exoskeleton robot systems, it is generally recommended to measure the muscular activity to identify the human intent and use it as control input.[3-5] This method can measure the signals of action processes of human cognitive processes, and studies are being conducted to predict the joint torque of the wearer from the muscular activity signals. The EMG sensor is generally used to measure muscular activity signals, but this sensor is disadvantageous in that it must be directly attached to the skin; it requires high sampling frequencies for signal collection; it is difficult to quantify the signals.[3] To overcome these shortcomings, researchers are developing various types of sensors using the physical characteristics of muscles that change during muscular activation, such as muscle stiffness sensors,[22] ultrasonic muscle activity sensors,[23] and mechano-myography.[24]

pHRI measurement is made possible by using physical measurement sensors such as force, acceleration, and pressure sensors to measure the physical changes of human and robot motions. These sensors cannot predict the motion intent before the occurrence of human motions. Rather, they measure the physical values resulting from human or robot motions. However, the power relation between human and robot, and the resulting changes in acceleration, speed, and position can be used as robot control inputs. Also, the obtained signals[1] are more reliable than biomedical signals such as EMG. Furthermore, because the sensors can be attached to the links of the robots or to the connection points between human and robot, it is easier to attach the sensors than cHRI sensors, which must be attached directly to the human body.

4. Human-robot cooperation control

As exoskeleton robots are combined with humans and form a closed loop from the control aspect, both the wearer and the exoskeleton robot must be considered when developing a controller. The control method for an exoskeleton robot system is based on the human-robot cooperation control, which is, in turn, based on the human-robot interaction. The appropriate control method must be applied depending on the purpose and application target. Many different control methods are being proposed according to the purpose of the development. Fig. 4 shows five representative control methods based on cHRI and pHRI.

4.1 cHRI-based control method

cHRI-based control methods use the cHRI signals as control inputs, and the representative methods are user-command control and myosignal control.

The user-command control is mainly used in exoskeleton robot systems to rehabilitate, to train muscle strength through repeated motions or to improve activity through power assistance in daily motions. This system receive signals from normal parts of the human body and generate motion command signals for the robot to assist abnormal parts of the human body. Yano[25] developed a system for patients with paraplegia, enabling them to walk by generating robot command signals. Johnson[26] controlled the joints of a paralyzed leg through the finger angle by attaching goniometers to the unaffected fingers to assist the gait of patients with paralysis. However, as this control method generates robot motion commands using the motions of normal body parts, the motions of the normal parts are limited. In addition, the users have a high level of anxiety due to an unnatural motion generation method.

The myosignal control predicts motions by measuring the body's micro electric signals that are generated when humans move. It is used in systems for power augmentation and assistance through human-robot cooperation system by generating robot motion command signals. Rosen[3] predicted the human joint torque needed for motions, by measuring EMG signals and the instrumental position data of joints in the human body and using them as input to the human muscle model (Hill-type model). It improved the efficiency of human-robot cooperation by calculating the input torque of robots multiplied by the torque amplification rate. Furthermore, Kiguch[4] developed a system to implement the degree of freedom of the shoulder by using muscular activity in human-robot cooperation motions using EMG signals and a fuzzy controller. This control method is advantageous because it can move quickly since it measures human motions in advance and predicts the torque and movement directions of the joints which are then used as robot control inputs. However, because biomedical signals differ by person, they are difficult to generalize. Also, signal processing is very difficult because fine electric signals must be amplified before measurement.

4.2 pHRI-based control method

pHRI-based control methods use pHRI signals as control inputs, and the representative methods are force control, master-slave control, and preprogrammed control.

Force control is generally applied to transporting or lifting of very heavy objects. Its basic purpose is to control the action force (external force) between human and robot in such a way that the human operator does not feel the robot. In general, a feedback controller is configured by attaching sensors to receive force information from the robot, and the human applies external force to the robot. Furthermore, for accurate force control, specific kinematic and dynamic models for the robot system are required. Force control methods can be categorized by sensor attachment method including direct force control,[27] which directly measures and controls external force, and virtual force/torque control,[1,15] which indirectly measures and estimates external force. Another control method is to use the ground reaction force of the robot. The direct force control method is most frequently used to implement the human-robot cooperation system. However, its drawback is that the contact points must be minimized because costly force sensors must be attached at every contact point to measure the action force between human and robot. The virtual force control method predicts human intent through an accurate dynamic model of the robot system, which is reflected in the force controller. This control method originated from the disturbance observer to overcome disturbance. The external force applied from human to robot is recognized as disturbance, and the human intent is predicted through the observer in the controller.

The master-slave control method is the most traditional robot control method. The robot reads human motions and implements the same motions. The closed loop control in the joint space uses the feedback information from the human joint angle and robot joint angle for the controller. For the closed loop control in the operation space, a kinematic model of human and robot is applied, which expresses motions for terminal parts of human and robot. This control method was applied to Hardiman,[28] a wearable robot developed by GE in the 1960s for transporting heavy objects. This control method is useful for human-robot cooperation motions because human motions are directly measured to drive the robot. However, when the human operator is inside the robot, such as with wearable robots, the wearer can feel the contact force by the robot if the joint positions and link lengths differ between human and robot.

The preprogrammed control method can be applied to exoskeleton robot systems to assist walking for rehabilitation using preprogrammed motions. Since this method uses preprogrammed motions, the wearer only inputs commands such as “Start” or “Stop” for driving the system. Vukobratovic[29] developed a system for walking that generates preprogrammed paths in the joints and changes the paths by judging position stability through the force sensor on the sole. Furthermore, Downes[30] developed a system that uses independent control depending on the walking section and inputs speed information in advance for the swing phase when the foot is in the air. This control method is advantageous because it can be applied to patients who cannot walk easily and induce them to step like an otherwise healthy person. However, stability control during walking is needed because natural motions by human intent are difficult to carry out.

5. Conclusions

This paper investigated and analyzed the characteristics of domestic and international research cases on exoskeleton robot systems for power assistance of the wearer from the perspectives of exoskeleton mechanism, identification of human intent, and human-robot cooperation control.

The purpose of exoskeleton robot systems can be divided into two: power assistance types that directly give power to human joints, and power augmentation types that augment the power of the wearer. Exoskeleton mechanisms are classified into anthropomorphic, quasi-anthropomorphic, and non-anthropomorphic types, depending on the alignment of the degree of freedom between human and robot joints. They can also be categorized by the shape of the robot joint into active, passive, and quasi-passive joints. To control exoskeleton robots, it is essential to identify the human intent, which is made possible by measuring the human-robot interactions.

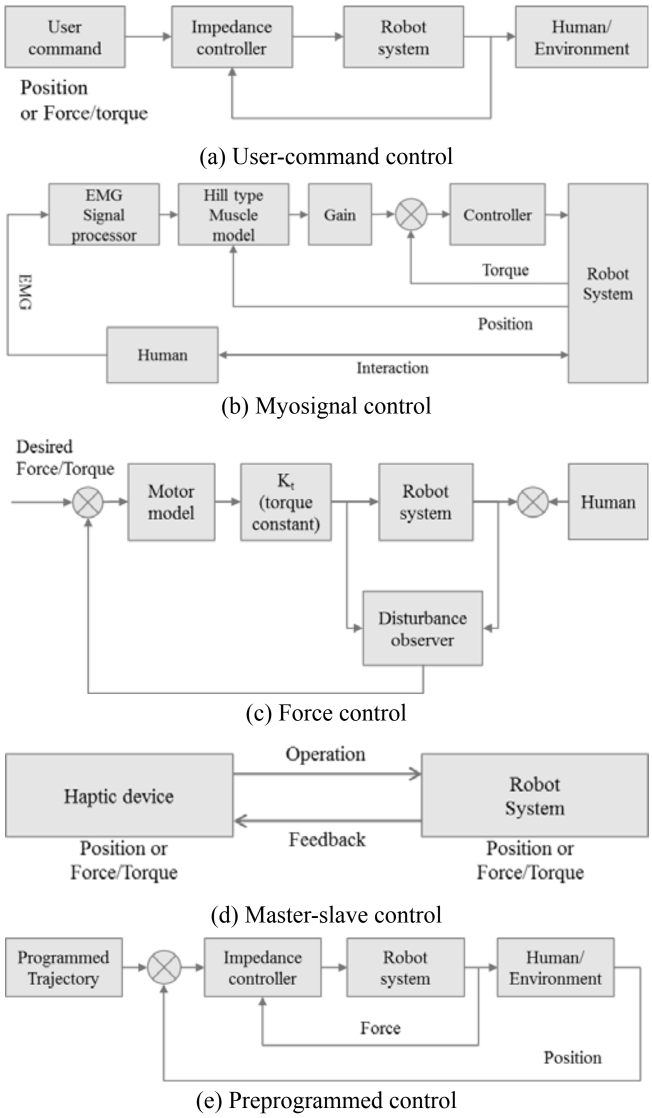


Fig. 5 Control methods of exoskeleton robot systems

Exoskeleton systems can be divided into cHRI- and pHRI-based systems, depending on the measurement method for human-robot interactions. Currently, various sensors to measure cHRI, pHRI and interfaces using them are being studied. Representative control methods using human-robot interactions as inputs are user-command control, myosignal control for cHRI-based systems and force control, master-slave control, and preprogrammed control for pHRI-based systems.

As mentioned above, since exoskeleton robots are attached to the human body, the purpose, application target, and operation environment of exoskeleton robots must be specified. Furthermore, sufficient understanding of the human body mechanisms and human-robot interactions is required. In additions, a control method that is appropriate for the control purpose must be applied.

ACKNOWLEDGEMENT

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