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Ergonomics and Industry 4.0

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Abstract

With the development of industrial technology, industry 4.0 has become the mainstream trend of modern industry. Under the influence of the wave of industry 4.0, the production and management methods of traditional industries are bound to change. In this context, more emerging technologies have emerged, covering a wide range of industries. Ergonomics is one of the key areas. Musculoskeletal disorders and other problems in industrial production involving human beings have attracted increasing attention. Therefore, how to solve the problem of ergonomics better by emerging technologies in industry 4.0 will become an important topic in the study of ergonomics in the new era, which is also the focus of this paper.

In this paper, a brief history and connotation of the development of industry 4.0, as well as the development requirements of ergonomics in the new era and the common features of the emerging technologies of man-machine engineering in industry 4.0 are introduced. Industrial exoskeletons, virtual reality and augmented reality and collaborative robots three chapters are the focus of this paper to discuss. These three types of technologies are also the most representative of the connotation requirements of industry 4.0 in the ergonomic technology market. By introducing the existing or prototype products technical data of various markets, as well as the corresponding studies in the field of ergonomics, this paper compares and summarizes how various emerging technologies can better serve industry 4.0 in ergonomics.

Keyword ： Industry 4.0, ergonomics, industrial exoskeletons, virtual reality, augmented reality, collaborative robots.

Contents

1 INTRODUCTION

Rapid development of industry is often accompanied by the excessive use and waste of resources. Nowadays, mankind needs to face the problem of resource shortage. Industrial production has also led to many serious environmental problems, such as global warming. In this context, industry 4.0 was born. Under the industrial 4.0 environment, the traditional industrial production mode will be changed, and the corresponding industrial production environment will be changed. In the new industrial production environment, the realization of man-machine engineering principles will also face new challenges. Advances in the field of ergonomics have made the principles of ergonomics more and more important in industrial production. In the industry 4.0 environment, more new technologies about the implementation of ergonomics principles will emerge, which is also the focus of this paper.

1.1 Industry 4.0

In the history of mankind, three times of industrial revolution changed human's life. In the first industrial revolution, the mechanical power represented by the steam engine replaced the traditional manual labor which leaded to the large-scale factory production and the rapid development of capital economy of the end of 19th century. At the beginning of the 20th century, the application of the electric power took the place of the steam power, mass production and assembly lines appeared. In the 1970s, information and digital technology improved the quality and speed of the control and production. In 2011, the concept of "Industry 4.0" was revived at the Hannover Fair. Innovations in industry 4.0 mainly are cyber-physical systems, the Internet of things, cloud computing and cognitive computing. Smart plants, smart control, smart products are the creations of industry 4.0.[1]

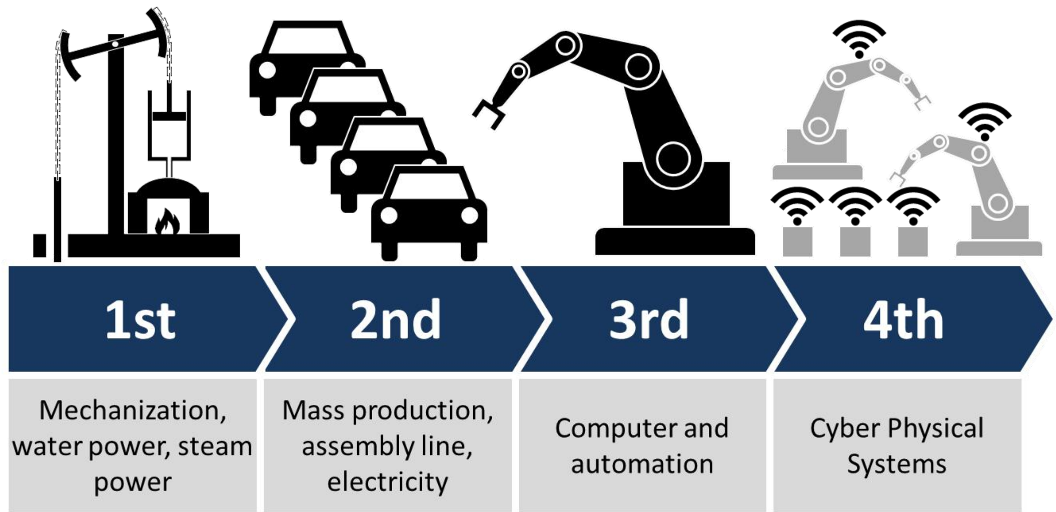

Figure 1.1 History of industrial revolutions [2]

Under the environment of industry 4.0, smart factory aims to produce precise, high-quality and personalized intelligent products, so as to achieve the efficiency and cost of mass production in small batch production of single parts. Intelligent production can carry out large-scale small batch customization for enterprise customers, or small batch single product customization for individual users. Factory production in industry 4.0 environment has the following characteristics:

- Intelligent production/customized production: the Internet of things can connect the production equipment and management information system. We can get the data in the production process and get better production efficiency and product quality through analysis. In addition, industry 4.0 will also bring personalized customized production in intelligent production. RFID technology provides convenience for products that require personalized customization. After the machine recognizes RFID, the controller can operate the robot hand to make changes in certain positions, such as spray painting patterns, product finalization, specification changes, etc. This process of producing different products in the same production line can make great differences between customized products with the progress of industry 4.0 and the improvement of technology.

- Production by servicing: smart products can collect user data, which manufacturers can obtain, and a new business model can be born that charges for services. By collecting product data, enterprises can better serve customers. The products manufactured by the factory can not only realize the functions of the product itself, but also send data to the factory so that the manufacturer can monitor its operation status and its loss, so as to better serve the customers after sale.

- Cloud factory: in the era of intelligent manufacturing, information is concentrated in the cloud. Through data analysis, we can see which factories are operating at full capacity and which are idle. These idle factories can then sell their capacity to produce for others in need. In this way, the production efficiency of industrial production will be greatly improved, which also makes it possible to realize small order production.

1.2 Ergonomics

Ergonomics is one of the cornerstones of the realization of the industry 4.0. Between the late 19th and early 20th centuries, ergonomics focused on human training to adapt the usages of the machines. During this period, main concentrations were on the psychology. From World War II to the 1960s, more factors like physiology, anthropometry, and biomechanics were applied in the ergonomics research, the importance of machinery and procedures to meet the needs of people became the major requirement. Starts from the '60 s, nowadays ergonomics emphasizes studying the “human - machine – environment” system as a unified entity, it continuously increased its importance in its applications through the industrial production.[3]

Ergonomics is a multidisciplinary cross discipline, is the core issue of research on different operation coordination between human, machine and environment. Its research methods and evaluation methods involve many fields such as psychology, physiology, medicine, anthropometry, aesthetics and engineering technology. Purpose of such study is through the application of interdisciplinary knowledge, to guide the work of equipment, working way and working environment design and transformation, so as to make the operations in efficiency, safety, health, comfort, etc.

1.3 Ergonomics in industry 4.0

In industrial 4.0, wide range of data sources and classification of fine, strong correlation, updated in real time, continuous time of big data technology; Cloud platform technology with unified data centralization, safe and reliable service, powerful function and real-time online; The whole-time and region-wide interconnection of Internet of things technology has a significant impact on the study of physiological human factors, cognitive human factors and organizational human factors, which is embodied in human-machine interaction, task and work design, personalized design, safety, health, comfort design, organization and management.

As the traditional equipment and workpiece change to the intelligent device and the intelligent workpiece, the interaction mode between the person and the equipment and the workpiece also change. In industry 4.0, all the IT controls installed in the production equipment, the processing artifacts, and the available devices of the crew are connected to the enterprise private cloud, controlled by the same smart terminal. In the context of intelligent man-machine interaction, intelligent devices will be guided by real-time information and take the initiative to select the most suitable object when needed and make interactive requests, and the interactive mode is also multidimensional. Because all devices are connected to the network, the interaction can be carried out in a variety of environments, which can be used for both remote interaction with mobile intelligent devices and on-site interaction. It can interact with input devices such as keyboard and touch screen, as well as voice recognition and gesture control. In addition, the basic decision-making ability and visualized presentation of information of smart devices will enable people to get rid of boring and stylized decision-making and move to more advanced intuitive and innovative decision-making. The nature of work, content and load will change fundamentally.

In the intelligent working space and environment, a large number of sensors collect environmental data in real time, and face recognition technology can remember personal characteristics. Wearable devices can monitor human state and collect data (humidity, brightness, noise, etc.), reflecting the personalized environment adjustment and providing a healthy and scientific work/life environment. The intelligent terminal can give hints on employees' working habits and operations. When employees have irregular operations, they will remind operators by voice or other information, and terminate their operations, so as to form a code of conduct control. On the other hand, the focus of employees' tasks has changed, such as changing from acquiring information to understanding information, and screening information to integrating information. And the routine work decreases, but the design class worker increases.

2 NEW TECHNOLOGIES IN THE FIELD OF ERGONOMICS IN INDUSTRY 4.0

Industry 4.0 integrates advanced technologies such as wired/wireless network, IT control, Internet of things technology, various wearable devices, big data, cloud computing, etc., which enriches the interactive mechanism of human and machine and environment. Under the influence of the industry 4.0, revolutions of system of “human - machine – environment” will continuously happen. With the development of ergonomics, how to make the "human-machine-environment" system work more harmoniously is a major research issue in industry 4.0. New technologies in ergonomics are now emphasizing how they can be better part of the system, not just how people used to adapt machines or machines to people. In the industry 4.0 environment, the new technologies related to ergonomics are mostly wearable devices. Informatization is the first feature of these emerging technologies. As we can see, technologies such as exoskeletons, assisted robots and AR/VR are all used by a large number of sensors. These sensors are used to collect various kinds of information in practical applications, and these information data will be recorded or used to adjust the deviation in actual use, so as to make the system operation more accurate and accurate. Interconnectivity is the second characteristic of these emerging technologies. Based on information technology, devices and devices will be connected through cloud technology. Not only are manufacturing and processing equipment connected, but various wearable devices will also be connected in the 4.0 environment. The application of interconnection technology provides a basis for the communication between equipment and equipment. Information such as the running state, working content and health status of the equipment can be shared among devices, making each small "human-machine-environment" system interconnected into a large system, so as to improve production efficiency and facilitate control. Innovation is the third characteristic of these emerging technologies. The units of small "human-machine-environment" systems provide the potential for production innovation. According to different production requirements, the reasonable scheduling and splicing of each unit will help to form a new production system, so as to better meet customer orders. In the field of ergonomics: exoskeletons, virtual reality and augmented reality, collaborative robots and other new technologies are leading the innovation of ergonomics.

3 INDUSTRIAL EXOSKELETONS

Because of the high frequency of physical labor, workers are often susceptible to Work-Related Musculoskeletal Disorders (WMSDs). The current industrial exoskeleton research is mainly based on the basic principles of ergonomics, which aim at reducing or even avoiding the occurrence of WMSDs through the mechanical structure or driving mode of the exoskeleton itself. The development of industrial exoskeletons is of great significance for improving production safety, reducing the risk of worker fatigue and injury, and improving productivity of the industry.

The industrial exoskeletons available in the market are mainly active and passive. The difference between them is that whether there is power drive or not, and this difference also makes them have different advantages and disadvantages. Also according to the different functionalities that the industrial exoskeletons want to realize, the industrial exoskeletons can be divided into different body segment using.
Mainly they are: upper limps industrial exoskeletons, trunk-assisted industrial exoskeletons, lower body industrial exoskeletons.

3.1 Upper limps industrial exoskeletons

The upper limps industrial exoskeletons aim at the power of the shoulders, arms or hand to enhance or better stress distribution. For the industrial exoskeletons of the arm assisting, they can be divided into the passive ones and the active one; most of the industrial exoskeletons for hand assisting are active ones or prototypes.

3.1.1 Passive shoulders/arms assisted industrial exoskeletons

These types of industrial exoskeletons are without actuators. They enhance arm muscle or better distribution of arm loads by different mechanical devices such as springs, levers, etc., to achieve improved arm performance. Examples are:

- ShoulderX by SuitX

Name	ShoulderX
Company	SuitX
Available on Market/Prototype	Available on market
Price	Around €3300
Active/Passive	Passive
Energy Store Mechanism	Mechanical support structure(leverage)
Body Segment	Shoulders/arms
Weight	5.4 kg
Suitable Physique	Suitable for 5%~95% of human dimensions, such as user height, waist size, shoulder width, chest depth, and arm length
Connection Points on Body	Shoulders, waist, arms
Human Movement Following	Adjustable

Related research/test	Rating the perceived exertion (BORG RPE10) in tool using task simulation. Avg. fatigue time without shoulderX: 2m15s ; Avg. fatigue time with shoulderX: 15m30s

Table 3-1 ShoulderX characteristics [4]

Figure 3.1 ShoulderX by SuitX [5]

- EksoVest by Eksobionics

Name	EksoVest
Company	Eksobionics
Available on Market/Prototype	Available on market
Price	Around €5000
Active/Passive	Passive
Energy Store Mechanism	Mechanical support structure
Body Segment	Shoulders/arms
Weight	4.3kg
Suitable Physique	Height: 152~193cm
Connection Points on Body	Shoulders, waist, arms
Human Movement Following	20" of adjustment
Related research/test	Research in using the exoskeletons in the drilling and wiring tasks in different working height level

Table 3-2-1 EksoVest characteristics [6]

Related research of the *EksoVest*				
Subjects	6 healthy males and 6 healthy females			
	Mean and SD		Female	Male
		Age	22.5 years ± 1.5	32.5 years ± 11.8
		Mass	63.8 kg ± 6.2	72.6 kg ± 9.1
		Stature	169.7 cm ±	179 cm ±

			5.2	3
Experimental Design	**Independent variables**	With (EXOS) and without (FREE) an exoskeleton		
		Shoulder height and an overhead work height		
	Measurement	Muscle activity (EMG: the anterior and middle deltoid, and the descending trapezius)		
		Perceived discomfort (RPD score neck, shoulder, upper arm, forearm, upper back, low back, and leg)		
		Donning & doffing time, shoulder ROM, postural control, and slip & trip risk tests		
		3D spine forces		
	Treatment	Repetitive drilling		
		Light assembly		
Testing Protocol	$\text{Drilling}_{\text{HEAVY}}$	Subjects were asked to complete the drilling job with 5.9kg drilling tool at shoulder height and an overhead work height separately		
	$\text{Drilling}_{\text{LIGHT}}$	Subjects were asked to complete the drilling job with 3.36kg drilling tool at shoulder height and an overhead work height separately		
	Wiring	Subjects were asked to connect five pairs of wires according to their colors at shoulder height and an overhead work height separately		
	Work Task conditions was counter-balanced using 3 × 3 Latin squares, the total experiments took 3.1 hour with two sessions(wearing the exoskeletons and working task)			
Results				

- Wearing the exoskeletons only changed the level of perceived discomfort for the forearm in different work simulations;
- The peak and median muscle activity of shoulder groups were significantly reduced (up to ~45% and ~50%, respectively to different working height);
- The working errors increased when using the exoskeletons, but the complete time is reduced by 20% in overhead work;
- Overall donning time is 67.1 (18.1) sec, overall doffing time is 17.4 (4.3) sec.;

●	Shoulder ROM was reduced with exoskeletons (4.3° (2.6%) in flexion and 16.2° (10%) in abduction);
●	Using the exoskeletons reduced spine loading at the lumbosacral joint, particularly at the shoulder work height and during the drilling task; but it also increased peak lateral shear force (FLAT) during the wiring task.

Table 3-2-2 Related research of the EksoVest [7],[8]

Figure 3.2 EksoVest by Eksobionics [9]

- Passive Arms by Robo-Mate

Name	Passive Arms
Company	Robo-Mate
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Passive
Energy Store Mechanism	Springs mounted in support arms
Body Segment	Arms
Weight	3.7 kg/arm
Suitable Physique	Height: 160~180cm
Connection Points on Body	Shoulders, waist, arms
Human Movement Following	-
Related research/test	Study of static holding and arm exertions in lab. Muscle activity, perceived musculoskeletal effort, contact pressure, local perceived pressure were measured

Table 3-3-1 Passive Arms characteristics [10]

Related research of the *Passive Arms*			
Subjects	4 healthy male and 4 healthy female		
	Mean and SD	**Age**	38 years ± 10
		Mass	72.6 kg ± 7.87
		Stature	1761 mm ± 50
Experimental	**Independent**	LOAD (0 kg and 2 kg)	

Design	**variables**	SYSTEM (with/without exoskeletons)
	Measurement	Muscle activity (EMG: Biceps Brachii, Medial Deltoid, Erector Spinae at level L3 and T9, Rectus Abdominis, Biceps Femoris, Rectus Femoris, Tibialis Anterior and Gastrocnemius) and perceived effort of the arms, trunk and legs.
		Additionally, local perceived pressure and usability for the 'with exoskeleton' conditions
	Treatment	Holding the load(2 kg with cylindrical diameter 5 cm)/no load overhead at a fixed height when standing upright, with shoulder and elbow flexed at 90°, wrist in a neutral position and hand closed
Testing Protocol	**Number of the test**	3 times holding with LOAD*2, SYSTEM*2
	Time of the test	Tasks were repeated three times for each condition with a rest of at least 1 min and 5 min between trials
Results		
● Muscle activity(for the 2 kg load) was significantly reduced(muscle activity of Medial Deltoid and Biceps Brachii were reduced by 62% and 49% respectively) with exoskeletons using; ● No significant negative effects on the lower body with exoskeletons using; ● Perceived effort of the arm was significantly reduced(41%) with exoskeletons using; ● No evidence of significantly increasing of muscle activity and perceived trunk and leg effort when using the exoskeletons.		

Table 3-3-2 Related research of the Passive Arms [11]

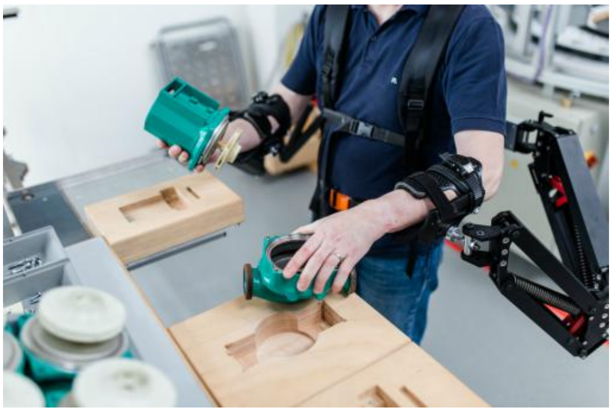

Figure 3.3 Passive Arms by Robo-Mate [12]

Research of the Passive Arm shows its good functionality in overhead holding task: With the help of the Passive Arm, when performing the overhead holding, the muscle activity of Biceps Brachii , Rectus Abdominis and Medial Deltoid of the users are decreased significantly comparing to the holding without this exoskeleton. Moreover, there is no significant muscle activity of the trunk and the lower body when using it. Also, according to the user's point of view, the Passive Arm using is comfortable with low pressure.[11] Same requests of these exoskeletons development are also need to be highlighted. To be lighter, more comfortable, and cheaper are the main direction of the further study. Surveys of the real industrial using also need to be performed to have a further improving.

- AIRFRAME by Levitate

Name	AIRFRAME
Company	Levitate
Available on Market/Prototype	Available on market
Price	-
Active/Passive	Passive
Energy Store Mechanism	System of pulleys
Body Segment	Shoulders/arms
Weight	-
Suitable Physique	Custom-fitted
Connection Points on Body	Shoulders, waist, arms
Human Movement Following	Full range of motion
Related research/test	Study of the AIRFRAME using in the static task and the precision task, to record the time of completion of the tasks of operators and their fatigue perception.

Table 3-4-1 AIRFRAME characteristics [13]

Related research of the *AIRFRAME*	
Subjects	31 healthy male

	Mean and SD	**Age**	51.5 years ± 4.7
		Mass	81.6 kg ± 9.1
		Stature	174.9 cm ± 4.3
Experimental Design	**Independent variables**	with (EXOS) and without (FREE) an exoskeleton	
	Measurement	Maintenance time, video assessment of posture, fatigue or discomfort sensation in static task	
		Endurance time, number of actions and fatigue or discomfort sensation in repeated manual material handling task	
		Number of arches traced by each operator, execution time, video assessment of posture, fatigue or discomfort sensation in precision task	
	Treatment	Static task	
		Repeated manual material handling task	
		Precision task	
Testing Protocol	Static task	Maintaining standing upright with extended arms (90° with respect to the trunk) while holding a car spoiler (3.5kg) placed on the forearm	
	Repeated manual material handling task	Moving an object(3.4 kg) between two positions in different heights(0.9 m from the floor and at worker's shoulder height); movement pace is 30 actions/min, maximum duration of the task is 600s	
	Precision task	Tracing a continuous wavy line between two premarket traces on a paper fixed on a billboard which is at a height with respect to the subject's shoulder with a felt-tip pen; the predominant arm is almost extended and the task ended with the subject's will or at the premarked guides	

Results
● Due to limitation of the size of the exoskeletons , only 29 subjects' data analysis were completed; ● During static task, no substantial differences of the posture was detected, static posture maintaining mean time were 183.9 s(EXOS) and 246.2 s(FREE), 25 subjects increased the holding time, 26 subjects were found that the exoskeleton perceived less fatigue; ● During repeated manual material handling task,12 operators endured the whole 600s task with/without exoskeleton, 11 operators decreased operation while 6 operators increased it, operators experienced some discomfort when using the exoskeletons; ● During the precision task, no substantial differences of posture were detected, 6 operators(FREE) filled all the 135 arches, while the number of operators increased to 19(EXO), subjects agreed to that the using of exoskeletons was beneficial for perceived fatigue and precision of the execution

Table 3-4-2 Related research of the AIRFRAME [14]

Figure 3.4 AIRFRAME by Levitate [15]

- Stronger by EXHAUSS

Name	Stronger
Company	EXHAUSS
Available on Market/Prototype	Available on market
Price	-
Active/Passive	Passive
Energy Store Mechanism	Springs mounted in support arms
Body Segment	Shoulders/arms
Weight	9 kg
Suitable Physique	-
Connection Points on Body	Shoulders, waist, arms

Human Movement Following	-
Related research/test	Study of using in manual handling task, muscle activity, upper limb kinematics, postural balance and cardiac cost were measured.

Table 3-5-1 Stronger characteristics [16]

Related research of the *Stronger*				
Subjects	4 healthy male and 4 healthy female			
	Mean and SD		Female	Male
		Age	31 years ± 2	33 years ± 2
		Mass	62 kg ± 10	78 kg ± 10
		Stature	166 cm ± 4	179 cm ± 3
Experimental Design	**Independent variables**	with (EXOS) and without (FREE) an exoskeleton		
	Measurement	Muscle activity (EMG: Anterior Deltoid, Triceps Brachii, Erector Spinae, Tibialis Anterior)		
		Upper limb kinematics		
		Heart rate		
		Perceived exertion		
		Postural balance		
	Treatment	Load lifting and lowering task (LIFT)		
		Walking with load carrying task (WALK)		
		Box unstacking and stacking task (STACK)		
Testing Protocol	LIFT	Load(5 kg for women, 9kg for man) lifting from low to high platform, and vice versa for 3 min at an imposed rate; 5 minutes for recovery		
	WALK	Walking over a distance of 30 m at free speed with carrying a two-handled toolbox(15 kg for men and 8 kg for women); four times repeated and 10s break between each repetition; 5 minutes for recovery		
	STACK	Unstacking and stacking 4 boxes (80 X 35 cm; 15 kg for men and 8 kg for women) with a 90° rotation of the operator on its longitudinal axis; 5 min work period		
Results				

● During LIFT and STACK, the muscle activity of the deltoid anterior was significantly lower with exoskeletons using; ● During LIFT, the muscles activity of the triceps brachii and tibialis anterior significantly increased with exoskeletons using; ● During WALK, the muscle activity of triceps brachii was significantly decreased with exoskeletons using; ● During LIFT, compared to FREE, the cardiac cost tended to increase with exoskeletons using; ● For all tasks, the upper limb kinematics were significantly different

Table 3-5-2 Related research of the Stronger [17]

Figure 3.5 Stronger by EXHAUSS [18]

3.1.2 Active shoulders/arms assisted industrial exoskeletons

This type of industrial exoskeletons usually has a drive. They enhance shoulders/arms function through different power drives.

- Active Arms by Robo-Mate

Name	Active Arms
Company	Robo-Mate
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Active
Actuator Type	-
Battery/Power Source	Outsource: 110/230 V
Body Segment	Shoulders/arms
Weight	2.3. kg/arm
Operation Temperature	-
Operation Time	-
Suitable Physique	Height: 160~180cm
Connection Points on Body	Shoulders, wrist, arms

Human Movement Following	-
Related research/test	-

Table 3-6 Active Arms characteristics [19]

Figure 3.6 Active Arms by Robo-Mate [20]

3.1.3 Active hands assisted industrial exoskeletons

As mentioned earlier, many of these exoskeletons are still in the prototype stage. With the help of a motor or gas driver, they can improve grip strength and loosen the fingers of the user who has a finger joint problem. Examples are:

- SEM Glove by Bioservo

Name	SEM Glove
Company	Bioservo
Available on Market/Prototype	Available on Market
Price	Around €7400
Active/Passive	Active
Actuator Type	Motor
Battery/Power Source	Lithium polymer batteries
Body Segment	Hand
Weight	700 g
Sensors	Pressure-sensitive sensors in fingertips
Suitable Physique	Suitable for left/right hand, size: XS/S/M/L/XL
Connection Points on Body	Fingers, palm
Human Movement Following	-
Related research/test	-

Table 3-7 SEM Glove characteristics [21]

Figure 3.7 SEM Glove by Bioservo [22]

- ExoHand by Festo

Name	ExoHand
Company	Festo
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Active
Actuator Type	Pneumatic actuators: 8 DFK-10 cylinders per hand
Battery/Power Source	-
Body Segment	Hand
Weight	-
Sensors	8 linear potentiometers(displacement sensors) per hand, 16 pressure sensors per hand
Suitable Physique	-
Connection Points on Body	Fingers, palm
Human Movement Following	-
Related research/test	-

Table 3-8 ExoHand characteristics [23]

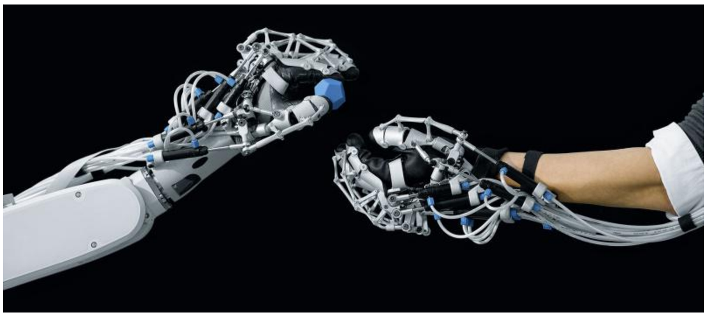

Figure 3.8 ExoHand by Festo [24]

- RoboGlove by GM/NASA

Name	RoboGlove
Company	GM/NASA
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Active
Actuator Type	Brushless motor, gear head and ball screw assembly
Battery/Power Source	-
Body Segment	Hand
Weight	-
Sensors	1 hall-effect sensor in each joint; 16 tendon tension sensors in palm; 1 phalange sensor in each finger
Suitable Physique	-
Connection Points on Body	Fingers, palm
Human Movement Following	-
Related research/test	Application in tool using and object holding, and showed it can provide steady load around 15-20 lbs. and a maximum 50 lbs.

Table 3-9 RoboGlove characteristics [25]

Figure 3.9 RoboGlove by GM/NASA [26]

The RoboGlove is developed by General Motors and NASA. It was inspired by the humanoid robot Robonaut 2 (R2). RoboGlove is a light-weighted device which is used for improving the strength of the user's fingers and palm, endurance, and also for the rehabilitation. Integrated by the technologies of the tactile sensing, on-board processing and miniaturized electronics, the RoboGlove can provide a stead load around 15-20 lbs. and a maximum 50 lbs. With the fingertip input command, the tests of the device showed its ability to provide the suitable gripping force for crimping the wire harness, also the ability to help to maintain a powered grasp for a long duration and diversely the relaxing. [26]

3.2 Trunk-assisted industrial exoskeletons

The trunk-assisted industrial exoskeletons are mainly used for protecting the user's spine by better allocation of the load when in the lifting operation, and reducing the user's fatigue.

3.2.1 Passive trunk-assisted industrial exoskeletons

Without actuators, these exoskeletons are designed to protect the user's spine while carrying out the lifting job, and by simple mechanical structure, the load is better distributed to the user's torso, some of them also provide chest support. Examples are:

- V2 by Laevo

Name	V2
Company	Laevo
Available on Market/Prototype	Available on market
Price	Around €2070
Active/Passive	Passive
Energy Store Mechanism	Mechanical support structure(leverage)
Body Segment	Trunk
Weight	V2.4: 2.5kg; V2.5: 2.8kg
Suitable Physique	Custom-fitted/XS~XL(5 sizes)
Connection Points on Body	Shoulders, waist, arms, thighs, chest
Human Movement Following	Kneeing, squatting, stretching outwards and upwards, twisting, walking
Related research/test	Study of static holding and simulated assembly in lab. Muscle activity, trunk posture, discomfort in the back, legs and chest were measured(Local Perceived Discomfort Scale)

Table 3-10-1 V2 characteristics [27]

Related research of the *V2*			
Subjects	9 healthy male and 9 healthy female		
	Mean and SD	**Age**	25 years ± 8
		Mass	71 kg ± 12.4
		Stature	1.76 m ± 0.1
Experimental Design	**Independent variables**	with (EXOS) and without (FREE) an exoskeleton	
	Measurement	Muscle activity (EMG: Trapezius pars Ascendens(TA), Erector Spinae Longissimus(ESL), Erector Spinae Illiocostalis(ESI), Obliquus External Abdominis(OA), Rectus	

		Abdominis, Biceps Femoris(RA), Biceps Femoris(BF)
		Trunk posture
		Discomfort in the back, legs and chest(LPD)
	Treatment	Picking, placing and removing 10 pairs of pins in a fixed order using the left and right hand simultaneously(Assembly Simulation)
		Hanging down the hands vertically with maintaining forward flexed trunk posture (40°)
Testing Protocol	Picking, placing and removing(Assembly Simulation)	Picking 2 pins from 15 cm below the Trochanter Major of the subjects and placing at a fixed position at shoulder height; When picking and placing, subjects adopted a 40° trunk flexion; Between pick and place, subjects adopt an upright neutral posture, with the hands hanging alongside the body for 30 s; Ten work cycles on the beat of a metronome (2/3 Hz).
	Static holding	Subjects rated their discomfort score when performing the static holding every 30 s, when rated 2 on the Borg scale, stop measurement and record the endurance time.
Results		

- Due to technical failure , only 17 subjects' data analysis were completed;
- During simulated assembly, significant reduction of the muscle activity(38% of ESI, 35% of ESL, 44% of TA, 20% of BF) was captured with the use of exoskeletons;
- During static holding, significant reduction of the muscle activity(44% of ESI, 37% of ESL, 50% of TA) was captured with the use of exoskeletons;
- During the simulated assembly, significantly lower LPD ratings of the back region and significantly higher discomfort of the chest region were found with the use of the exoskeletons;
- During static holding, the endurance time of holding with/without exoskeleton are (9.7 ± 4.9 min) and (3.2 ± 1.8 min) respectively.

Table 3-10-2 Related research of the *V2* [28]

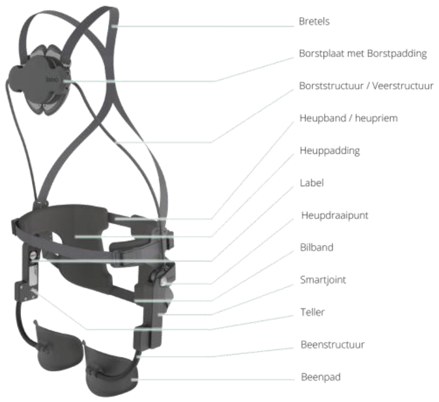

Figure 3.10 V2 by Laevo [29]

There are some studies of the previous version of the V2. Researchers designed an assembly task and a holding task for the volunteers. Participants simulated the assembly task with the bending forward posture and the static holding task. Results of the electromyography of the muscle showed that the muscle activities of the back, abdomen and legs are significantly decreased when using the exoskeletons. Also, from the level of the discomfort rated by the users, lower discomfort of the back could be found when using the exoskeletons. Moreover, the endurance time of the work is increased with the help of the exoskeletons. However, research also found that the knees of the users are in an over-extended position when wearing exoskeleton; this might be a risk when the longer task is performing. The weakening of the back muscle can also be a potential problem. [29]

- FLX by ErgoSkeleton

Name	FLX
Company	ErgoSkeleton
Available on Market/Prototype	Available on market
Price	Around €360
Active/Passive	Passive
Energy Store Mechanism	Mechanical support structure(leverage)
Body Segment	Trunk
Weight	1.13kg
Suitable Physique	S/M/L(3 sizes)
Connection Points on Body	Shoulders, waist, back
Human Movement Following	Free movement(mainly for postural support)
Related research/test	-

Table 3-11 FLX characteristics [30]

Figure 3.11 FLX by ErgoSkeleton [31]

- BackX by SuitX

Name	BackX
Company	SuitX
Available on Market/Prototype	Available on market
Price	Around €3300
Active/Passive	Passive
Energy Store Mechanism	Mechanical support structure(leverage)
Body Segment	Trunk
Weight	3.3kg
Suitable Physique	Suitable for 5%~95% of human dimensions, such as user height, waist size, shoulder width, chest depth, and arm length
Connection Points on Body	Shoulders, waist, arms, thighs, chest
Human Movement Following	Ajustable
Related research/test	Measurement of lower back (L5/S1) muscle activation when working with/without BackX: 66% of average reduction.

Table 3-12 BackX characteristics [32]

Figure 3.12 FLX by ErgoSkeleton [33]

3.2.2 Active trunk-assisted industrial exoskeletons

This type of exoskeleton is mainly carried on the user's torso, with additional devices attached to the user's shoulders, arms and thighs. Examples are:

- Muscle Suit by INNOPHYS

Name	Muscle Suit
Company	INNOPHYS
Available on Market/Prototype	Available on Market
Price	Around €4500
Active/Passive	Active
Actuator Type	McKibben artificial muscles
Battery/Power Source	Compressed air
Body Segment	Trunk
Weight	6.6kg+1.5kg(1.5L Compressed gas tank)
Operation Temperature	5~35℃
Operation Time	-
Suitable Physique	Height: 160~185cm(F size); 150~165cm(S size)
Connection Points on Body	Waist, thighs
Human Movement Following	-
Related research/test	-

Table 3-13 Muscle Suit characteristics [34]

Figure 3.13 Muscle Suit by INNOPHYS [35]

- Active Trunk by Robo-Mate

Name	Active Trunk
Company	Robo-Mate
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Active
Actuator Type	-
Battery/Power Source	Outsource: 110/230 V
Body Segment	Trunk
Weight	11kg
Operation Temperature	-
Operation Time	-
Suitable Physique	Height: 160~180cm
Connection Points on Body	Shoulders, hip, thighs
Human Movement Following	-
Related research/test	Study of dynamic lifting task in lab. Muscle activity, perceived musculoskeletal effort, contact pressure, local perceived pressure were measured

Table 3-14-1 Active Trunk characteristics [36]

Related research of the *Active Trunk*			
Subjects	12 healthy male		
	Mean and SD	**Age**	27 years ± 2
		Mass	75.38 kg ± 10.1
		Stature	1794 mm ± 6.56
Experimental Design	**Independent variables**	LOAD (7.5 kg and 15 kg)	
		SYSTEM (with/without	

		exoskeletons)
	Measurement	Muscle activity (EMG: Rectus Abdominis, Erector Spinae at level of L3 vertebrae, Biceps Femoris)
		Additionally, contact pressure, perceived musculoskeletal pressure and usability were assessed for the 'with exoskeleton' conditions
	Treatment	Lifting a box from mid-shin height to waist height
		Lowering a box from waist height to min-shin height
Testing Protocol	**Number of the test**	5 times lifting with LOAD*2, SYSTEM*2
		5 times lowering with LOAD*2, SYSTEM*2
	Time of the test	Muscles of subjects were maximally contracted for 3 s, there was a 1-min rest period between trials and minimum 5-min break between treatments
Results		
● One of the participants could not complete the experiments; ● With the exoskeletons, muscle activities of Erector Spinae and Biceps Femoris are significantly reduced (12%-15% for Erector Spinae, 5% for Biceps Femoris), greater induction happened in higher load tasks; ● Effort of the legs was similar when subjects working with/without exoskeletons; ● Perceived trunk effort was significantly reduced when using the exoskeletons (9.5%-11.4%).		

Table 3-14-2 Related research of the Active Trunk [37]

Figure 3.14 Active Trunk by Robo-Mate [38]

Recent research shows that with the help of the Active Trunk, when performing the lifting activities, the muscle activity of Erector Spinae and Biceps Femoris of the users are decreased significantly comparing to the lifting without this exoskeleton. Moreover, the loading of the trunk is significantly decreased assisting by the hip extensor torque. With the acceptable loading at the lower body according to the participants, the Active Trunk shows a good usability. [37] However, the result of this research is based on a series of short duration experiments. Further tests should be taken to prove that its usability to the long duration situation which is more closed to the real industrial working. Such kind of exoskeleton also will be towards lightweight development, so as to better fulfill the requirement of the ergonomics principles.

- MODEL A, MODEL Y by ATOUN

Figure 3.15 MODEL A by ATOUN [39]

Name	MODEL A(AWN-03B)
Company	ATOUN
Available on Market/Prototype	Available on market
Price	Around €10600
Active/Passive	Active
Actuator Type	High torque AC motor
Battery/Power Source	48.1V Lithium-ion battery
Body Segment	Trunk
Weight	6.7kg
Operation Temperature	0~40℃
Operation Time	Around 8 hours
Suitable Physique	Height: 155~185cm / Weight: 50~80kg
Connection Points on Body	Shoulders, hip, thighs
Human Movement Following	Automatic Detection: Lift, Maintain Posture, Carry, Unload, etc.
Related research/test	-

Table 3-15 MODEL A characteristics [40]

Figure 3.16 MODEL Y by ATOUN [41]

Name	MODEL Y
Company	ATOUN
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Active
Actuator Type	-
Battery/Power Source	-
Body Segment	Trunk
Weight	4.4kg (Including belts and batteries)
Operation Temperature	-
Operation Time	4 hours

Suitable Physique	-
Connection Points on Body	Shoulders, hip, thighs
Human Movement Following	Automatic Detection: Lift, Carry, Unload, etc.; Separate controllers for left and right
Related research/test	-

Table 3-16 MODEL Y characteristics [42]

3.3 Lower body industrial exoskeletons

This kind of exoskeleton is mainly used for leg support when the user is working with a squatting posture. They are almost active. To make the lower body as a "chair" is the core idea of this exoskeleton.

There is a simulated research of a passive lower body industrial exoskeleton which shows the benefit of these exoskeletons:

- Pure mathematical simulation of the passive lower body industrial exoskeleton
  The Honda Bodyweight Support Assist Device is a lower-body passive exoskeleton; this device aims at reducing the load at the wearer leg muscle when walking. This exoskeleton is an active type, but there is simulation research of a passive exoskeleton based on the Honda parameters.

Figure 3.17 Bodyweight Support Assist Device by Honda [43]

Simulated research of the *Honda*				
Exoskeleton type		Passive exoskeleton		
Body segment		Lower body		
Human model	**Mechanical model**	Planar anthropomorphic bipedal mechanism with massless feet		
	Parameters		Mass(kg)	Length(m)
		Total	61.86	1.75
		shin	4.66	0.55

		thigh	8.6	0.45
		trunk	48.6	0.75
Exoskeleton model	**Mechanical model**	Bipedal mechanism (massive, but with massless feet) with the same shape and DOF of the human model		
	Parameters		Mass(kg)	Length(m)
		Total	11.0	1.75
		shin	1.0	0.55
		thigh	2.0	0.45
		trunk	8.0	0.75
Experimental Design	**Independent variables**	Length of the step and its duration		
		With exoskeleton and without skeleton		
	Measurement(Calculation)	Consumption of energy		
	Treatment	Simulation of a biped transporting a payload in a short time and short distance		
Testing Protocol	Using the mathematical models to simulate and calculate the energy consumption of a biped(75kg, 1.75m) transporting a 40kg payload with/without exoskeleton in two different ways: (1) time T varies from 0.4-0.5s with fixed length L=0.5m; (2) L varies from 0.40-0.52m with fixed time T=0.45s			
Results				
● In the single-support motion, the energy consumption of biped with exoskeleton is higher than alone; ● In the double-support motion, the energy consumption is much more higher than the single-support motion; during this phase, the energy consumption of the exoskeleton using is lower than the single-support motion; ● The sum of the energy consumption of two phase walking shows a more efficient energy consumption of the using of the exoskeletons.				

Table 3-17 Simulated research of the Honda [44]

There are also other types of lower body industrial exoskeleton:

- Chairless Chair by Noonee

Name	Chairless Chair
Company	Noonee
Available on Market/Prototype	Prototype
Price	-
Active/Passive	Active
Motor Type	FAULHABER micro DC motor
Battery/Power Source	9V battery

Body Segment	Lower body
Weight	2kg
Operation Temperature	-
Operation Time	Around 24 hours
Suitable Physique	-
Connection Points on Body	Hip, thighs, shanks
Human Movement Following	Standing, Squatting.
Related research	-

Table 3-18 Chairless Chair characteristics [45]

Figure 3.18 Chairless Chair by Noonee [46]

- LegX by SuitX

Name	LegX
Company	SuitX
Available on Market/Prototype	Available on market
Price	Around €5000
Active/Passive	Active
Motor Type	-
Battery/Power Source	-
Body Segment	Lower body
Weight	6.2kg
Operation Temperature	-
Operation Time	-
Suitable Physique	Adjustable sizing
Connection Points on Body	Hip, thighs, shanks
Human Movement Following	Walking, ascending/descending stairs and squatting
Related research	-

Table 3-19 LegX characteristics [47]

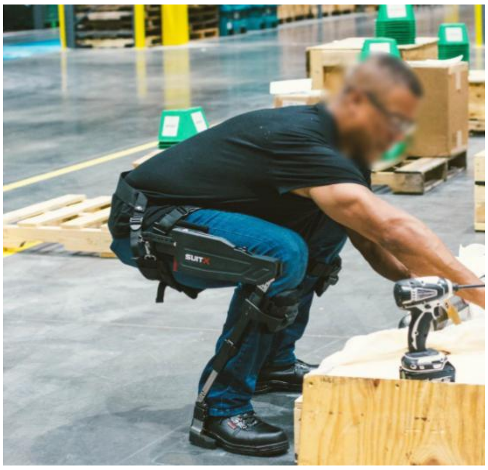

Figure 3.19 LegX by SuitX [48]

There are also some advanced exoskeletons which are still under development, such as full body exoskeletons and supernumerary robotic limbs. These exoskeletons are ambitious, but they now are also not practical.

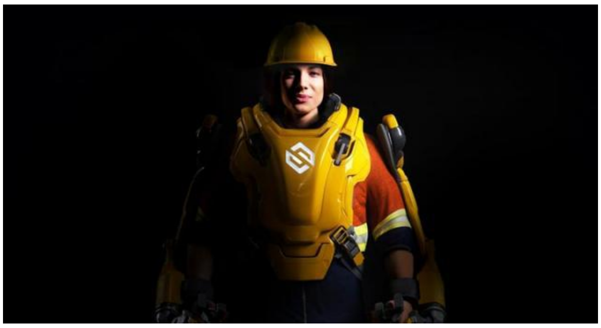

Figure 3.20 Guardian XO by Sarcos [49]

Industrial exoskeletons will gradually enter industrial production in the near future. We can see that industrial exoskeletons are good at reducing the risk of the WMSDs of workers during production. Also, how to make these exoskeletons cheaper, lighter, more practical and more comfortable is the main direction of their development. With the help of the technologies in Industry 4.0, the market of the industrial exoskeletons will grow up quickly.

4 VIRTUAL REALITY AND AUGMENTED REALITY

In the industry 4.0 environment, Virtual Reality (VR) and Augmented Reality (AR) new and important tools for the realization of ergonomic principles in industrial production. With the help of various sensors and the computer simulation system, the VR creates a virtual, interactive and immersion experienced environment with multi-source information. By capturing the real world in real time, with the camera, AR is able to add a variety of graphics, video, and 3-d models to the actual environment that the device screens show, so that the virtual environment interacts with the real world.

4.1 Virtual Reality

The core of VR technology is to create a completely new immersive virtual environment, so the position trackers, data handles, motion capture system and the Head Mount Display (HMD) are universal VR technical equipment. The most important of these is the HMD, which is a visual creation device that allows the user to go directly to the virtual environment. Nowadays, in fact, the so-called VR glasses or VR headsets are refers to the HMDs. There are two kinds of HMDs: console HMD and mobile HMD.

The console HMD is with cables which are connected to the PC. With the help of PC's powerful computing power, the console HMD can present an immersive virtual environment more clearly and in real time. Moreover, devices like position trackers, data handles and motion capture system always appear with the console HMD, which also make the console HMDs more expensive. In addition to high quality images and fast dynamic responses, the console HMD also ensures the moving of the users in six degrees of freedom (3-axis rotational tracking + 3-axis positional tracking) in a virtual environment.

The mobile HMD is more like a mobile phone's functional extension device. Smartphones are now with high-speed processor, HD display, optical sensors, distance sensor, gyroscope, and accelerometer and so on. These devices are the basic needs of virtual reality environment generation. The mobile HMD uses its own optical lenses to present a more three-dimensional picture of the smartphone to the user. Generally speaking, mobile HMD can only guarantee the users to move three degrees of freedom (3-axis rotational tracking) in the virtual reality environment. The virtual images presented by mobile HMD are less clear than that of console HMD.

4.1.1 Console HMD

It is indisputable that the maximum simulation of each element of the actual production work environment is the basic requirement of the application of VR technology in the study of ergonomics in the production process. This means that the console HMD which is with the better picture quality, sensitivity and higher degree of freedom will be the preferred device of the ergonomics research.

Nowadays, the market of console HMD is in the emerging stage, and the mature products that can be found in the market are mainly:

- VIVE/VIVE Pro by HTC

Name	VIVE	VIVE Pro
Company	HTC	HTC
Display Resolution	2160 x 1200; across two screens, 1080 x 1200 per eye	2880 x 1600; across two screens, 1440 x 1600 per eye
Dimension	199 x 122 x 122 mm	111 x 319 x 265 mm
Weight	470 g	555 g
Refresh Rate	90Hz	90Hz
Display Type	PenTile OLED	AMOLED
Field Of View	110°	110°
Tracking System	Vive Base Stations	Vive Base Stations
Room Scale Support	Yes	Yes
Built-in Microphone	Yes	Yes
Integrated Headphones	Only with optional Deluxe Audio Strap attachment	Yes
External Camera	Yes	Yes(Double)
Controllers	Vive controller	Vive controller
Connections	HDMI, USB 2.0, stereo 3.5 mm headphone jack, Power, Bluetooth	USB-C 3.0, DP 1.2, Bluetooth
Sensors	SteamVR Tracking, G-sensor, gyroscope, proximity	SteamVR Tracking, G-sensor, gyroscope, proximity, IPD sensor
Platform	SteamVR, HTC Viveport	SteamVR, HTC Viveport
Price	$499 of whole VR system	$799 standalone
Related Research	Research of VIVE using in the manufacturing planning	-

Table 4-1-1 VIVE/VIVE Pro characteristics [50]

Research of *HTC VIVE* using in the manufacturing planning		
Test setups position	Volvo headquarter in Göteborg, Sweden	
Subjects	**Number of subjects**	10

	Subject background		9 workers from different actor groups of Volvo; 1 senior researcher from Chalmers VR research group
Test process	1) Subjects were guided by training and then attended in the virtual environment of the factory; 2) Subjects were asked to navigate in the virtual factory; 3) Subjects were asked to modify, save and load the new layout; 4) Subjects gave feedback of the present layout based on their knowledge; 5) Subjects were asked to fill the questionnaires with both the open-ended and closed-ended questions to rate their experience of using the virtual tools and the virtual environment		
Test results	**Quantitative part**	● Most of the subjects recommended the usage of the VR method based on the results of the "potential benefit" rating; ● Due to the immaturity of the tool, the results of the "user experience" didn't show the similar results of the "potential benefit", but they were still positive; ● Top 3 recommended application fields of the VR method by the subjects are: 1) layout planning, 2) training and education, 3) simulation;	
	Qualitative part	Results of the open questions showed: ● The advantages of the VR method are: 1) easy using, 2) veracity, 3) closed to reality; ● The disadvantages of the VR method are: 1) possibility of dizziness causing, 2) problem of disorientation, 3) long time adapting ● Possible challenges of the VR systems: 1) cost, 2) organizational attitudes, 3) costly	

Table 4-1-2 Related research of the VIVE [51]

Figure 4.1 VIVE by HTC [52]

Figure 4.2 VIVE Pro by HTC [53]

- Rift by Oculus

Name	Rift
Company	Oculus
Display Resolution	2160 x 1200; across two screens, 1080 x 1200 per eye
Dimension	166 x 308 x 392 mm
Weight	4700 g
Refresh Rate	90Hz
Display Type	PenTile OLED
Field Of View	110°
Tracking System	Constellation
Room Scale Support	Requires a third sensor
Built-in Microphone	Yes
Integrated Headphones	Yes
External Camera	No
Controllers	Xbox One controller, Oculus remote, and Oculus Touch controllers

Connections	HDMI 1.3, USB 3.0, USB 2.0
Sensors	Accelerometer, gyroscope, magnetometer, Constellation tracking camera
Platform	SteamVR, Oculus Store
Price	$399
Related Research	Research of virtual riveting task with Oculus Rift

Table 4-2-1 Rift characteristics [54]

<table>
<tr><th colspan="3">Research of virtual riveting task with Oculus Rift</th></tr>
<tr><td>Test simulation</td><td colspan="2">Riveting sheet metal skins on the small to medium aircraft wings</td></tr>
<tr><td rowspan="2">Subjects</td><td>Number of subjects</td><td>9</td></tr>
<tr><td>Subject background</td><td>Unskilled operator</td></tr>
<tr><td>Test process</td><td colspan="2">1) Adjusted the sensor camera according to the subjects heights;
2) Subjects handled the tool and rivet to perform riveting in turns(20 holes in 4 minutes), the avatar will do the same job by following the subjects movement ;
3) Checked the feasibility of the model orientation and the method;
4) Subjects filled the questionnaires of : 1. the physical discomfort of the body during the task, 2. difficulties of performing the task, 3. reported the discomfort of the using of the HMD;
5) RULA, REBA and HAV protocol application to evaluate the ergonomics factors during the task.</td></tr>
<tr><td rowspan="2">Test results</td><td>Questionnaires</td><td>1. The most uncomfortable body parts are: right shoulder (8/10), right wrist (7/10) and right elbow (5/10);
The less painful body part are: knees, legs, left hand and elbow (0-1/10);
2. No clear difficulties were recorded;
3. Some dizziness was recorded.</td></tr>
<tr><td>RULA, REBA and HAV evaluation</td><td>For the main riveting posture:
● RULA scores: 6 (medium risk. Change soon);
● REBA scores: 6 (required);
Riveting for 2.4 hours per 8 hours shift with the vibration data of 5.6 m/sec^2:
● HAV Total Exposure Points: 157(changes should be undertaken)</td></tr>
</table>

Table 4-2-2 Related research of the Rift [55]

Figure 4.3 Rift by Oculus [56]

- PlayStation VR by Sony

Name	PlayStation VR
Company	Sony
Display Resolution	1920 x 1080; across two screens, 960 x 1,080 per eye
Dimension	187 x 185 x 277 mm
Weight	610 g
Refresh Rate	90Hz
Display Type	5.7" OLED
Field Of View	110°
Tracking System	PlayStation Camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	No
External Camera	No
Controllers	DualShock 4, PlayStation Move, Aim Controller
Connections	AUX port, HDMI output port, HDMI TV port, HDMI PS4 port, USB port
Sensors	Accelerometer, gyroscope
Platform	PlayStation Store
Price	$399 standalone
Related Research	-

Table 4-3 PlayStation VR characteristics [57]

Figure 4.4 Rift by Oculus [58]

- Odyssey by Samsung

Name	Odyssey
Company	Samsung
Display Resolution	2880x1600; across two screens, 1440x1600 per eye
Dimension	202 x 131.5 x 111 mm
Weight	645g
Refresh Rate	60/90Hz
Display Type	AMOLED
Field Of View	110°
Tracking System	Samsung camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	Yes
External Camera	Yes
Controllers	6 DOF Controller / Xbox One Controller Support
Connections	HDMI2.0 + USB 3.0
Sensors	Accelerometer, gyroscope, magnetometer, proximity sensor, and IPD sensor
Platform	Windows Mixed Reality
Price	$499 with controllers
Related Research	-

Table 4-4 Odyssey characteristics [59]

Figure 4.5 Odyssey by Samsung [60]

- HC102 by ASUS

Name	HC102
Company	ASUS
Display Resolution	2880x1440; across two screens, 1440x1440 per eye
Dimension	200 x 220 x 150 mm
Weight	400g
Refresh Rate	90Hz
Display Type	LCD
Field Of View	95°
Tracking System	ASUS camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	No
External Camera	Yes
Controllers	6 DOF Controller / Xbox One Controller Support
Connections	HDMI2.0 + USB 3.0+3.5mm Jack
Sensors	Accelerometer, gyroscope, magnetometer, and proximity sensor
Platform	Windows Mixed Reality
Price	$399 with controllers
Related Research	-

Table 4-4 HC102 characteristics [61]

Figure 4.6 HC102 by ASUS [62]

- Explorer by Lenovo

Name	Explorer
Company	Lenovo
Display Resolution	2880x1440; across two screens, 1440x1440 per eye
Dimension	185.1 x 94.8 x 102.1 mm
Weight	380g
Refresh Rate	90Hz
Display Type	LCD
Field Of View	110°
Tracking System	Lenovo camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	No
External Camera	Yes
Controllers	6 DOF Controller / Xbox One Controller Support/ Keyboard and mouse
Connections	HDMI2.0 + USB 3.0+3.5mm Jack
Sensors	Accelerometer, gyroscope, magnetometer, and proximity sensor
Platform	Windows Mixed Reality
Price	$349 standalone, $399 with controllers
Related Research	-

Table 4-5 Explorer characteristics [63]

Figure 4.7 Explorer by Lenovo [64]

- Mixed Reality Headset Developer Edition by HP

Name	Mixed Reality Headset Developer Edition
Company	HP
Display Resolution	2880x1440; across two screens, 1440x1440 per eye
Dimension	338.84 x 176.02 x 127.76 mm
Weight	843g
Refresh Rate	90Hz when paired to HDMI 2.0 port 60Hz when paired to HDMI 1.4 port
Display Type	LCD
Field Of View	95°
Tracking System	HP camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	No
External Camera	Yes
Controllers	6 DOF Controller / Xbox One Controller Support
Connections	HDMI2.0 + USB 3.0+3.5mm Jack
Platform	Windows Mixed Reality
Sensors	Accelerometer, gyroscope, and proximity sensor
Price	$329 standlone, $449 with controllers
Related Research	-

Table 4-6 Mixed Reality Headset Developer Edition characteristics [65]

Figure 4.8 Mixed Reality Headset Developer Edition by HP [66]

- Windows Mixed Reality Headset Model by Acer

Name	Windows Mixed Reality Headset Model
Company	Acer
Display Resolution	2880x1440; across two screens, 1440x1440 per eye
Dimension	195.8 x 94.8 x 106.59 mm
Weight	350g
Refresh Rate	90Hz when paired to HDMI 2.0 port 60Hz when paired to HDMI 1.4 port
Display Type	LCD
Field Of View	100°
Tracking System	Acer camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	No
External Camera	Yes
Controllers	6 DOF Controller / Xbox One Controller Support
Connections	HDMI2.0 + USB 3.0+3.5mm Jack
Platform	Windows Mixed Reality
Sensors	Accelerometer, gyroscope, magnetometer, and proximity sensor
Price	$299 standalone, $399 with controllers
Related Research	-

Table 4-7 Mixed Reality Headset Model characteristics [67]

Figure 4.9 Mixed Reality Headset Model by Acer [68]

- Visor by Dell

Name	Visor
Company	Dell
Display Resolution	2880x1440; across two screens, 1440x1440 per eye
Dimension	210 x 330 x 129 mm
Weight	145 g
Refresh Rate	90Hz
Display Type	LCD
Field Of View	110°
Tracking System	Dell camera
Room Scale Support	No
Built-in Microphone	Yes
Integrated Headphones	No
External Camera	Yes
Controllers	6 DOF Controller / Xbox One Controller Support
Connections	HDMI2.0 + USB 3.0+3.5mm Jack
Platform	Windows Mixed Reality
Sensors	Accelerometer, gyroscope, and magnetometer
Price	$349 standalone, $449 with controllers
Related Research	-

Table 4-8 Visor by Dell characteristics [69]

Figure 4.10 Mixed Reality Headset Model by Acer [70]

At this stage, the VR HMD is mainly used as a support device for virtual reality games. With the development of sensor technology, VR technology will be used more in military, medical, industrial production, commercial support and other fields. Through the accurate simulation of the industrial production process by VR technology, the ergonomic principle can be better reflected in the industrial production process design, thus improving the efficiency of industrial production.

4.2 Augmented Reality

Unlike VR technology, AR technology aims to add the specified patterns or model information to the realistic environment, so the AR device should be able to capture the real environment in real time and add virtual information to the captured dynamic images.

4.2.1 AR glasses

As a special kind of HMDs, AR glasses are the core equipment of AR technology. Like its name, AR glasses are mainly composed of "frames" and "lenses". The "lens" is the display of the AR glasses, and the "frame" generally integrates the camera and the processor. Compared with VR HMDs, AR glasses have the advantages of light weight and small volume. There are some AR glasses which are available in market or are in prototype:

- Google Glass Enterprise Edition by Google

Name	Google Glass Enterprise Edition
Company	Google
Available on Market/Prototype	Available on Market
Weight	40g
Processors	Intel Atom
Sensors	ambient light sensor, digital compass, wink sensor, blink sensor, barometer, capacitive head sensor, hinge sensor, assisted GPS & GLONASS
Camera	8MP

Human Understanding	-
Connections	Wi-Fi : dual-band 2.4 + 5 GHz 802.11a/b/g/n/ac; Bluetooth LE and HID
Storage and Memory	16-32GB for storage; 2GB for RAM
Endurance Time	5 hours
Price	$1735
Related Research	Research of Google Glass using in reducing anxiety while interacting with industrial robots

Table 4-9-1 Google Glass Enterprise Edition characteristics [71]

Research of *Google Glass* using in reducing anxiety while interacting with industrial robots		
Test field	Human-robot collaboration	
Subjects	**Number of subjects**	12
	Subject genders	2 females and 10 male (age: 20-35)
Test process	1) Subjects wore the three prototypes of Google Glass with interface based on text, traffic light symbols and icons separately, the interface showed three statement of the system: 1. Performing the task with robot halting in secured position, 2. subjects have to perform an unsupervised activity outside the reach of the robot, 3. dangerous position of the robot; 2) The robot grasped a heavy car engine to present before the subjects, then the subjects inserted four groups of screws and assembled an oil pan outside the reach of the robot when the robot was programming; 3) Subjects filled the STAI questionnaire after the task to report the State and Trait Anxiety.	
Test results	● Average value of the anxiety of the personality trait state is 37.00, SD: 5.26; ● Average value of the anxiety of the text prototype is 35.00, SD = 8.32; ● Average value of the anxiety of the icon prototype is 33.08, SD = 7.30; ● Average value of the anxiety of the lights prototype is 33.75, SD = 7.17; All the results showed the Google Glass using in the human-robot collaboration helped to reduce the anxiety of the workers.	

Table 4-9-2 Related research of the Google Glass [72]

Figure 4.10 Google Glass Enterprise Edition by Google [73]

- HoloLens by Microsoft

Name	HoloLens
Company	Microsoft
Available on Market/Prototype	Available on Market
Weight	579g
Processors	Intel 32 bit architecture; Custom-built Microsoft Holographic Processing Unit (HPU 1.0)
Sensors	IMU, environment understanding cameras x 4, depth camera, ambient light sensor
Camera	2.4 MP
Human Understanding	Spatial sound; Gaze tracking; Gesture input; Voice support
Connections	Wi-Fi : IEEE 802.11ac; Bluetooth 4.1; LE
Storage and Memory	64GB for storage; 2GB for RAM 1GB for HPU RAM
Endurance Time	2–3 hours of active use, or 2 weeks of standby time
Price	$3000

Table 4-10 HoloLens characteristics [74]

Figure 4.10 HoloLens by Microsoft [75]

<table>
<tr><th colspan="3">Research of Microsoft HoloLens in picking simulation</th></tr>
<tr><td>Test field</td><td colspan="2">Kit preparation of the material supply for a mixed-model automotive assembly</td></tr>
<tr><td rowspan="2">Subjects</td><td>Number of subjects</td><td>5</td></tr>
<tr><td>Subject genders</td><td>1 females and 4 male (age: 23-35, inexperienced)</td></tr>
<tr><td>Test process</td><td colspan="2">1) Subjects were trained to be familiar with HMD and the paper list;
2) Subjects were asked to perform four configuration of the kit preparation each cycle : 1. Pick-by-AR in Single-kit preparation, 2. Pick-by-paper in Single-kit preparation, 3. Pick-by-AR in Batch preparation, 4. Pick-by-paper in Batch preparation;
3) During the picking, the time consuming(average picking time per component) of each picking cycle will be recorded by two cameras;
4) During the picking, the picking errors of the operators were recorded in real time and were double-checked by the record of the cameras.</td></tr>
<tr><td>Test results</td><td colspan="2">● The average time consuming of the picking time(± 95% C.I.) rating were: 1) 3.06 ± 0.13s of the Pick-by-AR in Batch preparation, 2) 3.50 ± 0.12s of the Pick-by-paper in Batch preparation, 3) 4.31 ± 0.23s of the Pick-by-paper in Single-kit preparation, 4) 4.80 ± 0.40s of the Pick-by-AR in Single-kit preparation;
● The number of the picking errors(wrong picking or wrong placing) rating were: 1) 1 time in the Pick-by-AR in Single-kit preparation, 2) 5 times in the Pick-by-paper in Single-kit preparation, 3) 7 times in the Pick-by-AR in Batch preparation, 4) 11 times in the Pick-by-paper in Batch preparation;
● Results above showed the benefits of the pick-by-AR, especially when it was applied in the picking with more information. However, since the weight of the HMD is around 600g, the long-time using may also causes the</td></tr>
</table>

	problem of fatigue.

Table 4-10-2 Related research of the Microsoft HoloLens [76]

AR glasses are now entering industrial production. As a kind of auxiliary equipment, AR glasses can provide accurate and effective visual information in real time. It will appear more in industrial production activities such as warehouse activities, industrial vehicle driving, assembly activities, and human-computer interaction.

5 COLLABORATIVE ROBOTS

According to the ISO 10218-1:2011, the "collaborative operation" is defined as a workable state in which purposely designed robots can work within a defined workplace with the direct cooperation of a human [77] [78]. When performing the operation, the robot and the worker can make physical contact. For example, figure 1 shows a hand-guided artifact feeding action example. The operator guides the robot arm to the workpiece position and uses the hand guide device to make the arm grasp the workpiece in the collaborative working space. After that, he moves his arm into the automatic operating space, and once the arm crossed the security boundary, the robot will be transitioned to automatic operating mode for programmed processing.

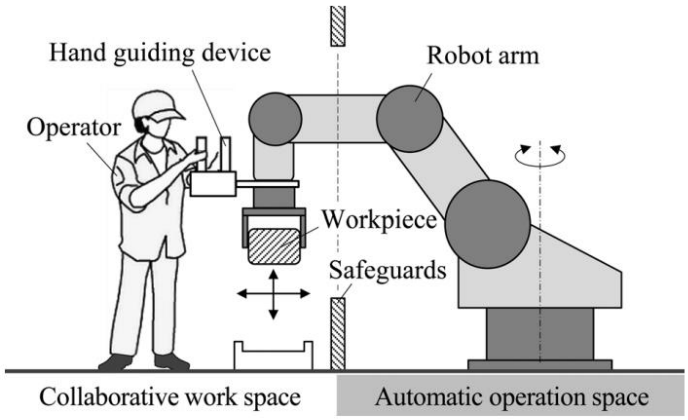

Figure 1. Example of a hand-guided artifact feeding action [79]

Four main types of collaborative operation are defined by the ISO 10218 and ISO/TS 15066, they are: "Safety-rated monitored stop", "Hand guiding", "Speed and separation monitoring" and "Power and force limiting" [80].

- Safety-rated monitored stop: when performing the operation, either the robot system or the person move, but they don't move at the same time. Before the operator entering the collaborative workspace, the robot remains standstill. In this situation, the drive power of the robot will remain on, motions of the robot resumes when the worker leaves the workspace. Also, when the stop condition is triggered, protective stop happens.

- Hand guiding: when performing the operation, both the worker and the robot can move at the same time. In this situation, the robot system is directly guided by the worker. Before the worker entering the collaborative workspace, the robot system will be in a safety-rated monitored stop. The worker can grasp the robot to perform operation, and non-collaborative operation resumes after the worker leaving the workspace.

- Speed and separation monitoring: when performing the operation, worker and robot system can concurrently perform movements in the collaborative workspace. Worker and robot system will maintain a minimum protective separation distance by the protective devices between each other at all times. In this situation, the operation speed will be lower and if the minimum protective separation distance is violated, protective stop happens.

- Power and force Limiting: when performing the operation, either intentionally or unintentionally physical contact can occur between the robot system and the worker. In this situation, robot systems are required to be design to fulfill the safety request of the power and force limiting. Incidental physical quasi-static (pressure/clamping) or transient (dynamic) contacts are possible to perform.

A collaborative robot is defined as a robot designed to interact directly with people in a collaborative area. The most important feature of cooperative robots is that they can work directly with people without using the safety fence for isolation, and their safety protection design is more demanding. The cooperative robot is flexible and user friendly. It can work closely with people, not only to save the space, but to meet the needs of the new consumer electronics industry miniaturization and precision, and to increase productivity. Collaborative robot is expected to fill the whole gap between manual assembly line and automatic production line. It used to be said that robots were replacing human labor, and robots are now more commonly seen as auxiliary tools. Rigid boundaries between inflexible automation and manual labor are being phased out. Efficient sensor, intelligent control technology and the most advanced software technology integration on the robot, ensure location and task flexibility in applications. In the actual production process, employees can use the required number of robots in different production locations and for different purposes.

There is a virtual research which showed the main characteristics of the effect of the collaborative robot application:

Virtual research of the collaborative robots effect by ergonomics indicator		
Test field	Virtual testing	
Subjects	**Number of subjects**	5(3 males and 2 females)
	Age	25-30 years old
	Average height	1.72 m (SD 0.1, min 1.53 m, max 1.82 m)
	Average body mass index	22.6 $kg.m^{-2}$ (SD 0.8, min 21.7 $kg.m^{-2}$, max 23.8 $kg.m^{-2}$)

Test process	1) Subjects were asked to perform ten times a drilling task(1 min each with 6 holes to drill) with 2.1 kg drill(the average normal force is 40N), they were using their right hand only to perform the test after training; 2) Forces sensors and motion capture system recorded the data of the subjects when they were performing the task; 3) Transferred all the data into a virtual environment; 4) Using the predefined formulas to calculate the correspondent ergonomics indicators of the virtual process; 5) Set up the collaborative robot model and created a human-robot system; 6) Using the virtual human-robot system to perform the drilling tasks, calculated the correspondent ergonomics indicators; 7) Compared the results of the ergonomics indicators of the human-alone system and the human-robot system.
Test results	Comparing the ergonomic indicators of the human-alone system and the human-robot system: ● The ergonomics indicators of the human-robot system in turns of the right arm position, back position, right arm velocity, right arm accuracy and dynamic balance are worse than the human-alone system; ● The ergonomics indicators of the human-robot system in turns of the right arm power, right arm torque, back torque, legs torque, balance stability are better than the human-alone system.

Table 5-1 Virtual research of the collaborative robots effect [81]

According to the structure of collaborative robot, collaborative robot can be divided into single-arm collaborative robots and dual-arm collaborative robots.

5.1 Single-arm Collaborative Robots

On the basis of the similar degree of freedom of the traditional single-arm manipulator, the single-arm collaborative robots add more types of sensors to assist human interaction. Moreover, the single-arm collaborative robots have the characteristics of light weight, high safety coefficient, high sensitivity and easy programming. Therefore, we can simply think that the single-arm collaborative robot is a more intelligent single-arm robot.

The market of single-arm collaborative robot is a relatively mature collaborative robot market. At present, a considerable number of single-arm collaborative robots have been put into practical industrial production and application, and many robot companies have developed mature related products:

- UR series by Universal Robots

Name	UR3	UR5	UR10
Company	Universal Robots	Universal Robots	Universal Robots
Weight	11 kg	18.4 kg	28.9 kg
Degrees of Freedom	6	6	6
Payload	3 kg	5 kg	10 kg
Reach	500 mm	850 mm	1300 mm
Repeatability	±0.1 mm	±0.1 mm	±0.1 mm
IP rating	IP64	IP54	IP54
Camera	No	No	No
Safety	TUV approved	TUV approved	TUV approved
Price	Around $35000	Around $45500	Around $56500
Related Research	Research of UR series application of safety, interaction and trust		

Table 5-2-1 UR series characteristics [82]

Research of *UR series* application of safety, interaction and trust		
Test field	Industrial applications: Safety, interaction and trust	
Subjects	**Number of the subjects**	38(36 male 2 female)
	Prior experience of the subjects	● 13% of the subjects worked with robots for more than 10 years; ● 8% of the subjects worked with robots for 6-10 years; ● 37% of the subjects worked with robots for 1-5 years; ● 48% of the subjects have no prior experience with robots.
Experiment design	Subjects were asked to fill in the questionnaires after the following test: ● Pointing gesture: subjects used a pointing gesture(finger extended) to show the tray position, then the cobot followed the gesture to pick up the parts and placed it on the corresponding position; ● Safety monitoring: when the cobot was moving, subjects were invited to reach out the cobot without direct touching, the monitoring system stopped the cobot when the distance between subjects and cobot was below a threshold; ● Manual guidance: subjects dragged the cobot's gripper to a position, the cobot recorded the place and returned to that place first before picking and placing parts on the trays; ● Collision: without the monitoring system, the cobot stopped	

	when it hit the subjects' arms.
Experiment results	● Interaction mechanisms: 1) the "usefulness" result of the pointing test is with a lower score while other parameters like "naturalness", "ease of use" and "reliability" were very positive, 2) in the dragging test, the results of the "effort needed to drag the robot", "usefulness" and "difficulty to perform" are positive, 3) large number of subjects found the problem of the effort acceptability of moving the robot; ● Safety: high agreement of the safety issue can be found by the subjects' perspectives; ● Workers opinion: ranking of the important issues of the cobot is: safety, usability, flexibility and efficiency.

Table 5-2-2 Related research of UR series [83]

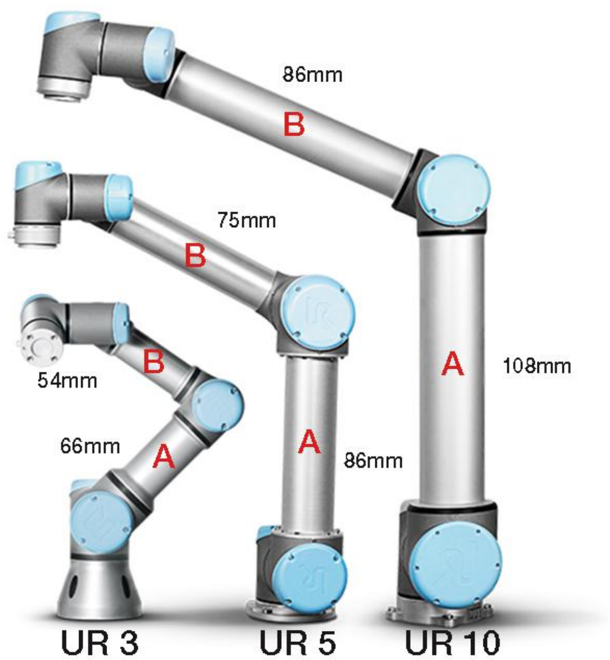

Figure 5.1 UR series by Universal Robots [84]

● I5 by AUBO

Name	I5
Company	AUBO
Weight	24 kg
Degrees of Freedom	7
Payload	5 kg

Reach	924 mm, 880 mm (working range)
Repeatability	±0.05 mm
IP rating	IP54
Camera	Gigabit ethernet camera
Safety	PL d
Price	Around $18000
Related Research	-

Table 5-3 I5 characteristics [85]

Figure 5.2 I5 by AUBO [86]

- LBR IIWA series by KUKA

Name	LBR IIWA 7	LBR IIWA 14
Company	KUKA	KUKA
Weight	22.3 kg	29.9 kg
Degrees of Freedom	7	7
Payload	7 kg	14 kg
Reach	800 mm	820 mm
Repeatability	±0.10 mm	±0.15 mm
IP rating	IP 54	IP 54
Camera	-	-
Safety	Uses SafeOperation software, Complying to ISO 10218; ISO 12100; ISO 13849	Uses SafeOperation software, Complying to ISO 10218; ISO 12100; ISO 13849
Price	Around $70000	Around $70000
Related Research	Research of KUKA IIWA using in optimization of the brake disc assembly process	

Table 5-4-1 LBR IIWA series characteristics [87]

Research of *KUKA IIWA* using in optimization of the brake disc assembly

process		
Test field	Brake disc assembly	
Task details	**Working time**	8 h/shift
	Assembly time	3 min each brake disc
	Disc weight	5 kg
Original assembly process	● Main assembly procedures: picking parts, placing parts, tightening screws; ● The worker needs to assemble 160 brake disc(800 kg) each day by original manual work, considering 200 working days, he will lift around 16000 kg each year; ● The original manual process time is around 180s for each assembly;	
Optimization of the assembly process	1) Using the Analytic Hierarchy Process (AHP) to find out the benefits of the human-robot collaboration, which are the improvements in productivity, human fatigue, safety and quality; 2) Constructed a human-robot system with a stop button which control the safety during the human-robot collaboration; 3) Using the hierarchal task analysis (HTA) to decompose the assembly task and rearrange it with the cobot intervening; 4) Simulate all the assembly elements in a virtual environment, design the new process by the previous results; 5) Found out the defects of the sight obstructing of the cobot and tried to optimize it.	
Research results	● Compared to the original assembly time(180 s), the human-robot system assembly time was little longer(210 s); ● The using of the cobot helps to replace all the lifting works and some tightening works of the assembly process, which significantly reduce the risk of the MSDs caused by the frequent lifting of the brake disc.	

Table 5-4-2 Related research of LBR IIWA [88]

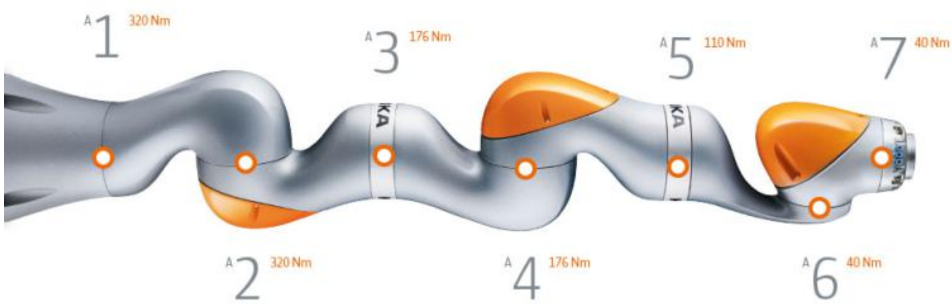

Figure 5.3 LBR IIWA series by KUKA [89]

- OB7 by PRODUCTIVE ROBOTICS

Name	OB7
Company	PRODUCTIVE ROBOTICS
Weight	24 kg
Degrees of Freedom	7
Payload	5 kg
Reach	1000 mm
Repeatability	±0.10 mm
IP rating	IP64
Camera	-
Safety	Power and force limited, compliant
Price	Around $ 20000
Related Research	-

Table 5-5 OB7 characteristics [90]

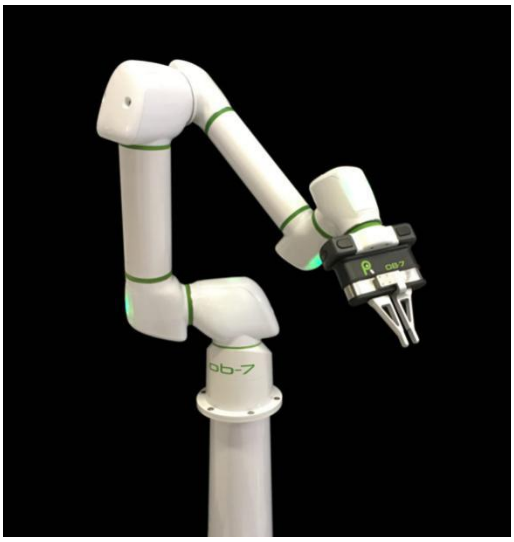

Figure 5.4 OB7 by PRODUCTIVE ROBOTICS [91]

- JACO2/ MICO2 by Kinova

Name	JACO2	MICO2
Company	Kinova	Kinova
Weight	4.4 kg	4.6kg
Degrees of Freedom	6	6
Payload	2.6 kg	2.1 kg
Reach	900 mm	700 mm
Repeatability	-	-
IP rating	-	-
Camera	-	-
Safety	-	-

Price	$30000 arm + $4950 gripper	$20900 arm + $4950 gripper
Related Research	-	-

Table 5-6 JACO2/ MICO2 characteristics [92]

Figure 5.5 JACO2 by Kinova [93]

Figure 5.6 MICO2 by Kinova [94]

- Speedy series by MABI

Name	Speedy 6	Speedy 12
Company	MABI	MABI
Weight	28 kg	35 kg
Degrees of Freedom	6	6
Payload	6 kg	12 kg
Reach	800 mm	1250 mm
Repeatability	±0.10 mm	±0.10 mm
IP rating	IP 54	IP 54
Camera	-	-
Safety	Soft external skin, force torque sensor at the base	Soft external skin, force torque sensor at the base

	of the robot	of the robot
Price	-	-
Related Research	-	-

Table 5-7 Speedy series characteristics [95]

Figure 5.7 Speedy 6 by MABI [96]

Figure 5.8 Speedy 12 by MABI [97]

- Racer series by COMAU

Name	Racer 3	Racer 5	Racer 5-0.80
Company	COMAU	COMAU	COMAU
Weight	30	32	32
Degrees of Freedom	6	6	6
Payload	3	5	5
Reach	630 mm	630 mm	809 mm
Repeatability	±0.02 mm	±0.03 mm	±0.03 mm
IP rating	IP54	IP54(IP65 Option)	IP54(IP65 Option)

Camera	-	-	-
Safety	-	-	-
Price	-	-	-
Related Research	-	-	-

Table 5-8 Racer series characteristics [98]

Figure 5.9 Racer 3 by COMAU [99]

Figure 5.10 Racer 5 by COMAU [100]

Figure 5.11 Racer 5-0.80 by COMAU [101]

- TX2-60 series by STÄUBLI

Name	TX2-60	TX2-60L
Company	STÄUBLI	STÄUBLI
Weight	51.4 kg	52.5 kg
Degrees of Freedom	6	6
Payload	3.5 kg	2 kg
Reach	670 mm	920 mm
Repeatability	±0.02 mm	±0.03 mm
IP rating	IP65	IP65
Camera	-	-
Safety	PL e Cat. 3 (According to ISO 10218-1)	PL e Cat. 3 (According to ISO 10218-1)
Price	Around $ 40000	Around $ 40000
Related Research	-	-

Table 5-9 TX2-60 series characteristics [102]

Figure 5.12 TX2-60 by STÄUBLI [103]

Figure 5.13 TX2-60L by STÄUBLI [104]

- CR 4iA by FANUC

Name	CR 4iA
Company	FANUC
Weight	48 kg
Degrees of Freedom	6
Payload	4 kg
Reach	550 mm
Repeatability	±0.02 mm
IP rating	IP 67
Camera	-
Safety	Soft external skin, force torque sensor at the base of the robot
Price	Around $ 45700
Related Research	-

Table 5-10 CR 4iA characteristics [105]

Figure 5.14 CR 4iA by FANUC [106]

- HCR-5 by HY ROBOTICS

Name	HCR-5
Company	HY ROBOTICS
Weight	20 kg
Degrees of Freedom	6
Payload	5 kg
Reach	915 mm
Repeatability	±0.10 mm
IP rating	IP 54
Camera	-
Safety	-
Price	-
Related Research	-

Table 5-11 HCR-5 characteristics [107]

Figure 5.15 HCR-5 by HY ROBOTICS [108]

- TM5 Series by Techman Robot

Name	TM5-700	TM5-900
Company	Techman Robot	Techman Robot
Weight	22.1 kg	22.6 kg
Degrees of Freedom	6	6
Payload	6kg	4 kg
Reach	700 mm	900 mm
Repeatability	±0.05 mm	±0.05 mm
IP rating	IP 54	IP 54
Camera	-	-
Safety	150N max. Force (ISO/TS 15066 Compliant)	150N max. Force (ISO/TS 15066 Compliant)
Price	-	-
Related Research	-	-

Table 5-12 TM5 Series characteristics [109]

Figure 5.16 TM5-700 by Techman Robot [110]

Figure 5.17 TM5-900 by Techman Robot [111]

- P-Rob 2R by F&P Robotics

Name	P-Rob 2R
Company	F&P Robotics
Weight	20 kg
Degrees of Freedom	6
Payload	3-5 kg
Reach	775 mm
Repeatability	±0.10 mm
IP rating	IP 40
Camera	-
Safety	ISO/TS 15066
Price	-
Related Research	-

Table 5-13 P-Rob 2R characteristics [112]

Figure 5.18 P-Rob 2R by F&P Robotics [113]

- MOTOMAN HC10 by YASKAWA

Name	MOTOMAN HC10
Company	YASKAWA
Weight	47 kg
Degrees of Freedom	6
Payload	10 kg
Reach	1200 mm
Repeatability	±0.10 mm
IP rating	IP 20
Camera	-
Safety	Pending Approval for TUV certifcation, Designed to meet EN ISO 10218-1 Cat 3 PL d. EN ISO 13849:2008 PI d
Price	Around $ 48000
Related Research	-

Table 5-14 MOTOMAN HC10 characteristics [114]

Figure 5.19 MOTOMAN HC10 by YASKAWA [115]

- COBOTTA by DENSO

Name	COBOTTA
Company	DENSO
Weight	4 kg
Degrees of Freedom	6
Payload	0.5 kg
Reach	310 mm
Repeatability	±0.05mm'2
IP rating	IP 30
Camera	-
Safety	ISO 10218-1:2011 ISO/TS 15066

	ISO 13849-1:2015 PL d
Price	-
Related Research	-

Table 5-15 COBOTTA characteristics [116]

Figure 5.20 COBOTTA by DENSO [117]

- SAWYER by RETHINK ROBOTICS

Name	SAWYER
Company	RETHINK ROBOTICS
Weight	19 kg
Degrees of Freedom	7
Payload	4 kg
Reach	900 mm
Repeatability	±0.10 mm
IP rating	IP 54
Camera	Wrist & head
Safety	ISO 10218-1 Compliant
Price	Around $ 37000
Related Research	-

Table 5-16 SAWYER characteristics [118]

Figure 5.21 SAWYER by RETHINK ROBOTICS [119]

- APAS assistant by BOSCH

Name	APAS ASSISTANT
Company	BOSCH
Weight	230 kg
Degrees of Freedom	6
Payload	4 kg
Reach	911 mm
Repeatability	±0.03 mm
IP rating	-
Camera	Overview & positioning camera
Safety	Certified by German Trade association
Price	-
Related Research	-

Table 5-17 APAS assistant characteristics [120]

Figure 5.23 APAS assistant by BOSCH [121]

- Panda by FRANKA EMIKA

Name	Panda
Company	FRANKA EMIKA
Weight	18 kg
Degrees of Freedom	7
Payload	3 kg
Reach	855 mm
Repeatability	±0.10 mm
IP rating	IP 30
Camera	-
Safety	PL d Cat 3. (EN ISO 13849-1:2008)
Price	Around $ 12000
Related Research	-

Table 5-18 Panda characteristics [122]

Figure 5.24 Panda by FRANKA EMIKA [123]

5.2 Dual-arm Collaborative Robots

Compared with the single-arm collaborative robot, the dual-arm collaborative robot generally has higher freedom, better sensitivity, and greater operating space. At present, many of the dual-arm collaborative robots in the market are equipped with visual sensors that can capture environmental information in real time. Higher operating freedom also increases the programming difficulty of such collaborative robots.

The existing dual-arm collaborative robots are mainly represented by:

- YUMI by ABB

Name	YUMI
Company	ABB

Weight	38 kg
Degrees of Freedom	7
Payload	0.5 kg per arm
Reach	599 mm
Repeatability	±0.02 mm
IP rating	IP 30
Camera	Yes
Safety	PL b Cat B
Price	Around $ 40000
Related Research	-

Table 5-19 YUMI characteristics [124]

Figure 5.25 YUMI by ABB [125]

- NEXTAGE by KAWADA INDUSTRIES

Name	NEXTAGE
Company	KAWADA INDUSTRIES
Weight	29 kg
Degrees of Freedom	15
Payload	1.5 kg per arm
Reach	577 mm
Repeatability	±0.03 mm
IP rating	-
Camera	Yes
Safety	Each motor is limited to 80 W (very low)
Price	Around $ 60000
Related Research	-

Table 5-20 NEXTAGE characteristics [126]

Figure 5.26 NEXTAGE by KAWADA INDUSTRIES [127]

- BAXTER by RETHINK ROBOTICS

Name	BAXTER
Company	RETHINK ROBOTICS
Weight	19 kg
Degrees of Freedom	7 per arm
Payload	4 kg
Reach	1260 mm
Repeatability	±0.10 mm
IP rating	IP 50
Camera	Yes
Safety	ISO 10218-1 Compliant
Price	Around $ 37000
Related Research	-

Table 5-21 BAXTER characteristics [128]

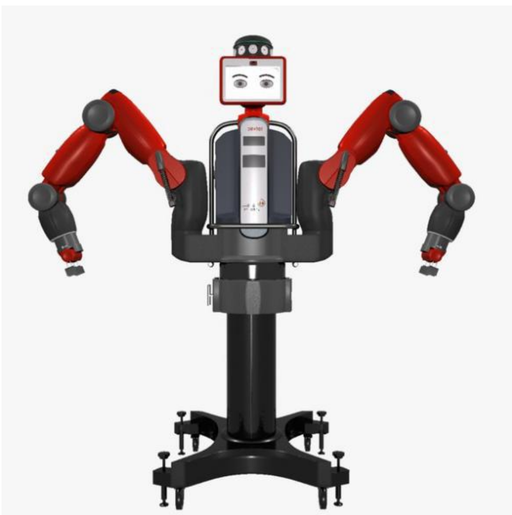

Figure 5.27 BAXTER by RETHINK ROBOTICS [129]

The emergence of collaborative robots has changed the role of industrial robots in industrial production. They offer the possibility of robots working with workers to accomplish tasks, not just tasks alone. Future developments in collaborative robots will focus more on security, agility, and ease of programming. The human-robot collaboration trend they are leading will enable humans and robots to play a better role in industrial production. This makes ergonomic principles better reflected in the process of industrial production design and implementation, thus reducing production risks and improving production efficiency.

6 CONCLUSIONS

Under the tide of industry 4.0, various emerging technologies mentioned in this paper are good media for better application of ergonomics principles in actual industrial production. In order to realize the harmonious integration of "human-machine-environment" emphasized in the new era of ergonomics, their cognition and corresponding studies in the field of ergonomics are discussed in this paper.

In history, there were three major industrial revolutions that changed human society and industrial production patterns. They are the steam age from the 1860s to the mid-19th century, the electrical age from the second half of the 19th century to the early 20th century and the technological age after the Second World War. The birth of industry 4.0 indicates that human society will enter the "intelligent era" represented by "intelligent factories", "intelligent production" and "intelligent logistics". The main characteristics of industry 4.0 are: intelligent production/customized production,

production by servicing and cloud factory.

Ergonomics, as a multidisciplinary cross discipline, involves many fields such as psychology, physiology, medicine, anthropometry, aesthetics and engineering technology. The core of the ergonomics is the coordination between human, machine and environment. In industry 4.0, ergonomics has its new features: integration of "Human - machine - environment" system, informatization, interconnection and innovation. Therefore, how to make use of the new technology born in industry 4.0 environment to better realize the requirement of ergonomics is the research focus in the field of ergonomics in the new era.

One of these new technologies is industrial exoskeletons. There are three main types of exoskeletons in the market for industrial exoskeletons: upper limps industrial exoskeletons, trunk-assisted industrial exoskeletons and lower body ind`ustrial exoskeletons. Depending on the drive type, these industrial exoskeletons can also be divided into active industrial exoskeletons and passive industrial exoskeletons. Many industrial exoskeletons are tested and studied through comparative experiments. The actual effects of industrial exoskeletons are verified through the collection of signals of various muscle activities during the execution of corresponding tasks by workers with or without an industrial exoskeleton and the questionnaire survey after the experiment. For industrial exoskeletons, researches show that their application will reduce the workers muscle activities well in the actual production activities. Through its own mechanical structure or drive unit, the worker's load will be better distributed to reduce the risk of spinal injuries and muscle injuries, so as to improve the production operation comfort and production efficiency.

VR and AR technologies are the best embodiment of ergonomic informatization. HMDs are the main devices used in the field of VR and AR. There are researches on factory layout design with VR applications. Research shows that VR technology has obvious advantages in layout planning, training and education, simulation and easy using. Of course, VR technology also has disadvantages such as dizziness, disorientation and long-time adapting. VR technology can also be used to capture the physical movements of workers during actual operation, and the captured data can be synchronously input into the computer to simulate in real time with dummy, so as to make more accurate assessment of ergonomics-related attitude assessment methods. The application of AR technology shows its great development potential. There is a study on the effect of Google glasses of worker anxiety in collaboration with robots. Results show that Google glass can help to reduce anxiety when cooperating with robot. Moreover, VR equipment showed great practical value in picking operation. Pick-by-AR reduced the picking errors and increasing picking speed.

Collaborative robots create new modes of production in which humans and machines collaborate. Also, they realize the intelligent cooperation between man and machine, and their emergence defines a new production mode of cooperation between man and machine, giving full play to the respective advantages of man and machine. According to ISO 10218 and ISO/TS 15066, four main types of collaborative operation are defined, they are “Safety-rated monitored stop”, “Hand guiding”, “Speed and separation monitoring” and “Power and force limiting”. Single-arm collaborative robots and dual-arm collaborative robots are the main types of collaborative robots. The simulation study on collaborative robots shows the difference of the ergonomic indicators between human-alone and collaborative robots. Ergonomics indicators on most jobs and most body parts show the superiority of collaborative robots. There are also researches which show that collaborative robots can help to reduce the frequent lifting so as to reduce the risk of the MSDs.

It is predictable that more intelligent technologies will emerge in the near future. Intelligent equipment, robot and so on science and technology will solve the problem of more production activities in ergonomics, so as to reduce human in the process of production the physiological and psychological risks, and to improve production efficiency. Industry 4.0 will certainly promote the development of ergonomics. More research fields and methods of ergonomics will be explored and discovered with the help of industry 4.0.

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