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Ergonomics in Manufacturing 4.0: An Overview of Enabling Technologies and Standards in China.

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INDEX

1 The Ergonomics History in China

1.1 Ergonomics in China

Ergonomics is a science that uses system science theory and system engineering methods to study the interaction between various human-machine system elements (human, machine, and environment) and design the best combination of human-machine-environment systems, with a wide range of research and application. The problem of ergonomics exists in everything that involves human beings. Therefore, the formation and development of ergonomics have effectively promoted social production development and improved quality of life.

Ergonomics started relatively late in China, and the common names include “engineering psychology", “ergonomics", “human engineering", “man-machine engineering", "human factors engineering” and “man-machine-environment system engineering”. With the progress of society, the development of science and technology, and the intersection of disciplines, its connotation are changing, so its definition and name will also change.

Startup stage

As early as the 1930s, applied psychology and industrial psychology were introduced to China from western countries. Zhou Xian’geng cooperated with Chen Li conducted research, trying to find out the way to promote workers' motivation from the perspective of psychology. In 1935, Chen Li wrote and published a book *Introduction to Industrial Psychology* [1], which for the first time systematically discussed the basic problems of industrial psychology in China in terms of environment, fatigue, rest, working methods, accidents, and efficiency. Tsinghua University has conducted a course in industrial psychology and was engaged in studies concerning the improvement of operative methods, working conditions, and productivity in the factories in Beijing, Nantong, and other cities.

Fig. 1 *Introduction to Industrial Psychology,* Chen Li

Growth stage

In 1949, the birth of New China brought a rapid recovery and development of the industry. In the following years, emphasis was given to the application of psychology to production. Psychologists visited factories and adopted workers to machines, often foreign-made, and environmental conditions. They conducted a series of surveys focusing on accident prevention, improving operational skills, training workers, and promoting technical innovation [2].

Since the late 1970s, China has begun a program of modernization. Research in the field of ergonomics has been revived once again. The Industrial Psychology course offered by Hangzhou University is the focal point of the discipline in China. It trains undergraduate and postgraduate students. In addition, several higher education institutions have recently introduced ergonomics courses.

Maturity stage

In 1980, under the National Ergonomics Standardization Technical Committee was established corresponding to ISO/TC 159, Technical Committee under the International Organization for Standardization in the field of ergonomics. This organization is responsible for organizing specialists to formulate and examine the national standards of ergonomics. In 1982, The 8^{th} seminar of the International Ergonomics Association (IEA), held in Tokyo, was the first time that China has attended [3]. In this decade ergonomic standardization work has been carried out on a large scale in China. In 1989, a national conference was held at Tongji University in Shanghai to establish the new discipline, which was named the Chinese Ergonomics Society (CES) [4]. and was accepted as a member of the IEA in 1992, indicating that ergonomics in China has entered a new stage of development.

In the last decade, ergonomics research and applications have expanded to ergonomics requirements and measurements for space stations, cockpit ergonomics design and for aircraft, intelligent interactive displays, ergonomics and reliability design for human-computer interaction in nuclear power plants, cognitive modeling, and medical ergonomics design, etc. promotes the intersection of the discipline with engineering and related fields. The 17^{TH} IEA2009 was held in Beijing, which is a new milestone in the development of ergonomics in China.

1.2 Ergonomics Generation and Development Worldwide

Empirical ergonomics

At the beginning of 20 century, Frederick W. Taylor created a new management theory and method for efficiency improvement in the factory based on conventional psychology experience. His research and *The Principles and Application of Scientific Organization* were the pioneers of ergonomics research[5]. In 1914, Hugo Munsterberg from Harvard University, the father of industrial psychology, published *Psychology and Industrial Efficiency* [6],

In this phase, researchers are mostly psychologists, and they're main studied on the selection and training of operators to adapt people to machines

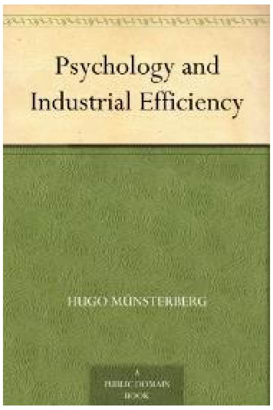


Fig. 2 *Psychology and Industrial Efficiency*, Hugo Munsterberg

Scientific ergonomics

In the 1920s, a group of American industrial psychologists conducted research at General Electric's Hawthorne plant to experiment with the effects of physical environments such as lighting on work efficiency, come up with the Hawthorne effect. During WWII, the study and application of the human factor in the military field have led to the creation of ergonomics.

In 1949, A. Chapanis published *Applied Experimental Psychology* [7], describing the methodology and theory for the first time.

In this phase ergonomics focus on the "human factor" in industrial and engineering design, aiming to adapt machines to human

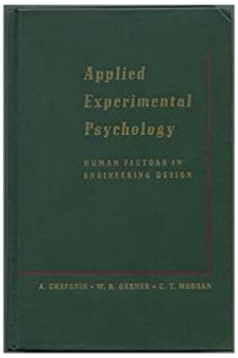


Fig. 3 *Applied Experimental Psychology,* A. Chapanis

Modern ergonomics

After the 1960s, with the help of control theory, information theory, and human science, ergonomics research could be conducted systematically. The human-machine-environment system is studied as a whole to create a harmonic machine and operating environment, The system is designed to achieve the highest overall efficiency.

1.3 Comparison of China Ergonomics Progress and Worldwide

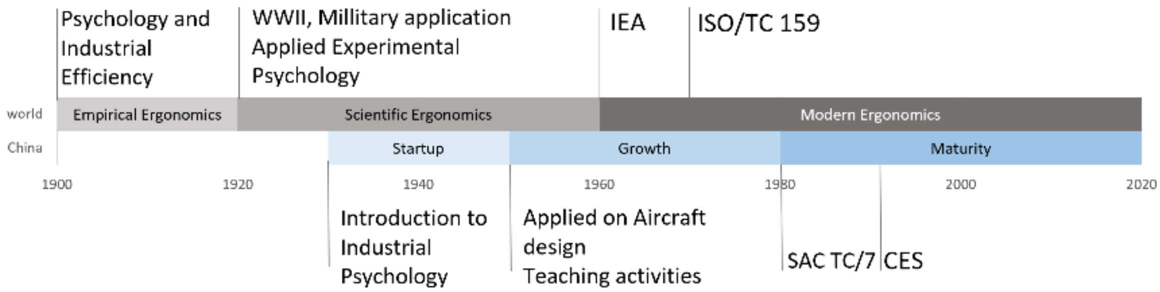


Fig. 4 Comparison of China ergonomics progress with the world

From the figure, we can see that ergonomics in China started relatively late. After 30 years of the birth of ergonomics, it has been introduced into China. Also, the establishment of standardization organization was 10 years later and the retard of the academy federation was 30 years. In the field of application, China is widely using ergonomics in production and design and is teaching and training a large number of engineers in related fields. Although the gap between the leading international levels is narrowing, it is still mainly in the position of following in academics and lacks a voice in the international

2 The Current Status of China National Standards of Ergonomics and the Comparison with ISO Standards

2.1 ISO Standards and China National Standards for Ergonomics

Ergonomics Technical Committee, ISO TC/159, is a subordinate organization of the International Organization for Standardization. Responsibilities include standardization of ergonomics, identifying human characteristics and performance, and defining the method of evaluating and analyzing the ergonomics performance of a product or environment. There are 27 participating members and 31 observing members in ISO/TC 159. It consists of 4 subcommittees. Till 2021, ISO TC/159 has 181 ergonomics standards, 153 of them have been published and 28 are under development [8].

Reference	Title	# Of standards published	# Of standards under development
ISO/TC 159/SC 1	General ergonomics principles	8	1
ISO/TC 159/SC 3	Anthropometry and biomechanics	26	9
ISO/TC 159/SC 4	Ergonomics of human-system interaction	84	10
ISO/TC 159/SC 5	Ergonomics of the physical environment	35	8
In Total		153	28

Table 1 Number of Standards of ISO/TC 159

China's ergonomics standardization technical committee was established in 1980, SAC/TC 7, is one of the earliest standardization technical committees established in China. Now it has built a relatively complete national standard system for human ergonomics, which mainly consists of anthropometry, human-machine interaction, and physical environment. There are 8 sub-committees: Basic, Anthropometric and Biomechanical, Control and Display, Labor Environment, Ergonomic Requirements of Work Systems, Color, Lighting, and Labor Safety [9]. Until 2022, SAC/TC 7 has published 89 ergonomics standards, consisting of 84 published and 5 under development. All 89 standards are nationally recommended standards, which means not legally compulsory. Any entity has the right to decide whether to adopt these standards, and there is no financial or legal liability for breach of such standards. However, once accepted and adopted, or agreed for inclusion in an economic contract, they must be observed and are legally binding.

Title	# Of standards published	# Of standards under development
General ergonomics principles	4	1
Anthropometry and biomechanics	22	0
Ergonomics of human-system interaction	36	3
Ergonomics of the physical environment	22	1
In Total	84	5

Table 2 Number of Standards of SAC/TC 7

2.2 Comparison between ISO Standards and GB

From the perspective of the number of standards by years

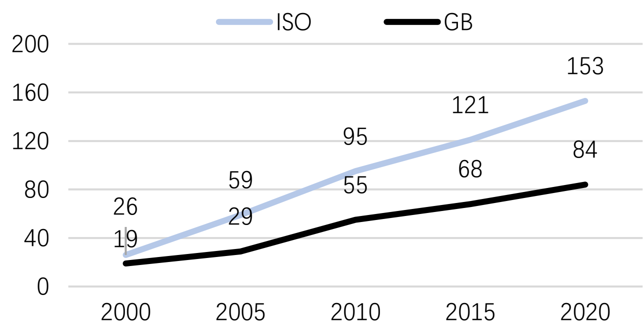


Chart 1 The accumulation of ergonomics standards from ISO and GB

Comparing the years of standards publication, it is evident that before 2000, the total number of national standards published in China was behind ISO, and it can be seen clearly that China started late in developing national standards for ergonomics. After 2000, due to the booming economy and the accession to WTO, China began to emphasize the introduction of relevant standards, and the number of national standards for ergonomics was further increased. Until now, the total number of national standards of ergonomics still has a certain gap with ISO, which is about 55% of ISO.

From the perspective of the adoption method

Based on ISO/IEC Guide 21 [10], the adoption from ISO or advanced foreign standardizing documents could be divided into three categories: identical (IDT), modified (MOD), not equivalent (NEQ), indicating the degree of correspondence with ISO standards.

- IDT: the national standards are identical to the international standard.
- MOD: The national standard is modified about the International Standard. Technical deviations are permitted provided they are identified and explained. The national standard reflects the structure of the International Standard.
- NEQ: The national standard is not equivalent to the International Standard in technical content and structure and the changes have not been identified.

Of the 89 national standards of ergonomics, 53 of them are adopted from ISO standards, 36 of them are made by China independently. 6 of them are modified from ISO standards, 1 is not equivalent to ISO standard.

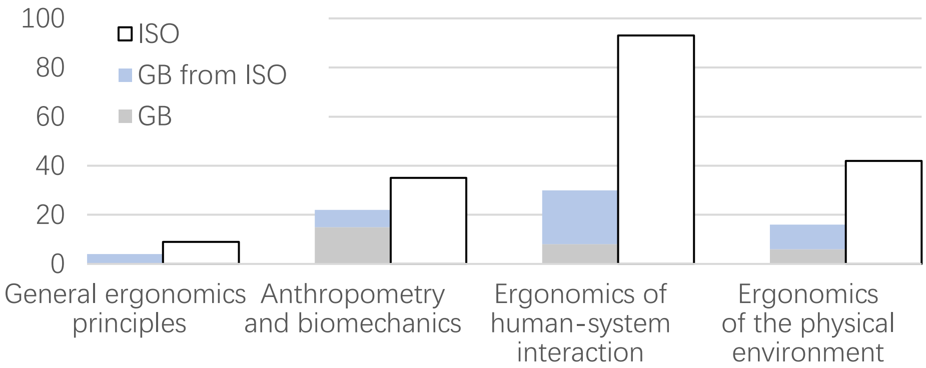


Chart 2 quantitively comparison of GB and ISO

Overall, Chart 2 quantitively comparison of GB and ISO quantitively comparison of GB and ISO shows that most of the standardization work in that China conducted independently is in the anthropometry and biomechanics field. In 2010 China has built its anthropometry database include human dimensions, head-face dimensions, hand, and foot size for adults and children. In the Ergonomics of human-system interaction and Ergonomics of the physical environment field, most of the national standards are adopted from the ISOs but the quantities are relatively small.

It is also important to note that in the 53 national standards from ISO there are 20 of them have adopted withdrawal iso standards. Most of them have been revised by newly published standards. The ISO ergonomics standards have been reviewed every 5 years. The development of Chinese national standards takes 2-3 years, and the focus is on the introduction of new standards, the approval process is relatively complex, so the update speed is behind the development of international standards

3 Academic and Teaching Activities of Ergonomics in China

Since the end of the 1980s, dozens of higher education institutions and research groups in China have carried out research and teaching activities on ergonomics. It is a comprehensive interdisciplinary that has developed rapidly in recent years with the advancement of technology and industrialization. It integrates physiology, psychology, anthropometry, biomechanics, computer science, systems science, and other multidisciplinary research methods, and study the interrelationship and influence between man, machines, and their working environment, achieving the goal of improving system performance and ensuring the safety, health, and comfort of people. Ergonomics focuses on all products and systems made by people, with human participation and utilization, and studies the interaction between people and systems to achieve goals of system safety, efficiency, and user-friendly.

3.1 Undergraduates: Content Varies from Majors

According to GB/T 13745:2009 Classification and Code of Disciplines, ergonomics is classified to the third-class discipline, segmented research directions. It's been divided into two according to the content: 190 Psychology-19055 Industrial Psychology-Ergonomics, and 630 Management-63050 Management Engineering-Ergonomics. [11]

In China, Undergraduate education is carried out according to *the Catalog of Undergraduate Majors in General Higher Education Institutions* by the Ministry of Education of the People's Republic of China. From the documents, it could be seen ergonomics has not been set as an independent major for an undergraduate student, but it has become a widely offered course among universities and different majors.

The expected learning outcome of ergonomics courses from Zhejiang Sci-tech University could be a typical example of ergonomics courses offered by universities.

1. master the basic theory and research methods of ergonomics engineering. And to model, calculate, and analyze engineering problems in human-machine systems.
2. master the model of information processing of humans and be able to apply the basic principles of mathematics and engineering science to analyze the basic elements and interactions and regularity in the model.
3. be able to analyze and evaluate human characteristics, machine characteristics, or other parameters and states in human-machine systems through measurement, testing, simulation, and analysis, or by using the software.
4. be able to evaluate the health, safety, legal and cultural impacts of various human factors engineering solutions, and to understand and evaluate the impact of human factors in the system on environmental and social sustainability

Majors	Key knowledge and ability	Common content
Industrial Engineering	Occupational health Human-machine Interaction Efficiency	-Anthropometry -Human biomechanics -Joint Motility and Body Motion -Information Input and Processing Model
Automotive/ Traffic Engineering/ Machine Engineering	Ergonomics design principles on a specific product, system,	
Industrial Design	Visual, auditory man-machine interface design	

Table 3 Content of ergonomics in different majors

The teaching contents of ergonomics vary to the different professional backgrounds of students. But overall, they have similar content.

Industrial engineering

It mainly studies the production process, to improve labor productivity, quality assurance, and cost reduction. For the students who major in industrial engineering, ergonomics courses are one of the professional basic courses, which is compulsory. The contents cover all perspectives of ergonomics, including background knowledge, physiology ergonomics, psychology ergonomics, and environment ergonomics. It emphasizes the engineering issues in man-machine systems in the manufacturing field. Distinguishing from other majors, students are supposed to master the method of workload evaluation, physically and mentally, and the ergonomics principle in machine design, workspace design to prevent MSDs, and mental fatigue.

The Universities that offer the ergonomics course for IE students: Tsinghua University, Tongji University, Beijing University of Aeronautics and Astronautics, Tianjin University, Harbin Institute of Technology, and most of the universities of science and technology, etc.

Other engineering majors

Vehicle engineering, traffic engineering, safety engineering, mechanical engineering, and other engineering majors are also required to study the course ergonomics based on their background. The main point is focused on anthropometrics and its design principles, the information input and process, and especially their application on the vehicle, public traffic, factory environment, and machine design, ensuring their human friendliness and adaptability. Most of the majors set ergonomics as professional core courses or elective courses.

The Universities that offer the ergonomics course for other engineering students: Beijing University of Aeronautics and Astronautics, Southeastern University, Southwest Jiaotong University, etc

Industrial design and product design

Industrial design and production design are under the school of design and art. besides anthropometry and visuality, auditory, education of ergonomics for these students are more concentrated on man-machine interface design and the design phycology and consuming psychology. Ergonomics is also one of the professional core courses in these majors.

The Universities that offer the ergonomics course for other engineering students: Beijing Institute of Fashion Technology, Zhejiang University, Sichuan Fine Art Institute, etc.

3.2 Postgraduate: Research Directions and Institutions

In China, the acceptance of postgraduate has through the Unified National Graduate Entrance Examination. It is a general term for the relevant examinations organized by educational admissions institutions for the selection of graduate students. It consists of 4 subjects including 1 professional discipline, which content is decided by the universities and the research direction of the department. In the examination, some universities include ergonomics in the examination scope to test students of the corresponding knowledge. Most of the directions with ergonomics in the exams are Industrial Design and Industrial Psychology.

Till now, some of the universities have set up labs to do research in the ergonomics field. Research on ergonomics in China covers research areas such as interface display, human-machine control interaction, human-environment interface, load and stress, safety and accident analysis, human-computer interaction. The basic research of ergonomics has developed from conventional directions such as anthropometry in the early stage to cognitive ergonomics, cognitive modeling, intelligent system interaction, etc. The application areas have also expanded from production, mechanical or electronic products, car driving, etc. to complex systems and daily life such as space station ergonomics, high-speed railway ergonomics analysis, aircraft, and ship ergonomics design.

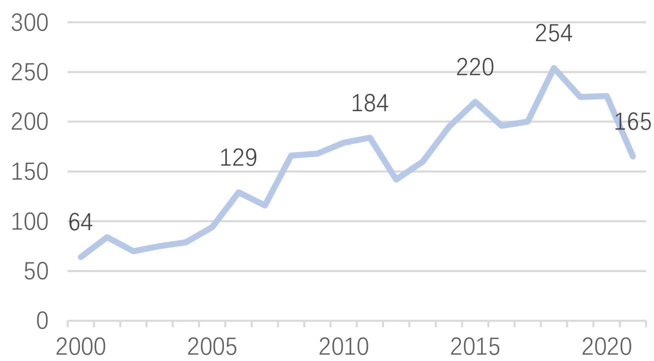


Chart 3 quantity of annual papers published about ergonomics

CNKI (China National Knowledge Infrastructure) is the largest Chinese academy platform. shows the result of annual papers published using ergonomics as a key world. The number of papers has been increasing year by year since 2000, indicating that ergonomics research has been drawn more attention. But compared to another field in great demand, the total quantity is still relatively small.

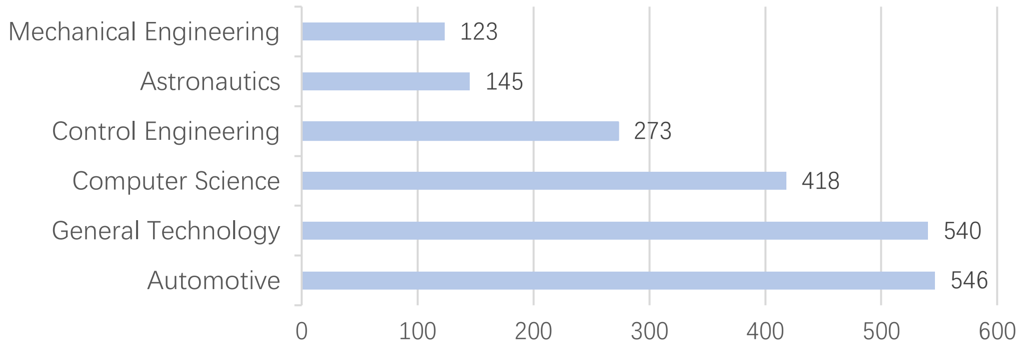


Chart 4 Categories Relative to Ergonomics

Automotive, general technology, computer science, control engineering, astronautics, and mechanical engineering are the top 6 categories under which there are most papers about ergonomics. It can be seen that the research about ergonomics in China is concentrated in the applied field.

Tsinghua University

Tsinghua University has set up the largest ergonomics lab, the Institute of Human Factors and Human-System Interaction [12] in China, under the industrial engineering department. Driving Safety and Driving Simulation Testing for analysis road traffic accident data and trends; research, testing of driver cognition, attitude, behavior, and ability; evaluation of the effectiveness of automotive safety devices; driving simulation testing techniques and theories; road Safety Management. IE-Psych Joint Behavior Simulation Research Platform combined the IE department and Psychology department to research driving behavior, wayfinding behavior, and Escape – Rescue behavior. Human Motion Tracking and Simulation lab research motion tracking of operational movements, simulation, and working efficiency evaluation. Anthropometry and Biomechanics Lab focused on 3-D body scanning, shape, and size modeling, and product design based on anthropometry data, occupational ergonomics, and risk analysis. Physical Load and Fatigue lab focuses on Physiological and sensory responses of Chinese construction workers during manual material handling, quantification, and neural network-based assessment of human factors in manual material handling, the study of the psychophysical and physiological effects of ground smoothness on manual material handlers. Other ergonomics labs include Office Ergonomics lab, Management and Organization Ergonomics lab, Usability and User Experience of IT Design lab, Cognitive Ergonomics and Human-Computer Interaction Lab, Human Decision Theory and Methodologies lab, Human Error and System Safety lab, Cross-Culture Design lab, and Social Computing lab.

Fig. 5 The simulation platform and biomechanics lab

Institute of Psychology, China Association of Science

An Industrial Psychology Lab has been organized in the Social and Engineering Psychology department [13]. The research in the Engineering Psychology Laboratory in recent years has focused on human factors in the field of public safety, such as monitoring of driving status, design of traffic signs/evacuation signs, measurement of situational awareness of drivers/air traffic controllers, and improvement of airport security screening efficiency, etc. By revealing human mental processes and information-processing mechanisms in complex information environments, such as spatial cognition, visual search, and working memory mechanisms, and proposing corresponding cognitive processing models for special operations, we provide the theoretical basis of engineering psychology for the development and evolution of high-tech systems.

Fig. 6 driving status monitoring and EEG lab

Zhejiang University

Center for Psychological Science at Zhejiang University [14] has conducted a series of research in the ergonomics field. Including study on the neural mechanism of visual function; Muscle fatigue and muscle strengthening techniques for muscle fatigue detection techniques, causes and mechanisms of muscle fatigue, muscle fatigue vibration intervention, and muscle enhancement techniques in extreme environments; Research on human factors engineering and intelligent socio-technical systems for intelligent interaction design theory, reciprocity principle in human-computer cooperation, operation intention recognition technology, continuous attention level monitoring technology

Fig. 7 Industrial psychology National Key Laboratory

Beijing University of Aeronautics and Astronautics

BUAA has set up a laboratory for ergonomics and environmental control, specified for aircraft, aerospace, navigation and weaponry, and other important national defense fields. The research includes integrated environmental control and simulation, ergonomics efficiency, and life support technology.

3.3 Prospect of China Ergonomics Education

Establishing a complete education system for ergonomics

The education of ergonomics in China's universities is not perfect. There are still many universities that have not established ergonomics as a discipline. It cannot meet the demand for ergonomics specialists from the industry. To increase the investment in ergonomics education, it is imperative to establish undergraduate majors in ergonomics and increase the doctor's and master's degrees. The admission of master's degree students should encourage interdisciplinary undergraduates to apply. In addition, ergonomics courses should be added to related majors such as computer science, engineering, and manufacturing.

The content of the ergonomics course is mostly basic concepts and theories. It should be kept up-to-date and connected with topics of industry interest. In addition, it should focus on practical teaching and combine experiments with teaching.

Establish a complete research system combining industry, academia, and research

The government should encourage cooperation among research institutions, universities, and enterprises. Encourage the establishment of joint company-university laboratories between enterprises and institutions to connect institutional research directly with applications. Combine production, education, and research.

4 Implementation of New Techniques to Solve Ergonomics Problems

Industry 4.0 describes a highly flexible, personalized, and intelligent manufacturing model through real-time connectivity and effective communication between customers, devices, and products. It is about shifting from large-scale economies to scope economies through automation technology and big data to build a heterogeneous and customized industry at a homogeneous cost. Industrial restructuring, it is a vital role.

To realize flexible production, production lines must have the versatility and variability of products and processes. Combining human intelligence with machines to reduce the intensity of workload, enhance work capacity is important meth achieve the requirement of flexibility on the production line.

4.1 Most Common Ergonomics Problem: MSDs

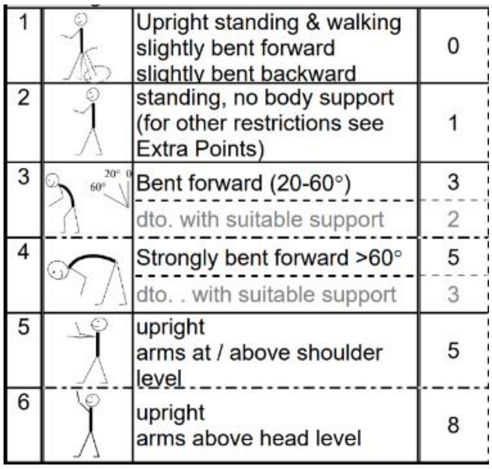
Musculo-Skeletal Disorders (MSDs) refer to a wide range of inflammatory and degenerative conditions affecting the nerves, tendons, muscles, ligaments, joints, peripheral nerves, and supporting blood vessels. when the prevalence of the disorder/disease is higher among the specific group of workers than in the average population, it could be defined as work-related MSDs (WMSDs). Main occupational hazard includes force, awkward postures, repetitive movements, duration of work, and adequate recovery periods.

Force

Applying force when greater than your mental and physical capabilities allow may lead to fatigue, MSDs, or injuries. The recommended applied force is decided on the age, gender, trajectory of the movement, grip, significant control, and frequency. NIOSH and ISO 11228 offer the method to calculate the force.

Awkward position

EAWS shows that for the same duration of the evaluation period, trunk bending forward will lead to a higher penalty compared with working on standing posture but could be improved by suitable support. Also, the posture upright arm above head level would result in a higher risk of fatigue and injury compared with arms below head level.



1		Upright standing & walking slightly bent forward slightly bent backward	0
2		standing, no body support (for other restrictions see Extra Points)	1
3		Bent forward (20-60°)	3
		dto. with suitable support	2
4		Strongly bent forward >60°	5
		dto. . with suitable support	3
5		upright arms at / above shoulder level	5
6		upright arms above head level	8

Fig. 8 EAWS Position section

High repetitive frequency movement

A high frequency of repetitive work may result in higher energy expenditure and fatigue both physical and psychological. A recovery time is needed after a period of work time depending on the intensive od workload.

The research studied the MSDs risks among automotive assembly line operators in China in 2013 [15]. The result shows that 66.5% of the operators have experienced the MSDs in the lower back in a year, and 57.5% and 51.3% of the operators had suffered MSDs in the shoulder and neck. MSDS has become the main problem that influences occupational health.

4.2 Collaborative Robots

4.2.1 Introduction of Collaborative Robots

Based on the definition in ISO 10218-2 [16], the design of a collaborative robot allows the users to interact with the robot directly within the collaborative workspace. This requires robots to be able to work together with humans and to perform different tasks together with them. These tasks include that humans cannot do, don’t want to do, and cannot do well, as well as complex tasks that can reduce human labor and improve the ergonomics of working procedures.

Unlike traditional industrial robots, collaborative robots can share a workspace with people without the need for safety devices such as fences to isolate them from people. At the same time, the load of collaborative robots is comparable to that of human beings, suitable for undertaking tasks originally performed by people. In addition, collaborative robots have the advantages of rapid deployment, ease of use, and affordability

Collaborative robots offer important advantages from an ergonomics perspective:

1. Take over manual processes that previously could not be automated and were not in a good ergonomic posture, and reduce the workload of workers, avoid MSDs.
2. Complete repeatable processes with high quality and high frequency, reduce the risks of fatigue.
3. A lower risk of injury compared with a traditional industrial robot. With the integrated sensors, the robot could recognize when it is approaching an operator and automatically slows down, without significant movement during the rest of the production operation. Once there is no operator within the robot's range of motion, the robot can operate at its previous high speed in its zone and continue to work normally.

4.2.2 Methods of Collaborative

When robots and people interact, human safety must be ensured, The International Organization for Standardization published the ISO/TS 15066 standard in 2016, which divides collaborative robot safety into the following four methods.

Safety-rated monitored stop

In this method, the people could not walk into the workspace when the collaborative robots are moving. Once walked in, the robot stops immediately, then the workers could execute certain operations like attaching workpieces to the robot for machining, changing tools, etc. Once the robot detected there is no one in the workspace, it could keep moving in the normal state.

Robot motion or stop function		Operator's proximity to collaborative workspace	
		Outside	Inside
Robot's proximity to collaborative workspace	Outside	Continue	Continue
	Inside and moving	Continue	Protective stop
	Inside, at Safety-Rated Monitored Stop	Continue	Continue

Table 4 Safety-rated monitored stop [17]

Hand guide

When the robot enters the safety-rated monitored stop state, the worker is allowed to enter the collaborative workspace and start hand guide mode, then a device is used to drag the end of the robot and input a pre-set trajectory into the robot to guide it to work. Once the robot has been taught, the robot can work according to the entered trajectory and instructions.

Speed and separation monitoring

A certain minimum safety distance has been determined in this method. The collaborative robots could still move at a relatively slow speed and work on their task even an operator is in the collaborative workspace. Once the operator approaches the minimum distance the robot should stop.

Power and force limiting

some robots could detect the contact force and operate within the set limitations of power and force. even a collision happened the robot won't cause injury to people.

4.2.3 Core Function: Collision Detection

To collaborate with operators, the robot must be able to detect before a collision happens. Collision detection is a function that collaborative robot must implement. It could be realized with the help of an electric current loop, flexible joint, dual encoder, electronic skin, and other methods [18].

Electric current loop

The external torque is estimated directly from the power loop (torque) feedback and the robot system dynamics equations. The most difficult part of this approach is the estimation of joint friction, which is affected by many factors such as robot position, speed, temperature, etc., and is difficult to model and identify accurately. Therefore, the accuracy of collision torque detection in this way is limited, but the cost is low, and it is mainly used in small robots at present.

Flexible joint

The external torque is estimated based on the feedback from the joint torque sensor and the dual encoder. This approach avoids friction modeling and estimation, and collision detection accuracy is high.

Dual encoder

Compared to the previous approach, a joint torque sensor is not needed. The harmonic damper has a lower stiffness and using the harmonic reducer as a joint moment sensor, it is possible to estimate the external force using the same algorithm as the flexible joint. However, the stiffness of the harmonic reducer is still much higher than that of the torque sensor, and the accuracy of external force detection is lower, but in principle, the effect of friction can also be avoided

Electronic skin

An external force is detected based on the pressure sensor on the surface of the robot arm. This method has sensitive detection and high accuracy, but the cost is too high and the assembly is complicated.

4.2.4 Implementation Scenarios

Different from the conventional robots which replace machines in the production line, collaborative robots are made to be part of the whole production line, and if an industrial robot breaks down, the whole production line may have to be stopped. In contrast, collaborative could replace workers, and the workers could also replace the collaborative robots, which are more flexible.

At present, collaborative robots are suitable for two types of scenarios. The first type is to use collaborative robots as a work station, which is suitable for SMEs that want to realize “machine replace man” and upgrade the production line without changing the deployment of current production lines. The second type is a large factory using robots as one of the workers, through the servers with AI algorithms to allow robots to complete more complex tasks.

Pickup and Placement

The pick-and-place task involves picking up and placing the workpiece in another location. Manual pick and place should be a repetitive task, sometimes with high frequency. The operation can easily lead to low accuracy and the highly repetitive movements can easily lead to fatigue and injury. This operation can be used in actual production to pick up items from pallets or conveyors for packaging. Picking from a conveyor also requires advanced vision system support. Collaborative robots in the pick-and-place tasks require a grip, either a fixture or a vacuum suction cup device.

Fig. 9 A collaborative robot is placing a chip on a conveyer, DOBOT

Machine Feeding

Machine feeding requires workers to stand for long periods in front of CNC machines, injection molding machines, or other similar equipment to keep attention on the machine's operational needs, such as changing tools or replenishing raw materials. In this case, using a collaborative robot not only frees up the workers, but one collaborative robot can maintain multiple machines, increasing productivity. Collaborative robots in this kind of task require hardware that docks to the devices. This hardware tells the robot when to move on to the next cycle or when it needs to replenish raw materials.

Fig. 10 A collaborative robot is feeding the lathe

Packaging and Stacking

Packaging and stacking is a special kind of pick and place. Products need to be prepared for shipping before they leave the factory, including packing, box assembly, loading, and placing pallets ready for shipment. This type of work is highly repetitive and contains relatively high loads, which are suited for replacing manual work with collaborative robots. This application requires a conveyor tracker to synchronize robot and conveyor movement. For products with different shapes, the application also requires a vision system.

Fig. 11 A collaborative robot is stacking boxes, ELIBOT

Processing

Machining operations are any process that requires the use of tools to work on a workpiece. Collaborative robots are commonly used for gluing and welding processes. Each of these machining tasks requires the use of tools to complete a fixed path. These tasks require a significant investment of time in training for a new worker. With collaborative robots, this can be replicated to other robots by completing the programming on just one robot. Collaborative robots also solve the problem of accuracy. Traditional welding robot systems require operators with knowledge of programming and welding. The advantage of collaborative robotic systems is that they can be implemented simply by recording the location and movements, simplifying robot programming, and allowing inexperienced workers to program. The robot is guaranteed to be able to put in the material at a constant rate.

Fig. 12 A collaborative robot is glutting the windshield

Surface Finish

Manual surface finish operations must be performed with tools and are often with a high workload. The vibration generated by the tools can also cause injuries to the operator. Collaborative robots can provide the force and repeatability required for finishing. The types of finishing operations that can be performed by robots include polishing and grinding. The force control system of the collaborative robots makes the robots more durable.

Fig. 13 A collaborative robot is polishing parts, JAKA

Quality Check

At last, collaborative robots can also perform quality checks of parts. This process involves a full inspection of the finished part, a photo inspection of the precision machined part, and a comparison of the part to the CAD model for confirmation. With cameras, a collaborative robot can automate the quality inspection process and quickly obtain results. Installation of tools with cameras, vision systems, and software is required to complete the inspection.

Fig. 14 A collaborative robot is doing a quality check with an X-ray detector

4.2.5 Market Size, Main Domestic Players and Products

From 2018 to 2019, the global collaborative robot market growth has slowed down significantly due to the continued impact of global economic and trade environment changes, especially the downward spiral of automotive and electronics industries. In 2020 and 2021, the outbreak of the epidemic in the world has made more companies begin to rethink the meaning of automation, and contactless has become the hotspot that many companies are most concerned about. Various collaborative robot manufacturers are seizing the opportunities and laying out their plans for the future.

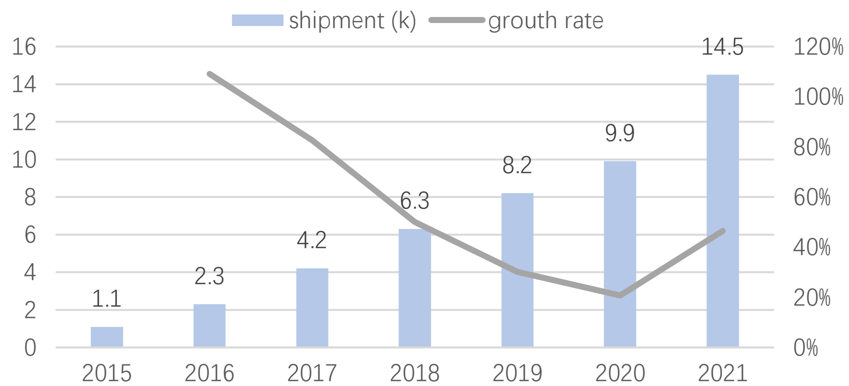


Chart 5, Shipment of Collaborative Robots in China [19]

According to the *China Robotics Industry Development Report* [19]by the Chinese Institute of Electronics, in 2021, China's robot market size is expected to be 83.9 billion yuan, far exceeding the global level. China's collaborative robot market has now become the largest collaborative market in the world, for more than 1/3 of the global market size in 2020. In 2021, China's collaborative robot shipments have reached 14,372 units, with a growth rate of 46%, exceeding other types of robots.

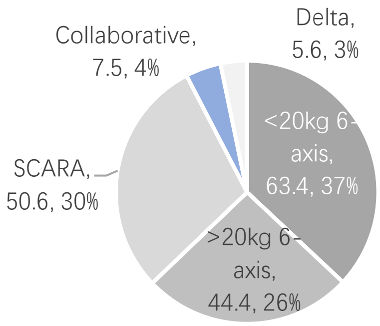


Fig. 15 share of the market of different kinds of robots [19]

Compared with conventional industrial robots, the market share of collaborative robots is relatively small, and there is still a huge market potential. Besides the industrial scenarios, collaborative robots can also be used in education, food, health, and other business to explore new markets. With the drive from industry and non-industry, market share is expected to increase further.

In addition, the investments in the robotics industry in the first half of this year is about 12 billion yuan, and for the collaborative robot field, the investment reaches 4 billion yuan, which shows the interest from the capital market, collaborative robotics has become the hottest segment of the robotics industry.

From the perspective of patents, there are more than 5,600 patents in the field of collaborative robots worldwide. Currently, China, Japan, the United States, and Germany are among the top four countries in the world in terms of the total number of patent applications in this field, of which China has about 1,700 patterns [20]. In terms of patent trends, China has been actively applying in the collaborative robotics field in the past five years, and the number of patent applications has been increasing year after year.

AUBO

Among the many collaborative robot manufacturers in China, AUBO was the first to enter the collaborative robotics industry. As early as 2010, their CEO led a team of researchers to start developing collaborative robots in the United States. In 2013, when the domestic collaborative robot market was still blank, Smokie Robotics, the predecessor of AUBO, launched its first-generation collaborative robot. In 2014, the U.S. R&D team of AUBO returned to China, In 2016, Oceanic completed the transition from technology to mass production, becoming the first domestic collaborative robot company to achieve mass production.

Their light collaborative robots have independent intellectual property and have achieved localization of the whole robot from the operating system, control system to key components, and have passed the NRTL， CE、KCs certification, and ISO 13849, ISO10218 certification. Till now AUBO owns 106 innovations and patterns and 31 software copyright.

AUBO				
Model	i3	i5	i10	i16
# of joint	6			
Payload [kg]	3	5	10	16
Weight [kg]	16	24	38.5	38
Reachability [mm]	625	886	1513	1130
Repeatability[mm]	±0.02		±0.03	

AUBO		
Model	c3	c5
# of joint	6	
Payload [kg]	3	5
Weight [kg]	16	24
Reachability [mm]	625	886
Repeatability[mm]	±0.1mm	

Table 5 product matrix of AUBO

SIASUN

SIASUN is a subsidiary of the China Academy of Science. It is one of the manufacturers with the widest robotics product matrix and owns the largest robot industrialization base in China. In November 2015, SIASUN launched the first independently developed 7-degree of freedom collaborative robot in China. 7-axis multi-joint robots with fast deployment, hand guide, visual guide, collision detection, and other functions are especially suitable for flexible production lines with compact layout and high precision.

SIASUN					
Model	SCR3	SCR5	GCR5	GCR20	GCR14
# of joint	7		6		
Payload [kg]	3	5	5	20	14
Weight [kg]	18.6	33.8	21	50	50
Reachability [mm]	600	600	917	1100	1400
Repeatability [mm]	±0.02		±0.03	±0.05	

Table 6 product matrix of SIASUN

ELIBOT

ELIBOT was founded in 2014 by the Robotics Institute of Beijing University of Aeronautics and Astronautics and Tsinghua University's Department of Precision Instrumentation, focusing on the development and manufacture of intelligent industrial robots for fifteen years.

ELIBOT developed its first robot control system in June 2016, and in 2018 they launched the EC series of six- and seven-axis collaborative robots. In 2020 they launched the CS series to compete with UR. ELIBOT owns 84 patterns and 6 software copyright including vision system, robotic estimation, and hand guide plate,

ELIBOT			
Model	EC63	EC66	EC612
# of joint	6		
Payload [kg]	3	6	12
Weight [kg]	13	17.5	31
Reachability [mm]	624	914	1304
Repeatability [mm]	±0.02	±0.03	±0.03

ELIBOT			
Model	CS63	CS66	CS612
# of joint	6		
Payload [kg]	3	6	12
Weight [kg]	14	20	33
Reachability [mm]	624	914	1304
Repeatability [mm]	±0.02	±0.03	±0.05

Table 7 product matrix of ELIBOT

DOBOT

Founded in 2015, DOBOT 's main business is to make robotic arms, and its products are mainly desktop-level robotic and collaborative robotic. However, unlike other robotics companies that integrate parts from suppliers, DOBOT develops servo drives and control systems. In the past 7 years, DOBOT has launched a variety of feasible collaborative robots, becoming the first company in the industry to have a full product matrix from 0.5kg to 16kg.

It is worth mentioning that in 2020, along with the release of the collaborative robot, DOBOT also released its product, the DOBOT Safe Skin, used for pre-collision sensing technology. Any intrusion from any angle can be sensed, maximizing human safety and machine efficiency.

DOBOT				
Model	CR3	CR5	CR10	CR16
# of joint	6			
Payload [kg]	3	5	10	16
Weight [kg]	16.5	23	38	37
Reachability [mm]	795	1096	1525	1223
Repeatability [mm]	±0.02			

Table 8 product matrix of DOBOT

JAKA

Founded in 2014, JAKA is a team of 10 professors from the Robotics Institute of Shanghai Jiao Tong University, with a team of 12 corporate post-docs and 50 senior engineers in the field of mechanics and control.

In 2017， JAKA launched the Zu series collaborative robots, The integrated joint technology has been used to optimize the motor, reducer, and drive control board to reduce the weight. realized force control impedance/conductance and force-position hybrid control. The whole algorithm includes force control application, hand guide, collision detection, constant force tracking, normal direction tracking, etc.

					
Model	Zu3s	Zu5s	Zu7s	Zu12s	Zu18s
# of joint	6				
Payload [kg]	3	5	7	12	18
Weight [kg]	13.5	23	22	41	35
Reachability [mm]	587	819	819	1327	1073
Repeatability [mm]	±0.02				

Table 9 product matrix of JAKA

4.2.6 Actual Implementation Cases

Collaborative robot implementations are mainly focused on upgrading production lines in large manufacturers and realizing automation in SMEs. Industries, where collaborative robots are used, include automotive, 3C, white goods, metal processing, daily chemical, injection molding, etc.

Case 1. SAIC-GM shanghai, glutting in body workshop [21]

In 2020 SAIC-GM conduct a test of introducing 2 collaborative robots in a body workshop to collaborate with 2 operators. The workstation requires 1 operator on each side of the line to first apply glue to the left and right rear wheel arch cover. Then each of them will put the left and right rear wheel arch cover to the loading port. These 2 operators suffer a high workload. In this case, 2 extra operators assist the job to meet the increasing production rate.

If a conventional industrial robot is used, the robot work area needs to be separated from the operator by fence and grating. However, the existing layout is already full of robots and there is no space for this additional equipment.

The optimal solution is to deploy 2 collaborative robots to the operator's side so that the automatic gluing can be achieved without additional protection. At this point, the 2 collaborative robots were already doing most of the operator's work, and the loading port was modified closer to the work station to reduce the operator's moving distance, allowing the rear wheel arch cover to be loaded, thus saving 2 operators in a shift.

Compared with the conventional industrial robot, the introduction of the collaborative robot solution saves the footprint, reduces investment in equipment of electrical safety accessories such as grating and fencing, realizes the automation of the glutting process.

Case 2. Injection molding plant, material pick and place and punching off [22]

This injection molding factory in Guangzhou has 250 employees and 40 injection molding machines. The operator picks and places the plastic parts from the machine tool and then puts them under the stamping equipment to complete the material removal, and then puts them into the package to complete the whole process.

The plant's production tasks are intensive and influenced by customer customization requirements, with a large number of injection-molded product batches. When calculating the actual production rate throughout the year, it was found that downtime due to reprogramming and commissioning of the robot due to changeover of the variety could account for up to 30% of the effective working time. If robot programming and commissioning time could be reduced, this would reduce operating costs in terms of system efficiency

In this application 1 robot corresponds to two machines - the injection molding machine finishes processing and demolding the plastic parts, and the collaborative robot removes the two plastic parts and puts them into the stamping machine. The robot arm picks up each plastic part after the stamping machine finishes punching it off, and drops both parts into the package. The programming time was reduced from 1-2 days to a few hours by using the collaborative robot's visual command programming.

It also improves safety by reducing employee exposure to harmful gases released during the production of plastics and polymers, and by protecting employees in the production line from possible hazards associated with plastic shavings and handling sharp objects.

Fig. 16 collaborative robot in Injection molding plant

4.2.7 Challenges and Opportunities

Collaborative robots, as technologies that collaborate with or replace people, have always been compared with the cost of labor. In early-stage collaborative robots were not price competitive. With the launch of domestic brands, the price of collaborative robots has dipped further, but it is still an investment that needs to be a trade-off for SMEs.

Currently, on the market, the mainstream price of collaborative robots from domestic brands is about 100,000 CNY, according to the National Bureau of Statistics report 2020 urban non-private manufacturing personnel average salary of 82,783 CNY [23]. Considering the labor cost of blue-collar is lower than the average salary and considering the tax, insurance, and another cost, the payback time for a collaborative robot is about 1.2 years.

Further price reduction

Developing and adopting domestic components, further increasing the localization rate, deproliferation the not necessary products, and adopting modulization design to reduce production costs. At the same time, pursue higher reliability and reduce the cost of enterprises due to equipment downtime, maintenance, and worn-out. For scenarios without high requirements for repeatability develop more feasible models.

More end effector

Develop more end effector to explore new implementation scenarios, which covers the needs of other labor-intensive industries.

Increase the level of intelligence

Artificial intelligence technology is an important engine for the development of collaborative robots, with deep learning, auditory-visual semantic reasoning and cognitive reasoning, natural language processing, emotion recognition, and interaction, and other key technologies, collaborative robots will reach a new level of human-machine interaction.

4.3 Exoskeleton

4.3.1Introduction of Exoskeletons

The exoskeleton robot is wearable equipment that combines human intelligence and mechanical energy. It's a biomechatronic device that interacts with the human body. The exoskeleton system is an artificial motion control system, the mechanism of which simulates the human motion control system. To achieve that, a comprehensive technology that integrates sensing, control, and computing.

	Human body	Exoskeleton
mechanism	Skeletal systems	Mechanical frames
actuators	muscles	Artificial actuators
controllers	nervous	Artificial controllers

Table 10 comparison of human body and exoskeletons

To achieve that, complex multi-systems are needed including sensing systems, control systems, drive systems, mechanical systems, and power systems

- Sensing systems: Sensors and signal processors, to collects information on body movement trends, position, posture, and force, providing data for the control systems.
- Control systems: Computers and control software, to analyze the information from the sensing system and operates the drive systems according to human intentions
- Drive systems: Actuators, driven by electric/hydraulic/pneumatic components and then transmitted to the mechanical system, which moves the mechanical frames.
- Mechanical systems: Provides support for the equipment, shares the load by integrating with the body.
- Power systems: power for equipment by battery, pressed gas, or internal combustion engine

4.3.2Different Classifications

Exoskeletons can be classified in different ways according to different division criteria. According to the material, it can be classified as rigid exoskeleton and soft exoskeleton, according to the supporting body parts, it can be classified as upper limb exoskeleton, lower limb exoskeleton, whole-body exoskeleton, and a certain joint exoskeleton, etc. According to the different actuators, it can be classified as passive exoskeletons and active exoskeletons, which consist of motor-driven, hydraulic-driven, pneumatic-driven, passive-assisted, etc. According to the use and function, it can be classified as body movement assistance, body protection, strength enhancement, and motion capture.

Functions	Type
body movement assistance	Medical exoskeleton
body protection	Military exoskeleton Disaster rescue exoskeleton
strength enhance	Industrial exoskeleton Sports exoskeleton
motion capture	Remote control robots

Table 11 functions for different types of exoskeletons

Rigid exoskeleton and soft exoskeleton

With the further development of exoskeleton research, two paths have gradually emerged - the rigid exoskeleton and the soft exoskeleton. The rigid exoskeleton mainly imitates the human skeleton, using a metal frame to maximize the load capacity with the help of mechanical force, but the user's mobility is limited by the design features of the exoskeleton; on the contrary, a soft exoskeleton is designed to fit the body, where the user's joints are not bound by the rigid structure, reducing the interference of the exoskeleton with the body's movements. the soft exoskeleton allows the human and the exoskeleton to interact and collaborate by simulating the human muscle action. While power is limited, it assists the body rather than taking the load, to relieve the user's fatigue and reduce the probability of injury.

In terms of energy consumption, the rigid exoskeleton is heavier, increasing energy requirements. although the rigid exoskeleton system is now free from cables, the issue of power supply is still an obstacle to future development. The flexible exoskeleton with a smaller mass and less powerful functions requires correspondingly low energy consumption of less than 100W.

In short, whether rigid or soft exoskeletons, their goal is to enhance human strength and speed.

Fig. 17 soft exosuit, Wyss Institute

Passive exoskeletons

Unlike powered exoskeletons, which provide a constant source of energy, passive exoskeletons are powered by consumed wasted work during motion. By appropriately force transferring and energy storing, and releasing this energy when the muscles are required to perform positive work, the muscle load can be reduced, thus saving energy.

When walking, the center of gravity moves in a wavy curve. The swing, flexion, and extension of the lower limbs not only provide force forward but also expend a lot of energy in the vertical movement. When bending down to lift a heavy object, the trunk is bent up mainly by the muscles on the lumbar. During movement, elastic elements such as elastic bands, torsion springs, gas springs, and memory alloys are deformed and thus store energy. The passive lumbar back exoskeleton assists the hip joint and reduces fatigue in the lower back during the upper body lifting phase. The passive walking exoskeleton assists the ankle, providing elasticity when the support leg stirring to increase walking efficiency. The passive load exoskeleton usually assists the knee, providing high stiffness to the knee joint of the supporting leg during the walk cycle to support the load.

Fig. 18 passive lumbar back exoskeleton and passive load exoskeleton，
Mebotx Intelligent Technology

Active exoskeletons and actuators

The active exoskeleton is a drive system with high power density actuators that are not rigidly attached to the body to assist in the movement of limbs. The active exoskeleton is equipped with sensors, which are installed in various parts to obtain data and transmit it to a control processing unit, which calculates and adjusts the movements of the exoskeleton and completes a series of movements through the actuators

The actuators of an active exoskeleton should not be self-locking, which means the person can resist the actuators by forcing them to stop to avoid hurt. The main types of actuators currently used in exoskeleton robots include motor, hydraulic drive, pneumatic drive, and artificial muscle drive.

4.3.3Sensing system for active exoskeletons

In an exoskeleton system, the controller uses sensors such as pressure sensors, torque sensors, myoelectric sensors, acceleration sensors placed on the human body to obtain precise information on the user's posture, speed, acceleration, and force in real-time. By measuring the information about the human body, the processor will analyze and calculate the amount of torque required for each joint movement and control the corresponding actuators. Meantime the controller compares the movement of the human body and the exoskeleton, creating feedback to ensure that the exoskeleton responds accurately to human movement.

Currently, there are two ways of obtaining human intent.

One is direct recognition. direct recognition of the operator intent can be obtained from surface electromyography (sEMG) data. By applying the EMG patch sensor on the skin, electrical signals can be detected before the muscle receives the nerve signal from the spin. But the noise of the signal requires filtering and amplification. The operator intent can also be detected by measuring the interacting force between the human body and the exoskeleton. Current sensors for the direct acquisition of operator intent are not yet mature enough.

The other method is indirectly recognition of the operator's intent, mainly by using the exoskeleton joint actuator (Serial Elastic Actuator) signals to estimate human intent. Measuring the relative displacement between the human and the exoskeleton and using the model to calculate the acceleration that the exoskeleton should exhibit is called impedance control. In contrast, measuring the interacting force and calculating the distance that each joint of the exoskeleton should move is called conductance control. This approach has some problems, the most serious of which is the inability to distinguish between the operator's force and the external force, which can lead to instability or loss of control.

4.3.4Implementation Scenarios

The exoskeleton was originally designed for factory or warehouse workers in some logistics fields. The exoskeleton gives strong support to the workers' muscles and the skeletal protects the shoulders and spine during long-term work and helps them to complete some repetitive work such as carrying, lambing, bending more easily.

Using exoskeletons could help with reducing the force applied to muscles, and improve the awkward position. In the industrial field, in some cases such as carrying weight and other positions in poor ergonomics conditions, the accumulation of injuries can cause irreversible injuries to workers. At the same time, workers are difficult to maintain high efficiency in the whole working cycle due to fatigue. In addition, there are a large number of cases in industrial applications, due to the strains of workspace, making it difficult to use large material handling equipment. If the advantages of industrial robots and the flexibility of human strength could be combined under various environments through exoskeletons, they can reduce work fatigue and extend continuous work time.

A typical example could be seen in the automotive manufacturing industry.

Standing Dynamic Operations: lower back exoskeletons

For long periods of standing work, such as parts sorting, material handling between work stations, assembly, and other operations, the workers are switching frequently between the positions of bending and standing straight, if introduce the exoskeleton robot into such operations, workers wearing waist exoskeleton can effectively reduce the strain on the abdomen, spine and neck and other body parts.

Currently， the lower back exoskeletons wildly used are passive and few are active. However, with the solution of the control algorithms and the emergence of new exoskeleton actuators, the active lower-back exoskeleton will have better potential in the future.

In tests of the sEMG, the average decrease in a passive exoskeleton can reach around 15-25% for lifting, and up to 60% for trunk bending forward positions. In contrast, the EMG signal during lifting with an active exoskeleton is significantly reduced, usually by 50% or more, as the actuator replaces the force output of the human muscles.

Fig. 19 A passive lower back exoskeleton and an active lower back exoskeleton

Standing Static Operations: Upper limbs exoskeletons

Usually used for people who work in positions where the arm needs to be lifted repeatedly for long periods. For example, in the assembly, welding of parts at the bottom of the car body, the upper limbs of the workers need to hold the tools for a long time to maintain the working posture. The purpose of upper limbs exoskeletons is to balance the weight of the arm and the weight of the tool, which is about one-ninth of the weight of a human. When this part of the weight is balanced, the strain on the shoulder muscles can be relieved. Using the upper limb exoskeletons appropriately could prevent shoulder injuries and fatigue and significantly improve efficiency.

Toyota has been evaluating experimentally the use of upper limbs exoskeletons since 2016, and in 2018 they are gradually being used on a larger scale. To date, 600+ exoskeletons are in use at ten plants across the US for 27 types of work, with 200 types of work planned so far. 2018 has seen a direct reduction in shoulder injuries and economic losses to zero thanks to the exoskeleton.

Fig. 20 Passive upper limbs exoskeleton, Crimson Dynamics

lower limb exoskeleton, Chairs

Usually used in the car assembly line to maintain a squatting posture for a long time. By setting a cushion between the human body and the exoskeleton, and setting limit motility at the knee of the exoskeleton, the operator squats to a certain angle and fixes the thigh and calf parts to generate support. The damping device at the knee joint provides the worker with external support at an appropriate speed when squatting, reducing the damage to the knee.

Fig. 21 lower limb exoskeleton chair, Hyundai

4.3.5Market Size, Main Domestic Manufacturers and Products

The development of the exoskeleton has gone through more than 50 years. The global leaders in exoskeleton robotics are mainly located in developed regions such as the US, Japan, and Europe, such as Ekso Bionics, CYBERDYNE, and ReWalk, which have 20 years or more of technology accumulation.

Research on exoskeleton robots in China began around 2000. Universities such as Tsinghua University and research institutions have been researching exoskeleton technology. Huazhong University of Science and Technology developed a wearable soft exoskeleton robot in 2004 [25], and Shanghai Jiaotong University developed a medical exoskeleton in 2011.

Over the past ten to fifteen years, technology diffusion and start-ups have driven a new wave of exoskeleton development. The number of exoskeleton start-ups in China has grown rapidly over the past five years but is still at an early stage.

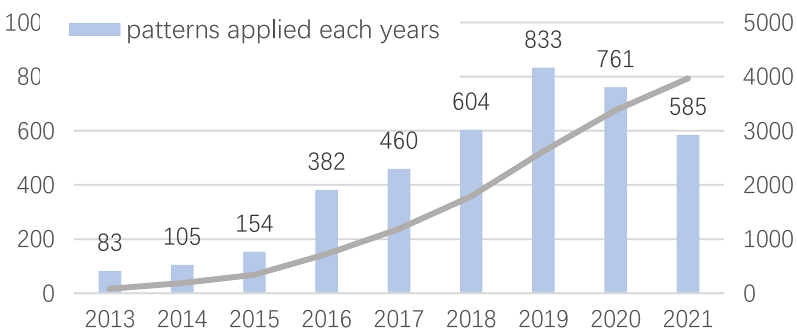


Chart 6 Patterns Applied about Exoskeletons in Recent 10 Years in China [20]

From the number of patents applied each year, it can be seen that the domestic research in the field of exoskeletons has shown a significant upward trend, from 83 in 2013 to 585 in 2021; while the last 2 years shows a certain convergence trend, might due to the large number of technologies stacked in the previous decade, research and patents on the lower levels of exoskeleton technology have become saturated, while higher-level technological breakthroughs require more time and resources to be invested.

In terms of total patent applications, the total number of patents filed before 2012 was less than a hundred, while the total number of patents till 2021 is over 4000. The increase in the number of patents in 14 years, reflects the high level of research on exoskeletons in China in recent years.

Hyetone

Guangzhou Hyetone Industrial Technology Co., Ltd. was established in November 2004, a conventional intelligent equipment enterprise integrating R&D, design, manufacturing, and marketing. Based on the innovation of key power-assisted components technology, it is developing human-machine interaction equipment products with the help of ergonomics, shape imitation technology, motion capture, motion recognition, haptic interaction, live monitoring, and simulation.

Acetone has been working on exoskeletons since 2016. It owns 25 patterns of exoskeletons including 22 inventions and utility models. Its customers include PLA, Nissan, Foxconn, Toyota, Volvo, Honda, CNPC, BYD, abb, VW, and other automotive OEMs and Logistics companies.

Hyetone				
Model	PWIND0102	PWIND0401	PWIND0701	PUIND0101
Soft/rigid	soft		rigid	
Support body part	back	Lower back	Lower back and upper limbs	Upper limbs
Passive/ active	passive			
Weight	1 kg	3.5 kg	3.5 kg	2.3 kg
Reduce muscle load	>40%	>60%	>60%	>70%

Hyetone				
Model	PLIND0101	EXO-PLES	PWIND0901	EXO-AHES
Soft/rigid	rigid			
Support body part	Lower limbs	Upper limbs	Upper limbs and lower back	Lower back
Passive/ active	Passive			Pneumatic
Weight	3.5 kg	4 kg	4.1 kg	4 kg
Reduce muscle load	>70%	>60%	>60%	>60%

Table 12 product matrix of Hyetone

Compared with other companies, Hyetone pays more attention to the ergonomics performance of its products and conducts detailed ergonomic tests and evaluations on each product. The evaluation dimensions include labor intensity index, energy consumption, endurance, metabolic index, and Borg scale, demonstrating their deep understanding of ergonomics. Also, their products can be equipped with life-detection systems, and through the dynamic data collected by the micro-sensors, the working status could be monitored, which can improve the efficiency of the enterprise.

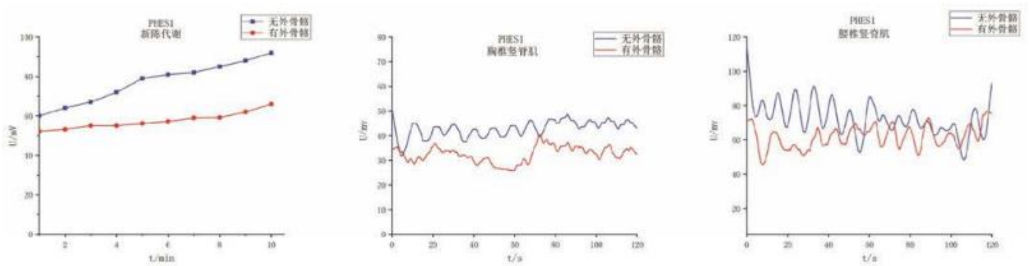


Chart 7 The reduction of the metabolic index, Labour intensity index of erector spinae after using PWIND0102

Due to the large space and high profitability of the medical rehabilitation market, Exoskeleton companies are choosing to enter the medical field, in which several outstanding startups have emerged like Fourier Intelligence, Mile Bot, and the Buffalo Robot, which products obtain National Medical Product Administration Certification. A few of them are involved in or only focus on industrial exoskeletons and attracted the attention of the capital market.

C-exoskeletons (Tie Jia Gang Quan)

Their project started in 2014 and their first product came out in 2016. After 1 year C-exoskeleton was funded and cooperated with the Chinese largest online shopping company in the logistics field, which makes it the first exoskeleton company to get the 2B orders. They own 41 patterns including 30 innovations and utility models and 3 software copyright. In 2017 and 2019 they got angel investment and pre-A investment more than 30 million CNY in total.

Their products are independently researched and developed. The frame is made of titanium and lightweight materials such as aerospace aluminum for a lighter weight. And they develop adaptive algorithms for different individuals based on machine learning.

C-exoskeletons (Tie Jia Gang Quan)			
Model	CEXO-E03	CEXO-A02	CEXO-S01
Actuators	motor	pneumatic and motored	passive
Support Body Part	Lower back	Lower back	Lower limbs (chairs)
Weight (kg)	5.6	5	1.5
Load support (kg)	50	25	
Battery Life (h)	8	8	

Table 13 product matrix of C-exoskeletons

Crimson Dynamics

Crimson Dynamics is a China-based joint venture industrial exoskeleton R&D company set up in 2017. They work closely with manufacturers at the very beginning of the project to ensure adaptability and pursue continuous engineering evolution, and their passive upper-limbs industrial exoskeletons were introduced to the market in 2020. Till now they own 21 innovation and utility models.

	Model	CDYS
		Passive
	Support body part	Upper limbs
	Weight (kg)	2.4

Table 14 CDYS

Mebotx

Mebotx was founded in 2018 and their team was from Soochow University. The works on technology development and transformation of the exoskeleton, intelligent man-machine interaction, mobile robots, and vision systems.

With many years of experience in the field of artificial intelligence technology, their products are not only industrial exoskeletons but also exoskeletons research platforms, fully independently developed joint actuators, and collaborative robots. Their product YETI is an exoskeleton platform for application development, intergraded with EMG, EEG, voice, and other control interfaces that can be used for research on physical tight coupling, gait analysis, and learning, intent control, and other ergonomics, robotics, biomechanism research. Their customers include many research institutions including iFLYTEK, Beijing Institute of Technology, University of Toronto, and other industrial customers like SIMENS, FAW.

They own 52 innovations and utilities about exoskeletons, control algorithms, communication protocol and simulation modeling methods, and 19 relative software copyright. In 2019 and 2021 they got more than 30 million CNY of angel investment and Pre-A.

Mebotx				
Model	Wasp	Chebi	Black Bear	YETI
Actuators	Passive	Motor	Motor	Motor
Support body part	Lower back	Lower back	Lower back and lower limbs	Lower limbs

Table 15 product matrix of Mebotx

ULS Robotics

ULS Robotics was set up in 2018, based in shanghai, provides exoskeleton products and supporting solutions mainly for the industrial market. It is one of the few exoskeleton robot companies that can develop and own the core technology independently. ULS develops the basic elements and subsystems including motion control chipset, motor drive unit, transmission system, etc.

ULS has worked extensively with customers in industrial and logistic fields including Beijing Airport, China State Grid, Haier, CATL, General Motor, VW, Bayer, and other automotive manufacturers. ULS has its own 31 inventions and utilities and 6 software copyright about CAN bus driver, kinematics control algorithm, and intention recognition. It has received about 10 million CNY of Pre-A investment by the end of 2020.

ULS Robotics			
model	MAPS-E	HEMS-L	HEMS-GS
actuators	motor	motor	motor and pneumatic hybrid
support body part	Upper limbs	Lower back	Lower back and lower limbs (weight-bearing)
weight(kg)	8	5.5	16
load support	20	30	50 for lower-back 100 for weight-bearing
battery life	6h	6h	6h

Table 16 product matrix of ULS Robotics

4.3.6 Actual Implementation Cases

Many domestic industries are currently conducting a wide range of experiments for their product, and several plants are gradually moving into practical application， especially in the assembly line and logic field.

Case 1, Crimson Dynamics

Crimson Dynamics's first CDYS passive upper limbs exoskeleton has been launched in 2020, targeting manufacturing companies in Europe and the US. The device has been tested in-depth at BMW's Spartanburg plant and Toyota's plant in the USA, and experiments based on MEG and metabolic index have been carried out at BMW's headquarters in Germany. The experiments compared the performance of the CDYS upper limbs exoskeleton with products from the US and Europe. [24]

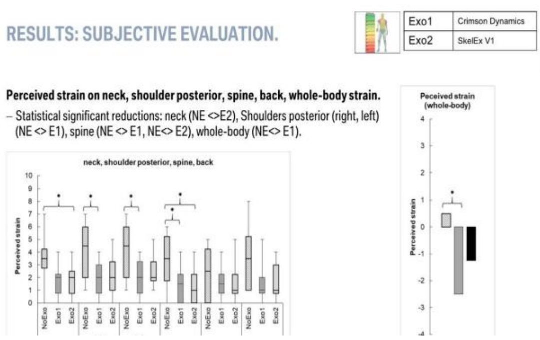


Chart 8 the exoskeletons reduce sEMG significantly [24]

The research was carried out on 8 male associates whose work is mainly assembly on the car chassis and need to work overhead frequently. The result shows a notable decline in the MEG after using the CDYS, which means the exoskeleton could decrease the load on the shoulder and upper limbs. The result of metabolic evidence includes oxygen consumption, heart rate, energy expenditure shows no change, represent no extra workload with the weight of the exoskeletons.

Case 2, SHENDONG Coal Mine Group Co., Ltd.

On July 25, 2021, the first generation of passive upper limbs exoskeleton product "Strong Hand" developed by CHenergy SHENDONG Coal High-End Equipment R&D Centre and Hyetone Industrial Technology has been put on trial by about 10 people in 16 shifts during the installation of the tape machine in the 22521 chutes of Haragou Coal Mine and 52108 chute of Yujialiang Coal Mine. [26]

The handling of parts has always been an important part of mine operations, but the manual handling of heavy equipment can cause serious damage to the workers' lumbar spine, shoulders, and knees, which can easily lead to occupational injuries. The ‘strong hand’ was designed for miners to relieve the muscle strain caused by overexertion or long-term bending. After testing, "Strong Hand" can reduce the average 60% of tension and torque in the shoulder, elbow, wrist, and finger joints, reduce the fatigue strength of employees' biceps by 60.5%, reduce the fatigue strength of lumbar erector spinae by 58.1%, and reduce the metabolic rate of workers by 35.8%.

Fig. 22 the exoskeleton used in the mining industry

Case 3, Cable Branch of Beijing Electric Power Engineering Co Ltd

On December 6, 2021, at the cable laying site of the Mijiabao 110kV transmission and substation project, construction workers in the tunnel lifted the cable into position with the help of a wearable waist-assisted exoskeleton robot [27]. This human-machine interaction and cooperation not only effectively reduced the labor intensity but also enhanced the work efficiency and effectively shortened the construction period.

The power exoskeletons have the function of upward-lifting assistance and downward buffering assistance, which can provide 20 to 30 kg of assistance to the user and reduce more than 50% of the load for heavy-duty jobs. For the lifting into a position of a 110 kV power cable with a coil length of 600 meters and a cross-section of 800 square millimeters, the traditional construction method requires eight people, while the exoskeleton is used to assist the construction with only five people, which can increase the efficiency by 12.5%, and for larger cross-section cables, the efficiency is increased even more.

Fig. 23 construction workers move the cable with exoskeletons

4.3.7 Challenges and Opportunities

As the problem of the aging population increases, labor costs will be much higher in the future. The exoskeleton can be an effective tool to improve labor efficiency and productivity

Many domestic companies are currently doing tests on exoskeletons, proving that the acceptance of exoskeletons by companies is high. However, some studies have shown that the willingness of operators to use exoskeletons as safety protective equipment is not very high. One reason is the latency of WMSDs may belong, the operator can’t realize the benefit of exoskeletons immediately. The other is the trouble that wearing, preservation, and use of exoskeleton equipment is more bothering.

Improvement of the usability

Exoskeletons as ergonomic equipment should focus on the human-machine interaction, with the improvement of strength assistant, the comfort of the users should also be improved. Weight reduction, a more user-friendly binding system, higher reliability, lower threshold of use, a less complex system could be benefits for the promotion of exoskeletons.

A clear product positioning

Exoskeletons are used for preventing occupational harm, rather than enabling operators to match the workload that is beyond their capability. More effort should be paid to the ergonomics performance rather than the mechanical performance of the product. For operators in the industrial field, completed training is needed to prevent the injured by using in a wrong way.

5 Conclusion

Ergonomics studies started in 1930, compared with worldwide it was relatively late. The amount of current national standards of ergonomics is half of ISO with 1/3 of them being adopted from withdrawal ISO standards, showing a low publish and update speed. The teaching activities are widely conducted among universities, and the academy of ergonomics in China is rapidly developing.

On the contrary, the implementation of ergonomics enabling technologies including collaborative robots and exoskeletons has made great progress. Collaborative robots are widely used to collaborate or replace operators with jobs with occupational injuries and trials on exoskeletons are performed in factories. Startups are emerged in these markets and come up with competitive products with feasible costs.

As the largest single market in the world, ergonomics has huge application prospects in China. With the help of new technologies such as AI and VR, the development of ergonomics will face more opportunities and challenges.

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