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Human Hybrid Robot, next-generation support technology for manual tasks: challenges, perspectives and economic implications

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Abstract

Despite the increasing application of automated systems, manual tasks still plays an important role in industrial production. The intelligence and flexibility of human enable quick response and adaptive production for the individual requirements and the changes in market. Moreover, some manufacturing tasks with sensible and high-value components (e.g., in electronic and aircraft production) requires attentive manual handling. Regarding the requirement of increasing productivity as well as ergonomic improvement and the aging of the employees, there is a significant need for technologies which support the staff individually by performing tasks. Human Hybrid Robot, a hybrid system with direct coupling (serial and/or parallel) of human and mechatronic elements, is a new trend in application of robotic technologies for supporting manual tasks. It realizes a synchronous and bidirectional interaction between human and mechatronic and/or mechanic elements in the same workspace. This paper will discuss the challenges to realize the concept of Human Hybrid Robot for industrial application. According to the challenges we will give an overview of relevant technologies. Finally, it will concludes with the economic implications of such systems as well as an outlook on future research.

1. Introduction

Under the impact of globalization and demographic trends, today's manufactures are facing the following challenges: rapidly changes in global market, more stringent customer demands, aging employees, increasing heterogeneity of staff (e.g., skills and knowledge) and intense world competition. In order to meet the more specific, diverse and individualized customer requirements, manufacturing process are becoming more complex. Production systems also need to be more flexible for reconfiguration due to the uncertainty of changing market demand. Under this circumstance, it is significant and necessary to keep manual tasks in production today and in future. The high intelligence, adaptability and agility of human enable them to handle the increasing complexity and flexibility of manufacturing. Moreover, manufacturing companies are forced to improve the productivity and efficiency of their production for a long-term in order to remain competitive.

Despite the staff qualification as well as production planning and control, another two factors have growing influence on productivity and production quality in manual tasks: working ergonomics and aging of workforce. Substantial evidence have been found that working ergonomics is directly related to productivity and production quality as well as worker's compensation cost and employee turnover [1], [2]. Musculoskeletal disorders (MSDs) are the most common occupational disease as well as factor which may adversely affect the health of workers due to poor ergonomic working conditions, e.g., awkward postures, lifting or moving heavy objects and using vibrating equipment. According to the report from European Commission about 40% of the worker's compensation cost are attributable to MSDs in some EU Member States [3]. Regarding the demographic change in Europa, more than a quarter of all employees will be older than 50 years in 2020 [4], and elderly people are more susceptible to MSDs. Many companies have taken appropriate measures to reduce ergonomic-related problems, e.g., production-oriented product design, ergonomic design of workstations, implementation of lift assist device or other ergonomic handling devices. However, a considerable part of the problems is still not resolved. In summary, there is an obvious demand on new support technology that enables workers to perform manual tasks comfortably, safely, quickly and accurately without replacing by machines.

1.1 Human Hybrid Robot

The concept of Human Hybrid Robot (HHR) can be characterized by direct coupling of human, technical systems, tools and functionalities (e.g. mechanism for integrated quality assurance) [5]. The main idea is the integration of technical and biological elements as well as the realization of a synchronous and bidirectional interaction between human and mechatronic and/or mechanic elements in the same workspace. HHR is a complementary approach which combines the strengths of both human and machines (i.e., robots): people have high intelligence, adaptability and skillful hands to deal with complex tasks and uncertainties; machines, on the other hand, are powerful, tireless and precise for repetitive and heavy tasks. Figure 1 illustrates the working principle of support systems based on the HHR-concept (abbreviate it as HHR support system). For a given task, the worker use tool to finish the task with the help of technical system, tool and other functionalities (e.g., cognitive assist), collectively referred as HHR support system. The technical system is a mechatronic and/or mechanic system, which can fit the human motion and provide physical support like reduction of musculoskeletal stress and opportune power augmentation. Cognitive assist functionalities mainly address process monitoring and quality control. The entire HHR support system is always under the control of worker and work as a part of the human body. This paper will mainly focus on the relevant technologies for the technical system and cognitive assist functionalities.

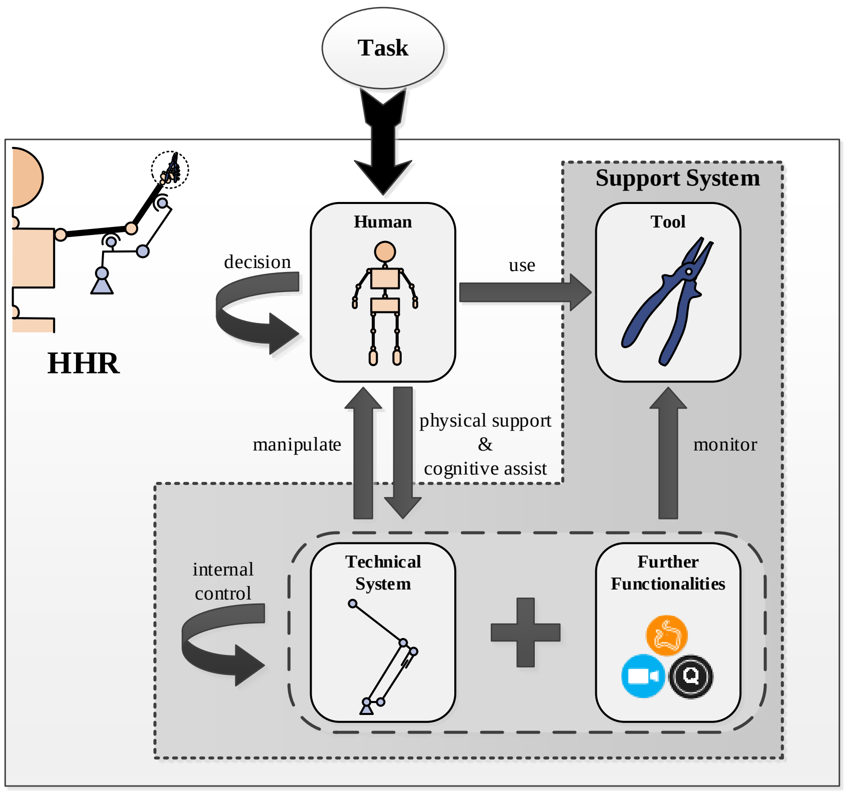

Figure 1. Working principle of Human Hybrid Robot (based on [5]).

1.2 Requirements

An overlook of main requirements of HHR support systems (not complete, but real examples) is presented in Figure 2. They are derived from three perspectives: user, business and production. The primary requirement of HHR support systems is to realize comfortable, safe, efficient and accurate manual tasks. Comfort means that, the system should fit the natural human motion rather than constrain or disturb the worker. In addition, intuitive operation is also very important for user acceptance and working efficiency. The variance in skill of workers and the difference in working status of every worker have influence on product quality. Thus, cognitive assist functions are needed to fill the gaps. Moreover, most manual tasks must be done in a complex and dynamic environment with movable co-workers, valuable devices and products. In order to avoid injuries and prevent accidental product or infrastructure damage, soft materials, safety mechanism and "fail-safe"-function are necessary.

Besides the primary requirement, the following aspects should also be considered by developing HHR: special restrictions, adaptability as well as adjustability, power supply, reliability and cost. Various restrictions from workstation should be considered by system design. For example, limited workspace and payload in fuselage only allows compact and lightweight system. Due to the diversity of manufacturing tasks, the support system should be able to satisfy different support demands, such as stabilisation of certain body part for awkward position and power augmentation for heavy payload. A fixed support system may be enough for sitting works, but is not suitable for tasks with high mobility. Under this circumstance, there is a justifiable need for a system which can be easily adapted to different use cases. On the other hand, the system should be easily adjustable for different workers. It is uneconomical to equip personalized support system for high staff turnover. For a successive production without interrupt, the system must keep robust even by rugged environment or error. Furthermore, power supply has to be provided independently and they should cover at least one shift (or an 8 hour use). The investment costs of the system should be as low as possible.

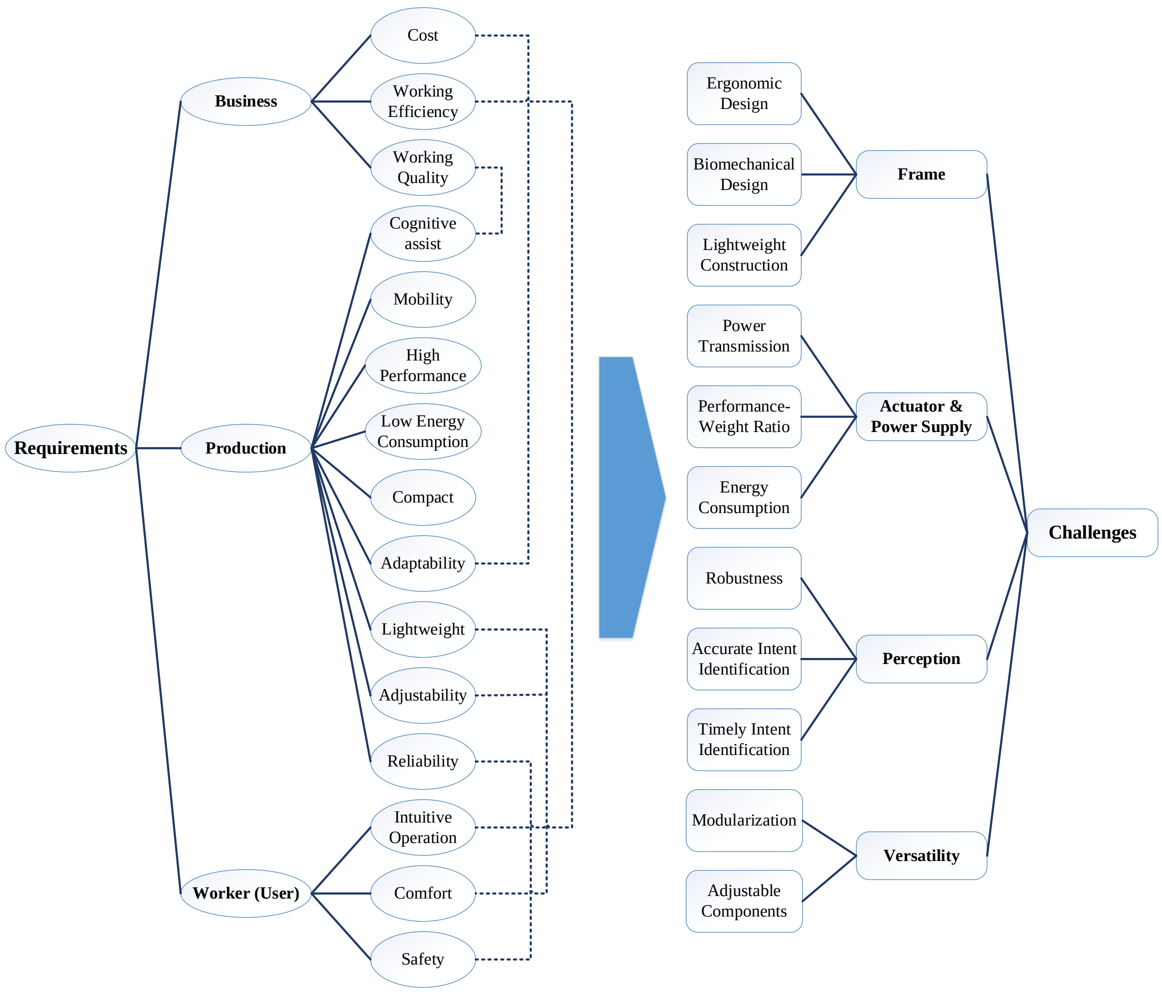

Figure 2. An overlook of main requirements and challenges of HHR support systems

2. Challenges for HHR Support Systems

According to the requirements mentioned above, a perfect HHR support system is a portable, skin-tight, adaptive and cost-efficient system with high performance and low energy consumption which can support the worker without giving discomfort and burden to him. To realize such a system, there is a series of challenges in terms of system frame, perception, actuation, power supply and versatility (see Figure 2).

The main purpose of system design is to maximize the motion compatibility between system and human. In other words, the constrained degrees of freedom on the human body should be as less as possible. For this reason special effort have to be put into biomechanical design to generate the natural human motion due to the complexity of the human musculoskeletal structure. An accurate biomechanical model is obviously needed here and it is highly dependent on further research in biomechanical engineering. Another important issue for the system design is the power transmission inside the system as well as the transmission to human body. Despite the optimal power transmission ergonomic design should also be involved in human interface for a better use comfort, regarding material, form and location. Moreover, new technologies as well as new discoveries in the area of material and lightweight construction will help to provide a higher loading-mass ratio and to compact the system size.

An accurate and timely intent sensing is significant for an intuitive and synchronous interaction. Sensor technology, data processing methods and biomechanical analysis of human motion are relevant to this problem. Considering the uncertainties in human motion extensive information is necessary for intent identification or motion prediction. Appropriate sensors, e.g., force sensor, motion sensor and muscle activity sensor, should be firstly selected to build up a hybrid sensor system concerning their accuracy, precision, measuring speed and sensitivity. The determination of optimal measure point is another issue for a successful measurement. The total planning of the sensor network depends on the mechanical structure, type of actuators and the control strategy. As mentioned in section 1.2, the sensors should be robust enough for industrial application, e.g., in rugged work environment with disturbance.

Another big barrier for compact and lightweight system structure is the actuators and their power supply. For the most actuators, the improvement of performance is normally followed by increasing mass or size. This rule is also valid for the capacity of power supply and their mass or size. Small size actuator as well as power supply with high performance-weight ratio are essential for the perfect HHR support system. Advanced power transmission technology is also necessary for that.

The diversity of worker, tool and support demand in manual tasks requires an adaptive system which can be easily adjusted or reconfigured for different applications. Adjustable design needs to be involved in the whole system, e.g., tool interface as well as user interface, for personal requirements. Modular design is a possible solution to improve the adaptability and flexibility of the system. The difficulty in modularization is the development of universal interface for easy build and transformation of force, information as well as energy.

3. Overview of relevant technologies for HHR Support System

According to the requirements for industrial application and the challenges mentioned above, we will discuss the possibility and feasibility of different schemes for HHR support systems. Some representative example will be mentioned below in respect of physical support and cognitive assist. The recent advancements in the field of wearable robotic device, exosuit, orthopedic provide divers fundamentals for the development of HHR physical support system. An overview of the fundamentals will be conducted in following aspects: system construction, human intent estimation and actuation.

3.1 System Construction

The construction of HHR support systems deals with system architecture, human interfaces and materials. According to the support effect the system construction can be interpreted in two different ways: working as extra body parts, e.g., a third arm, or working as an external frame surrounding the human body.

A HHR support system which works as extra body parts is not limited to anthropomorphic design. It allows any possible mechanical construction as long as the human motion never be disturbed. This provides the possibility to avoid design difficulties caused by mimicking the complex musculoskeletal structure. However, the safety problem becomes more prominent. On the one hand, the system should prevent collisions with operator as well as its surroundings; on the other hand, the system should not force the operator's body part out of their joint range of motion. Brown invented a dynamic support arm for holding and stabilization of payload such as camera [6]. The support arm functions like an unpowered lift mechanism driven by iso-elastic spring. The original application of the dynamic support arm is the "Steadicam" tool. Figure 3 a) shows an exemplary solution with the support arm for manual assembly tasks [7]. The arm is attached to the torso of user via a vest and hold payload for the user. It works like a passive third arm leaded only by the operator. A tool holder with integrated functions of position compensation and quality control is connected to the support arm. Equipois integrated the iso-elastic lift mechanism to an exoskeletal arm "X-Ar" for manual tasks [8]. One end of the arm is attached to chair or workstation, while the other end is connected to the operator's arm. Its joint mechanisms allow the operator to work with full degree of motion. A further example is the Supernumerary Robotic Limbs, two wearable robotic arm designed by Parietti and Asada for aircraft fuselage assembly [9]. Each arm has 3 degrees of freedom and is powered for holding and positioning objects as well as stabilization and securing the human body.

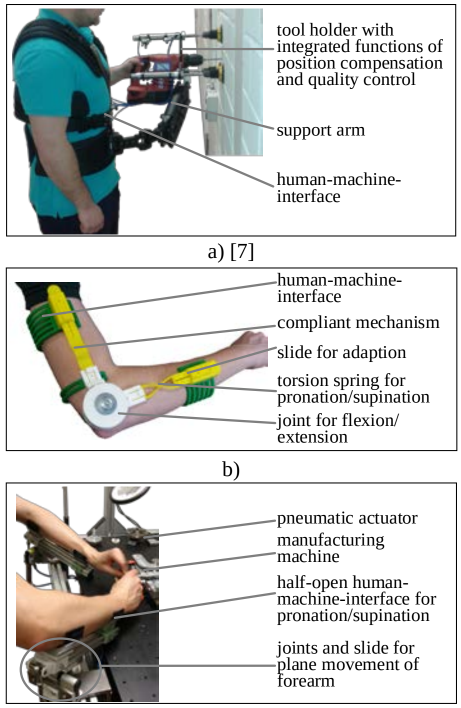

Figure 3. Exemplary system constructions

Another type of HHR support system is like a frame fitting closely to the human body and able to follow the human motion. For example, Figure 3 b) illustrates the concept design of a skin-tight, modular arm exoskeleton. Its joint, torsion spring as well as the compliant mechanism allows free movements of the forearm. This kind of system structure nearly eliminates the possibility of collision between human and machine. However, it is not easy to mimic the human kinematic exactly due to the complexity of human biomechanics. Even slight misalignment can cause discomfort. The human body has around 230 joints with 244 degrees of freedom which are controlled by 630 muscles [10]. Many design issues arrive when trying to realize same degree of freedom as well as range of motion for each joint, like axis alignment and singularity. Some arm rehabilitation robot have been developed to simulate the 7 degrees of freedom in human arm: three in shoulder for flexion/extension, abduction/adduction and internal/external rotation; two in elbow for flexion/extension, pronation/supination; two in wrist for flexion/extension and radial/ulnar deviation. For instance, (CADEN)-7 designed by Rosen and Perry is a 7-DOF arm exoskeleton, allows all possible arm movements for the operator [11]. In order avoid the singularity problems in control, they moved singular configurations away from the workspace of human arm by optimizing joint arrangement. They introduced open design into human interface, semi-circular bearings with different orientations. This reduced discomfort caused by small misalignment and muscle flex. Tsagarakis and Caldwell developed a rehabilitation exoskeletal arm with seven degrees of freedom [12]. The system structure is mainly made from metal composite materials which is light, low cost but stable.

Safety and comfort are particularly important for rehabilitation robots due to the sensitivity of the patients. Anthropomorphic design enables the robot motion to align with the human motion. However, to realize full degree of freedom in the human body leads to increased complexity in system design and control. In order to simplify the problem, most available exoskeletons chose a construction whose kinematics approximates to the human kinematics. The Berkeley lower Extremity Exoskeleton (BLEEX), for example, modeled knee joint as simple rotary joint [13]. Similar to BLEEX, HAL-5 reduces the degree of freedom in elbow, shoulder, hip and knee joint to one for flexion and extension [14]. These simplification leads to obvious kinematic differences between wear and system. Large strain will be applied on wearer during inconsistent movement, if the whole system is tightly attached to wearer. Thus, it is very important to introduce compliant connection and reduce rigid connection. Rigid connections are generally located on torso, feet and forearm. A perfect connection plan should enables the system to be attached to wearer without restrictions. Based on force analyze of walking movement, the Honda walking assist aims to reduce the floor reaction force of wearer [15]. Different to other wearable robotic device, the walking assist is placed between the two legs with a seat to hold the torso. The weight of the user is transferred from the seat across the structure on to the ground through the shoes which are the only rigid connections between the device and user. Figure 3 c) presents an support system which is mounted on a classic work bench for supporting manual tasks in e.g. microproduction. It is used to hold as well as stabilize worker's arm during the precise operations.

Every armrest of the illustrated system has three degrees of freedom that enables necessary plane movements of the forearm. The half-open design of the human-machine-interface avoids rigid connections which would limit elbow pronation/supination.

Although many efforts have been made, there are still two big problems for rigid-frame exoskeletons: comfort and weight. The rigid frame adds more or less restrictions on the wearer's natural movement. Despite the misalignment of mechanical and biomechanical joint, the rigid frame impose their inherent inertia on the wear. To overcome this inertia more power are required for actuation. That in turns leads to more payload from actuator as well as power supply on wear. Moreover, the compactness requirement from industrial application is another challenge for the rigid frame. To address these issues, some researchers have pay attention to develop soft frame with fabric linkage instead of rigid linkage. Wehner et al. developed a soft exosuit for augmentation of functional leg muscles in healthy body, comprising strong fabric bands and pneumatic muscle actuators [16]. The bands are inextensible and build up a triangular web with actuator attached. Alan et al. designed a cable-driven soft exosuit that can provide assist moments at the ankle and hip during walking [17]. The suit uses series of belts and traps to create a path to transfer loads between the ankle and the pelvis. The system frame is light and allows natural human motion without restrictions due to its fabric construction.

3.2 Human Intent/Motion Estimation

According to the requirements, the support system should follow the human motion and provide opportune and moderate support. That is to say, the system works only in the way the operator desires. This requires an accurate and timely identification of human intent, which could be measured generally in three different ways: direct measurement of the joint movement, detecting the interaction forces caused by the human motion and measurement of muscle activities. Relevant sensors are exemplary listed in Table 1.

Every human motion involves joint movement and can be identified by angular position, velocity and acceleration of particular joint. Angular sensors are commonly used to detect the actual joint position, e.g., the Wearable-Agri-Robot developed by Toyama et al. for agricultural work [18]. Alwasel et al. use a magnetoresistive angle sensor to measure human joint angles [19]. Strain sensors can be applied to measuring the bending position of joint indirectly. It is placed normally around the joint and deformed with joint movement, leading to change of its electrical resistance which can be directly measured. In this way, the orientation changes of the joints can be identified. Park et al. use an in silicone rubber layer embedded strain sensor to experience the angle change of the ankle joint [20]. Gatti et al. integrate conductive fibers into skin-tight fabrics surrounding a joint for multi-axis joint angle measurements [21]. Inertial sensors, such as accelerometer and gyroscope, are widely used to monitoring the physical state thanks to their accuracy and unobtrusive wear experience during daily life in long time [18], [22]. The orientations of the body parts (e.g., arm and leg) as well as the intensity of physical activities can be estimated by using the joint angular velocity from gyroscope and the acceleration from accelerometer.

The human intent can also be estimated by measuring the force/torque from the operator on the system structure during particular movement. The detected force/torque, in this way, can be interpreted as command from human to system and used directly for actuator control. The selection of sensor type and their install location depend on the system structure and its working principle. For instance, force and pressure sensors are normally placed in human interface, while torque sensors are located around the mechanical joints [11], [13]. Honda walking assist device is equipped with force sensors to measure floor reaction force and use it as input for assist force control [15]. Moreover, pressure sensor and footswitch are also applied for detecting foot ground contact and identify the gait cycle event [20], [17].

Muscle produce the force/torque necessary for human motion. Thus, analyzing muscle activity is another way to determine human motion especially the muscle force. EMG sensor detect the bioelectrical signal containing the motion intent transmitted from brain to muscle. This enables prediction of muscle movement before it occurs. For this reason, many exoskeletons use EMG signals as control input to make their assist action simultaneous with musculoskeletal actions, e.g., the robot suit HAL [14]. Other sensors like ultrasonic sensor, strain sensors and pressure sensors are used to monitoring the physical status of muscles. Koyama et al. developed an ultrasonic muscle activity sensor which can be integrated into clothe for muscle force detection. It estimate the muscle force by measuring the transmitting time of ultrasonic in muscle, which is changing with muscle movement [23]. Meyer et al. designed a pure textile, capacitive pressure sensor to measure muscle stiffness during musculoskeletal movement [24].

In summary, different kind of motion information are needed for an accurate and timely estimation of human intent. Interaction forces/torques can be used as command signal, while the required support force (set value for control) can be better calculated from the muscle activity information. The joint movement information shows the actual physical status of the human body and gives feedback to controller for verifying the support force. Furthermore, the measurement of joint movement and muscle activity allow a preventive monitoring of worker's physical status by working.

Table 1. Sensors for human intent/motion estimation

Measurand	Sensors
Joint Movement	Angle Sensor (e.g., Goniometry), Magnetic Sensor (e.g., Hall Sensor), Inertial Sensors (Accelerometer and Gyroscope), Strain Sensor (e.g., Fiber), Encoder, etc.
Interaction Force	Force Sensor, Torque Sensor, Pressure Sensor, Strain Sensor, Piezoelectric Sensor, Tactile Sensor, etc.
Muscle Activity	EMG, Pressure/Force Sensor (capacitive) as Muscle Stiffness Sensor, Strain Sensor, Ultrasonic Muscle Activity Sensor etc.

3.3 Actuation

Lightweight actuator with high performance and low energy consumption is always an important topic for robotics. For wearable support device “soft” is an additional requirement for actuators. In the following we will discuss both traditional and new actuator technologies which have been applied in exoskeletons and active orthosis. Table 2 shows a list of the actuators that could be used for HHR support system.

Electric motors are most widely used actuators due to their versatility, high-developed control technology and convenient power supply also for portable application, e.g., battery. According to power transmission technology, motor-actuated systems generally falls into one of the three categories: gear drive [14], [15], direct drive [25] and cable/belt drive [9], [11], [17]. Gear and cable/belt drive can save the motor mass by amplifying the motor torque. However, it results in undesired tradeoffs like friction, backlash and nonlinear dynamics, which lead to difficulties in accurate control. Direct drive motor must be placed close to the joint, but increases rotational inertia. This could be critical for wearable system with high power requirements due to the low power-weight ratio. Cable/belt drive allows long distances power transmission without friction or backlash inherent to gears. Moreover, it is suitable for soft-frame support systems. Nevertheless, appropriate measurements are needed to overcome the difficulties caused by cable routing and nonlinear dynamics during system construction and control.

Hydraulic actuators have high performance-mass ratio, ideal linear characteristic low energy consumption and quick response. For this reason, BLEEX choose double-acting linear hydraulic actuators to assist walking [13]. Breitfeld et al. presented a soft hydraulic actuator made from elastomeric bellow, inspired by dimensional peristaltic movement in worms [26]. By selection and implementation of hydraulic actuators, the leakage problem of hydraulic fluid should be carefully considered. Pneumatic actuators share the advantages of hydraulic actuators and avoids the leakage problem by using compressed air. Additionally, they are practically suitable for soft actuation application like human-robot interaction due to their inherently compliant behaviors. Tsagarakis and Caldwell developed an arm exoskeleton with pneumatic muscle actuators [8]. McKibben pneumatic actuators were chosen by Wehner et al. for a lightweight soft exosuit because of their compliance, muscle-like force length properties and easy driven by an off-board compressor [16]. Kadota et al. equip a power-assist robot arm with pneumatic artificial rubber muscles to mimic the motion of biarticular muscles [27]. Translating torques and rotational motion into linear forces is necessary for control of hydraulic and pneumatic actuators. Unlike traditional pneumatic actuator, pneumatic muscles have non-linear property which could not be ignored in control.

Shape memory material (SMM) are one kind of smart materials, which have the ability to return to a previously defined shape or size by external stimulus like temperature, stress, magnetic and electric field [28]. Recently, the shape memory effect have been found in a large variety of alloy, polymers and gel. All these materials can applied to generate force by giving particular inducement. Today many researches have been conducted to study shape memory alloy (SMA) and use it to develop new actuators. Stirling et al. use SMA to actuate an active soft orthosis for knee [29]. They form NiTi shape memory alloy wires into springs and attach them to a fabric frame. The SMA actuator is controlled by current to heat the spring and induce phase transition. De Laurentis and Mavroidis developed a prostetic hand actuated with SMA artificial muscles [30]. The challenge for using SMA actuator is considering its hysteresis behavior by modeling and control. In compare with SMA, shape memory polymer (SMP) have easy shaping, high shape stability and adjustable transition temperature.

Table 2. Actuators for HHR

Actuator	Power Supply
Electric Motors (e.g., gear drive, direct drive, cable drive)	Electrical Energy (e.g., Battery)
Pneumatic Cylinders	Pneumatic Energy (e.g., Compressor, Pump)
Pneumatic Muscles (e.g., McKibben, Rubber Muscle)	Pneumatic Energy (e.g., Compressor, Pump)
Hydraulic Actuator (e.g., Cylinder)	Hydraulic (e.g., Accumulator, Pump)
Shape Memory Materials (e.g., Alloy, Polymer, Gel)	Electrical or Pneumatic Energy

3.4 Cognitive Assist

The primary objective of the HHR support system for industrial application is improving ergonomics as well as increasing productivity and product quality. Despite the physical ergonomics, the cognitive ergonomic has direct impact on productivity and product quality. By increasing complexity of manufacturing process and tasks, there is an obviously growing demand on cognitive assist, such as sensing augmentation, intelligent working instruction and quality control. On the other hand, worker's skill level vary with people and their physical as well as psychological state. Cognitive assist is able to reduce the influence of this variance and keep worker's effective working time as long as possible. For example, Figure 4 illustrates an active support system with integrated cognitive functions for manual tasks. Besides physical support the robot also enables intelligent interaction with user, e.g. motion monitoring and haptic feedback for error prevention. The touch screen shows working instructions for the current assembly task and give user apropos feedback about his working states. A camera system is implemented for verifying the result of every assembly steps. Caudell and Mizell proposed an advanced technology to project a computer-produced diagram on a real-world object [31]. It enables a flexible, dynamic visualization of working instruction and information without displays fixed in place. This leads to improvement of working efficiency in manual tasks. Molineros and Sharma developed an Augmented Reality interface for guiding manual assembly [32]. It is a wearable display which can present assembly information on workstation and monitor the manual operations.

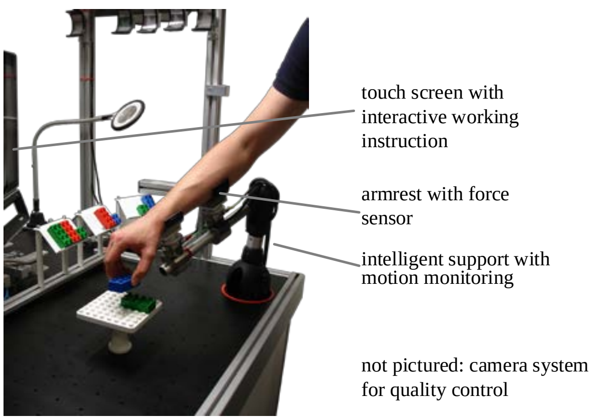

Figure 4. An active support system with cognitive functions (based on [7])

4. Perspectives

Although many advancement have been made in relevant technologies, there are still a large part of challenges need to be addressed. In order to meet the flexibility and adaptability requirements, a wearable structure will be the main direction for system design. There are two trends of the system construction: One is rigid-frame based on human skeletal structure; another is soft-frame inspired by muscle system. The focus for rigid-frame system is to realize a lightweight and compact structure. This needs new materials which are light, low cost but strong enough, like composite materials. Small size actuators with high power-weight ratio and low energy consumption are especially expected to improve the system performance without mass incensement. The advancement of soft-frame system depends highly on the development of soft actuators, particularly the textile-integrable actuators. Despite the structure and actuators, power supply is another big payload for the operator. For a portable system, a lightweight, standalone energy storage device is significant when it enables long-term application. Efficient power transmission technologies is a further factor for the system performance. An additional research point is accurate and opportune measurement of human intent/motion. Reliable and wearable sensor systems is necessary for day-to-day applications. The development of intelligent textile and clothing, which can be integrated with sensor, actuator, power supply and control unit, will cause an evolution of the wearable support system.

The development of HHR Support system can also benefit from some other advanced approaches and technologies, such as modular design, 3D printing and virtual imaging. Modular architecture enables high flexibility and adaptability for the system. Instead of developing a completely new system, a new variant can be finished by reconfiguration of available modules. New functionality can also be easily added to recent systems due to modularity. This will lead to reduction of development cost. 3D printing and scanning enables relative low-cost production of system frame and quick response to personal demands. Additionally, the individually customized system frame, especially the human interfaces, provide a more comfortable wear experience.

5. Economic Implications

Development and utilization of economic potentials of the systems based on the HHR concept by employees receiving work support on the one hand and companies using these technical support systems on the other have an enormous impact on national and international economy – especially under consideration of demographic change (see Figure 5). The focus here is on both preventative and operative measures with respect to working processes in order to deal with disability among an aging workforce. Human-machine interaction will induce changes in existing occupational structures. Above all, reduced invalidity is expected as a result if particularly physically strenuous work situations can be gradually avoided through the use of HHR concepts. This subsequently means lower costs for disability benefits or disability pensions as well as more capable taxpayers and contributors to social protection. As a welcome side effect, the number of people in employment will also preserve macroeconomic manpower as well as ensuring employee productivity through supporting working processes. Thus, investments in innovative support systems help to increase the added value. In turn, a reduction of charges on labor can be achieved due to an expected declining invalidity rate. In this way, the future development of the unit labor costs is positively influenced and, moreover, international competitiveness is enhanced.

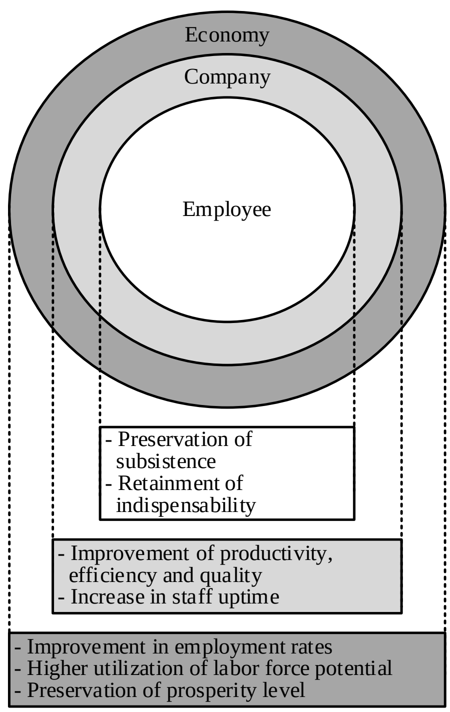

Figure 5. Compound social implications of Human Hybrid Robots.

6. Summary

Support systems based on HHR concept are supposed to be a new generation of technologies for supporting manual tasks in industrial production. The primary object of such systems are reducing physiological as well as psychological stress of workers and improving their productivity as well as working quality simultaneously. This paper discussed development challenges for HHR support systems based on the general requirements. The recent advance in the field of biomechanical engineering, robotics, material and mechatronic engineering shows different possibilities for realization of HHR concept. An overview of relevant technologies for system construction, human intent sensing, actuation and cognitive assist is presented. Several perspectives for future research are identified. In addition, the economic implications of those systems for manufactures are briefly analysed.

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