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A State Of Art Review on Kinematics and Control Aspects of Exoskeletons

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ABSTRACT

The first practical application of exoskeleton robots was done on soldiers to increase their capacity of carrying load as well as to help them for walking long distances. After realising the incredible performance of exoskeleton in this field, researchers used this technology in medical field for improving the physical capabilities of physically challenged persons through many techniques such as rehabilitation and tele-operations. In medical field this technology is presently in its early stage and demands multiple technical approaches to short out many complex technical issues. Involvement of human life in these devices enhances the severity of any consequences due to failure of the system. This paper reviews the development of active exoskeleton. Paper contains an overview of major development occurred in earlier stage, milestones during evolution and main obstacles in developing advanced level robots in the present day context. Moreover, paper focuses on classification, a comparison and provide the knowledge of different actuation and power transmission methods used in active exoskeleton that have been found in the literature. A brief review on the control methods of assistive exoskeleton robots is also presented.

Index Terms—exoskeleton, assistive robots, rehabilita-tion.

I. INTRODUCTION

A powered exoskeleton (also known as powered armor, exoframe, hardsuit and exo-suit) is a wearable mobile machine that is powered by a system of electric motors, pneu-matics, levers hydraulics, or a combination of technologies that allow for limb movement, increased strength and endurance. The initial concept of the exoskeleton was developed in 18th century by Vangestine [1]. In 1917, United States inventor Leslie C. Kelley developed what he called a pedomotor, which operated on steam power with artificial ligaments acting in parallel to the wearers movements [2]. After more than 50 years from concept initiation,first implementation came into real-ity in 1936 [3]. In this, exoskeleton robot was attached to a wheelchair for designing a foot operated feeder mainly for polio victims [3]. As shown in Figure 1 [3]. The wearer was able to feed by herself and the actuation of the elbow flexion/extension was provided through the foot pedal [4]. After the success of this "foot operated feeder", several other feed-ers were developed by Goergia Warm Spring Foundation [5].

Figure 1. "foot-operated feeder" by G. Warm Spring Foundation [3].

In 1950, C clamp feeder was designed and it was attached to the table [3]. First powered feeder (Corset-based feeder) fitted directly to the body came into existence in 1953 [3]. Study on active controlled orthoses was started in 1956 and it was the beginning of first generation of exoskeleton research. In 1960 US Department of Defence initiated the first gen-eration of exoskeleton system that can be used as a suit of body armour [7]. At that period, General Electric and the United States Armed Forces were the main mover into this field of exoskeletons. During same period Cornel Aeronautical Laboratory started work on man-amplifier system [7]. The motion intention of the user should be identified to generate the control commands of the power assist robot [4]. Therefore, in 1960s, research work move to investigate myoelectrically controlled stimu-lator to generate motor commands to emulate a paralysed muscle [8]. First attempt to use bio-logical signals for controlling Myo-electrically controlled stimulator for paralysed muscle was done in 1961 [9]. The first true exoskeleton in the sense of being a mobile machine integrated with human movements was co-developed by General Electric and the United States Armed Forces in 1961 named as Hardiman. It was a full body master slave suit powered by hydraulics and electricity [6]. GE had main focus of using it for many dangerous work such as military operations (bomb and land mines disposing, bomb loading on aircraft carriers), deals with hazardous atmosphere (poisonous or radioactive environment) , nuclear power plants and in outer space constructions [9]. Hardiman amplified operators strength by a factor of 25, so that lifting 25 kilograms was as easy as lifting one kilogram without the suit. Vukobratovic´ et al., proposed three lower-limb exoskeleton robots from 1969 to 1973 [10]. At the beginning of 1980, Rabischong developed a robotic upper limb orthotic device [11]. However, the real development of upper-limb exoskeleton robot was first appeared in 1990 and was developed in the University of Min-nesota with the objective of increasing the limb strength of the human [12], [13]. Kazerooni et al. set a key milestone by developing the second generation of exoskeleton robots with the concept of human robot interaction in the University of California, Berkeley [12], [13]. At the same instant Kanagawa Institute of Technology, Japan developed a power assist suit in order to assist human limb motions [14]. In 1994 Stanger et al. did a survey for robotics in rehabilitative human services and re-established the area of industrial research for exoskeletons [15]. A work on methods to provide force feedback to the human operator in the virtual environment was proposed by James C. Edwards et al., Iowa State University, Ames, IA, U.S.A. in 1997 [16]. This design is based on coupling the robotic exoskeleton with the human operator with the help of an electro-magnetic interface. During 1990s, Sankai et al. started studies on Hybrid Assistive Limb (HAL) [17]. After a lot of attempts for im-proving the design of HAL, finally designers gave a commercially available assistive suit for daily motion [18]. First active orthoses was developed by Rahman et al. in starting of 21st century [19]. Laura Gastaldi et al. gave a design, construction and experimental testing of an active gait orthosis intended to assist locomotion in paraplegic subjects in 2001 [20]. Jun Fujimori et al. worked on Teleoperation master arm system with gripping operation devices in 2001 [21]. Throughout the history many designs were proposed for enhancing the strength of physically disabled persons by rehabilitation, tele-operations and power assist-ment [22], [23], [24], [25], [26]. After 2004, the world entered into the third generation of exoskeletons with commercialized products. Many designs are now available commercially. ARMIN developed by Nef et al. in 2005 is now available for practical application as up-per limb rehabilitation [27], [28]. Hydraulic master–slave land mine clearance robot hand controlled by pulse modulation was designed by R Yuasa et al. in 2005 [29]. Wolbrecht et al. proposed a pioneer work in robot assisted neuro-rehabilitation [30]. NRS Costa et al. designed a biomimetic “soft-actuated” lower body 10 DOF exoskeleton system for patients with brain/spinal cord/sport injuries or stroke in 2006 [31]. Chen at el. designed hybrid con-trol of the pneumatic force-feedback systems for Arm-Exoskeleton by using on/off valve in 2007 [32] . During same period, Kiguchi et al. designed 3DOF intelligent artificial arm based on EMG signals of the user's remained active muscles [33]. Rotary series elastic actuators were used for exoskeleton robots in 2009 [34]. Articles covering full spectrum of the body (upper and lower limb including ankle) exoskeletons and design improvement in last decade are available [35]-[45]. Latest research work in this field on design solutions for the elbow module of a haptic arm exoskeleton used for remote control of robots in space was presented by Erwin-Christian et al. in 2017 [46]

II. CLASSIFICATION

Assistive robotic devices can broadly categorized in two parts: prosthesis and orthosis. Prosthesis is an arti-ficial substitute that one can wear in place of a missing body part. Orthosis is an orthopaedic apparatus that can be used to support and correct deformities of a person or to improve functionality of movable parts of the body [47]. Orthosis can further be divided into two categories: first one are devices designed for align end-effector with the users and second one designed for joint to joint alignment with the users known as exoskeleton. The former one is used for supporting at particular position and latter type of device is a wearable mobile machine which is worn by controller for enhancing the strength and having direct correspondence with the human joints and limbs [4] . Exoskeleton give a major breakthrough to assist the physically challenged persons. Exoskeleton devices can be classified on the basis of usages, type of human robot interaction, types of actuators, power transmission methods, control methods and point of application. Brief classification of it given in Table I.

Table I
CLASSIFICATION OF EXOSKELETON ROBOTS.

Exoskeleton robots

Usages : (a) Rehabilitation (b) Power assist (c) Human power augmentation and (d) Haptic interaction.
Human-Robot interaction : (a) PHRI- physical human robot interaction (b) CHRI- cognitive human robot interaction
Actuators : (a) Electric motor actuator (b) Pneumatic actuator (c) Hydraulic actuator and (d) Ultrasonic actuator
Power transmission methods : (a) Gear drive (b) Belt drive (c) Cable/wire drive and (d) Linkages
Control methods : (a) Impedance control (b) Fuzy-Nuero control (c) Force control
Point of application : (a) Upper limb (b) Lower limb (c) Ankle

Kazuo Kiguchi et al. [4] categorised exoskeleton ro-bots in four categories according to actuators used in their hardware systems as

(a) Type A - Electric actuation
(b) Type B - Hydraulic actuation
(c) Type C - Pneumatic actuation
(d) Type D - Other type of actuation

Majority of the devices use electric motors for actu-ation purposes. Figure 2 provides comparison for usage of actuation methods for upper limb exoskeleton sys-tems.

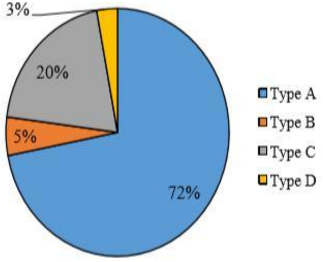

Figure 2. Usage of actuation method for upper limb exoskeleton systems [4].

Similarly Figure 3 shows comparison for usages power transmission methods for upper limb exoskeleton robots. Motor based cable and gear drives are most preferred transmission system in majority of devices.

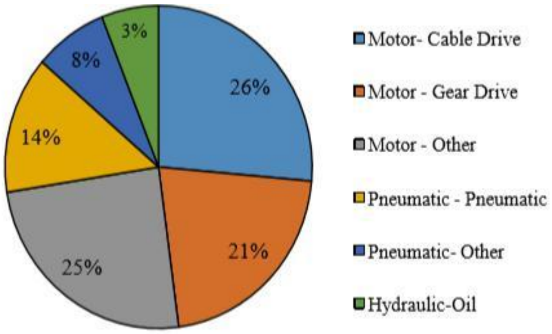

Figure 3. Usage of power transmission method for upper limb exoskeleton systems [4].

III. KINETOSTATIC ANALYSIS

Fundamental kinematics of upper limb and hand mechanism is discussed here. Section contains basic linkage diagrams and fundamental equations. Analysis of the mechanical design of the robots is a crucial element in the construction of an effective exoskeleton robotic system.

A. Kinematics of upper limb

An upper limb includes the upper arm and forearm. The upper arm in is pictured from the glenohumeral (GH) joint S to the elbow joint E, and the forearm extends from the elbow joint E to the middle of the palm of the hand H. The segmental lengths of the upper arm and the forearm are rSE and rEH, respectively [48]. The hand is usually held in a neutral position during forearm movements. Therefore, the gravitational variation due to the wrist motion is negligible. Hence, the upper limb can be modelled as a two-link linkage. Positions of the centres of mass, Mu and Mf. The kinematic model for the arm linkage is shown in Figure 4, and the GH joint in the human skeleton, which connects the scapular and the humerus, was modelled using a 3-DOF ball joint at point S. where r_u and r_f are the mass centre position vectors of m_u and m_f referenced for each corresponding CS, and the quantities $r_{u;x}$,$r_{u;y}$,$r_{u;z}$,$r_{f;x}$,$r_{f;y}$ and $r_{f;z}$ are the corresponding local coordinates. For CS 0, the quantities $r_{u;z}$ and $r_{f;z}$ are zero. The total gravitational potential energy of an objective model of free-weight exercise can be formulated as

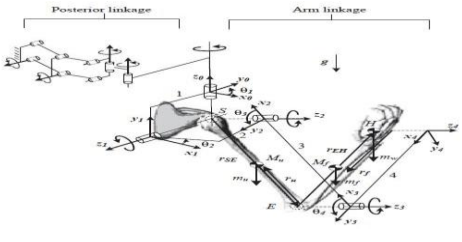

Figure 4. Kinematic model and coordinate system of right upper limb [48].

$$v_g = [\ m_u g(r_{SE} \quad r_{u;x}) \quad (m_f + m_w)gr_{SE}] \sin {}_2 \cos {}_3 [m_f\, g(r_{EH}\, r_{f;x}) + m_w gr_{EH}\ ] \sin {}_2 \cos({}_3 + {}_4)$$

The gravitational joint torque ${}_i$ on the joint i is calculated as

$${}_i = \frac{@\ v}{@\ {}_i} \qquad i=1,2,3,4$$

Above equations and modal design was proposed by Tzong-Ming Wu et al. in 2011[48].

B. Kinematics of human hand

In the past years, the interest has shifted towards hand exoskeleton devices, coming from both the academic and the industrial world. A basic model is shown in Figure 5.

A revolute joint at point E, which provides only elbow flexion-extension. Four Cartesian coordinate systems (CSs), CS 1, 2, 3, and 4, were attached to each link, and CS 0 was attached to the ground. The link parameters established between links i and i-1 are described based on the definition of D-H (Denavit-Hertenberg) notation [48]. An external load m_w grasped in the middle of the palm H. m_u and m_f are masses of upper and forearm respectively. According to Tzong-Ming Wu et al. [48] the gravitational potential energy can be expressed as

$V_g = m_u g(r_{SE} + r_u)\ m_f\ g(r_{SE} + r_{EH} + r_f\ )\ m_w g(r_{SE} + r_{EH}\ )$

$= m_u(\ gk_{\boldsymbol{0}})(\ r_{SE}i_{\boldsymbol{3}} + r_{u;x}i_{\boldsymbol{3}})\ m_f\ (\ gk_{\boldsymbol{0}})\ (\ r_{SE}i_{\boldsymbol{3}}\ r_{EH}\ i_{\boldsymbol{4}} + r_{f;x}i_{\boldsymbol{4}})$
$m_w(\ gk_{\boldsymbol{0}})*\ (\ r_{SE}i_{\boldsymbol{3}}\ r_{EH}\ i_{\boldsymbol{4}})$

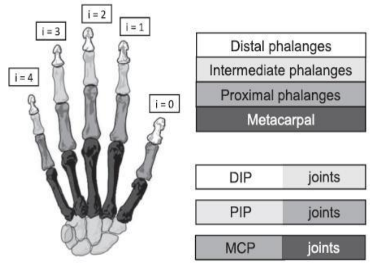

Figure 5. "Schematic of the human hand" [49].

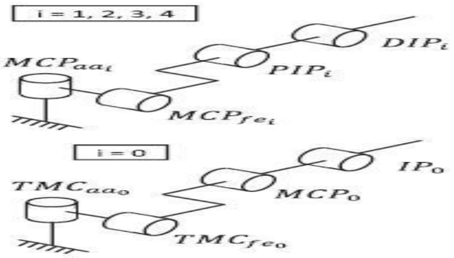

Figure 6. Kinematic model of human hand [49].

is 1-DOF remote-center mechanism and second one is 2-DOF serial chain mechanism [49]. Angular displacement and position can be understood with Figure 7.

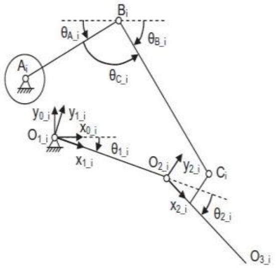

Figure 7. Scheme of the i-th single-finger module [49].

Figure 7 shows the planar structure of the i-th module of a single finger: the gripper part, namely segments $O_{\boldsymbol{1}\ i}$, $O_{\boldsymbol{2}\ i}$ and $O_{\boldsymbol{3}\ i}$, includes elements $A_iB_i$and B_iC_i. A pulley placed at point A_i. A fixed coordinate system $x_{\boldsymbol{0}\ i}y_{\boldsymbol{0}\ i}$ is placed at

i=0 represents the thumb and the four fingers are labelled as i going from 1 to 4. The kinematic model of human hand is presented into Figure 6. (TMCaa) used for trapezio meta carpal abduction /adduction , (TMCfe) for flexion/extension, (MCP) for metacarpophalangeal joint, (IP) interphalangeal joint, (PIP) proximal interphalangeal, (DIP) distal interphalan-geal joints and (ROM) for range of motion. Alessandro Battezzato proposed two different models for finger firs

point $O_{\boldsymbol{1}\ i}$, and it also sets a reference horizontal direction, necessary to define many rotation angles. The coordinate system $x_{\boldsymbol{1}\ i}y_{\boldsymbol{1}\ i}$ is linked to the bar $O_{\boldsymbol{1}\ i}\ O_{\boldsymbol{2}\ i}$, obtained from $x_{\boldsymbol{0}\ i}y_{\boldsymbol{0}\ i}$ through a $_{\boldsymbol{2}\ i}$ rotation. Similarly, a $_{\boldsymbol{2}\ i}$ rotation angle leads to the coordinate system $x_{\boldsymbol{2}\ i}y_{\boldsymbol{2}\ i}$, linked to the $O_{\boldsymbol{2}\ i}O_{\boldsymbol{3}\ i}$ bar. The bar A_iB_i rotates with respect to the $x_{\boldsymbol{0}\ i}$ direction of the $_{A\ i}$ angle, while the $_{B\ i}$ angle quantise the rotation of the bar B_iC_i. Finally $_{C\ i}$ is the supplementary angle of the sum ($_{A\ i}$ + $_{B\ i}$) [49].

The closed-loop position equation is

$PO_{\boldsymbol{1}\ i}O_{\boldsymbol{2}\ i} + PO_{\boldsymbol{2}\ i}C_i - PO_{\boldsymbol{1}\ i}A_i = PA_iB_i + PB_iC_i$ and the other angles can be calculated as

$$(\qquad = \cos^{\boldsymbol{1}}\left(\frac{{}^{l}A^{\boldsymbol{2}}{}_{i}B_{i}\ {}^{+l}B^{\boldsymbol{2}}{}_{i}C_{i}\quad {}^{l}A^{\boldsymbol{2}}{}_{i}C_{i}}{{}^{2l}A_{i}B_{i}\ {}^{l}B_{i}C_{i}}\right)$$

$$i$$

$$\boldsymbol{1}\ \frac{{}^{l}A^{\boldsymbol{2}}{}_{i}C_{i}\ {}^{+l}B^{\boldsymbol{2}}{}_{i}C_{i}\quad {}^{l}A^{\boldsymbol{2}}{}_{i}B_{i}}{} \qquad \boldsymbol{1}\ \frac{{}^{p}A_{i}\ C_{i}Y}{{}^{p}A_{i}\ C_{i}\ X}$$

$${}_{B\ i} = \cos \qquad {}^{2l}A_{i}C_{i}\ {}^{l}B_{i}C_{i} \qquad)\ \tan$$

$$A\ i^{=} \qquad C\ i \quad B\ i$$

IV. CONTROL SYSTEMS

Control system of exoskeleton robot is mainly a com-bination of two controllers : robot controller and human brain. Both controllers work parallel to each other. Correlation between robot controller and human motion intention is major key point for success of any control system. Identifying the exact human motion intention is still under at research level. Therefore, understanding and optimizing the best control method is difficult.

A simple and effective control system easily enhances the reliability accuracy and popularity of any machine. Many control strategies were developed in last few decades to make the system easier. Overview on some of them is given here.

A. Position-based tracking control

In position-based tracking control strategy the device was first passively attached to the limb to record the stepping kinematics during manual assistance. The recorded kinematics was then replayed to gener-ate a participant-specific stepping trajectory by using proportional-derivative (PD) controller. This method is able to reproduce the gait patterns in high accuracy with the subject's stepping trajectory with slight alterations only. Major complexity in this method is generation of proper trajectory. Emken et al. proposed a trajectory generation method by using teach-and-replay technique with the ambulation-assisting robot ARTHuR [50]. Block diagram of position based tracking control is shown in Figure 8.

A new technology Complementary Limb Motion Es-timation (CLME) for online trajectory generation has been proposed by designer of LOPES gait rehabilitation robot [51]. In this study, the reference motion for the affected leg was generated based on the movements of the other unimpaired leg by adopting instantaneous mapping between them.

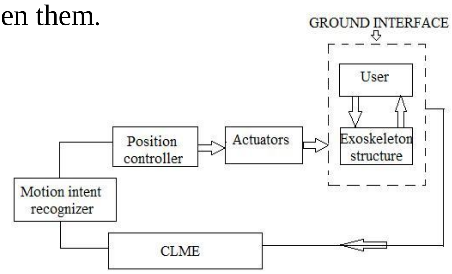

Figure 8. Block diagram of position based tracking control.

B. Force and impedance control

Force control/hybrid position: This method can be adopted for strengthening exercises. Ju et al. designed a hybrid position and force controller which can guide the patient move along a linear or circular trajectory and maintain a constant contact force [51]. Since the system may become unstable in this direct addition con-trol scheme, Simon et al. from University of Michigan introduced a novel method for controlling the interaction force during lower limb extensions [53]. The purpose of this study is to provide the target resistance force to the impaired limb for improving force symmetry in the limbs. The established haptic interface was used to read the foot position and orientation and then exert resistive forces for lower-extremity training with an interactive virtual environment (VE) simulation [54]. A distinct advantage of such hybrid position/force strategy is that it enhances the involvement of patient in control system.

However, such control strategies only allow the par-ticipant to exert certain resistance force along a fixed trajectory and do not allow voluntary active movements of the patient. Structure of force control system is represented in Figure 9.

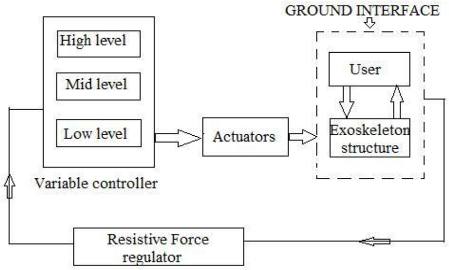

Figure 9. Structure of force/impedance control system.

participation and allow patient's natural variability, real-time adjustment of desired dynamic relationship between robot position and contact force. MIT-Manus utilized impedance model to adjust the robot compliance [55]. Lokomat also used impedance controller to regulate the patient's gait speed and traction force for each leg [56].

Impedance control also have some problems such as parameters should not be always fixed and patient's movement ability is changing over time, the impedance parameters have to be re-selected to match patients' capabilities and progress.

C. Bio-signal based control

Bio-signals contain more accurate and sound inform-ation about human limb movements. It enables the robot to be controlled in a more natural way by using EMG (Electromyographic) signals recorded from participant's muscles. It has been found that a considerable cor-relation exists between EMG signals, limb movement, and muscle activities. EMG signals are generated before limb muscle contraction, so it can be used to predict the movement intention in advance [57]. Krebs et al. [58] proposed a performance-based progressive robot control mode, which allowed the patient to move the limb without assistance first, and when the EMG value reached a certain threshold, the robot assistance would be triggered. Kiguchi et al. [59] designed an advanced neuro-fuzzy controller to identify the movement pattern of the forearm by using EMG signals.

Although EMG control encourages self-initiated movement by patients, but, when the robot is driven to provide assistance after being triggered, typically passive training will be performed in EMG control to achieve the necessary movement, so the patient is not in a fully com-pliant environment when assistance is provided. Figure 10 represents the Bio-signal based control strategy.

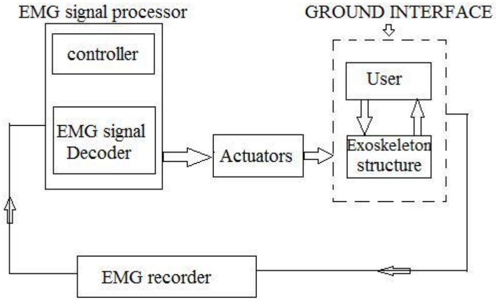

Figure 10. Bio-signal/EMG signal based

2) Impedance control: Impedance control strategy is control system one of the most appropriate approaches to increase active

D. Adaptive control strategies

Adaptive impedance control provides better rehabilit-ation effects by making the robot's behaviour more flex-ible and adjustable to the patient's capabilities, progress, and participation. In this strategies movement capability of patient can be estimated from contact force/torque, quantitative efforts, or trajectory tracking errors. By using adaptive controller, the robot assistance force can be adjusted according to patient's physical movement ability. The adaptive impedance controller applied to adjust the robot assistance according to human contact force, in which the robot assistance was reduced when patient's active force increased, and vice versa [54]. This study is supposed to be inspired by the ''patient-cooperative'' strategy proposed by Riener et al. [60]. This is in fact an adaptive impedance controller that utilizes the patient's contact force information to adapt the robotic assistance and impedance level.

E. Adaptive control strategies

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An important advantage of the EMG control is that the robot can be controlled in a more natural way using his/her own muscles. Unfortunately, it is found that only a few studies have introduced EMG signals into the whole robot control life cycle.

V. DISCUSSION AND CONCLUSION

A review on development of exoskeleton is presented. Special consideration is given to the history, classific-ation and control strategies. Table I provide a broad classification of exoskeleton. Some basic design model and equations are also presented in the paper. Robot-assisted limb rehabilitation has a variety of advantages over traditional manual therapy and training, and shows encouraging clinical outcomes and recovery efficiency. As for the control strategies, impedance control becomes more and more popular in the control of limb exoskel-etons and platforms and EMG signals have also been widely used to estimate the human intention prior to the system control.

Although most exiting rehabilitation robots are able to provide systematic and prolonged treatment and train-ing sessions, there are drawbacks associated with their designs.

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