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A Review Study on the Design of an Exoskeleton Robot

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Abstract: *Exoskeleton devices have a wide range of therapeutic and assistive utilities in life and they can provide essential support for limb movements with increased strength and endurance. This paper is presented to review the development of different approaches in controller design, actuation method, and transmission for exoskeletons. Here, the coupled nonlinear dynamics of the user and exoskeleton are a significant factor in developing and realizing effective control algorithms. So, after a short review of dynamic modeling of an exoskeleton, the application of some common controllers is provided. Also, due to the direct interaction of the user's body, it is necessary to utilize appropriate and convenient hardware components. In addition, a suitable combination of actuator and transmission systems can noticeably improve the performance, precision, and functionality of the robot. This review is represented to aid researchers in the fields of robotic therapy and exoskeleton devices in ascertaining their design process.*

Keyword*: Exoskeleton; Control system; Actuator; Transmission.*

I. Introduction

The patients with neurological disorders caused by diseases or injuries, in addition to the elderly, may have a lack of control, muscle weakness, and other kinds of disabilities [1]. Lower and upper limb dysfunction is a common complication in these people. They might experience different probable effects, like insufficient force/torque at the hip joints, unnatural gait patterns, and poor quality of life. Such impairments may limit an individual's independence in performing activities of daily living and cause them to face limitations in social participation, mobility, and self-care [2-4]. The application of rehabilitation robotic systems has become one of the most promising approaches to assist individuals with disabilities.

Robot-assisted therapy is an innovative kind of physical therapy using different kinds of robotic devices. These robots are capable of enabling the implementation of intensive, repeatable, accurate, quantifiable and patient-tailored movement therapy, and physical training [5-7]. The exoskeleton is a type of rehabilitation robotic system, which can be worn by the users and is connected to them at multiple points. The joints of the robot have a one-to-one correspondence with the human joints, and each joint is guided along a designed trajectory [8, 9]. Due to their capacity to provide precise and adaptive movement assistance, exoskeletons have demonstrated extensive feasibility and clinical potential in assisting the physical therapeutic process [10, 11]. These robots can be developed for medical and/or non-medical applications. Medical applications focus on gait recovery, motor performance, and rehabilitation therapy for the elderly, patients with a stroke and spinal cord injury, and other related diseases or injuries that could have muscle weakness [12, 13]. On the other hand, non-medical applications focus on haptic interfaces or providing additional strength for more demanding tasks. It can be used on human performance augmentation, improving the physical abilities of individuals during walking, and manual handling of heavy goods [14, 15].

The resulting diversity between the different exoskeletons can be illustrated by the elaborate overviews on the control algorithm, how the user intention is detected and intention detection systems they use, the actuation technology, and hardware components of the device [16, 17]. These choices have an impact on the overall robot performance, which includes: ease of adoption by the user, physical burden exerted on the user, required level of external assistance before and during operation, operating time, and eventually cost of the device. Accordingly, this paper is presented to review some commonly used methods in the software and hardware design of exoskeleton robots. In this review, first, the role of the control system in exoskeletons is studied and examples of common control algorithms are provided. Then, the function and examples of the commonly used actuator and transmission types are provided. Finally, this document is terminated with a discussion to commit an overview of the represented topics.

II. Controller design

To study the importance of the control system, an overview of the exoskeleton dynamic model is presented first.

1.1. Dynamic modeling

As is shown in Fig. 1, an exoskeleton robot either for upper or lower limb application can be generally considered with three links (l_1, l_2, l_3) and three joints (j_1, j_2, j_3).

Let's consider $M(q)$ as the mass matrix, $C(q, \dot{q})$ as the Coriolis's matrix, $g(q)$ as the gravity vector, and n as the DOF of the exoskeleton and the supported human-limb if exoskeleton is sufficiently rigid. Also the parameters q, $\dot{q}$, and $\ddot{q}$ represent the position, velocity, and acceleration vectors of the exoskeleton respectively. So then, based on the Lagrange dynamics method, the torque requirement for the exoskeleton as a vector τ_{exo} is given by equation (1).

$$M_{exo}(q).\ddot{q} + C_{exo}(q, \dot{q}).\dot{q} + g_{exo}(q) = \tau_{exo} \tag{1}$$

If we assume axes of human extremity are perfectly aligned with those of the exoskeleton, then q, $\dot{q}$, and $\ddot{q}$ vectors would be the same for human as well. Therefore, the required torque τ_h for human extremity is given by equation (2).

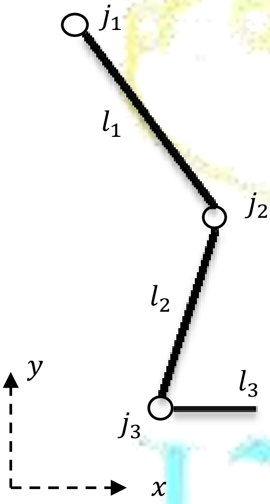
$$M_h(q).\ddot{q} + [C_h(q, \dot{q}) + B_{opt}]\dot{q} + g_h(q) + K_{opt}(q - q_o) - \tau_{opt} = \tau_h \tag{2}$$

where B_{opt} and K_{opt} represents the diagonal optional damping and stiffness matrix of the human, q_o is the most recent joint position, and τ_{opt} is the optional torque applied by the human. For complete assistance of the human limb by the exoskeleton, the net torque requirement τ_{exo+h} is given by equation (3) [18-20].

$$M_{exo+h}(q).\ddot{q} + [C_{exo+h}(q, \dot{q}) + B_{opt}]\dot{q} + g_{exo+h}(q) + K_{opt}(q - q_o) - \tau_{opt} = \tau_{exo+h} \tag{3}$$

1.2. Control system

As can be seen, the dynamics of human limbs and exoskeleton are not only nonlinear but uncertain as well. The assistance magnitude and duration and its onset timing are key factors for the control system, and the exoskeleton joint angles and torques shall be online modified according to the user's conditions. With s suitable control approach, the exoskeleton can generate the assistive torques as needed, and the joints of the human–exoskeleton system can share the same motions in a comfortable and safe mode [21]. Also, it is necessary to optimize the training paradigm so a user can receive beneficial treatments to improve mobility and musculoskeletal health. The essence of training paradigms is how the robots interact with the patients from signal perception to physical contact [22]. For designing a better application of the rehabilitation robot system, the training paradigms are classified according to several aspects that should be included in the control system. Some of these aspects refer to the user’s status during interaction and the properties of force applied to the limb [23, 24].



Link 1	Upper-arm/Thigh
Link 2	Forearm/Shin
Link 3	Hand/Foot
Joint 1	Shoulder/Hip
Joint 2	Elbow/Knee
Joint 3	Wrist/Ankle

Figure 1: A general scheme of an exoskeleton robot

The adaptive control method is widely used for exoskeletons due to its robustness and accurate tracking errors even in the presence of model uncertainties and changes in the dynamics of the exoskeleton. To provide forearm movement assistance, a fuzzy-based adaptive back-stepping control method is developed for an exoskeleton in [25]. A nonlinear adaptive controller is used as a backlash compensation in [26] to improve the accuracy in position tracking by compensating for time-varying backlash hysteresis and continuously updating the model parameters. Adaptive estimators are used in [27, 28] to compensate for the disturbance torques caused by input nonlinearities of an exoskeleton. Adaptive position/force control can be used to dynamically identify the robot's nonlinear features and to enable the movement intention-directed trajectory adaptation [29, 30]. An adaptive integral terminal sliding mode controller is designed in [31] to guarantee trajectory tracking accuracy of exoskeleton when assisting disabled patients to execute arm rehabilitation training. To support the individuals with a disability to perform repetitive rehabilitation training, a neural-fuzzy adaptive control algorithm is proposed in [32] for trajectory tracking control with parametric uncertainties and environmental disturbances for arm movement assistance.

Assistive or assist-as-needed (AAN) refers to control methods based on assisting the user only as much as needed to successfully perform a specific task. It enables the user with consistent effort and active involvement by providing minimal robotic assistance for completing the task execution [33-35]. In the design of AAN strategies, the patient's strength is somehow evaluated, e.g. by using a gameplay interface, and the required amount of assistance is determined accordingly [36, 37]. AAN can boost the voluntary participation of the user by assisting according to the ability of the wearer in performing the assigned task. In [38], an adaptive torque controller based on a generalized fuzzy model was integrated into the control loop of an exoskeleton to ensure that the assistance is accurately supplied to the user.

One way to modulate the assistance provided by the robotic device is to modify the mechanical impedance generated by the exoskeleton. The impedance control is a strategy that can realize compliant behavior in the robotic manipulators, where the impedance is defined as any dynamic operator that outputs a force/torque from a linear/angular position or velocity input [35, 39]. One impedance control to be considered is the impedance control based on joint space formulation which avoids problems that might arise from inverse dynamics calculations. An alternative option to a joint space is an end-point space formulation, in which the reference trajectory is defined according to an anatomical landmark around an end-point [40-42]. This method has been used for a lower limb exoskeleton to control the magnitude and direction of the forces required in task trajectories [42] and to assist in walking and maintain walking stability was developed in [43]. In [44], the integral impedance shaping algorithm is designed to obtain a desired shape for the frequency response magnitude and achieve the desired dynamic response. To obtain the optimal stiffness parameters of the impedance controller, a model predictive control method is designed in [45] so it can maximize the patient's active participation by increasing their joint torques.

III. Hardware system

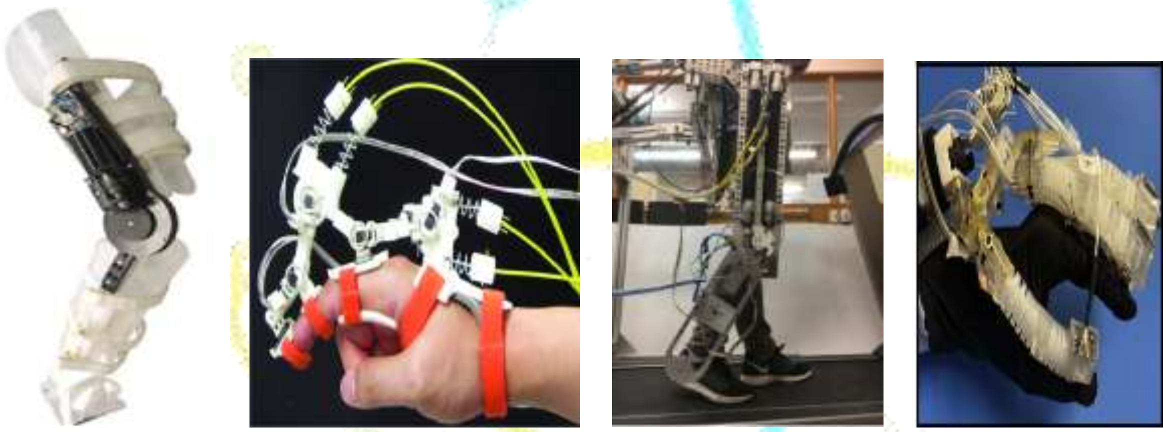
Analysis of the hardware system of the robot is an important step in the fabrication of an exoskeleton system. For designs that focus on the hardware parts, they may work on the safety issues of the mechanism and the portability or flexibility of devices. Some special matters like the function and application of the robot need to be paid attention to. For example, in a hand exoskeleton, safety becomes more essential because any mechanical problems would do serious harm to the human hands and fingers. Or, a clinical device can be used for the rehabilitation process at the clinic with a reduced active workload for the professional caregiver [46]. The combination of actuator and transmission is a major part of hardware design of exoskeletons.

1.3. Actuator types

The actuation system plays a significant role during the development of an exoskeleton robot because it generally affects the portability, output speed and force/torque, and efficiency of the device. According to studies, electrical and pneumatic motors have represented more application in exoskeletons.

Electrical motor: The electrical motor has widely been used in the design of exoskeletons, due to its advantages such as availability, fast operations using high-speed motors, precision, and higher controllability using advanced motion control. For assistance applications, the lower torque-to-speed ratios of electrical motors need to be reduced to coincide with the higher ratio demands for human movement. As a result, gearheads are added to reduce the high speeds, adding backlash, and reducing the inherent back-drivability of the device [47]. The series elastic actuator (SEA) is generally composed of an electric motor, a compliant element, a drive, and a type of transmission. SEAs have the advantages of low intrinsic output impedance, high force fidelity and back-drivability, good force control bandwidth, a low-pass filter, natural torque sensor and the possibility of energy storage, and the capability of storing energy in the flexible elements [48, 49]. Compliant elements such as springs can be implemented into the actuators to reduce the total mechanical impedance. SEA can measure external torques directly, employing a torsional spring coupled directly to the user's joint, in series with the joint actuator. In such systems, the instantaneous external joint torque is obtained from the product of the SEA’s torsional spring deformation and the known spring constant [50]. SEA can be used in exoskeletons to assist hip flexion and extension movements of individuals with heavy-duty tasks or to reduce the metabolic cost of healthy individuals during walking [48].

Pneumatic motor: This motor mainly contains a rubber tube and two closed ends. One end is usually connected to a valve to regulate the pressure inside the motor, while the other exerts an axial-direction contractile force. This actuator has advantages such as fewer requirements of maintenance, inherent compliance, and safety features and can be stopped under a load without causing damages. The pneumatic muscle actuators are intrinsically compliant, lightweight, act similar to natural muscles with high power-to-weight ratios [51, 52]. The disadvantages of pneumatic actuation are noise, size, and lower accuracy because the actuators are difficult to control for their time variability and nonlinear nature. To solve the nonlinear characteristics during operation, an adaptive back-stepping sliding mode control [53] and an iterative feedback tuning control scheme [54, 55] were designed to estimate the external disturbance and to tackle the human-exoskeleton uncertainties in rehabilitation. Antagonistic configuration can provide bidirectional assistance to the patient’s joints. One pneumatic motor antagonistic pair consists of two motors connected through a cable and a pulley. By regulating the pressure inside each motor, the configuration can provide one rotational DOF assistance and increase the torque and motion range of the joint. This configuration is used in the shoulder [56] and knee [57] exoskeletons to help patients to complete the assigned movement tasks. Due to the high stiffness output and low inertia force, parallel pneumatic motors are designed to achieve multi-DOF motion from one actuating joint. This configuration has been used in ankle [58], knee [59], and waist [60] exoskeletons for multi-DOF joint recovery. Fig. 2 shows examples of exoskeleton robots actuated by electrical and/or pneumatic motors.



(a) (b) (c) (d)

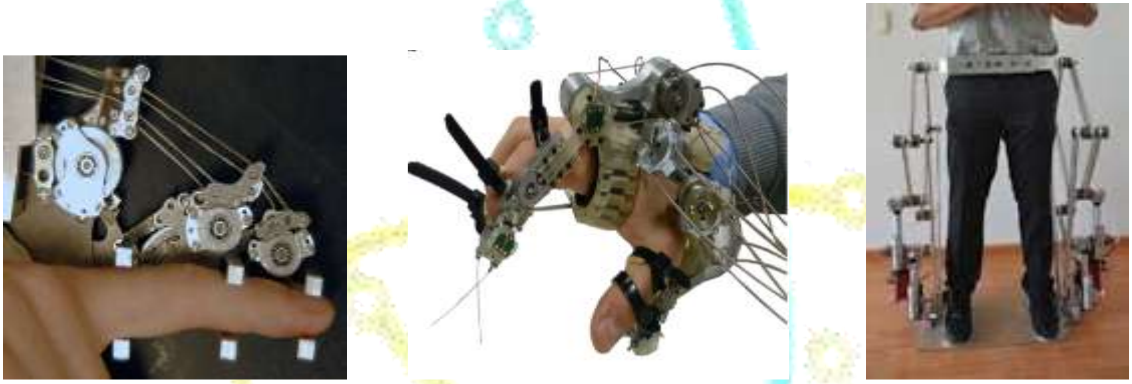
Figure 2: Examples of the use of electrical motor in (a) lower limb [49] and (b) upper limb [61]; and pneumatic motor in (c) lower limb [57] and (d) upper limb [51] exoskeletons

Functional electrical stimulation: This technology has recently been used to assist users in producing physical movements, the recovery of motor functions, and to facilitate the individual's muscle contraction training. Muscle contractions can be orchestrated to produce coordinated grasp movement, thumb positioning, wrist extension/flexion, forearm pronation, and elbow extension for patients with spinal cord injury [62, 63]. Functional electrical stimulation (FES) improves the plasticity of the cerebral cortex and can be easily performed by therapists because it does not require extensive manual operations [64]. Recently, the modular organization of multiple muscle activations has led to the formulation of synergy-based FES strategies. This approach provides a feasible solution for multi-channel FES control using residual muscle activities from the patient [65]. In these systems, FES can selectively administer therapeutic feedback responses only when the correct brain signals are detected [66, 67]. A study on a traumatic spinal cord injury patient revealed the role of FES in performing coordinated reaching and grasping movements using his own paralyzed arm and hand [68]. FES therapy targeting the extension of the affected limb can be effective in enhancing reduction in vertical subluxation, improve shoulder flexion and abduction, and hand functional recovery of stroke patients [69, 70].

1.4. Transmission

The transmission method to be used is mostly a consequence of the choices of the actuator. For example, along with electric motors, transmission may include gear drives, cable drives, belt drives, or ball screws. In pneumatic motors, pneumatic piston and cylinder or cable drives are used for transmission. Also, transmission methods for hydraulic and hybrid actuators vary according to the application [71].

The cable is widely used as the transmission method in exoskeletons, including the pulley cable and Bowden cable. Pulley cable systems are spatially constrained and require a continuous control of cable tension to maintain traction on the pulleys, which limits the use [72, 73]. On the other hand, Bowden cable systems have the advantages of simplicity, dexterity, and essentially flexibility, but introduce variable and high friction forces dependent on curvature. This cable can be used to transmit remote mechanical power through the narrow tortuous space by the relative motion between the inner cable and outer hollow sheath. The driving torque from the motor can be transmitted to the exoskeleton joint via the inner cables attached to the proximal and distal grooved pulleys [32]. An antagonistic pair of Bowden cables are used in [74] coupled with SEA, to effect flexion and extension movements of the exoskeleton. This cable consists of a proximal stage, extending from the actuator to a coupling module worn on the upper arm, and a distal stage, which directly drives each of the exoskeleton joints. Fluidic transmissions are generally more efficient for larger channel diameters and can provide a more efficient alternative compared to a similar cable mechanism [75]. In comparison with hydraulics, a pneumatic transmission can offer faster responses due to the use of low-viscosity fluids [76]. The linkages are light, convenient, and can be easily controlled in a generated trajectory. On the one hand, the problem of coincidence of the rotational axis can be solved by using the cross-joint structure. Also, the complexity of the device can be reduced by using the linkage structure [77]. Fig. 3 shows exoskeletons equipped by Bowden cable and/or linkage.



(a) (b) (c)

Figure 3: The use of (a) pulley cable [78], (b) Bowden cable [74], and (c) linkage [77] for an exoskeleton robot

IV. Discussion

The first step in designing an exoskeleton robot is to determine its application, whether this is for a therapeutic or assistance application. Each of these applications requires special adjustments in the control system parameters and a different trajectory and training paradigm. The control system may focus on error convergence in trajectory tracking or may utilize an observer for disturbance rejection. In addition, the choices of actuator and transmission can have a noticeable impact on the functionality, safety, and performance of the device. In this paper, the function and application of different common approaches in controller design, actuation method, and transmission for exoskeletons were studied to assist researchers in establishing their schemes and design procedure. Future work in this area is to evaluate and compare the clinical results for different types of exoskeletons.

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