Research on Strategies and Methods for Improving the Efficiency of Exoskeleton Servo Drives

ZHANG Nan
(Beijing Haizhi Automation Co., Ltd., Beijing 100095,China)

Abstract:Exoskeleton robots, as key assistive devices for human motion, hold broad application prospects in fields such as medical rehabilitation, industrial production, and military logistics. However, exoskeleton systems powered by electric motors are limited by battery capacity, making insufficient endurance a critical bottleneck hindering their practical implementation. As the core component responsible for energy conversion and motion control, the efficiency of servo drives directly determines the overall system energy efficiency. This paper systematically reviews the physical mechanisms behind energy losses in exoskeleton servo drives, identifying switching losses, copper and iron losses, mechanical transmission losses, and braking energy consumption as the primary sources of inefficiency. Based on this analysis, a comprehensive technical framework for improving efficiency is established from four dimensions: modulation strategy optimization, motor design, transmission system matching, and energy recovery management. The study particularly examines the effectiveness of discontinuous pulse width modulation (DPWM) in reducing switching losses under heavy-load conditions, evaluates the advantages and limitations of serial elastic actuators (SEA), parallel elastic actuators (PEA), clutch elastic actuators (CEA), and quasi-direct drive (QDD) technologies in terms of energy recycling and low-impedance transmission, and proposes an adaptive energy-efficiency management architecture based on digital twin technology. Results show that coordinated multi-strategy optimization can improve drive efficiency by 10% - 15% and extend system endurance by over 20%. This work provides theoretical foundations and technical references for designing high-efficiency exoskeleton servo drive systems.

Key words:Exoskeleton; servo driver; efficiency enhancement; discontinuous pulse width modulation; compliant actuation; energy recovery; quasi-direct drive

1 INTRODUCTION

1.1 Research Background

An exoskeleton robot is a mechatronic system worn externally on the human body that enhances or assists limb movement. Since General Electric of the United States developed the first powered exoskeleton, Hardiman, in the 1960s, over half a century of development has transformed exoskeleton technology from science fiction into engineering reality. Today, exoskeletons are helping spinal cord injury patients stand and walk again in medical rehabilitation, reducing physical strain for industrial workers, and enhancing individual load-carrying capacity in military applications, demonstrating significant social value and economic potential.

Motor-driven systems are currently the mainstream power solution for exoskeletons, offering advantages such as high control precision, fast response speed, and clean, pollution-free operation. As the core electronic component of an exoskeleton system, the servo drive functions similarly to human joint tissues—precisely executing position, velocity, or current commands while also providing certain sensing capabilities to enable force feedback and flexible control. The performance of the servo drive directly affects the exoskeleton's motion accuracy, power output, and overall energy efficiency. However, energy supply remains the key bottleneck limiting the development of motor-driven exoskeletons. Typical lower-limb exoskeletons consume between 100 and 500 watts, whereas current high-energy-density lithium batteries offer specific energy of approximately 200 - 300 Wh/kg. This means just one kilogram of battery can support system operation for only 0.5 to 2 hours. For rehabilitation patients requiring continuous use or military personnel performing long-duration missions, this endurance falls far short of requirements. Simply increasing battery capacity leads to added weight and greater user burden. Therefore, before revolutionary breakthroughs in battery technology occur, improving the energy conversion efficiency of servo drive systems represents the most practical path toward extending exoskeleton operating time.[1,2]

1.2 Current Research Status at Home and Abroad

The efficiency of exoskeleton servo drive systems has recently attracted extensive attention from both academia and industry. Research in this area has primarily developed along the following directions.

At the modulation strategy level, Ma Yu et al. conducted a systematic comparison of pulse width modulation (PWM) strategies for permanent magnet synchronous motors, proposing an efficiency-optimized control strategy based on discontinuous PWM (DPWM). By keeping the switching devices inactive within specific sectors, this method reduces switching losses. Experimental results show a significant improvement in driver efficiency under heavy load conditions. This approach effectively taps into the energy-saving potential of inverters without increasing hardware costs.

At the motor level, high-torque-density motors have become a research focus for exoskeleton applications. Studies on permanent magnet synchronous motors (PMSMs) with various topologies concentrate on improving torque density, suppressing torque ripple, enhancing efficiency, and optimizing thermal management to refine motor performance. PMSMs and brushless DC motors (BLDCs) are currently the mainstream choices, while emerging topologies such as axial flux motors and reluctance motors show potential to surpass the torque density limits of conventional radial flux motors.

At the transmission configuration level, Laschowski and McPhee systematically reviewed two energy-efficiency design principles: series elastic actuation (SEA) and high backdrivability. They pointed out that negative work phases exist in human gait, which can be exploited by storing and recovering energy through elastic elements, thereby reducing peak motor power and overall energy consumption. Meanwhile, a quasi-direct drive (QDD) approach combining high-torque-density motors with low gear reduction ratios enables energy regeneration while maintaining backdrivability. Related elastic actuation technologies also include parallel elastic actuators (PEAs) and clutch-based elastic actuators (CEAs). The former stores and releases energy by connecting an elastic element in parallel with the drive component, while the latter uses a clutch mechanism to control the engagement or disengagement of the elastic element, enabling energy storage or release during specific time intervals, thus significantly improving energy efficiency. [3]

At the system level, the integration of digital twin technology with intelligent control algorithms has been explored to optimize exoskeleton energy efficiency. Real-time monitoring and adaptive adjustment of control parameters can substantially enhance system energy efficiency. Additionally, the selection of servo drives for exoskeletons must comprehensively consider multiple constraints including reliability, power consumption, heat dissipation, size, and cost.

2 Analysis of Energy Loss Mechanisms in Servo Drives

2.1 Drive system architecture and loss distribution

A typical exoskeleton servo drive system consists of a battery, inverter, permanent magnet synchronous motor, reducer, and controller. Energy flows from the battery to the inverter, where it is modulated by power switching devices to drive the motor rotation. The motor's output torque is then amplified by the reducer and transmitted to the joint. Along this energy transmission chain, each component incurs losses to varying degrees.

Losses in the inverter stage mainly consist of switching losses and conduction losses. Switching losses occur due to voltage-current overlap during the transient turn-on and turn-off processes of power devices (IGBTs or MOSFETs), and their magnitude depends on switching frequency, bus voltage, conduction current, and the device's inherent turn-on/turn-off times. Conduction losses arise from the product of saturation voltage drop and current when the device is conducting, becoming particularly significant under heavy load conditions.

Losses in the motor stage include copper losses (resistive heating in stator windings), iron losses (hysteresis and eddy current losses in the core), mechanical losses (bearing friction and aerodynamic drag), and stray losses. Copper losses are proportional to the square of the current, while iron losses are proportional to the square of both frequency and flux density; together, these two constitute the major portion of motor losses.

Losses in the transmission stage result from gear meshing friction, bearing friction, and viscous damping due to lubrication. Exoskeletons traditionally employ high-reduction-ratio motor-transmission systems, but such designs fail to fully exploit the passive dynamic characteristics of the human body, leading to low efficiency and requiring larger battery capacity. Harmonic drives can achieve efficiencies of 80% – 85%, although performance drops further under high-speed, heavy-load conditions.

Additionally, in braking or deceleration phases, conventional systems dissipate kinetic energy as heat through braking resistors, representing a form of hidden energy waste. If this energy could be recovered, system efficiency would significantly improve. Research indicates that negative joint mechanical work occurs during walking, and harnessing these periods for energy recovery can enhance overall efficiency.[4]

2.2 Mathematical representation of losses

Inverter switching losses can be approximately expressed as:

$$Psw=12VdcIL(ton+toff)fsw$$

Here, Vdc is the bus voltage, IL is the load current, ton and toff are the turn-on and turn-off times of the switching device, and fsw is the switching frequency. As shown in the equation, switching loss is directly proportional to the switching frequency; reducing the switching frequency linearly decreases the loss, but results in increased current ripple and degraded THD.

The copper loss and iron loss of the motor are represented as:

$$Pcu=3Is2Rs \quad (1)$$

$$Pfe = khfB\alpha + kef2B2 \quad (2)$$

where Is is the stator phase current, Rs is the phase resistance, kh and ke are the hysteresis and eddy current loss coefficients, respectively, f is the magnetic field alternating frequency, B is the flux density, and α is the Steinmetz constant (typically 1.5 – 2.5).

The transmission system efficiency can be modeled as:

$$\eta_{gear} = T_{out}\omega_{out} / T_{in}\omega_{in} = T_{out} / T_{in} \times i \approx 1 - P_{loss,gear} \quad (3)$$

where i is the gear ratio, and $P_{loss,gear}$ is the power loss due to gear meshing and bearing friction.

The overall system efficiency is the product of the efficiencies of each component:

$$\eta_{sys} = \eta_{inv} \times \eta_{motor} \times \eta_{gear} \quad (4)$$

Considering that exoskeletons operate under transient conditions involving frequent starts and stops and varying loads, steady-state efficiency metrics are insufficient to fully reflect actual energy performance. Therefore, an energy efficiency metric over a task cycle should be introduced:

$$\eta_{task} = \int P_{out}\,dt / \int P_{in}\,dt = E_{out} / E_{in} \quad (5)$$

2.3 Impact of Typical Operating Conditions on Exoskeleton Efficiency

The operating conditions of exoskeletons are characterized by distinct periodicity, impact, and asymmetry. Taking the gait cycle as an example, a single lower limb undergoes stance phase (approximately 60%) and swing phase (approximately 40%) within one gait cycle (about 1 - 1.5 seconds). The stance phase requires substantial joint torques (peak torques at hip and knee joints can reach 1 - 2 Nm/kg), while the swing phase demands much lower torque. This imbalance in torque requirements causes motors to operate under frequent acceleration and deceleration. As a result, there is a "mismatch" between the constant switching frequency of inverters and output power—switching losses become relatively more significant under light loads, leading to a notable drop in efficiency.

Moreover, negative work phases during human motion (such as energy absorption upon heel strike or braking during late swing) account for 15% - 25% of total energy expenditure. If this energy is simply dissipated through braking resistors, system efficiency is further reduced. Therefore, efficiency optimization for exoskeleton servo drives cannot simply follow the constant-load design approach used in industrial servo systems; instead, customized strategies must be developed to address their variable load, periodic nature, and inclusion of negative work。 [5-7]

3 Efficiency Optimization Based on Modulation Strategy

3.1 Switching Loss Analysis of Traditional SPWM and SVPWM

Sinusoidal Pulse Width Modulation (SPWM) and Space Vector Pulse Width Modulation (SVPWM) are the two most mature modulation strategies in industrial servo systems. SPWM generates switching signals by comparing a modulating wave with a carrier wave, offering simple implementation but low DC voltage utilization (only 0.866). In contrast, SVPWM synthesizes the target voltage vector, increasing the utilization of the DC bus to 1.0 and providing superior harmonic performance, making it widely used in AC motor drives.

However, in SVPWM, each phase leg of the three-phase bridge performs one switching action per switching cycle, resulting in a fixed number of six switches per cycle (two per phase). This means that even under light loads or when the motor is held stationary, switching losses remain relatively high. For applications such as exoskeletons, where load conditions vary dramatically, the "fixed switching" characteristic of SVPWM leads to poor efficiency at light loads.[8]

3.2 Principle and Implementation of Discontinuous Pulse Width Modulation (DPWM)

The core idea of discontinuous pulse width modulation (DPWM) is to clamp a certain phase to the positive or negative bus during specific intervals when the modulating wave amplitude approaches the extreme values of the DC bus voltage, thereby keeping the corresponding phase switch either permanently on or off within those intervals. This reduces the number of switching events and lowers switching losses.

The implementation of DPWM can adopt the zero-sequence component injection method. In traditional SVPWM, the zero-sequence component V_z is added to the three-phase modulation waves V_a^*, V_b^*, and V_c^*, resulting in the final modulation waves as follows: $V_a^{**}=V_a^*+V_z, V_b^{**}=V_b^*+V_z, V_c^{**}=V_c^*+V_z$ By adjusting the waveform of the zero-sequence component, switching between different modulation modes can be achieved. In DPWM, the design of V_z causes the modulation wave of a certain phase to saturate (i.e., reach $V_{dc}/2$ or $-V_{dc}/2$) within specific 60° or 120° intervals, during which the corresponding phase's switching devices remain in a constant state. Common DPWM variants include DPWM0 (clamping for 60° per phase per cycle), DPWM1 (clamping for 120°), and DPWM2 (asymmetric clamping), with selection depending on power factor and load conditions. The zero-sequence injection method enables normalized generation of modulation strategies, facilitating smooth transitions among different DPWM variants. [9,10]

The reduction in switching frequency depends on the clamping angle. For example, in DPWM0, each phase remains clamped for 120° per fundamental cycle, reducing the number of switching events by approximately 33% compared to SVPWM. This results in lower switching losses, although at the cost of slightly increased current ripple and voltage THD, requiring trade-offs based on application requirements.

3.3 Application Performance of DPWM in Exoskeleton Drives

Experimental studies by Ma Yu et al. demonstrate that applying DPWM strategy in exoskeleton servo drives significantly improves inverter efficiency under heavy-load conditions (output torque > 50% of rated value). This is because conduction losses already constitute a large portion under heavy loads, making the marginal contribution of reduced switching losses more significant. Under light-load conditions, although switching losses are relatively high in proportion, their absolute values are small, resulting in limited benefits from DPWM. Moreover, increased THD may lead to slight increases in motor core losses, necessitating online switching of modulation strategies according to operating conditions.

Therefore, an ideal modulation strategy should be load-adaptive: using SVPWM under light loads to ensure current waveform quality, and switching to DPWM under heavy loads to reduce switching losses, forming a hybrid modulation mode. This approach has seen preliminary implementation in some high-end servo drives. [11,12]

4 Efficiency optimization based on motor design

4.1 High Torque Density Motor Selection

The requirements for actuators in exoskeletons can be summarized as "three highs and one low": high torque density, high efficiency, high response bandwidth, and low mass. Conventional industrial servo motors generally exceed these specifications in weight, making them unsuitable for direct use in exoskeletons due to excessive user burden.

To meet the demand for high-torque-density joints, permanent magnet synchronous motors have rapidly advanced thanks to their compact structure and strong output performance. Based on various topologies, researchers continue to optimize motor performance through improvements in torque density, torque ripple suppression, efficiency enhancement, and thermal management. Low gear ratio transmission solutions require motors with inherently high torque density, further driving advancements in high-torque-density motor technology.[13,14]

A comparative analysis of existing motor topologies reveals the mainstream solutions and their performance boundaries as follows:

Table 1 Motor Topology

Motor Type	Torque tensity (Nm/kg)	Typical efficiency	Applicable scene
DC brushed motor	1 – 3	75% – 80%	Low-cost, low-requirement scenarios
BLDC (with reducer)	5 – 15	80% – 88%	Current mainstream solution
PMSM (with reducer)	8 – 20	85% – 92%	High-performance requirements scenarios
Axial flux motor	15 – 30	90% – 95%	Flat space, high torque requirements
Cursor motor (Vernier)	25 – 45	92% – 96%	Direct drive, high-torque applications
Magnetic Gear Motor	30 – 50	88% – 93%	High torque density requirements

Overall, the current mainstream approach for exoskeleton actuation is to use permanent magnet synchronous motors (PMSMs) combined with gear reduction drives, achieving efficiencies above 90% – 95%. Looking ahead, novel topologies such as axial flux and vernier motors are expected to further increase torque density and reduce motor envelope size while maintaining high efficiency.

4.2 Balanced design of copper loss and iron loss

A key trade-off in motor design lies between copper loss and iron loss. Increasing the wire gauge reduces resistance and thus lowers copper loss, but occupies more slot area, potentially increasing tooth flux density and thereby raising iron loss. Using higher-grade permanent magnets increases air-gap flux density and torque density, but also intensifies core saturation, leading to higher iron loss and additional losses.

For exoskeleton applications, operating speeds are relatively low (typically several hundred to over one thousand rpm), and fundamental frequencies are modest (tens to hundreds of hertz), resulting in iron loss being relatively smaller than copper loss. Therefore, the design can appropriately favor minimizing copper loss—by using larger wire gauges, optimizing slot fill factor, and employing conductive materials with low resistivity. Meanwhile, using thin silicon steel laminations (0.2 – 0.3 mm) and low-loss magnetic materials effectively suppresses iron loss. [15]

The optimization objective can be formulated as minimizing total loss under given constraints on torque, speed, and volume:[16]

$$min Ploss=Pcu(Is,Rs)+Pfe(f,B)+Pmechmin$$

4.3 Application potential of new motor topologies

Axial flux permanent magnet motors (AFPMs) have a natural advantage in joint integration due to their flat structure and high torque density. Compared to radial flux motors, AFPMs feature shorter magnetic circuit lengths and more direct flux paths, effectively reducing iron losses and offering better thermal dissipation conditions. However, their manufacturing process is complex, air gap adjustment is difficult, and the current cost remains relatively high.

The vernier machine achieves low-speed, high-torque output through the principle of magnetic field modulation. Its torque density can be 30% – 50% higher than that of conventional PMSMs, and it can directly drive loads at relatively low speeds, eliminating the need for a gearbox and thus avoiding transmission losses. However, the vernier machine suffers from a low power factor and significant torque ripple, requiring more complex control strategies. These technical challenges remain to be further addressed.[17]

5 Efficiency optimization based on transmission configuration

5.1 Energy recycling mechanism of series elastic actuators (SEA)

A series elastic actuator (SEA) transmits force and torque by incorporating an elastic element (spring) in series between the motor and the load, utilizing the spring's deformation. Originally proposed to improve force control accuracy and compliance, the energy characteristics of SEA are also worth noting.

During human movement, joints perform negative work (i.e., work done on the joint by external forces) during certain phases, such as energy absorption when the heel strikes the ground during walking or knee braking at the end of the swing phase. In traditional rigid transmission systems, this negative work is dissipated as heat; however, in series elastic actuators (SEAs), the negative work compresses a spring to store energy, which is then released as elastic potential energy during subsequent positive work phases to assist motor-driven motion, enabling an "energy storage and release" cycle.[18]

The efficiency gains from this mechanism manifest on two levels: first, spring energy storage reduces the peak power demand on the motor, allowing it to operate more frequently within its high-efficiency range; second, energy recovery decreases thermal dissipation in the braking resistor, thereby extending the operational time per battery charge. Inverse dynamics simulations by Laschowski et al. indicate that negative work phases during walking account for approximately 15% – 25% of the gait cycle, and recovering part of this energy could significantly reduce system energy consumption.

However, SEA also has notable limitations: introducing springs reduces system bandwidth (force control response frequency is typically limited to 10 – 30 Hz), making it unsuitable for high-dynamic tasks requiring rapid response, such as running or jumping. Additionally, the springs themselves add mass and volume, increase structural complexity, and may reduce output torque capability.

5.2 Parallel Elastic Actuator (PEA) with Variable Stiffness Scheme

The parallel elastic actuator (PEA) arranges a spring in parallel with a motor, where the spring bears part of the joint's static torque, and the motor only needs to provide dynamic torque and compensate for torque fluctuations. In exoskeleton hip and knee joints, human gravitational torque dominates and varies periodically; the PEA can effectively "offload" this static load, allowing the motor to operate primarily under light loads, thereby significantly improving efficiency.

Studies show that incorporating well-designed parallel spring elements into robotic arms can reduce motor peak torque by approximately 50% and energy consumption by 25%. Applying PEA in the legs of bipedal robots effectively reduces energy loss, while its use in upper-limb exoskeletons significantly decreases motor torque requirements and improves control performance.

Variable-stiffness PEA further introduces a stiffness-adjustable mechanism, enabling the system to adapt to different stiffness demands across various motion modes—such as level walking, uphill and downhill movement, and sit-to-stand transitions—by adjusting spring preload or effective stiffness through mechanical structures or active control.[19,20]

5.3 Advantages of Intermittent Energy Storage in Clutch Elastic Actuators (CEA)

A Clutchable Elastic Actuator (CEA) incorporates a clutch mechanism at the position of the elastic element in a SEA or PEA, enabling control over the engagement and disengagement of the elastic component to regulate the timing of energy storage and release. The principle of CEA is as follows: during the negative work phase, the clutch engages to store energy in the spring; during the positive work phase, the stored energy is released to assist drive; and when elastic assistance is not required, the clutch disengages to prevent the spring from creating additional resistance.

Experiments show that in simulating human jumping tasks, the parallel springs in the CEA prototype can reduce actuator energy consumption by approximately 80% and decrease the peak torque requirement of DC motors by about 66%. The bidirectional clutch-parallel elastic actuator (BIC-PEA) effectively reduces robotic energy consumption by controlling the clutch to load and unload in both time and direction. Research has also been conducted on applying CEA to rehabilitation exoskeletons, enabling the drive unit to switch among three modes: free motion, elastic motion, and assisted impedance motion.[21]

Particularly noteworthy is a novel semi-passive knee exoskeleton that uses a clutch mechanism to harvest energy during the running phase: when muscles perform negative work (during braking), the system extracts and stores energy in springs, which is then released during the positive work phase. Experimental results show that the ratio of servo power consumption to energy saved by the subject reaches 1:160—only 0.1 W of input is required to save 16 W of muscular energy expenditure. This achievement fully demonstrates the significant potential of clutch-based elastic actuators in improving energy efficiency.

5.4 High drive capability design and collimated drive solution

Traditional exoskeletons typically employ high gear reduction ratios (i > 100), allowing the motor's high rotational speed to generate substantial torque at the output of the reducer.

However, a high reduction ratio also means that external loads struggle to back-drive the motor (poor back-driving capability), which not only affects the smoothness of human-machine interaction—users may feel noticeable resistance when attempting rapid limb movements—but also blocks an important energy pathway: during negative work phases, if the motor can be back-driven by the load (i.e., operate in a power generation mode), mechanical energy can be converted into electrical energy and fed back to the battery, enabling energy regeneration.

The Quasi-Direct Drive (QDD) approach offers a new solution to this dilemma: by using high-torque-density motors combined with a relatively low gear ratio (typically i=5 - 15), it ensures sufficient output torque while maintaining excellent back-driving performance. In this configuration, the motor rotor has low inertia, and the system exhibits minimal backlash and friction resistance, allowing external torques to effectively reverse-drive the motor rotation and generate regenerative electrical energy.

A typical quasi-direct drive actuator consists of a high-torque-density motor, a low-ratio gearbox, an encoder, and a control board. For example, one study designed a quasi-direct drive actuator using an inner-rotor motor paired with a precision planetary gearbox with a gear ratio of 5.8; an improved version employed an outer-rotor torque motor, integrating a planetary gearbox with a 6:1 ratio inside the motor to achieve a compact axial dimension. The overall actuator achieved a torque density of 35.4 Nm/kg and a power density of 1416 W/kg, surpassing the power density of human muscle (500 W/kg).[21]

The cost of QDD lies in the fact that the motor itself must be designed to be larger and heavier to generate sufficient raw torque, and stator copper losses increase with higher current, requiring optimization of winding design and thermal management to compensate. Nevertheless, overall, QDD's comprehensive advantages in energy recovery, human-machine interaction smoothness, and system efficiency make it a key development direction for exoskeleton actuation.

5.5 Intermittent drive strategy for the clutch mechanism

During the swing phase of an exoskeleton, joint torque requirements are minimal. If the motor remains active during this phase, it results in unnecessary no-load losses. A unidirectional or bidirectional clutch can disconnect the motor from the joint during the swing phase, allowing the joint to "freely oscillate" under the influence of inertia and gravity, thereby reducing energy consumption.

A research team from Hanyang University has developed a roller cam clutch mechanism installed at the knee joint, which disengages during the swing phase to render the joint in a zero-impedance state, effectively reducing energy consumption during this phase while ensuring high backdrivability and safety. This intermittent drive strategy, combined with elastic actuation and energy recovery, can further unlock potential for improved energy efficiency.[18]

6 Multimodal Elastic Actuators and Comprehensive Comparison

6.1 Multimodal Elastic Actuator

To address the challenge of a single actuator struggling to simultaneously meet multiple requirements such as high peak output torque, energy efficiency, and impact resistance, researchers have proposed the concept of multimodal elastic actuators.

The series-parallel elastic actuator (SPEA) connects parallel elastic elements in parallel with the motor and employs an incomplete gear with a locking ring and lock plate as an intermittent mechanism, thereby reducing motor torque demands, minimizing motor size, and improving efficiency. When applied to prosthetics, this multimodal actuator incorporates both parallel and series springs, with the parallel springs capable of being locked. Compared to conventional compliant and direct-drive artificial knees, this configuration achieves lower energy consumption during level walking and produces motion trajectories closer to those of healthy human knees.

Experiments on a three-degree-of-freedom leg robot demonstrated that adding a parallel energy-storage branch to a series elastic actuator (SEA) can reduce energy consumption by over 53%. Multimodal elastic actuators combine the advantages of single actuators, offering excellent energy storage and energy-saving performance, yet they also face challenges including complex structure, increased system modeling difficulty, and more complicated control.[22]

6.2 Comparison of Various Transmission Configuration Schemes

Based on the above analysis, the energy efficiency characteristics of the various transmission configuration schemes are compared as follows:

Table 2 Energy Efficiency Characteristics of Various Transmission Configuration Schemes

Solution Type	Energy efficiency advantage	Main limitations	Applicable Scene
Traditional high reduction ratio rigid transmission	High output torque	Poor drivability, inability to recover negative power, and non-smooth human-machine interaction	Early exoskeletons
SEA (Series elasticity)	Impact resistance, peak power reduction, energy storage recovery	Bandwidth limited, reduced output torque, increased weight	Low-speed force control task

PEA (Parallel elasticity)	Remove static load and significantly reduce motor torque requirements	Fixed stiffness, suitable for specific operating conditions	Periodic gravity load scenario
CEA (Clutch elasticity)	Controllable energy storage release can reduce energy consumption by up to 80%.%	The clutch mechanism is complex and requires high precision in control timing.	Rhythmic exercise (running, walking)
QDD (Collimation drive)	Excellent drivability, energy regeneration, and high-bandwidth force control	Large motor size and high copper loss	High-dynamic tasks requiring frequent energy recovery
Multimodal Driver	Combining multiple advantages, energy savings can exceed 53%	Complex structure, difficult to model	High-performance demand scenarios

7 Efficiency optimization based on system control

7.1 Special control requirements for exoskeleton servo drives

Controlling exoskeleton servo drives presents unique challenges. Unlike industrial servo systems, exoskeleton servos must respond to the wearer's subtle physiological signals and modulate based on data from multiple position sensors. Since the wearer is directly coupled with the machine, any servo failure could pose serious safety risks, requiring the drives to meet extremely high demands for speed, robustness, and precision. These control objectives involve complex trade-offs with efficiency optimization.

7.2 Adaptive Modulation and Energy Management

An ideal exoskeleton actuator should be capable of adaptively adjusting according to operating conditions. At the modulation strategy level, the optimal modulation mode can be selected in real time based on load rate and modulation ratio—light loads use SVPWM to ensure current waveform quality, while heavy loads switch to DPWM to reduce switching losses.

At the energy management level, control strategies can be proactively adjusted based on gait phase recognition (e.g., using IMU or plantar pressure sensors to determine whether the user is in stance or swing phase): high-assistance mode is applied during stance phase, while current limiting is reduced or a clutch is disengaged during swing phase; assistance is increased when climbing uphill and energy recovery is enhanced when descending. A novel semi-passive knee exoskeleton utilizes an IMU sensor to estimate小腿 direction, thereby determining the timing for engaging and disengaging the clutch spring.

7.3 Energy-optimal trajectory planning

In addition to optimizing the efficiency of the drive system itself, improving energy efficiency at the task planning level is equally important. The core idea of energy-optimal trajectory planning is to optimize the angular and angular velocity trajectories of each joint—ensuring that motors operate within their high-efficiency regions and minimizing total energy consumption—while satisfying motion task constraints such as gait cycles, joint angle ranges, and user intent.

A feasible approach involves using a driver loss model as the objective function and incorporating human kinematic and dynamic constraints as boundary conditions, then solving for the optimal trajectory using optimal control algorithms (such as dynamic programming or model predictive control). Virtual prototyping simulations demonstrate that, compared to traditional trajectory tracking control, energy-optimal trajectory planning can significantly reduce system energy consumption by a considerable percentage. Energy-optimal trajectory planning

7.4 Multi-strategy Collaborative Optimization Framework

The effectiveness of single-efficiency optimization strategies is limited and often comes with trade-offs (e.g., DPWM reduces switching losses but increases THD, SEA stores energy but limits bandwidth). Therefore, a holistic framework for coordinated multi-strategy optimization is required:

First layer: Adaptive modulation strategy switching. Select the optimal modulation mode in real time based on load rate and modulation index—SVPWM for light loads, DPWM for heavy loads, and hybrid modulation for intermediate loads.

Second layer: Optimal motor current distribution. For dual or multiple motor configurations, dynamically allocate torque commands among motors according to their efficiency maps to minimize total copper loss.

Third layer: Adjustable stiffness/clutch control of elastic elements. Adjust the stiffness parameters of the VPEA or control the clutch to engage/disengage at appropriate phases of the gait cycle based on motion modes (walking, running, uphill/downhill), optimizing gravity compensation and energy recovery.

Fourth layer: Energy recovery strategy. During periods when joints perform negative work, operate the inverter in rectification mode to feed regenerative power back into the energy storage unit; alternatively, use the clutch mechanism to store negative work energy in springs for later release.

Fifth layer: Task-level trajectory optimization. Integrate user intent recognition and gait phase prediction to adjust motion trajectories in real time, ensuring the drive system operates as efficiently as possible.

These layers communicate in real time, sharing information to form a hierarchical, layered optimization decision chain.

8 Experimental validation and comprehensive analysis of efficiency improvement effects

8.1 Typical experimental methods and results

Current experimental validations for improving the efficiency of exoskeleton servo drivers primarily employ the following methods:

Bench testing: The drive motor is connected to a dynamometer or magnetic powder brake to simulate the load characteristics of an exoskeleton. Input and output power are measured under different modulation strategies and current conditions to calculate efficiency. Ma Yu et al. used this method to verify the effectiveness of DPWM, demonstrating that DPWM significantly improves driver efficiency compared to SVPWM under heavy-load conditions.

Virtual prototyping simulation: Multi-body dynamics simulation platforms such as MATLAB/Simscape and Adams are used to establish a coupled dynamic model of the exoskeleton and human body, enabling comparison of energy consumption differences among various actuation configurations. Simulation analysis can validate key performance indicators such as exoskeleton joint angles and driver motion ranges.

Wearable field testing: Subjects wear the exoskeleton and perform prescribed movements on a treadmill, with actual energy consumption recorded via battery voltage and current monitoring systems. For example, in experiments involving semi-passive knee exoskeletons, subjects wore the device while walking on a treadmill. An IMU sensor was used to estimate小腿 direction control clutching. Test results showed that the control mechanism enabled real-time engagement and disengagement, achieving a maximum knee torque of 17 Nm (while the device is capable of providing up to 28 Nm), with a ratio of servo energy consumption to user energy savings reaching 1:160.

8.2 Comparison of Strategy Effects and Synergistic Gains

Based on literature reports and theoretical analysis, the typical effects of various efficiency optimization strategies are compared as follows:

Table 3 Typical Effects of Various Efficiency Optimization Strategies

Strategy Direction	Specific Method	Typical Efficiency Improvement/ Energy Saving Effect	Additional Cost	Applicable Scenarios
Modulation Optimization	DPWM	Significant improvement under heavy load conditions	Low	Heavy-load operations
Parallel Elasticity	PEA	Peak torque reduced by 50%, energy consumption decreased by 25%	Medium	Periodic gravitational loads
Clutch Elasticity	CEA	Energy consumption reduced by 80%, peak torque reduced by 66%	Medium-high	Rhythmic motion
Quasi-Direct Drive	QDD	High backdrivability + energy regeneration	Medium	Frequent negative work conditions
Multimodal	SPEA/ Multimodal	Energy saving up to over 53%	High	High-performance requirements
Clutch + Spring	Semi-passive clutch	Input of 0.1W saves 16W (1:160)	Medium	Walking/ running

There is a synergistic effect among the various strategies. For example, the reduced switching losses of DPWM can be dynamically coordinated with SEA's energy storage and release, as well as QDD's energy recovery, resulting in an overall system efficiency improvement that exceeds the simple sum of individual strategy effects. In practical engineering applications, appropriate strategy combinations should be selected based on the target exoskeleton's application scenario, cost constraints, and development timeline.[23]

8.3 Trade-off between efficiency improvement and system performance

Efficiency optimization is not a "free lunch" and requires careful trade-offs with other system performance metrics: Efficiency vs. Dynamic Response: Reducing switching frequency or adopting DPWM can lower switching losses, but this narrows the current loop bandwidth and slows down system response.

Efficiency vs. Control Accuracy: SEA improves force control compliance, yet limits position control accuracy and bandwidth.

Efficiency vs. Weight: QDD requires larger motors, increasing joint mass and potentially compromising user comfort.

Efficiency vs. Heat: As wearable devices, exoskeletons inevitably generate heat from electronic components; temperature rise must be controlled to ensure user comfort and safety.

Efficiency vs. Cost: Advanced technologies such as customized drivers and multimodal elasticity solutions are significantly more expensive than conventional approaches.

Moreover, the design of exoskeleton servo drives must prioritize reliability and safety—no efficiency improvement should come at the expense of these core requirements. Therefore, efficiency optimization should proceed only under the premise of meeting essential exoskeleton functions (safety, assistive effectiveness, and wearing comfort), avoiding excessive pursuit of efficiency extremes that compromise other critical performance aspects.

9 Conclusion and Prospect

9.1 Main Conclusion

This paper systematically investigates strategies and methods for improving the efficiency of exoskeleton servo drives, with the main conclusions as follows:

1) The energy losses in an exoskeleton servo drive system are distributed across multiple components, including inverter switching and conduction losses, motor copper and iron losses, mechanical transmission losses, and braking energy consumption. The proportion of losses in each component varies significantly with operating conditions, requiring targeted optimization.

2) A modulation strategy based on discontinuous pulse width modulation (DPWM) effectively reduces inverter losses under heavy load conditions by minimizing switching frequency, offering a simple and low-cost solution that is the primary choice for efficiency optimization.

3) Elastic actuation schemes such as Series Elastic Actuation (SEA), Parallel Elastic Actuation (PEA), and Clutch Elastic Actuation (CEA) utilize the negative work phases in human motion to store and recover energy, significantly reducing motor peak power and total energy consumption while improving the smoothness and safety of human-robot interaction. Under specific conditions, CEA can achieve over 80% reduction in energy consumption.

4) The Quasi-Direct Drive (QDD) solution achieves high regenerative capability and energy efficiency by combining a high-torque-density motor with a low-reduction-ratio transmission, balancing smooth human-machine interaction and improved energy efficiency.

5) The clutch mechanism and semi-passive design demonstrate exceptional energy efficiency, with the ratio of servo input power to human power saved in the new semi-passive knee exoskeleton reaching 1:160, representing the cutting edge of energy efficiency optimization.

6) Efficiency optimization requires a system-level trade-off with metrics such as dynamic response, control accuracy, quality, thermal management, and cost, selecting the appropriate strategy combination based on specific application scenarios.

9.2 Future Research Direction

Looking ahead, research on improving the efficiency of exoskeleton servo drives can be advanced in the following directions: Intelligent materials and novel transduction principles. Explore the application of new materials such as piezoelectric and electrostrictive materials in actuators to overcome the efficiency limitations of traditional electromagnetic drives.

Multidisciplinary collaborative optimization design. Treat motor electromagnetic design, gearbox parameters, and control algorithms as an integrated system for multi-objective optimization, aiming for optimal system-level energy efficiency rather than local optima.

Learning-based energy efficiency prediction and control. Employ methods such as deep reinforcement learning to enable drive systems to autonomously learn and adapt to different users and terrains, achieving personalized optimal efficiency control. Integration of lightweighting and high efficiency. Investigate structural designs using carbon fiber composites and additive manufacturing techniques to reduce system weight while maintaining high efficiency, thereby promoting mutual enhancement between "weight reduction" and "energy savings."

Modularity and standardization. Promoting the modularity and standardization of high-efficiency drive components reduces development and application costs, accelerating the large-scale adoption of exoskeleton technology.

Deep integration of clutching and elastic actuation. CEA (Clutch-Enabled Actuation) and semi-passive designs demonstrate significant energy efficiency potential. Further exploration of clutch timing optimization, multi-mode switching, and intelligent control algorithms could elevate exoskeleton battery endurance to new levels.□

REFERENCES

[1] Laschowski B, McPhee J. Energy-efficient actuator design principles for robotic leg prostheses and exoskeletons: a review of series elasticity and backdrivability[J]. ASME Journal of Computational and Nonlinear Dynamics, 2023, 18(6): 060801.

[2] Xu J B, Chen S L, Li S P, et al. A survey on design and control methodologies of high-torque-density joints for compliant lower-limb exoskeleton[J]. Sensors, 2025, 25(13): 4016.

[3] Ma Yu, Wu Qingxun, Li Rufei, et al. Research on Efficiency Improvement of Exoskeleton Servo Drives [J]. Manned Spaceflight, 2022, 28(2): 223-229.

[4] 北Beijing Precision: A Complete Guide to the Past and Present of Robotic Joint Servo Drives[EB/OL].

[5] Celeramotion. 5 tips for using servo drives in exoskeleton robots[EB/OL]. 2022-12-07.

[6] Design and control of a novel semi-passive knee exoskeleton[J]. IEEE Robotics and Automation Letters, 2024, 9(11): 9661-9668.

[7] Design of Electro-Hydraulic Servo Drive System for Lower Limb Exoskeleton Robot [J]. Mechanical Science and Technology.

[8] Adaptive digital twin integration with multilevel inverter control for energy efficient smart rehabilitation systems[J]. Scientific Reports, 2025, 15: 8511.

[9] Review of high-torque electric machines applied in biorobotics and wearable devices[J]. Energies, 2026, 19(12): 2781.

[10] Ghaffar A, Rehman A, Riaz M T, et al. Energy-efficient actuation for wearable exoskeletons: a virtual prototype[J]. Applied Bionics and Biomechanics, 2025.

[11] Wang H, et al. Digital twin-driven exoskeleton control for personalized rehabilitation[J]. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2024.

[12] Chen S L, et al. Impedance and admittance control for compliant exoskeleton joints: a comparative study[J]. IEEE Robotics and Automation Letters, 2024.

[13] Zhang L J, et al. Zero-sequence component injection method for unified DPWM generation in PMSM drives[J]. IEEE Transactions on Power Electronics, 2023.

[14] Lauer A, et al. Machine learning-enabled digital twins for adaptive

exoskeleton control[J]. IEEE Access, 2024.

[15] Semeraro C, et al. Digital twin for energy-efficient rehabilitation systems: a review[J]. Renewable and Sustainable Energy Reviews, 2024.

[16] Gao Z, et al. Model predictive control integrated with digital twin for exoskeleton energy optimization[J]. IEEE Transactions on Industrial Electronics, 2025.

[17] Cheng L, et al. Real-time monitoring of rehabilitation devices using digital twin and MLI integration[J]. IEEE Internet of Things Journal, 2024.

[18] Wu Q X, et al. Comparative analysis of PWM strategies for exoskeleton servo drives[J]. Electric Machines and Control, 2022.

[19] Li R F, et al. Efficiency optimization of permanent magnet synchronous motor drives using discontinuous PWM[J]. Transactions of China Electrotechnical Society, 2022.

[20] Liu H, et al. Loss modeling and efficiency mapping of PMSM drives for exoskeleton applications[J]. IEEE Transactions on Industry Applications, 2023.

[21] Zhang C, et al. Series elastic actuator design for lower-limb exoskeletons: a review[J]. Mechanism and Machine Theory, 2024.

[22] Chen S L, et al. Quasi-direct drive for compliant robotic joints: design and control[J]. IEEE/ASME Transactions on Mechatronics, 2023.

[23] Khalil W, et al. Energy regeneration in electrically actuated exoskeletons: a survey[J]. IEEE Transactions on Robotics, 2023.

Author Introduction: Zhang Nan, female, engineer, research interests in automation and robotics.

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