An electrohydraulic actuator for bipedal robots with active-passive combination

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Abstract

Bipedel robots have great potential for rehabilitation and service due to their bionic morphology and adaptive mobility. These robots' systems require advanced knee actuation mechanisms, such as dynamic force modulation, precise control, and adaptive impedance properties, to support a variety of movement modes. This study describes an electrohydraulic knee actuator which can work in three modes: active, passive and burst model. It integrates three accumulators, a rotary direct-drive servo valve and a rotary switching valve together into a hydraulic cylinder. The core of the design is to achieve high precision control in active mode, variable stiffness and damping control in passive mode, force burst in burst mode, through coordinating the operation of valves and accumulators. This combination not only supports robot manoeuvres such as walking, jumping and landing by precisely controlling the displacement, stiffness, damping and force of the hydraulic actuators, but also reduces energy consumption effectively.

Keywords: integrated electro-hydraulic actuator, active and passive, rotary switch valve, rotary direct-drive servo valve, bipedel robot

1 Introduction

Bionic-legged robots, with their superior mobility and adaptability to the environment, outperform traditional wheeled or tracked robots in reducing operational blind spots through a gait control mechanism that utilizes discrete contact points. This makes them invaluable in various applications, including exploring hazardous environments, aiding in rehabilitation medicine, and providing intelligent services[1].

The joint driving methods for bipedal robots primarily include motor drive and hydraulic drive. Hydraulic drive offers higher power density and better load characteristics compared to the motor-reducer combination.

The legs of hydraulic legged robots are typically made up of multiple hydraulic actuators connected in series or parallel. The design, manufacturing, and control of these actuators are crucial in determining the leg's motion performance and load-bearing capacity. Hydraulic actuators usually employ linear motion servo cylinders, which excel in low-speed stability, hydraulic stiffness, minimal internal leakage, and are compact in weight and volume.

In the lower limb structure of bipedal robots, the knee joint actuator is pivotal. It assists the leg in flexion and extension movements during walking, supporting the robot's weight and enabling gait control. Moreover, the knee joint actuator must be capable of absorbing impacts when the foot contacts the ground.

Boston Dynamics unveiled the BigDog quadruped hydraulic robot in 2006, featuring a hydraulic actuator that integrates servo valves, servo cylinders, displacement sensors, and force sensors to enable closed-loop force/position control[2]. In 2008, the company upgraded the hydraulic actuator with the lighter MOOG E024 two-stage nozzle flapper electro-hydraulic servo valve and concurrently optimized the cylinder structure. These enhancements resulted in a more compact, smaller, and lighter hydraulic drive unit, thereby enhancing its overall compactness[3].

In China, research institutions such as HIT[4], SDU[5], and BIT[6] have delved into this field, developing hydraulic actuators with structures akin to BigDog's integrated valve-controlled system. These designs incorporate various components within the hydraulic drive unit's cylinder. Despite utilizing numerous small components, the level of integration remains moderate. The servo valve and hydraulic cylinder are

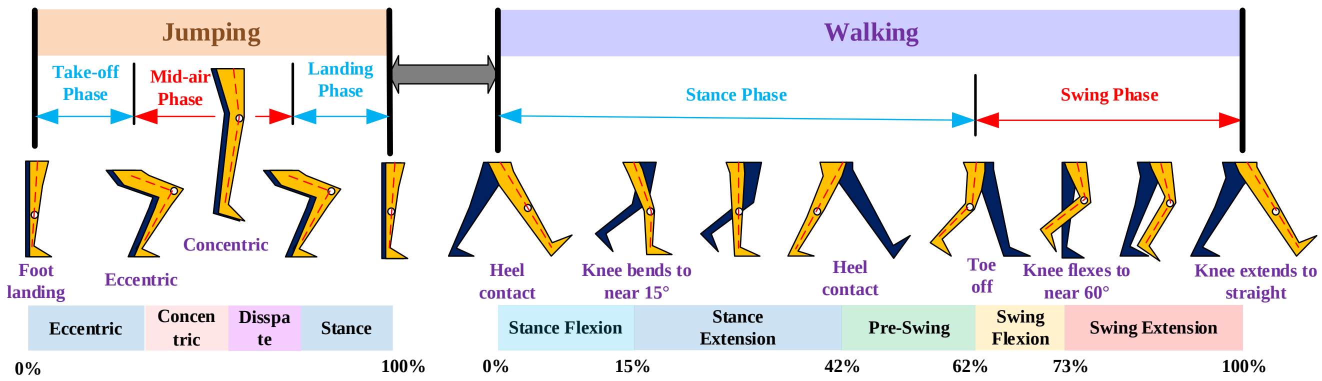

Figure 1 Human Vertical Jumping and Walking Gait Cycles

connected via a plate, which increases the actuator's overall volume. In contrast, the Baby Elephant, introduced by the SJTU team, features a distinct hydraulic actuator structure. It comprises a servo cylinder, a moving slide valve motor, and a pressure sensor, achieving a high degree of multifunctional integration within the hydraulic drive unit[7].

In 2018, MOOG and IIT joined forces to develop highly integrated Integrated Smart Actuators (ISA) using additive manufacturing. These actuators incorporate servo valve structures directly into the actuator bodies, eliminating the need for interfaces, and feature multifunctional built-in controllers for high-performance control[8]. This collaboration has provided valuable references and research insights for many scholars.

However, these are active actuators, which rely on control algorithms to softly absorb the buffering experienced by the actuator. This approach inevitably increases the overall power consumption and decreases the power-to-weight ratio of the entire actuator. Consequently, some researchers are exploring the introduction of passive regulation modes for actuators.

In 2011, researchers at the Polytechnic University of Madrid engineered a bionic agility leg with adjustable flexibility. This innovation merged tandem elasticity with magnetorheological dampers, mimicking the functionality of a horse's leg[9]. Moving forward to 2020, Shandong University revealed a hydraulic actuator capable of passive flexibility. This was achieved by integrating an accumulator within the piston chamber of a hydraulic cylinder, allowing the actuator to modify its stiffness passively upon pressurization, thereby cushioning the impact between the foot and the ground[10]. Separately, the research team from HIT developed the Series Elastic Actuator (SEA) [11] and the Variable Stiffness Actuator (VSA) [12]. These actuators feature an elastic element positioned between the actuator's output and the negative cut. By manipulating the deformation of this elastic element, they attain variable damping and stiffness, producing the necessary output force. Nonetheless, this design enhancement leads to a considerable increase in the actuator's size.

In the design of knee joint actuators, a detailed analysis of the natural human gait cycle was performed. This cycle consists of two main phases: the Stance Phase and the Swing Phase, which account for about 60% and 40% of the walking cycle, respectively, as illustrated in Figure 1.

Biomechanical analysis reveals that the knee joint plays five key roles during the gait cycle. During the Stance Flexion Phase, the knee joint slightly flexes (by approximately 10°-15°), absorbing and dissipating impact energy through elastic deformation. This effectively reduces ground reaction forces on the lower limb joints. In the Stance Extension Phase, the knee joint extends fully to the neutral position (0°), maintaining lower limb stability through bone support and muscle coordination. This ensures efficient mechanical energy transfer during the weight-bearing period.

In the Pre-Swing Phase, the knee joint rapidly flexes (by about 30°-40°), creating enough ground clearance for the lower limb's swing. During the Swing Flexion Phase, the knee flexion velocity decreases progressively through the coordinated control of opposing muscle groups. This restricts the posterior swing angle of the lower leg to a physiological range (about 60°-70°), maintaining gait coordination. Finally, in the Swing Extension Phase, the knee extension velocity shows a decelerating trend, achieving terminal deceleration through damping control. This guides the foot to the optimal landing position, preparing for the next gait cycle[13].

The analysis indicates that during the natural human gait cycle, the knee joint primarily acts as a support mechanism rather than facilitating swinging motions for the majority of the cycle. Additionally, an examination of the human vertical jumping cycle reveals that it consists of three main phases: Take-off, Mid-air, and Landing. The knee joint performs five essential functions for the lower limbs: eccentric knee flexion for energy storage; concentric rapid extension from flexion to release energy and generate force output; and subsequent knee flexion for impact absorption. The analysis shows that during the natural vertical jumping cycle, the knee joint plays crucial roles in energy storage, rapid force generation, and efficient impact absorption [14].

To enhance the compactness and energy efficiency of electro-hydraulic actuators for hydraulic bipedal robots, this study introduces a novel, highly integrated electro-hydraulic actuator that combines active and passive systems, drawing inspiration from the natural human walking gait cycle. The proposed actuator allows for seamless switching between active and passive modes, providing high load capacity with adjustable stiffness and continuously variable damping. This innovative actuator, incorporating a uniquely designed hydraulic system and novel core components, mimics the functional characteristics of the human knee joint during movement. It combines the versatility of active systems with the energy-saving benefits of passive systems.

The paper's structure is outlined as follows: Section 2 presents a comprehensive overview of the target platform and the specific performance requirements for the actuator. Section 3 provides a detailed explanation of the hydraulic principles underpinning the active-passive electro-hydraulic actuator, including the design of its essential components, the integration of the active and passive systems, and the validation of its performance metrics. In Section 4, a nuanced discussion of the results is offered, followed by concise concluding remarks in Section 5.

2 Overall design and requirements

The currently developed lower limb system for bipedal robots is capable of performing various movements, including walking, squatting, and running. The knee joint is actuated by a linkage mechanism forming triangle ΔABC, with the geometric relationship between the knee joint angle and actuator length illustrated in the left-side of Figure 2.

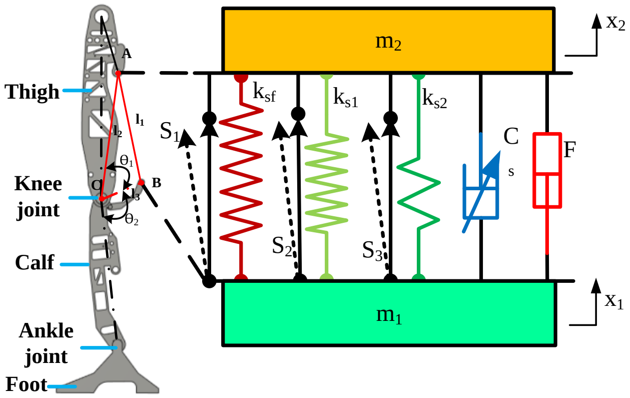

Figure 2 Kinetic Model of "IKPSA"

To meet the structural, load-bearing, and gait cycle requirements of the entire bipedal robot system, the actuator must adhere to the following specifications:

1. The actuator's structure should be compact to fit within the limited installation space in the robot's lower limb, with a stroke of 55mm.
2. Based on the experimental data from the current lower limb part of the robot, the actuator must have a maximum output force exceeding 10,000N at a rated pressure of 21MPa. It should also be capable of operating in both active and passive modes.
3. The actuator should feature high integration and plug-and-play capabilities in both its active and passive modes.

In line with the high integration design objectives and characteristics of the actuator, it has been named the IntelliKnee-Plug Servo Hydraulic Actuator, or "IKPSA" for short.

In response to the system-level requirements, a dynamic model of the actuator has been developed.

$$m_1\ddot{x}_1 + k_s(x_1 - x_2) - F + c(\dot{x}_1 - \dot{x}_2) = 0 \quad (1)$$

$$m_2\ddot{x}_2 + k_s(x_2 - x_1) + F + c(\dot{x}_2 - \dot{x}_1) = 0 \quad (2)$$

The actuator's output force is primarily determined by the fluid pressure and the piston's effective area.

$$F = p_1A_1 - p_2A_2 - F_{\text{visc}} \quad (3)$$

The stiffness adjustment capability of the IKPSA in passive mode, along with its shock absorption and energy source functions in burst mode, are all derived from the specially designed metal bellows accumulator integrated within the IKPSA. This component serves dual purposes as both an energy source and a shock absorption mechanism. To quantify the dynamic behavior of the accumulator, a pressure-flow relationship is based on gas thermodynamics. Assuming adiabatic conditions for rapid actuation scenarios, the pressure change rate in the accumulator can be expressed as

$$\dot{P}_i = \frac{\gamma Q_i P_i}{V_{acc}} \left(\frac{P_i}{P_{pc}}\right)^{1/\gamma} \quad (4)$$

Furthermore, the effective stiffness of the system, governing shock absorption performance, is derived from the linearized force-displacement relationship:

$$k_s = \frac{\gamma A_c^2 P_{pc}}{V_{acc}} \quad (5)$$

3 Actuator Design

3.1 Hydraulic Principle

"IKPSA" is a hybrid hydraulic actuator combining active and passive elements, which constitutes an independent closed-loop hydraulic system. As shown in Figure 3, the major components of IKPSA are a hydraulic cylinder, two relief valves, two 3-way 3-position valves, four switch valves, and three accumulators. It is important to highlight that all four switch valves depicted in the figure are housed within a single Rotary Switch Valve and rotate simultaneously.

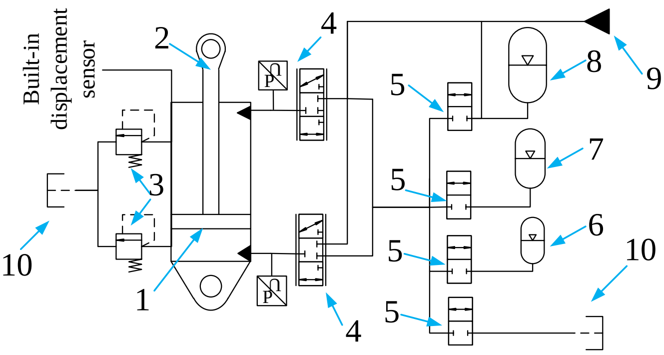

Figure 3 Hydraulic principle of IKPSA(1. Piston, 2. Rod, 3. Relief valve, 4. three -way three -position valve, 5. Switch valve, 6. Accumulator A, 7 Accumulator B, 8 Accumulator C,9 Oil inlet/ constant pressure, 10. Tank.)

The hydraulic system employs an asymmetric cylinder design, with both ends connected to the biped robot's knee joint hinges. Figure 4 illustrates key integration enhancements implemented in this configuration. High-pressure hydraulic fluid (denoted by red arrow H) enters the system through two Rotary Direct-Drive Servo Valves before being distributed to the actuator. These valves feature working ports connected to individual chamber ends of the hydraulic cylinder, enabling independent control of both load chambers. The servo valves' opposite ends connect to a Rotary Switch Valve that coordinates low-pressure fluid distribution (marked by blue L) to the accumulator array.

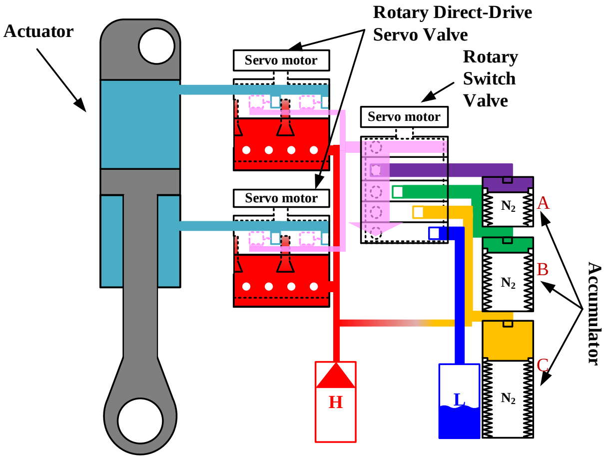

Figure 4 IKPSA schematic diagram

In Active Mode, the Rotary Switch Valve (RSV) maintains direct hydraulic connectivity to the low-pressure port via servo-driven spool alignment, bypassing all accumulators. The dual Rotary Direct-Drive Servo Valves (RDDSVs) function as three-position four-way valves, enabling independent pressure regulation in the cylinder's dual chambers. This configuration provides precise trajectory control of knee flexion-extension during the swing phase.

In Passive Mode, terrain adaptation is achieved by reconfiguring the RSV to allow fluid flow through selectable metal bellows accumulators (A, B), enabling adjustable stiffness of the actuator. The RDDSVs transition to variable-orifice dampers, where spool rotation modulates the overlap area between T-ports and working chambers, enabling real-time damping adjustment. This dual-parameter tunability enhances stability on irregular surfaces.

In addition to "Active Mode" and "Passive Mode," the IKPSA features a "Burst Mode," specifically designed to emulate the knee joint's biomechanical behavior during human jumping motions, thereby enabling hydraulic bipedal robots to perform jumping maneuvers.

Prior to engaging "Burst Mode," accumulator C is pre-charged through the high-pressure port to store energy. Upon activation, the pre-charged accumulator connects directly to the cylinder through fully opened RDDSV T-ports, bypassing servo control, implementing a differential drive principle. Consequently, the piston rod achieves both high force output and rapid extension. This mechanism enables the knee joint to perform explosive extension during jumping motions, providing essential support for the robot's overall jumping capability.

In summary, the IKPSA achieves seamless switching between "Active Mode," "Passive Mode," and "Burst Mode" through the coordinated operation of three rotary control valves and accumulators. Through the design of specialized fundamental components and innovative hydraulic principles, the IKPSA is capable of replicating human knee joint motion states, including stiffness adaptation for various conditions, continuously variable damping adjustment, gait modulation, and high-power burst capabilities. Moreover, the hydraulically-driven IKPSA possesses significantly greater load-bearing capacity compared to both human joints and existing electric motor-based joints. Complemented by its integrated housing design, the IKPSA offers plug-and-play functionality, facilitating easy installation and replacement.

3.2 Rotary Direct-Drive Servo Valve

The knee joint actuator's operational phases involve transitions between active and passive modes, along with motion damping control. To address these requirements, this study developed a Rotary Direct-Drive Servo Valve (RDDSV), a three-position three-way spool rotary direct-drive servo valve characterized by its simple structure and superior performance. Employing a cartridge-style design for integration, the RDDSV's structure primarily consists of a valve sleeve, valve spool, motor, and sensors, as illustrated in Figure 5(a).

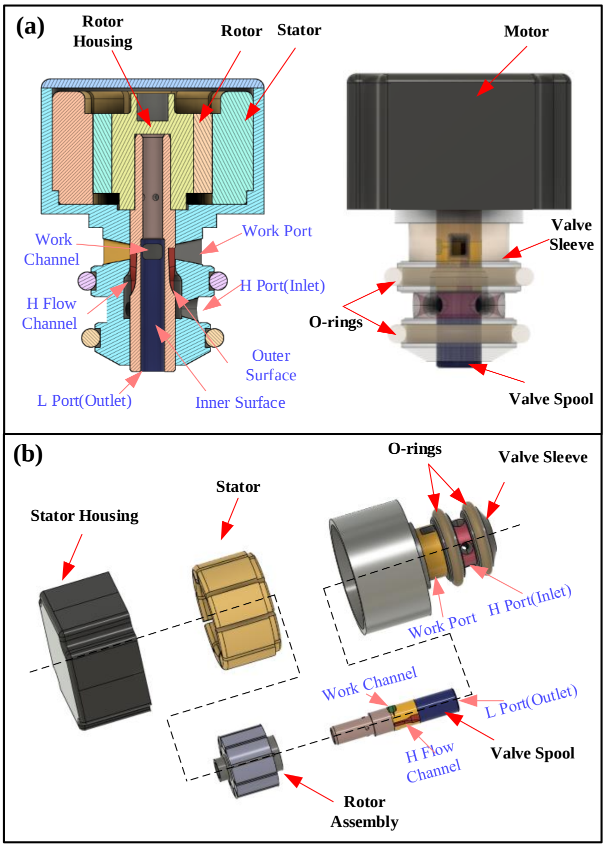

Figure 5 Structural composition of RDDV.

The operational principle of the RDDSV is based on the relative rotation between the valve spool and sleeve, as shown in Figure 5(b). When the valve spool rotates, the cavities formed by the H Flow channel and work channel in the spool align with the circumferential cavities in the valve sleeve, creating various flow path configurations. These flow path combinations determine the direction of fluid energy transfer and the actuator's motion characteristics.

The valve sleeve features an annular groove that serves as the High Pressure inlet, with a circumferential array of ports. Corresponding internal grooves are machined on the sleeve's inner wall, forming cavities that ensure uniform distribution of high-pressure oil across the valve spool surface. A work annular groove, connected to the actuator's load chamber, is equipped with rectangular ports designed to align with corresponding ports on the valve spool. The High Pressure port and Work port are isolated by sealing elements. The valve spool has a hollow tubular structure with both external and internal surfaces. The external surface contains an oil passage (H Flow channel) extending from the H Port to the Work port, formed within the spool's wall thickness without penetrating it, as illustrated in Figure 5(b). The internal surface incorporates axial through-holes that radially traverse the spool, connecting to the Low Pressure port (L Port), thereby facilitating fluid transfer from the actuator's load chamber to the Rotary Switch Valve.

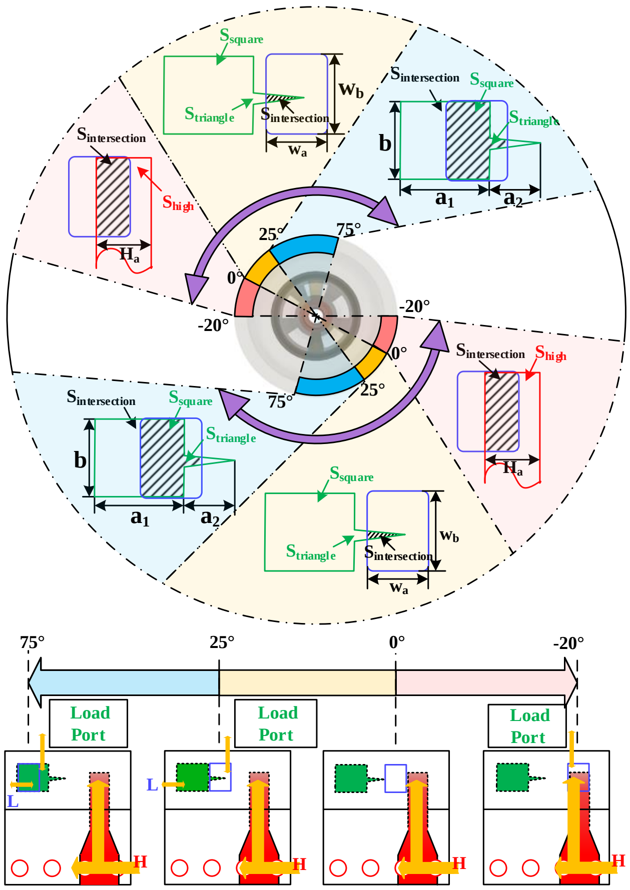

Figure 6 Change in flow area during valve spool rotation.

3.3 Rotary Switch Valve

To achieve these improvements, we developed a directly servo-driven Rotary Switch Valve (RSV). The spool-type rotary valve utilizes motor control algorithms for precise angular positioning, enabling adaptive fluid distribution across pressure gradients. As shown in Figure 8, the cartridge-integrated assembly comprises: a valve sleeve, spool, rotor, stator, rotor seat, bearings, and sensors. This modular architecture supports flexible pressure selection through controlled spool rotation while maintaining operational stability.

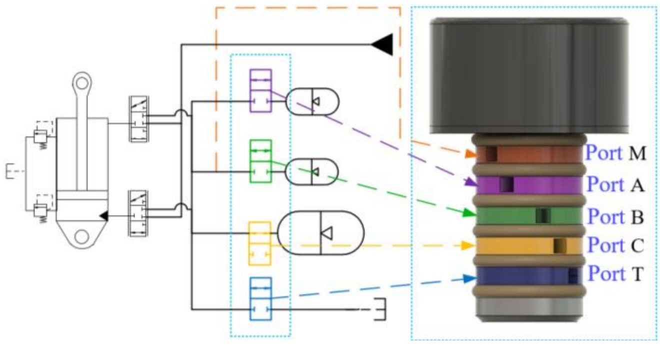

Figure 7 A single RSV control the fluid flow direction.

The valve spool is integrated with the rotor assembly for synchronized rotation, enabling control over various hydraulic circuits to facilitate switching between active and passive modes, servo control in active mode, and damping adjustment in passive mode, as shown in Figure 6. The valve spool's rotational range is 90°. When rotating clockwise between 0° and 20°, high-pressure fluid enters through the sleeve's H Port into the H Flow channel on the spool's external surface, then exits through the sleeve's Work port to enter one load chamber of the actuator, driving piston movement. Simultaneously, the RDDSV connected to the actuator's other load chamber has its spool positioned at a counterclockwise rotation of 25° to 50°, allowing fluid to flow from the load chamber into the sleeve's Work port, pass through the square area of the spool's work channel, and exit through the spool's axial through-hole to connect with the Low Pressure port (L Port). This configuration of both RDDSVs achieves the actuator's active mode setup, enabling active control of fluid flow to drive IKPSA motion.

When the RDDSV spool is in the counterclockwise rotation range of 0° to 25°, it operates in passive mode for damping adjustment. By controlling the overlapping area between the triangular region of the spool's work channel and the sleeve's Work port, a variable-area damping orifice is formed, allowing for adjustment of the IKPSA's passive damping characteristics.

In summary, the RDDSV primarily assumes responsibility for oil circuit closure, active-passive mode switching, and passive damping control. When transitioning to passive mode, the RDDSV switches to the low-pressure port (T-port) by rotating the valve spool, thereby regulating the opening area to modulate the damping force within the passive system.

This mechanism simultaneously facilitates impact absorption, establishing a fundamental design basis for compliant control in the passive system and enhancing overall energy efficiency of the complete system.

As shown in Figure 8(a), the valve sleeve contains four functional selection ports (Ports A, B, C, T) and one main port (Port M). The selection ports are configured to interface with multiple pressure sources - derived from metal bellows

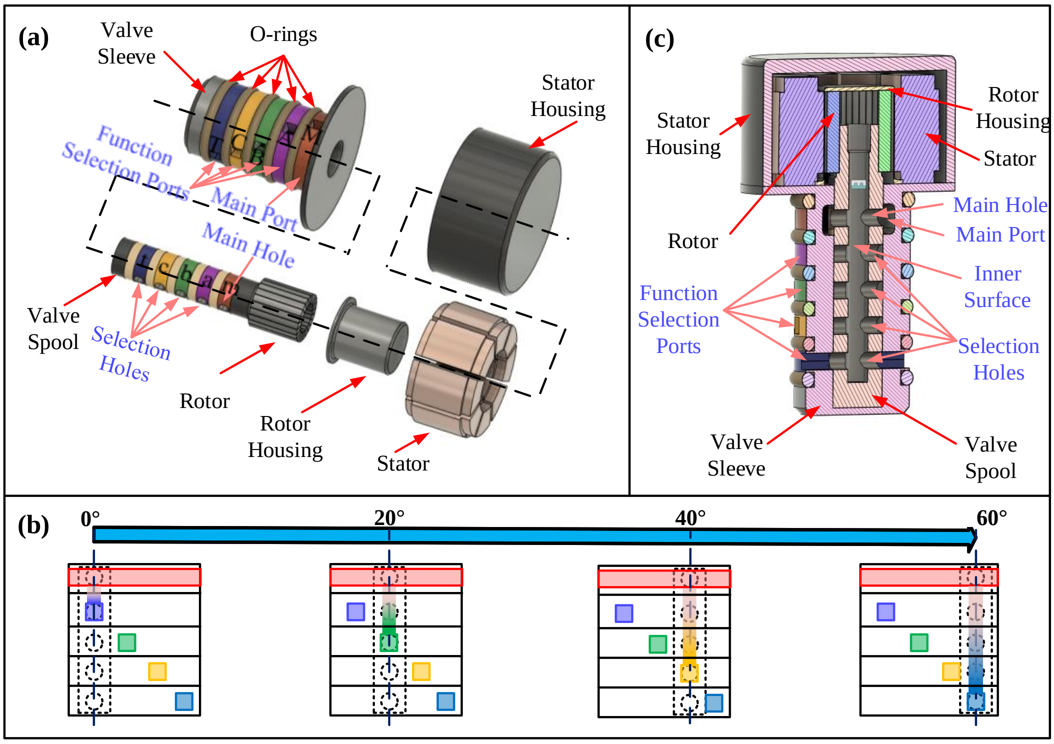

Figure 8 Structural composition of RSV.

accumulators with varying performance characteristics and the system's fluid outlet. Port M connects to the low-pressure (L) ports of both Rotary Direct-Drive Servo Valves (RDDSVs), receiving return flow from the hydraulic cylinder's dual load chambers. This integrated configuration enables system-wide stiffness matching while supporting IKPSA mode switching through coordinated pressure management.

The valve sleeve features helically distributed functional selection ports, spanning a total angle of 60°, with each port positioned at 20° intervals. To balance the hydrodynamic forces on the valve spool, an additional set of four corresponding functional selection ports is symmetrically distributed along the axis, maintaining identical angular arrangement.

The valve spool, located within the valve body, comprises an Inner Surface, eight Selection Holes, and one Main Hole. The Selection Holes and Main Hole facilitate fluid introduction into the Inner Surface and enable intercommunication. The rotor, rotor seat, sensors, and other components are directly connected to the valve spool, forming an integrated structure that rotates in response to controller commands. A magnetic encoder sensor is employed to detect the position of the valve spool relative to the sleeve, enabling the controller to determine the rotational motion.

The operational principle of the Rotary Switch Valve initiates with the controller selecting the desired stiffness level. Based on the position of the selection ports and information provided by sensors, the controller determines the required rotational angle for the valve spool and drives its rotation to align with the selected port. When the spool's selection opening aligns with the chosen port, it establishes a pathway between the internal chamber and the valve body, allowing fluid at the specific hydraulic stiffness level to access the control port.

The rotary rapid switching valve achieves high-speed fluid control through continuous rotational motion, while maintaining a compact structure with minimal spatial footprint.

3.4 Active-passive combined system integration

To enhance the actuator's integration level, an integrated housing was designed to incorporate various interfaces, control valves, accumulators, sensors, and the hydraulic cylinder using a tubeless configuration. Internal channels were engineered to interconnect these components, forming an integrated hydraulic circuit that fulfills the system's design requirements and functional objectives. The controller, mounted on the side of the integrated housing, manages mode switching and knee joint control of the IKPSA. Figure 9 (a)(b) presents the exploded view and cross-sectional diagram of the IKPSA, while Figure 9(c)(d)(e) illustrate schematic diagrams of each operational mode, respectively. A smulation model was established to analyze the performance characteristics of the IKPSA across various operational modes, with all performance simulations conducted under no-load conditions.

Considering the constraints of the existing lower limb platform, the specific parameters of the IKPSA are presented in the accompanying table.

Table 1 IKPSA's parameters

Parameter	Value
Rated pressure	21.0 MPa
Maximum output force	14000.0 N
Piston diameter	30.0 mm
Rod diameter	22.0 mm
Length of stroke	55.0 mm
Estimated weight	2.5 kg
Accumulator A volume	35.0 ml
Accumulator B volume	20.0 ml
Accumulator C volume	10.0 ml
Spool diameter of RDDSV	5.0 mm
Sleeve Maximum diameter of RDDSV	13.5 mm
Spool diameter of RSV	6.4 mm
Sleeve Maximum diameter of RSV	13.5 mm
Height of actuator	35 mm
Weight of actuator	142 mm

Figure 10 illustrates the temporal relationship between force and displacement of the IKPSA in active mode. Figure 10(a) shows the performance of IKPSA's rods during one cycle of active retraction. The blue line represents displacement, and the magenta color represents force. After the signal is obtained at 0.1s, the piston displacement is gradually retracted to the end of the stroke while the pull force is gradually increased to about 7000N. Figure 10(b) also shows the force versus displacement versus time when the rod of the IKPSA is actively extended during a cycle, with the blue line and magenta color having the same meaning as in graph (a). From the graph, it can be seen that after getting the signal at 0.1s, the piston rod gradually extends and reaches the maximum stroke at 0.86s, and the maximum thrust is able to reach 15000N at 1s.

Figure 11 illustrates the force-time characteristic curve of the IKPSA in burst mode, showing the force variation of the IKPSA during differential drive. A step signal is input to the IKPSA, and upon switching the control valve, the piston begins to move as hydraulic fluid flows in, causing the thrust to increase rapidly. At 0.5 seconds, the thrust force reaches a maximum of approximately 2,500 N, reflecting the maximum output force that the hydraulic cylinder can provide in differential drive mode.

The IKPSA's passive mode operation demonstrates its capacity to resist and absorb external disturbances through controlled mechanical response. Figure 12(a) compares force-displacement curves for two accumulator configurations, revealing distinct stiffness characteristics. Accumulator B's steeper curve indicates enhanced stiffness adjustability compared to Accumulator A, with measurable performance differences during pressurized retraction cycles. The system achieves tunable stiffness between 300 N/mm and 7000 N/mm through accumulator selection.

Moving on to Figure 12(b), this figure illustrates the adjustment of the damping characteristics of the IKPSA by driving the spool of the RDDSV to rotate in passive mode. The angle here is the rotational position of the spool, which controls the flow of liquid through the orifice. As can be seen, the spool rotation in the range of 20° ~ 48° allows a fast and wide range of adjustment of the damping force in the range of 500 ~ 20,000 N, and a fast and infinitely variable adjustment of the damping rate in the range of 40 N·s/mm ~ 2000 N·s/mm.

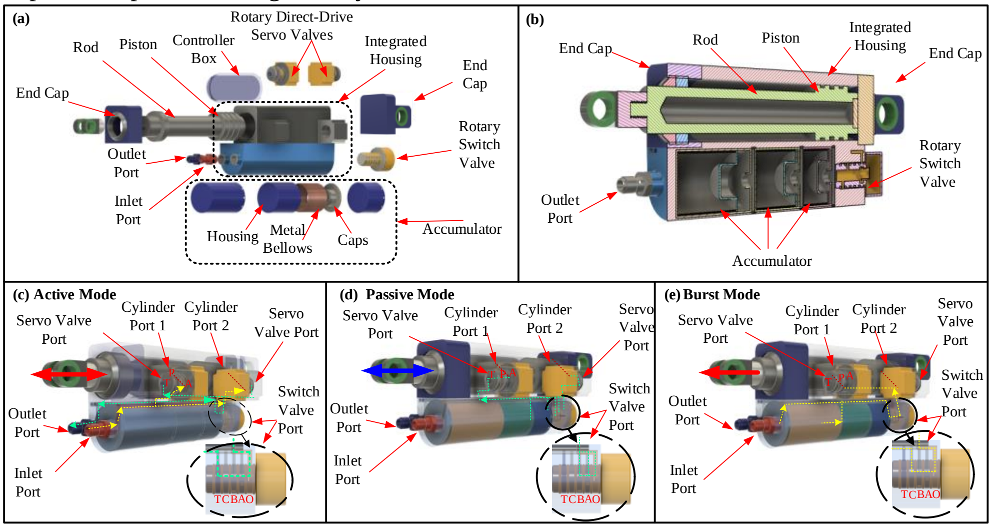

Figure 9 Structural composition of IKPSA and mode switch

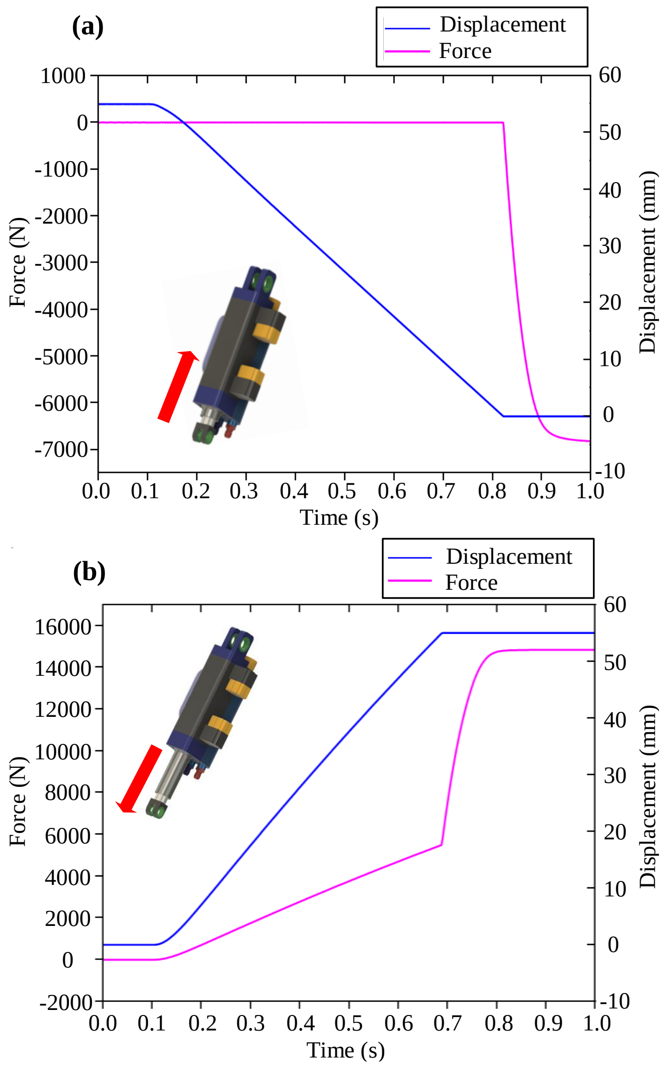

Figure 10 Relationship between force and displacement with time in Active Mode

Simulation data show that IKPSA can support the walking and vertical jumping functions of the biped robot by switching each mode.

4 DISCUSSION

The primary objective of this paper is to design an electro-hydraulic valve-controlled actuator with three modes of operation active, passive, and burst for the existing hydraulic bipedal robot lower limb platform. This design aims to achieve large load capacity, stiffness adjustment, damping adjustment, and high burst performance, inspired by the tasks and functions that human beings undertake during the gait cycle of walking and vertical jumping.

For bipedal robots, especially bipedal robots with large load capacity, in order to reduce the impact between the robot's lower limbs and the unknown environment, it is necessary to ensure that the body has a certain compliance, which is often neglected in the previous actuator design of hydraulic robots.

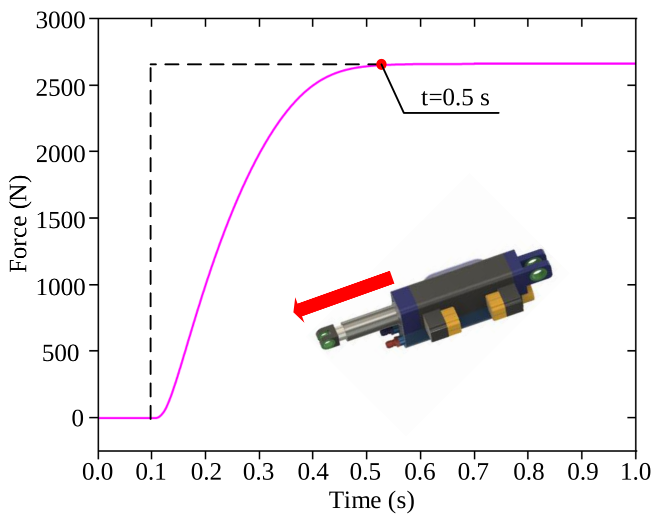

Figure 11 Force-Time Properties in Burst Mode

In IKPSA, through the design of parallel accumulators as well as RDDSVs, we achieve the compliance of the hydraulic knee with an active adjustment. The inherent advantage of hydraulic drives is their ability to carry large loads, but for the hydraulics, increasing the force-to-weight ratio and improving integration is always a goal to be pursued, and although the IKPSA's housing has been designed to maximise the high level of integration, the weight of the IKPSA was able to be further reduced by using a flow channel optimisation algorithm to calculate the flow channel, ditching the process hole technology, and using 3D printing technology, which will be realised in the next work. The IKPSA's modular architecture employs plug-and-play components and standardized interfaces to enhance both operational performance and maintenance efficiency in bipedal robots. This integrated design philosophy incorporates an embedded controller and hydraulic quick-connect couplings, enabling versatile actuator deployment across multiple robotic platforms. A key integration improvement stems from the implementation of cartridge-style rotary control valves with pivot shafts, which streamline hydraulic circuit configuration. The system features dual-functionality components where the Rotary Direct-Drive Servo Valve (RDDSV) simultaneously operates as a precision flow regulator and adaptive damping controller, while a single Rotary Switch Valve (RSV) replaces four conventional on/off valves. When synergized with advanced control algorithms, this optimized configuration demonstrates superior dynamic response characteristics compared to traditional hydraulic systems.

However, it cannot be denied that due to the relatively complex design of the hardware system, higher requirements have been imposed on the final overall machine control and the algorithms for active-passive switching.

5 CONCLUSION

In this paper, a valve-controlled electro-hydraulic actuator (IKPSA) with active-passive combination for bipedal robots is designed to provide different characteristics at different times, simulating the function of the human knee joint during walking and vertical jump cycles. The hydraulic principle, key basic components, and integrated performance of this actuator are described in detail. The compactness and light weight of the actuator system are enhanced by the integrated housing and the new Rotary Direct-Drive Servo Valve and Rotary Switch Valve to control fluid flow, resulting in a more responsive actuator system. The control system can output commands to the Rotary Switch Valve and Rotary Direct-Drive Servo Valve to control the length, stiffness, damping, and force of the hydraulic cylinder extension.

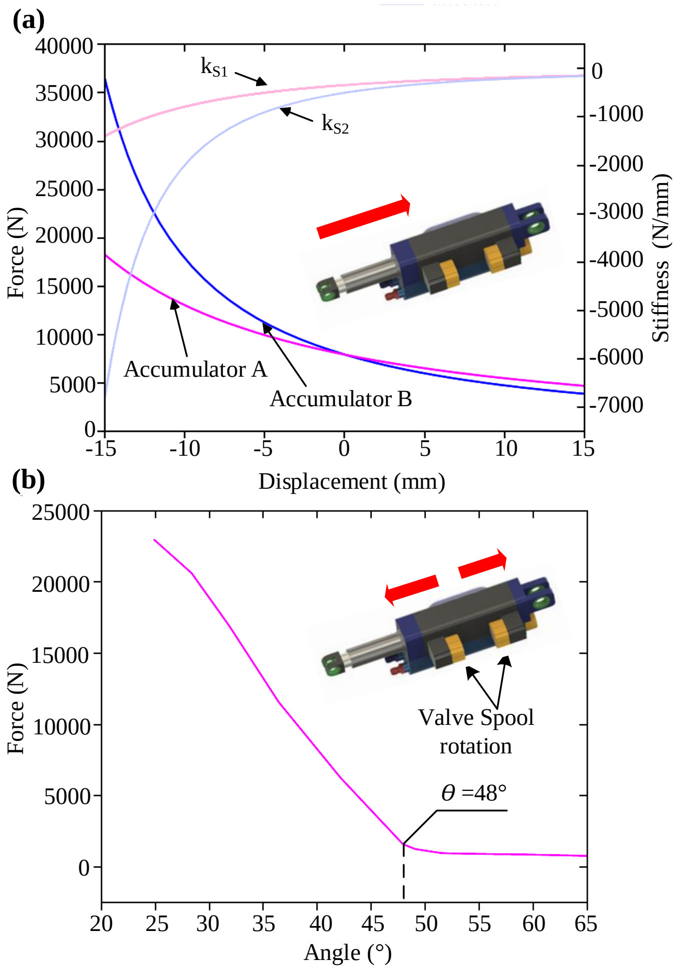

Figure 12 Passive mode (a) Stiffness characteristic curves with different accumulator switching (b) Damping characteristics at spool rotation angle

In IKPSA's active mode, the actuator can actively extend and retract to complete the swing phase of the walking cycle, and at the same time, it is capable of outputting a maximum thrust of 15,000N. In passive mode, the actuator absorbs the impact between the foot and the unknown environment, completes the stance phase of the walking cycle, and completes the landing phase of the vertical jump cycle. It is capable of actively adjusting the actuator stiffness from 1200 N/mm to 300 N/mm and infinitely adjusting the damping from 2000 N·s/mm to 40 N·s/mm. In Burst Mode, energy can be stored to deliver 2,500 N of thrust in 0.41s to complete the Take-Off Phase of the vertical jump.

Nomenclature

Designation	Denotation	Unit
F	Rod Force	N
P_i	Cylinder load chamber pressure	Pa
A_i	Piston area	mm^2
F_{visc}	viscous forces	N
m_{i}	Masses carried at hinge points	kg
k_s	Actuator stiffness	N/mm
x_{i}	Hinge point displacement	mm
c	damping ratio	N·s/mm
Q_i	Cylinder load chamber flow	Pa
V_{acc}	Accumulator volume	ml
A_C	Accumulator gas-liquid baffle contact area	mm^2
P_{pc}	Gas precharge pressure	bar
γ	polytropic index	-

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