Proceedings of the 4th International Conference on Machine Learning and Automation
DOI: 10.54254/2755-2721/2026.38381

Drive Structures and Whole-Body Coordinated Control Methods for Humanoid Robots

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Abstract. Humanoid robots require both high-performance drive structures and effective whole-body coordinated control to achieve dynamic motion, load transportation, and complex whole-body movements. This paper reviews the relationship between mechanical drive design and coordinated control methods for humanoid robots, with particular emphasis on the constraints imposed by actuator torque, mass distribution, transmission characteristics, and real-robot dynamics. At the hardware level, high-torque-density modular joints, lightweight transmissions, hybrid serial-parallel mechanisms, and drive-layout optimisation are examined in terms of their effects on joint torque, moving mass, and motion capability. At the control level, multi-joint coordinated motion control, model predictive control, reinforcement learning, and dynamics adaptation methods are discussed for maintaining stability and improving actuator utilisation under contact and joint constraints. The review further considers the differences between idealised simulation models and physical robots caused by friction, hysteresis, drive-torque deviations, contact compliance, and communication delays. The analysis indicates that drive structures establish the hardware boundaries of humanoid motion capability, while whole-body coordinated control determines how effectively these capabilities can be realised during operation. The paper therefore highlights the importance of integrated electromechanical and control co-design, including joint parameters, drive layouts, mass distribution, state estimation, and dynamics adaptation, as a potential direction for improving the robustness and efficiency of humanoid robots.

Keywords: Humanoid Robots, Drive Structures, Whole-Body Coordinated Control, High-Torque-Density Joints, Dynamics Adaptation

1. Introduction

Humanoid robots possess broad general-purpose compatibility due to their morphological structures and motion capabilities, which closely resemble those of humans. They hold considerable application potential in industrial manufacturing, social services, emergency rescue, and specialised operations [1]. However, fully exploiting this potential requires robots to achieve key motion capabilities, including rapid start and stop, load transportation, and complex whole-body movements. These capabilities depend not only on advanced control algorithms but also on hardware factors such as joint output torque, actuator mass, transmission efficiency, and overall

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DOI: 10.54254/2755-2721/2026.38381

mass distribution. In particular, during highly dynamic tasks, lower-limb joints must provide high instantaneous torque within strict size and weight constraints. High-power-density actuation and appropriate mechanical layouts therefore provide a critical foundation for improving robotic motion capabilities.

In recent years, structural research has increasingly focused on frameless torque motors, modular joints, low-inertia transmissions, and multi-joint coordinated actuation. Meanwhile, control research has begun to incorporate joint coordination, reinforcement learning, and online dynamics adaptation. These approaches aim to achieve better matching between control outputs and the friction, torque deviations, and dynamic response characteristics of real actuators [2].

Under highly dynamic task requirements, lower-limb joints must provide high instantaneous torque within limited size and weight constraints. However, conventional rigid torso designs restrict the motion and load-carrying capabilities of humanoid robots. To address this issue, Abdullah et al. proposed a bio-inspired compliant spine based on tensegrity structures. Its modular multi-segment design combines rigid struts with compliant cables, enhancing torso bending and lateral swinging capabilities while maintaining structural strength [3]. Tang et al. designed and analysed a high-torque-density joint for bipedal humanoid robots. By optimising electromagnetic and structural parameters, they improved the torque output per unit mass. These studies provide feasible hardware foundations for improving the explosive force, agility, and load-carrying capability of humanoid robots [4].

From the perspective of control, conventional control strategies are often based on idealised actuator models and therefore have difficulty adapting to friction, torque deviations, and dynamic response delays in real joints. To address this problem, Ji et al. introduced reinforcement learning to achieve robust and energy-efficient walking for a bipedal humanoid robot. The control policy can thereby adapt online to actuator nonlinearities. Other research has adopted hierarchical reduced-order model predictive control to improve the stability of dynamic walking while maintaining computational efficiency. These approaches effectively reduce the performance gap between control algorithms and physical hardware, thereby enhancing the motion robustness of robots in complex environments [5].

High-performance drive structures provide the hardware foundation for robotic motion capabilities, whereas whole-body coordinated control determines whether these hardware capabilities can be fully exploited during actual operation. Based on this relationship, this paper first analyses the effects of joint design and drive layout on motion output. The analysis covers the integrated design of high-torque-density modular joints and the reduction of joint loads through drive-layout optimisation. Whole-body coordinated control methods are then discussed, with particular emphasis on multi-joint coordination strategies and dynamics adaptation under real-robot conditions. Based on a systematic review of research on mechanical structures and control, this paper focuses on the intrinsic relationships and constraints between the two aspects and their effects on motion capability. The aim is to provide a useful reference for the coordinated design of electromechanical systems in humanoid robots.

2. High-performance drive structures of humanoid robots

2.1. High-torque-density modular joints

In very dynamic operating conditions like running and jumping, the actuation of the lower limbs of a humanoid robot should be able to generate a high enough instantaneous torque in frequent start and stop events to counteract the effects of gravity and friction. It may have an overload capacity of 10-

DOI: 10.54254/2755-2721/2026.38381

20 times the rated load. Concurrently, decreasing the lower-limb mass is crucial towards enhancing agility in motion. Joint units should consequently be able to attain the greatest possible torque density with a minimal size and weight. These are the demands that have led to the trend towards integrated designs of high-torque-density modular joints. The design incorporates fundamental elements, such as motors, reducers, bearings and encoders, into small actuation units. The objective of this method is to maximise the output torque and dynamic response and maintain the volume and mass.

Tang et al. designed and analysed a high-torque-density joint module of bipedal humanoid robots. The magnetic-circuit method and a multi-objective optimisation approach resulted in the team optimising the electromagnetic parameters of an outer-rotor frameless torque motor. In the case of the transmission system, a light high-reduction-ratio reducer was employed, which meant that the joint was able to generate high torque with relatively low motor speeds. In the meantime, the reducer, bearing, and encoder were positioned in a small mechanical integration scheme to fit in a coaxial arrangement. This was successful in decreasing the length of the axial dimension of the joint and limiting the redundant connecting elements. The experiment also created two highly combined modular joint designs, and implemented them on a humanoid robot with bipedalism. The work offers a viable engineering strategy of high-power-density integration of lower-limb joints of humanoid robots. The optimisation of magnetic circuit and choice of lightweight transmission components in particular have a lot of significance and gives direct reference to the further development of modular joints [4].

To enhance joint torque density, the optimisation of the motors and transmission components is only one part but also the structure of the joint mechanism. One of the studies introduced a new hybrid serial-parallel shoulder joint mechanism to satisfy the two needs of a large working area and a high carrying capacity of shoulder of humanoid robots. Serial and parallel branches were connected on the same branch, some actuation units were encountered on the base or proximal links, which minimized distal moving mass. The parallel branches were the same in the amount of external torque produced during the transportation of loads and support activities in the shoulder. The workspace analysis revealed that the hybrid configuration enhanced joint load-bearing stiffness without reducing its large range of motion. This study demonstrates that the performance of modular joints needs to be matched with the mechanism configuration and drive layout. Specifically, a suitable hybrid serial-parallel design, in the case of highly loaded upper-limb joints, can lower the torque load per actuation unit and mechanism-level assistance to the use of high-torque-density joints [6].

Top-limb robotic arm systems have also been designed using the concept of modular-joint design. One of the studies suggested a seven degree of freedom electrically powered design of a humanoid robotic arm. The design was targeted towards joint-module selection, driving set-up, and arm-structure integration. The design incorporated the drive motor and reducer within or near the joint reducing end effector dynamic response and distal inertia. This paper shows that the high-torque-density modular joints can be used in lower-limb motion joints, as well as, in multi-degree-of-freedom dexterous manipulation of the upper limbs. It is thus a good source of information on the system-level modular and lightweight design of drive-structures [7].

2.2. Drive layout and joint load optimisation

Modular joints are developed to give the hardware base of high-torque output, and joint-load optimisation and drive layout to give the utilisation of torque at the whole-robot level. The location of actuators, cross-sectional shapes and sizes of links, joint configurations and coupling of motions

DOI: 10.54254/2755-2721/2026.38381

between joints all have an impact on the load properties and dynamic response of each joint in real motion. The motion efficiency and stability of the whole robot can be improved, without altering the hardware configuration, by optimisation of mass distribution and motion allocation to minimise peak torce needs at local joints.

To explore the relationship between structural parameters and control performance of bipedal robots, SUN et al. suggested a design optimisation strategy using joint coordinated control. The study systematically tested the actuator installation locations and link geometries during a closed-loop iterative process that included control-algorithm design, simulation-platform validation and structural-parameter optimisation. In the case of a hip joint, the research team suggested a coordinated-drive structure and compared analytically joint loads during various drives structures in a simulation platform. It was found that the coordinated design that minimized the peak torque demand of the hip-yaw motor by about 40%. By reducing the peak torque, higher power density and lower mass motors and reducers can be chosen. This in turn decreases joint rotational inertia and establishes a positive design cycle where less mass and less mass reinforcement by less load.

To estimate the state, the paper used a combination of timing and event-detection to accurately identify the point of ground contact. Joint-encoder data and inertial measurement unit data were also fused using a Kalman filter which effectively estimated the state of motion of the robot. The result of the simulation also revealed that the error position was less than 1 percent in a 10 m range. It is based on this that the research team created a real bipedal robot and experimentally validated the system, which demonstrated the practicability of the suggested system under a real system [8].

The ankle is a vital part of a humanoid robot at the joint level to help sustain and propel the robot. It is greatly dependent on its design parameters in terms of lower-limb load distribution. One of the studies suggested an optimisation model of the ankle joint of humanoid robots. Design variables were chosen to be the stiffness of the series elastic element, the geometry of the parallel linkage and at what point the drive motor should be installed. Optimisation objectives were stability in the support phase, peak drive torque and propulsion efficiency. Then a multi-objective optimisation was used to find the set of Pareto-optimal solutions. The outcome of the simulation suggested that the optimised ankle joint had the capability of decreasing peak ankle drive motor torque requirement during walking and support-phase stability. It also enhanced the apportionment of the plantar forces. This paper presents a joint-level design technique of the drive-layout and load optimisation in a systematic way. It is used to complement drive-layout optimisation on the entire robot scale [9].

Ji et al. discussed the main purpose of drive-layout optimisation in the light of control strategy: how to ensure that control outputs are more tuned to the intrinsic physical properties of actuators. The team created a walking controller designed on reinforcement learning of a bipedal humanoid robot. Its major innovation was that, it trained an actuator network with actual joint drive-torque data thus successfully closing the gap between desired torque and actual torque output. The method fills in the nonlinear and hysteretic behavior of the layout and transmission of the drive system at the control level. This enables the advantages of hardware level optimisation to be better realised in the real operation. The results of experiments revealed that the experimental control strategy provided robust and energy efficient bipedal walking with only proprioceptive information. The robot was also able to adapt to rough terrain [2].

Peak joint loads may be reduced through drive-layout optimisation at the hardware level, and adaptation to actuator characteristics enhanced by reinforcement-learning and other control strategies at the software level. The two technical approaches are not independent since they complement one another. On the one hand, structural design offers better hardware-boundary

DOI: 10.54254/2755-2721/2026.38381

conditions of control algorithms. Control methods, on the other hand, give quantitative feedback of the output of structural optimisation. This bi-directional connection offers a good technical channel through which the overall efficiency of motion of humanoid robots can be enhanced.

3. Whole-body coordinated control of humanoid robots

3.1. Multi-joint coordinated motion control

Whole-body coordinated control considers a humanoid robot a coupled multibody system comprising of the hips, knee, ankle, torso and upper limbs. It aims at the coordination of the distribution of whole-body linear momentum, angular momentum, and contact forces subject to contact constraints, joint limits, and actuator saturation. There are relevant reviews that show that embodied intelligence in humanoid robots implies coordinated development of mechanics, perception and control [10].

The primary support and propulsion during bipedal locomotion is primarily through the hips, knees, and ankles. Angular momentum is controlled by the torso and the reaction forces produced by the lower limb are counterbalanced by the upper limbs, as the arms swing. Using ankle joints alone as a source of balance may readily lead to an overload of the torques. Predictive control with ankle, hip and stepping strategies can be used in predictive control to allow selection of appropriate balancing actions in the presence of disturbances, thus spreading the actuator load [11].

The HROM predictive control is hierarchical and provides reduced-order computational demands online yet is dynamically stable in walking and has provided a foundation of real-time whole-body coordination. Multi-constraint model predictive control is applied to contact forces, friction cones and joint constraints across the prediction horizon, allowing the physical feasibility of lower-limb and torso motion [12]. In the light of model predictive control, these methods reveal that contact, joint and actuator constraints must be taken into account as part of a single optimisation machine that would enable successful whole-body coordination.

Learning-based approaches can extend the range of coordination once model predictive approaches are able to offer a framework to manage constraints. Whole-body motion imitation systems learn the motion priors of human data, scale the resulting motions to full-size humanoid robots, and coordinate the upper limbs, torso, and lower limbs by using redundant degrees of freedom [13]. Whole-body control frameworks based on keyframe control plan complex actions in a small set of key poses, making it easier to plan in high-dimensional joint space [14].

Whole-body skill generation using reinforcement-learning can be used to generate whole-body skills in various tasks, where different parts of the body can be involved in the generation of action together [15]. To enhance locomotion on rough surfaces, dynamic balance can be used in conjunction with reinforcement learning to allow the torso and upper limbs to be involved in balance control and enhance capability to negotiate unstructured terrain [16]. LSTM networks with reinforcement learning methods incorporate temporal information to organize whole-body movement to enhance continuity and stability of multi-joint movements [17]. Ji et al. suggested a bipedal humanoid robot that has walking control through reinforcement-learning. The policy was based solely on proprioceptive information and demonstrated strong and energy-efficient walking on uneven surfaces. This method illustrates that learning-based controllers have the ability to coordinate joint outputs of the lower limbs without necessarily modeling all of the contact states, which eliminates the effects of model errors on walking behavior [2].

Structural-level coordinated design may also minimize actuator loads. The optimisation of the whole-robot reported by SUN et al. demonstrated that coordinated hip driving decreased the peak

DOI: 10.54254/2755-2721/2026.38381

torque of the yaw motor by a factor of about 40, and the position error was less than 1% over a range of 10 m [8]. The proposed ankle optimisation framework by Cervettini et al. minimised the peak-torque during the support phase and enhanced the distribution of plantar-force where the stiffness of the series elastic element, parallel-linkage geometry and the position of the motor installation played a role. These findings suggest that coordinated drive layouts and multi-joint coordinated control can be used to enhance efficiency in the utilisation of drives and the overall coordination of whole-body motions [9].

3.2. Optimisation of dynamics correction and control

Simulation models and real robots differ in the friction, hysteresis, deviations of drive-torque, contact compliance, and communication delays. When reinforcement-learning policies are directly trained in idealised simulations, gait degradation or torque saturation may often happen once the policies are transferred to the real robot.

To minimize this gap, one of the strategies is to correct control outputs with real actuator data. In bipedal walking control Ji et al. trained a network of actuators using joint drive-torque data. The network made up the difference between desired and actual outputs of the torque, enabling the policy to keep the walking robust and energy-efficient with the help of proprioceptive information. This method brings in actuator nonlinearities to the learning loop as opposed to the assumption that the joints can generate optimal torque [2].

Along with actuator-data compensation, online dynamics adaptation is an option. A study that combined contact-rich motion priors with online dynamics adaptation enabled the policy to adapt to the dynamics of real hardware without losing the desired motion style [18]. Contact priors give an array of reference structure of the whole-body motion, whereas the online adaptation estimates or compensates the variation of friction, load, and drive response. This aids in minimizing the sim-to-real gap.

Another important role of state estimation is dynamics correction. SUN et al. combined the data of joint-encoders and inertial measurement unit and obtained a position error of less than 1% in a distance of 10 m. This offered comparatively trustworthy condition responses in online dynamics compensation and whole-body control. Multi-constraint model predictive control has the capability of reallocating contact-force and joint-torque based on state estimates in a receding horizon, thus enhancing constraint satisfaction [8, 12].

Reinforcement-learning control policies can be used to provide better motion performance on hardware through the combination of actuator-data compensation, dynamics online dynamics adaptation and state estimation. The gains achieved in structural optimisation of the torque and mass can be more conveniently converted into real motion capability.

4. Conclusion

This paper reviews the mutual constraints between drive structures and whole-body coordinated control in response to the motion requirements of humanoid robots performing highly dynamic tasks, transporting loads, and executing complex whole-body movements. At the hardware level, high-torque-density modular joints improve instantaneous torque output within limited size and mass through magnetic-circuit optimisation of frameless torque motors, lightweight high-reduction-ratio transmissions, and coaxial integration.

The bio-inspired compliant spine enhances torso bending and lateral swinging through a combination of modular segments, rigid struts, and compliant cables. Hybrid serial-parallel shoulder

DOI: 10.54254/2755-2721/2026.38381

joints and seven-degree-of-freedom electrically driven arms place some actuation units on the base or proximal links. This reduces distal moving mass, while the parallel branches share the load. At the whole-robot level, coordinated hip driving reduces the maximum torque requirement of the yaw motor by approximately 40%, with a position error below 1% within a range of 10 m. Multi-objective ankle optimisation reduces peak torque during the support phase and improves plantar-force distribution.

At the control level, hierarchical reduced-order model predictive control reduces online computational requirements while maintaining dynamic walking stability. Multi-constraint model predictive control incorporates contact forces, friction cones, and joint constraints into a unified optimisation framework. Predictive control based on ankle, hip, and stepping strategies can distribute actuator loads. Learning-based methods improve the continuity of multi-joint movements and environmental adaptability through human motion imitation, keyframe-based organisation, whole-body skill generation, dynamic balance on narrow terrain, and LSTM-based temporal coordination.

After training a network using real actuator torque data, a bipedal robot can compensate for deviations between desired and actual torque outputs. It can also achieve robust and energy-efficient walking using proprioceptive information. These results indicate that structural design establishes the hardware boundaries, while control strategies determine the extent to which performance within those boundaries can be realised.

Existing research shows that structural optimisation and control design are still often developed separately. Differences remain between simulation models and real hardware in terms of friction, hysteresis, drive deviations, contact compliance, and communication delays. Actuator nonlinearities and online computational demands can limit the practical performance of highly dynamic whole-body movements.

Future research could promote integrated electromechanical and control co-design by jointly optimising joint parameters, drive layouts, mass distribution, and predictive-control or learning strategies within a single closed loop. Multi-source information fusion should also be strengthened. For example, joint torque, encoder, and inertial measurement unit data could be used for online identification and dynamics correction. This could improve the reliability of state feedback and extend the accuracy advantage of less than 1% error within a 10 m range to more complex scenarios.

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