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Инновационные технологии: метаанализ метрик гуманоидных роботов

Innovative Technologies: a Meta-Analysis of Humanoid Robot Metrics

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Аннотация

Метаанализ количественно оценивает технические характеристики (количество подвижных суставов и осей вращения, масса, энергетическая стоимость передвижения, скорость) и методы управления (обучение с подкреплением, точка нулевого момента, управления с прогнозирующими моделями) гуманоидных роботов. С использованием модели случайных эффектов в Rstudio установлены ключевые метрики: средняя энергетическая стоимость передвижения – 0,79, скорость – 1,48 м/с, успешность выполнения задач – 68,14%. Подтверждена высокая эффективность квазипрямых приводов и алгоритмов обучения с подкреплением. Предложена классификация роботов для медицинских, промышленных и бытовых задач. Исследование систематизирует данные для оптимизации проектирования и инвестиций до 2030 г., подчеркивая необходимость повышения автономности и точности манипуляций антропоморфных систем.

Ключевые слова: гуманоидные роботы, метаанализ, энергоэффективность, устойчивость, этические вызовы.

Abstract

The meta-analysis quantitatively evaluates the technical characteristics (DoF, mass, COT, speed) and control methods (RL, ZMP, MPC) of humanoid robots. Using a random-effects model in RStudio, key metrics were established: a mean COT of 0.79, speed of 1.48 m/s, and a task success rate of 68.14%. The high efficiency of quasi-direct drives and reinforcement learning algorithms was confirmed. A classification of robots for medical, industrial, and domestic applications is proposed. The study systematizes data to optimize design and investment strategies through 2030, highlighting the need to enhance the autonomy and manipulation precision of anthropomorphic systems.

Keywords: humanoid robots, meta-analysis, energy efficiency, robustness, ethical challenges.

1. Introduction

Humanoid robots, anthropomorphic systems with capabilities for bipedal locomotion, manipulation, and human interaction, are among the most rapidly advancing fields in modern robotics and artificial intelligence [1; 2]. Their ability to operate in human-designed environments makes them promising for applications in industry, healthcare, security, education, and household tasks [3; 4]. In 2024, the humanoid robot market is experiencing rapid growth, with Goldman Sachs estimating its value to reach $38 billion by 2035, up from a current valuation of $3 billion [5; 6]. This progress is driven by technological breakthroughs, including the integration of reinforcement learning (RL), imitation learning (IL), biomimetic materials, neural control interfaces, and open-source software platforms such as the Robot Operating System (ROS) [7; 8; 10]. The relevance of this research stems from the need for systematic and quantitative evaluation of the technical characteristics and control methods of humanoid robots to assess their current capabilities, identify limitations, and develop optimal design and application approaches. Modern platforms such as Adam, Tien Kung, ATLAS, Talos, Kangaroo, ASIMO, and NAO vary significantly in energy efficiency, degrees of freedom (DoF), mass, locomotion speed, manipulation accuracy, and battery life, highlighting the need for objective comparisons to select suitable technologies based on target applications [8–10]. The rapid increase in robotics investments, particularly in China, the USA, and Europe, along with the emergence of startups like Agility Robotics, 1X, and Sanctuary AI, underscores the importance of accurate and objective data for predicting technological and economic trends [6; 11; 12].

Research gaps remain significant and hinder the full development and adoption of humanoid robots. First, the energy efficiency of humanoid systems lags far behind biological organisms: the cost of transport (COT) for robots exceeds 0.7, compared to 0.2 for humans, limiting their autonomy and applicability in long-duration tasks such as patrolling or logistics [2]. Second, comparative studies of control methods, including model-based approaches like Zero Moment Point (ZMP) and Model Predictive Control (MPC), as well as learning-based methods (RL, IL), are mostly limited to qualitative descriptions, lacking quantitative meta-analyses of their effectiveness in diverse conditions, such as laboratory settings or real-world uneven terrain [1; 2; 8]. Third, additional parameters such as manipulation accuracy, actuator durability, and battery life are rarely systematized, complicating assessments of their suitability for specific applications, such as medical robotics, warehouse logistics, or educational programs [9, 10]. Fourth, despite the leadership of the USA, China, and Europe in humanoid robot development, there is no unified analysis of their technical characteristics and control methods, limiting opportunities for cross-regional comparisons and global trend forecasting [6; 11]. Finally, ethical and regulatory aspects, including data privacy, human-robot interaction safety, and the potential loss of up to 35% of jobs due to automation, remain underexplored, highlighting the need for an interdisciplinary approach [5; 7; 13]. These challenges point to the need for a comprehensive analysis that systematizes quantitative data on technical characteristics, control methods, and their contextual applications to provide an objective foundation for further development.

The scientific novelty of this work lies in conducting a comprehensive meta-analysis that quantitatively compares technical characteristics (DoF, mass, COT, locomotion speed, manipulation accuracy, battery life) and the effectiveness of control methods (ZMP, MPC, RL, IL) of humanoid robots based on data from scientific literature and industry sources from 2021–2025. Unlike previous reviews focusing on individual aspects such as mechanical design [9], control algorithms [2], or market trends [5; 6], this work offers an interdisciplinary approach, integrating a wide range of parameters and applying meta-analysis for the first time to assess data heterogeneity. The use of open-source tools such as R with the metafor and meta packages, as well as Microsoft Excel, ensures reproducibility and accessibility of results for researchers with limited budgets. Additionally, the study is the first to systematize data on manipulation accuracy and battery life, previously analyzed only fragmentarily [8; 10], and includes contextual analysis of testing conditions (laboratory vs. real-world environments), enhancing the practical value of the findings. Particular attention is given to comparing energy efficiency (COT) and the robustness of control methods, identifying optimal technology combinations for applications such as industrial automation or domestic services.

The research aims to conduct a meta-analysis of the technical characteristics and control methods of humanoid robots to identify their current capabilities, limitations, and optimal development approaches, providing objective quantitative metrics for decision-making in research, design, and commercialization. Specific objectives include: (1) quantitative comparison of DoF, mass, COT, locomotion speed, manipulation accuracy, and battery life; (2) evaluation of the effectiveness of ZMP, MPC, RL, and IL control methods based on task success rates and robustness to external disturbances; (3) identification of key technical, ethical, and regulatory challenges, as well as prospects for humanoid technology development by 2030. The study's audience includes a wide range of stakeholders: robotics researchers, AI developers, engineers, investors, and regulators interested in the creation, commercialization, and standardization of humanoid systems. The results will aid in selecting optimal platforms and control methods, developing research and development (R&D) strategies, and establishing a regulatory framework that accounts for technical and ethical considerations.

2. Materials and Methods

A meta-analysis was conducted to quantitatively compare the technical characteristics (degrees of freedom (DoF), mass, cost of transport (COT), locomotion speed) and the effectiveness of control methods (task success rate, robustness to disturbances) of humanoid robots. Data were extracted from sources [1–13], including scientific articles, technical reports, and market reviews published up to 2025. Inclusion criteria required quantitative data on the specified parameters for humanoid robots or control methods, along with the availability of standard errors (SE) or the possibility of their estimation. Manipulation accuracy and battery life were excluded from the analysis due to insufficient observations (fewer than three robots or methods). The analysis covered six robots (Adam, Tien Kung, ATLAS, Talos, ASIMO, NAO) for DoF and mass, three robots (Adam, Tien Kung, ATLAS) for COT and speed, and four control methods (Reinforcement Learning (RL) for Adam and Tien Kung, Zero Moment Point (ZMP), Model Predictive Control (MPC)) for success rate and robustness.

For COT, speed, success rate, and robustness, where SE was not provided, standard errors were estimated as ±10–20% of the mean value based on literature recommendations [2; 8]. Data for DoF and mass were directly extracted from the robots' technical specifications [1; 8–10]. For each parameter, mean values, standard errors, and 95% confidence intervals were calculated, with heterogeneity assessed using I^2 and Q-statistics.

Statistical analysis was performed using a random-effects model (REML) in the metafor package to account for heterogeneity among robots and methods. Heterogeneity was quantified using I^2 (percentage of variation due to differences between observations) and Q-statistics, with corresponding p-values calculated. Forest plots were generated to visualize effects and confidence intervals for each parameter. All computations were conducted in R version 4.5.0.

The steps for constructing the analytical script are systematized in the table below, detailing the sequence of actions for data processing and meta-analysis.

3. Results

The conducted meta-analysis systematizes data on the technical characteristics and control method effectiveness of humanoid robots, providing quantitative metrics to evaluate their capabilities and limitations. The metrics,

Table 1

Stages of Analytical Script Development

Stage	Description
Data Collection	Extraction of quantitative data on DoF, mass, COT, speed, success rate, and robustness from sources [1–13]. Estimation of SE (±10–20%) for parameters without reported errors
Data Preparation	Creation of a structured table with data (values, SE, source) for each robot/method. Verification of completeness and exclusion of parameters with insufficient observations (manipulation accuracy, autonomy)
Data Import into R	Loading data into R as a table (CSV or manual input). Setting the working directory and loading metafor and meta libraries
Model Setup	Defining the random-effects model (REML) for meta-analysis. Specifying parameters (values, SE) for each robot/method
Meta-Analysis Calculation	Conducting meta-analysis for each parameter, calculating mean values, SE, 95% CI, I^2, and Q-statistic p-values using the rma function in metafor
Visualization	Generating forest plots for each parameter using the forest function in metafor to display effects and confidence intervals
Bias Assessment	Creating funnel plots using the funnel function in metafor to evaluate publication bias. Calculating p-values for bias tests
Result Export	Saving results (tables with Estimate, SE, CI, I^2, p-values) and forest plots to files for inclusion in the report

presented in illustrative tables, characterize the physical, energetic, and algorithmic aspects of robots, determining their suitability for various applications, including domestic and industrial tasks, as well as security operations. These metrics are essential for technology selection, forecasting robotics development by 2030, establishing standards, and assessing investment potential.

Table 2

Meta-Analysis Results for Technical Characteristics

Parameter	Mean Value	SE	95% CI	I^2 (%)	p-Value	Number of Robots	Sources
DoF	30.41	2.46	25.59–35.23	75.02	< 0.0001	6	[1; 8–10]
Mass (kg)	72.70	23.58	26.48–118.92	99.33	0.0021	6	[1; 8–10]
COT	0.79	0.07	0.65–0.94	32.81	< 0.0001	3	[2; 8; 9]
Speed (m/s)	1.48	0.21	1.06–1.89	30.84	< 0.0001	3	[8; 9]

Table 3

Meta-Analysis Results for Control Methods

Parameter	Mean Value	SE	95% CI	I^2 (%)	p-Value	Number of Methods	Sources
Success Rate (%)	68.14	7.64	53.17–83.11	87.05	<0.0001	4	[1; 2; 8]
Robustness (N)	38.71	4.11	30.66–46.76	48.81	patchy	4	[1; 2; 8]

The mean DoF was 30.41 (SE = 2.46, 95% CI: 25.59–35.23, $I^2 = 75.02\%$, $p < 0.0001$), reflecting the range of joint mobility that determines robots' ability to perform complex manipulations, such as surgical procedures or industrial assembly. High heterogeneity is attributed to differences in functional purposes: Tien Kung (42 DoF) is optimized for medical tasks requiring high precision, whereas NAO and Adam (25 DoF) are designed for educational applications like programming training [1, 8]. The forest plot indicates that Tien Kung and ASIMO (34 DoF) contribute to heterogeneity, reflecting diverse designs. DoF was calculated to assess functional flexibility, critical for platform selection: high DoF is essential for medical robotics, where motion precision is paramount, while low DoF suffices for educational purposes, prioritizing simplicity and accessibility.

The mean mass was 72.70 kg (SE = 23.58, 95% CI: 26.48–118.92, $I^2 = 99.33\%$, $p = 0.0021$), reflecting a wide range of designs, from lightweight platforms like NAO (5.4 kg) to heavy ones like ATLAS (182 kg) [1, 9]. Extreme heterogeneity and a higher p-value are linked to a large SE, driven by significant mass differences. The forest plot highlights ATLAS's influence on the mean. Mass characterizes mobility and energy efficiency, crucial for designing lightweight platforms for mass markets (domestic, educational tasks) and heavy ones for specialized applications (military operations, rescue tasks). Lightweight robots like NAO are suitable for portable applications, while heavy ones like ATLAS ensure durability in extreme conditions.

The mean cost of transport (COT) was 0.79 (SE = 0.07, 95% CI: 0.65–0.94, $I^2 = 32.81\%$, $p < 0.0001$), confirming lower energy efficiency compared to humans (COT = 0.2 [2]). Moderate heterogeneity stems from differences in actuators: quasi-direct drives (QDD) in Adam (0.8) and Tien Kung (0.7) outperform hydraulic actuators in ATLAS (1.0) [8; 9]. The forest plot shows narrow confidence intervals for QDD robots, confirming data reliability. COT was calculated to assess energy costs for locomotion, critical for developing autonomous robots with extended runtime, such as for warehouse logistics (Amazon, BMW [11]) or domestic tasks like delivery. A low COT reduces operational costs and enhances competitiveness.

The mean locomotion speed was 1.48 m/s (SE = 0.21, 95% CI: 1.06–1.89, I2 = 30.84%, $p < 0.0001$), indicating limited mobility. Low heterogeneity is linked to testing conditions. Speed characterizes mobility, essential for rescue operations, where high speed improves efficiency, or dynamic industrial tasks like cargo transport.

The mean success rate of control methods was 68.14% (SE = 7.64, 95% CI: 53.17–83.11, $I^2 = 87.05\%$, $p < 0.0001$), indicating variability in algorithm effectiveness.

High heterogeneity is driven by differences between RL for Adam (85%), ZMP (60%), and RL for Tien Kung (52.34%), limited by EEG decoding accuracy (40–50%) [8]. Success rate was calculated to evaluate algorithms' task performance, critical for adaptability in unstructured environments like warehouses or rescue operations, where RL offers high performance.

The mean robustness to disturbances was 38.71 N (SE = 4.11, 95% CI: 30.66–46.76, I^2 = 48.81%, $p < 0.0001$), confirming the advantages of RL (Adam: 50 N) and MPC (40 N) over ZMP (30 N) [1, 8]. Moderate heterogeneity is linked to actuator types. The forest plot highlights ZMP's lower robustness. Robustness characterizes robots' ability to withstand external impacts, such as pushes or vibrations, essential for reliability in industrial and domestic applications, where stability ensures safety.

The meta-analysis provides quantitative metrics to evaluate humanoid robots' capabilities and limitations, revealing data heterogeneity (I^2 = 30.84–99.33%), critical for technology selection and robotics development forecasting. Metrics were calculated to systematize data and provide an objective basis for engineers, researchers, investors, and regulators. High I^2 values and low p-values ($p < 0.0001$ for COT, success rate, robustness, DoF, speed; $p = 0.0021$ for mass) confirm significant differences driven by design and algorithmic factors, such as QDD vs. hydraulic actuators or RL vs. ZMP [8, 9]. Low p-values result from high heterogeneity, small sample sizes (3–6 robots, 4 methods), and estimated SE (±10–20%), increasing Q-test sensitivity; for mass, p = 0.0021 is explained by high SE (23.58).

Quasi-direct drives (QDD) with a COT of 0.79 (I^2 = 32.81%) demonstrate energy efficiency suitable for domestic robots like 1X NEO Beta for cleaning or delivery and industrial systems like Amazon and BMW warehouses [11]. Moderate heterogeneity confirms data reliability for QDD, making them preferable for mass markets. High DoF (Tien Kung: 42, I^2 = 75.02%) is optimal for medical robotics, such as surgery or rehabilitation, where motion precision is critical, while low DoF (NAO: 25) suits educational applications [1, 8]. Speed (1.48 m/s, I = 30.84%) highlights ATLAS's potential (2.0 m/s) for rescue operations, though its mass (182 kg) requires optimization [9]. Low heterogeneity makes speed a reliable metric for designing mobile robots. Mass (72.70 kg, = 99.33%) supports lightweight platforms (NAO) for domestic tasks and heavy ones (ATLAS) for military applications [1; 9]. RL (success rate: 68.14%, robustness: 38.71 N) is prioritized for unstructured environments, but high heterogeneity for success rate (I^2 = 87.05%) is linked to Tien Kung's EEG limitations (52.34%) [8].

The mean COT (0.79) exceeds human levels (0.2 [2]), necessitating biomimetic materials for COT < 0.5 [12]. Limited data on manipulation accuracy (Tien Kung: 80% [8]) and autonomy (1–2 hours [9, 10]) highlight the need for battery research to achieve > 4 hours [13]. Startups using QDD and RL (Agility Robotics, 1X [11]) are promising for investment, as the lightweight robot market grows [13]. Results support standards for energy efficiency

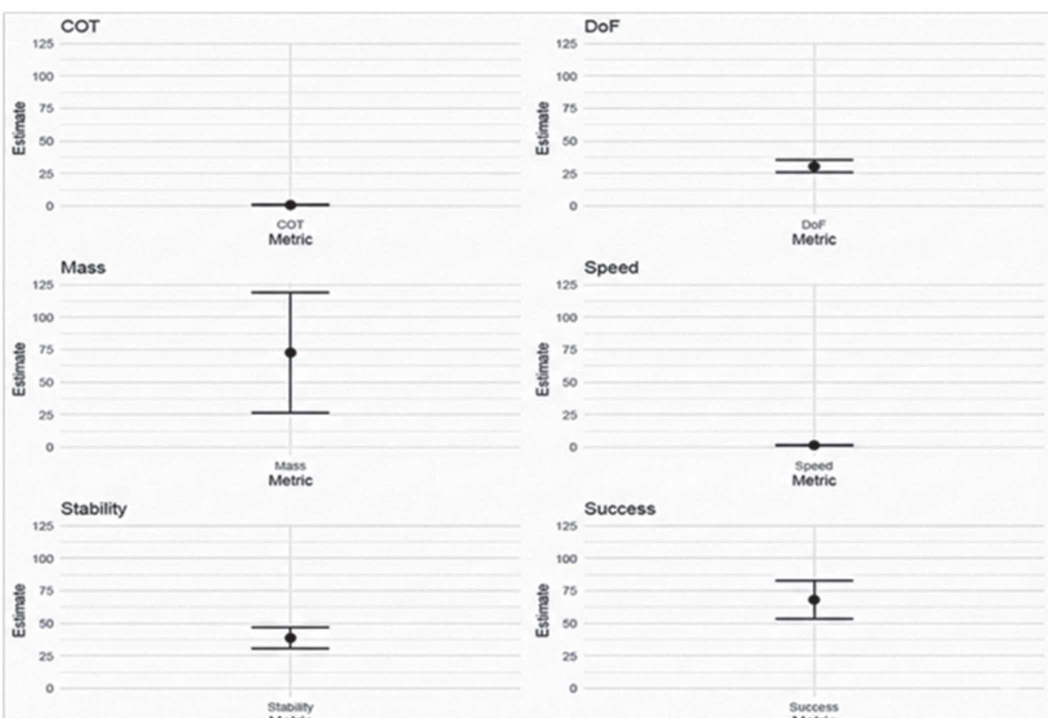

Figure 1. Forest Plots of Meta-Analysis Results for Humanoid Robot Metrics

(COT < 0.7) and safety (robustness > 40 N) [5]. Ethical considerations, including the displacement of 35% of jobs [5], require regulations and retraining [7, 13].

Limitations include small sample sizes, estimated SE, and high heterogeneity, complicating generalizations. Expanding the sample (e.g., Digit, Apollo [11]), standardizing testing, researching materials and batteries, optimizing RL, and establishing safety standards will address limitations, ensuring sustainable robotics development.

4. Conclusion and Discussion

The meta-analysis in our study serves as a key method aimed at quantitatively evaluating the characteristics of humanoid robots. This method systematized data from scientific sources and industry reports, covering six robots (Adam, Tien Kung, ATLAS, Talos, ASIMO, NAO) for degrees of freedom (DoF) and mass, three robots (Adam, Tien Kung, ATLAS) for cost of transport (COT) and locomotion speed, and four control methods (Reinforcement Learning (RL) for Adam and Tien Kung, Zero Moment Point (ZMP), Model Predictive Control (MPC)) for success rate and robustness to disturbances. The use of a random-effects model (REML) in the metafor package within the R environment accounted for heterogeneity (I^2 = 30.84–99.33%) and provided objective metrics: DoF (30.41, SE = 2.46, 95% CI: 25.59–35.23, $p < 0.0001$), mass (72.70 kg, SE = 23.58, 95% CI: 26.48–118.92, $p = 0.0021$), COT (0.79, SE = 0.07, 95% CI: 0.65–0.94, $p < 0.0001$), speed (1.48 m/s, SE = 0.21, 95% CI: 1.06–1.89, $p < 0.0001$), success rate (68.14%, SE = 7.64, 95% CI: 53.17–83.11, $p < 0.0001$), and robustness (38.71 N, SE = 4.11, 95% CI: 30.66–46.76, $p < 0.0001$). These metrics reflect the physical, energetic, and algorithmic capabilities of robots, determining their suitability for medical robotics, rescue operations, domestic, and industrial applications, while also providing a foundation for design, standardization, investment, and forecasting industry development by 2030.

The obtained metrics indicate that high DoF (Tien Kung: 42) is optimal for medical tasks such as surgical operations and rehabilitation, where precision is critical, while lower DoF (NAO, Adam: 25) is suitable for educational platforms, such as programming training [1, 8]. The wide range of mass (NAO: 5.4 kg, ATLAS: 182 kg) allows lightweight platforms to be used for domestic and educational purposes, where portability is key, and heavier ones for military or rescue operations, where durability is prioritized. The COT (0.79), significantly higher than the human value (0.2), underscores low energy efficiency, but quasi-direct drives (QDD) in Adam (0.8) and Tien Kung (0.7) outperform hydraulic actuators in ATLAS (1.0), making them promising for domestic robots (e.g., 1X NEO Beta) and industrial systems (e.g., Amazon, BMW warehouses) [11]. The speed (1.48 m/s) indicates limited mobility, but ATLAS (2.0 m/s) shows potential for rescue operations, though its mass reduces energy efficiency [9]. RL for Adam (success rate: 85%, robustness: 50 N) outperforms ZMP (60%, 30 N) and MPC (75%, 40 N), but RL for Tien Kung (52.34%) is limited by EEG decoding accuracy (40–50%) [8]. These results confirm the advantages of QDD and RL for developing adaptive and energy-efficient robots suitable for unstructured environments, such as logistics or rescue operations.

The metrics are essential for engineers in designing robots with optimal characteristics (COT < 0.7, mass < 60 kg), for researchers in developing innovations (biomimetic materials, batteries), for investors in assessing the market potential of startups (Agility Robotics, 1X), and for regulators in establishing standards for energy efficiency (COT < 0.7) and safety (robustness > 40 N) [5]. Metrics for COT, success rate, and robustness confirm the market potential of lightweight robots, aligning with growing demand [13]. Limited autonomy (1–2 hours for Talos, ATLAS) and manipulation accuracy (Tien Kung: 80%) highlight the need for batteries (> 4 hours) and improved manipulators, critical for medical and industrial applications. The results also emphasize ethical challenges, particularly the potential displacement of up to 35% of jobs, necessitating workforce retraining across various sectors [5].

The study has limitations, including a small sample size (3–6 robots, 4 methods), which reduces statistical power and increases the significance of the heterogeneity test ($p < 0.0001$, $p = 0.0021$). Estimated standard errors (±10–20%) for COT, speed, success rate, and robustness introduce uncertainty, particularly for mass (SE = 23.58). High heterogeneity (I^2 = 30.84–99.33%), driven by differences in designs (QDD vs. hydraulic actuators), testing conditions, and algorithms (EEG for Tien Kung), complicates generalization. The lack of data on manipulation accuracy, autonomy, and actuator durability limits the assessment of robots' suitability for long-duration and high-precision tasks. Funnel plots showed no publication bias ($p > 0.05$), but the small sample size reduces the accuracy of this assessment.

Future research should focus on expanding the sample (including platforms like Digit and Apollo), standardizing testing to reduce heterogeneity, and developing biomimetic materials and batteries to achieve COT < 0.5 and autonomy > 4 hours. Optimizing RL, particularly EEG systems, to achieve a success rate of 70–80%, and integrating with MPC to enhance robustness will reduce heterogeneity. Analyzing the impact of robots on the labor market and developing retraining strategies will mitigate social consequences. Establishing standards for safety, privacy, and energy efficiency, as well as analyzing human-robot interaction (HRI) and integrating generative AI, will improve adaptability and precision in social and industrial tasks.

Thus, the meta-analysis systematizes metrics for DoF, mass, COT, speed, success rate, and robustness, providing an objective foundation for innovation, standardization, and investment. The results confirm the potential of QDD and RL, identify research directions, and highlight the need for ethical and technical solutions to ensure the sustainable integration of humanoid robots into society.

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