Balancing Act: Compliance in Bipedal Robotics

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Introduction & Definition

Compliance is the ability of a mechanism to achieve force and motion transmission through elastic body deformation [1].

A robot is actively compliant if it employs advanced control methods to generate compliance tasks at its end effector and joints. On the other hand, a passive-compliant robot relies on mechanical elements to absorb and respond to impacts.

Fig. 1.: New generation of AR Digit. [2]

Inspired by animals, engineers design compliant robots using flexible materials and spring-like mechanisms to mimic natural movement. These robots use compliant joints and actuators to absorb shocks and remain stable on varied surfaces, improving efficiency and safety and making them adept at navigating complex environments like their biological counterparts.

Introducing compliance in robotics enhances human-robot interaction by enabling gentle task performance, reducing injury risks, and allowing delicate object handling. It also improves robots' adaptability to diverse and unpredictable environments, such as uneven terrains. Consequently, compliant robots are suited for caregiving and collaborative manufacturing activities, ensuring safe human interaction and complex manipulation capabilities.

Compliant Walking in Nature

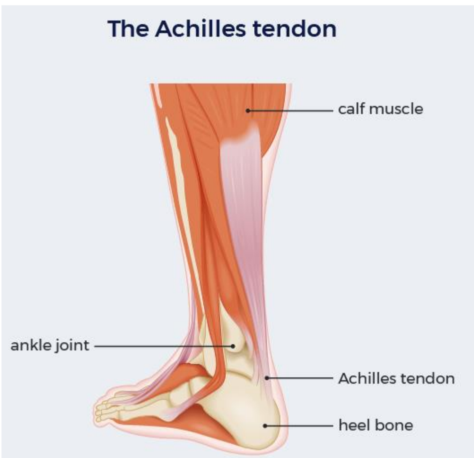
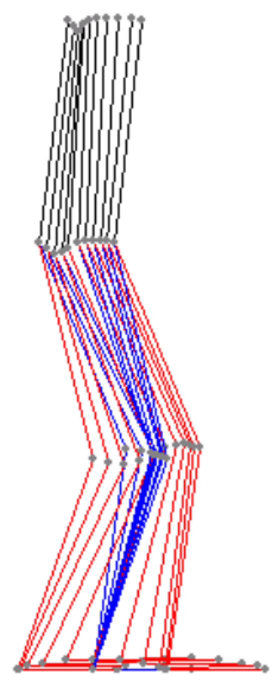


Fig. 2.: Achilles tendon anatomy [3]

Bipedal animals, such as humans and birds, use compliance in their muscles, tendons, and joints to walk efficiently and adapt to varied terrains. The human Achilles tendon, for instance, stores and releases energy with each step, reducing effort and enhancing stability. Birds utilize flexible joints and compliant leg structures to maintain stability and agility on uneven ground. This natural compliance helps them **balance, absorb shocks, and prevent injuries**, demonstrating the importance of flexibility in achieving efficient and stable movement.

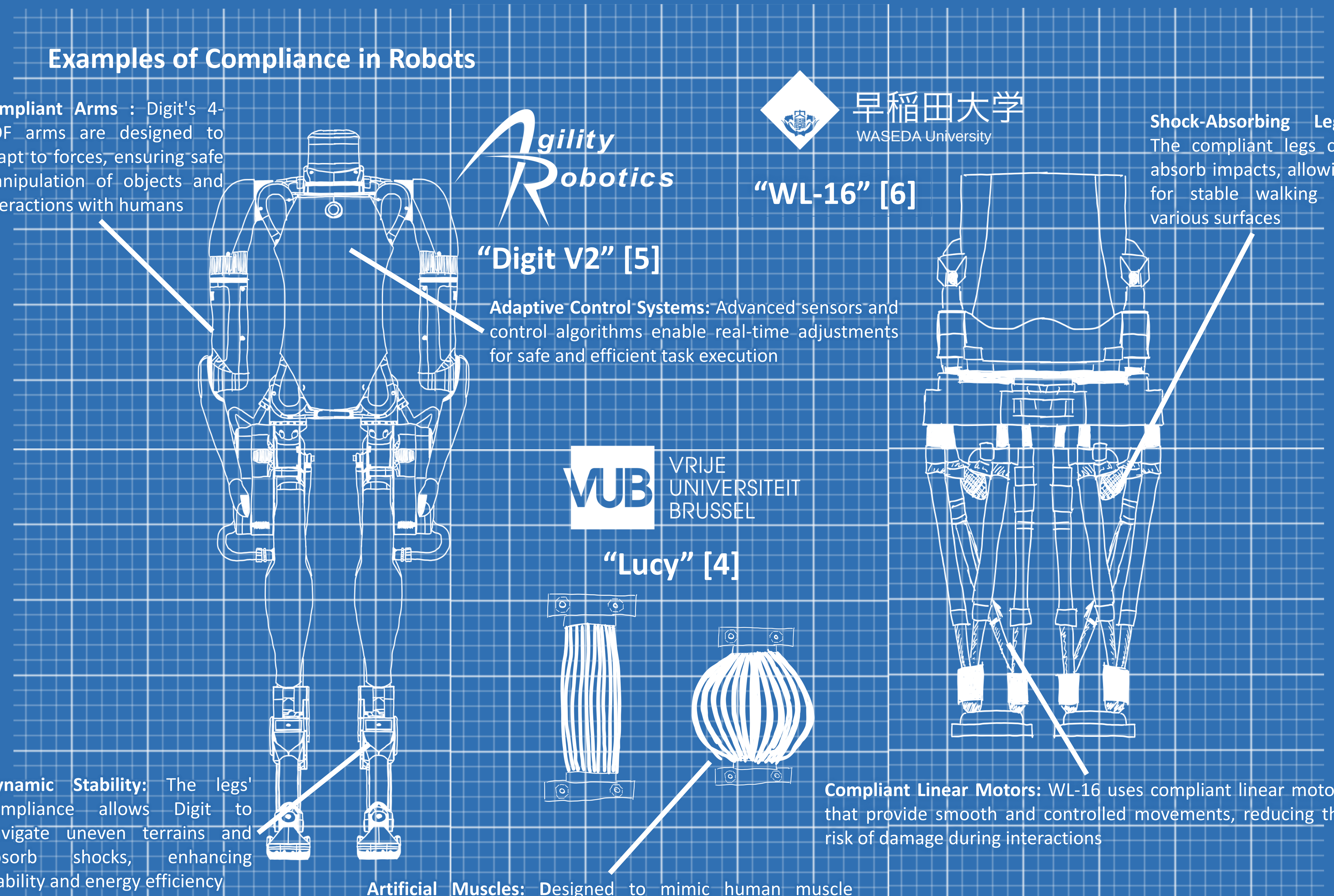
Compliant Walking in Nature

Fig. 2.: Stick diagram of walking dynamics of Lucy. The diagram shows the sequential motion of Lucy's limbs during walking: black lines represent the upper body, red lines denote the forward swing phase, and blue lines indicate the stance phase. [4]



References

Examples of Compliance in Robots



Compliant Arms : Digit's 4-DOF arms are designed to adapt to forces, ensuring safe manipulation of objects and interactions with humans

Adaptive Control Systems: Advanced sensors and control algorithms enable real-time adjustments for safe and efficient task execution

Shock-Absorbing Legs: The compliant legs can absorb impacts, allowing for stable walking on various surfaces

Dynamic Stability: The legs' compliance allows Digit to navigate uneven terrains and absorb shocks, enhancing stability and energy efficiency

Artificial Muscles: Designed to mimic human muscle behavior, providing movement flexibility and adaptability.

Compliant Linear Motors: WL-16 uses compliant linear motors that provide smooth and controlled movements, reducing the risk of damage during interactions

Advantages & Challenges of Compliant Robots in Bipedal Walking [7][8]

Biological study: Replicating animal or human-like gait in robots aids in developing and refining biological models, enhancing understanding of locomotion.

Dynamic Balance: Compliant elements provide shock absorption that improves walking stability and reduces touch-down impact on the robot

Energy efficiency: Compliant elements (such as springs) store and return energy during the gait cycle, causing a reduction in dissipation losses compared to rigid systems

Safety: Compliance reduces the risk of accidental injury in interaction with humans

Gait adaptivity: Variable stiffness in compliant legs offers adaptivity to different terrains and speeds

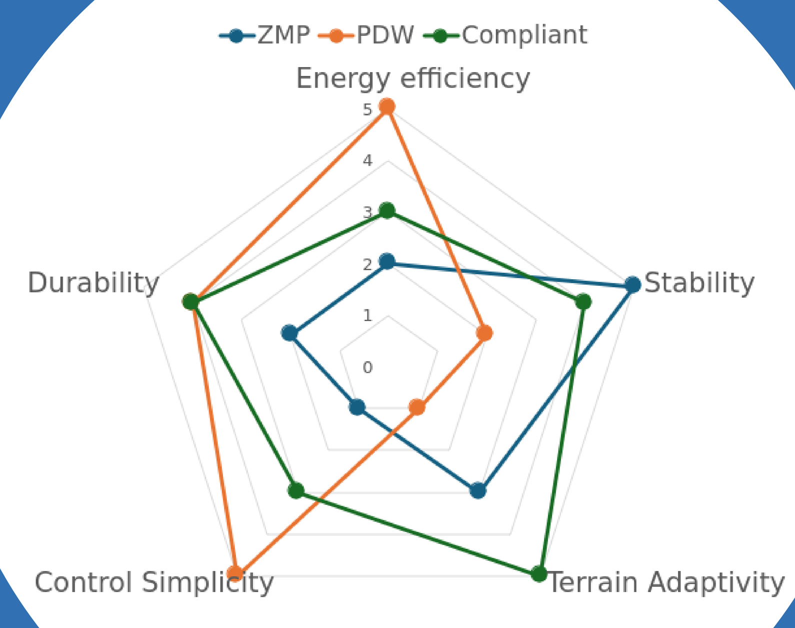


Fig. 8: Diagram comparing strengths and weaknesses of different robots on a scale from 1 to 5

Compliance Optimization: Determining the optimal level of compliance for different joints is resource-intensive

Mechanical Design: Choosing suitable materials for the required stiffness and dampening criteria for a bipedal walk can be challenging.

Control complexity: Sophisticated control strategies are necessary to account for compliant dynamics

Flexibility/Stability Tradeoff: High flexibility of a system makes it more prone to losing its balance during dynamic movement, but increasing the stiffness too much reduced the beneficial effects of introducing compliance

Active Compliance

Active compliance involves the real-time adjustment of joint stiffness and damping using **sensors and actuators**. This approach allows for precise control of robotic movements, enabling dynamic adaptation to varying terrains and external forces. It requires control algorithms and real-time processing to continually monitor and adjust the joints.

*<u>Example</u>: **Digit** and **WL-16** use active complaint components to adapt to complex terrains by changing their stiffness and dampening using sensors and actuators.*

Passive Compliance

Passive compliance relies on the **natural flexibility** of **materials** and **mechanical structures**, such as springs and dampers, to absorb shocks and adjust to forces without a closed-loop control. It uses fewer sensors and actuators, making it simpler and more energy-efficient than active compliance.

*<u>Example</u>: **Lucy** uses passive compliance through its pleated pneumatic artificial muscles, which adapt their stiffness dynamically, allowing the robot to absorb shocks without relying on an active control systems.*

Control of Compliant Robots

Control is achieved by making use of real-time feedback sensors such as…

- **…Force/torque sensors** measure the forces between the robot and the environment.
- **…Position sensors** track the location of the robot's parts, providing accurate and controlled movements.

Main Control Algorithms Used in Compliant Robots

- **Adaptive Control:** This strategy aims to dynamically adjust motion in response to changing environmental conditions through parameter modification. Model Reference Adaptive Control and Self Tuning Regulators are standard methods.
- **Admittance Control:** The aim is to regulate the robot's mechanical admittance, which is the inverse of impedance. This approach measures the forces and torques and calculates the desired motion commands. It modifies the robot's joint position and velocity to achieve a desired motion behavior according to the forces, a compliance strategy. For instance, In a study utilizing a COMAN robot, compliance is achieved by admittance control "using closed-loop feedback of 6-axis force/torque sensors in the feet" [9].
- **Impedance Control:** One of the force control algorithms. Controlling the relationship between the force exerted by the robot and its motion. The goal is to regulate the robot's mechanical impedance (stiffness, damping, and inertia) according to motion (velocity, position) input [10].

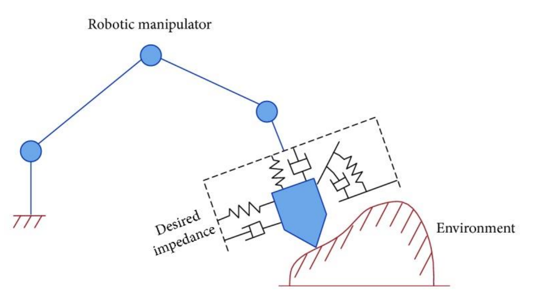


Fig. 6.: Description of impedance control for a robot in contact with the external environment [5]

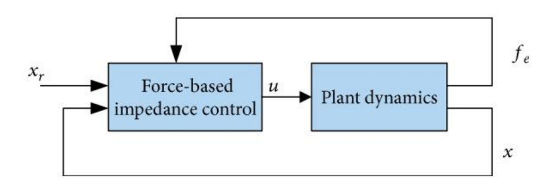


Fig. 6.: Generic diagram of force-/torque-based impedance control [5]