Survey of Semi-Passive Locomotion Methodologies for Humanoid Robots

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Wheel-based locomotion is the most commonly used by mobile robots, due to its simplicity and robustness. However, when facing uneven terrain, such as steps or rocky terrain, its mobility is greatly reduced. Biped robots, in contrast, have a greater adaptation potential to these challenges due to the suitability of its structure. In spite of this, the traditional biped locomotion methods used by these platforms cause high energy consumption and display low adaptability to uneven terrain. The semi-passive or hybrid approach for biped locomotion allows for the (1) maximization of energy efficiency and (2) significant improvement of adaptability to uneven terrain. On one hand, this approach explores the dynamics of passive elements, like springs or rubber bands, in order to develop structures and walking gaits that minimize energy consumption. On the other hand, using passive elements grants complacency to the movement which increases the gait's stability, specially on irregular terrains. This paper presents a survey of methodologies for hybrid locomotion, ranging from the addition of basic passive elements to incorporating complex compliant actuators and implementing control algorithms.

Keywords: Humanoid robot, Legged Locomotion, Semi-Passive

1. Introduction

A typical actuator is able to move to a target position or track a trajectory with great precision and maintain its goal even if other forces are applied to its drive. Most robotic tasks require the precision and speed these stiff, high bandwidth actuators provide. This kind of control presents several challenges when applied to some areas, such as legged locomotion or human interaction. The high torque values involved lead to high energy consumption and results in instability for small error or noise values, which adds to the natural instability of legged locomotion. Also these forces can be quite dangerous in cases of human interaction - which is usually the goal of using anthropomorphic robots.

Passive elements are usually elastic mechanisms, like springs, rubber bands or compliant sheets, that are able to deform and store energy. When added to a robotic frame or in series with an actuator, these elements add compliance to the system, which means that each joint will have an equilibrium position but small deviations are allowed and a torque is applied while the joint is displaced from this position. The joint is transformed into a low bandwidth system, which reduces the instability and absorbs vibrations from the foot-ground impacts. This is also a very important feature for robots that interact with humans, since it reduces the torques in action. The elasticity also allows the storage of energy that can be reused to power the joints, drastically reducing the power consumption.

There are many uses for passive elements and compliant actuators in legged locomotion, most of them based on biological examples. Using springs in the knees and ankles in order to absorb and release energy allows to reduce motor consumption and wear;[1] adding return springs in the knees to control the swing movement of the leg;[2] placing spring-like pads under the feet, to reduce the vibrations of impact with the ground;[2,3] adding passive toes joints to increase stability by increasing the total time of foot-ground contact and use compliance for the entire frame of the robot.[4] These methods are explained further and examples are given in Section 3. In Section 4 the work of research groups that have focused on creating compliant actuators is presented. Finally, in Section 5 we present solutions for modelling, simulating and controlling legged semi-passive locomotion.

2. Historical Background

Research on the area of bipedal locomotion can be traced back to the 70s, when WABOT-1 was built at Waseda University.[5] This robot was able to walk, transport objects and communicate with humans and was equipped with a vision system and tactile sensors. In the 80s, the WABOT-2 was built and research concerning bipedal robots balance[6] and walking and running dynamics was developed.[7,8] Honda started a humanoid project with the presentation of E0 in 1986, a biped robot consisting only of the lower limbs. Since then, Honda has released over a dozen humanoid robots, ASIMO being the most recent and widely known[a]. The typical approach to biped

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[a] Honda Humanoids webpage - http://world.honda.com/ASIMO/

locomotion requires that a robot is kept in balance throughout the walking movement. This is achieved by maintaining the center of mass of the robot within some boundaries, using methods like the ZMP, and by controlling the servo actuators with great precision and stiffness. When using vision and force sensors, these robots can climb stairs, avoid obstacles and even run. However, the gaits that arise from these methods feel unnatural and all these models share the common trait of low energetic autonomy, caused by large energy dissipation in the actuators. The current solution is to store batteries on a "backpack" on the robot, which still only allows running times up to 1 hour.

The concept of passive walker, a mechanism or robot that is able to walk down a slope without actuation, was introduced in robotics in 1988, when Tad McGeer published two articles[9,10] concerning the development of a biped robot that required little actuation to walk, based on a toy mechanism that was able to walk down a ramp with no actuation. The difference between the two approaches is obvious: in this case, the robot is kept in a constant unbalanced state and the movement is completely powered by potential energy and gravity. However, a passive walker is not able to avoid obstacles, climb up a ramp or even walk on a horizontal platform.

This work was a starting point for a new array of biped robots, which aimed to lower energy consumption on humanoid robots. A hybrid walker follows the philosophy behind passive walkers, taking advantage of passive elements that are able to store and reuse energy while minimizing active actuation. The hybrid walker's actuators are much more compliant in order to absorb shocks and external disturbances and their gaits feel more natural. Due to these characteristics, the number of research groups dealing with passive and semi-passive (or hybrid) methodologies has grown in the last few years.

The specific cost of transport c_T is a dimensionless metric that quantifies energy efficiency on ground locomotion, indicating the energy needed to transport a unit weight for a unit distance. Cornell University has developed a humanoid robot with a $c_T = 0.2$,[11] the same as a human being, and their Ranger has a $c_T = 0.28$,[12] while Honda's ASIMO has c_T values higher than 3.

3. Passive Elements

As was explained before, adding passive elements to the frame or actuators of a robot can serve multiple purposes and many platforms are being adapted or build in order to accommodate for these solutions. One of these solutions is to replace typical actuation with compliant actuators, and these devices are discussed in greater detail in the next Section.

3.1. *Foot Pads*

Most mammals have some sort of padding underneath their feet, some in the form of fur others in the form of fat deposits. The padding will ensure that the impact forces between the padded foot and the ground smaller less than between a rigid foot and ground. The advantages of this approach are twofold: (1) increases stability of the platform by reducing vibrations (2) decreases sensor noise caused by the impact. In,[2] it is suggested that the padding must have a non-linear stiffness k, that is small for light loads, in order to prevent chattering (foot lifting off the ground after the initial impact), and that it becomes stiffer under heavier loads, so that the padding doesn't completely contract under the load. A possible model and setup for a spring padding is presented in,[3] and it is shown that impact forces are reduced through simulation.

3.2. *Ankle springs*

One of the most common approaches for the design of feet for passive locomotion is to create a arched feet in order to avoid impacts and maintain the robot in a controlled state of unbalance. However, this design is hardly anthropomorphic, the contact does not create enough friction in order to avoid yaw rotation and it renders the robot unable to stop walking and stand in an upright position. The solution presented in[1] replaces this design with a flat foot featuring torsion springs in the ankles on several passive robots. Not only this solves the disadvantages of arc-shaped feet, but stability and sensitivity to disturbances are quite similar when the right stiffness is chosen.

3.3. *Passive Toes*

The foot design is obviously of extreme importance for a humanoid robot since it will determine how stable the robot can be. While one can argue that a arc-shaped foot is not human-like, a flat foot model is a very rough approximation of a human's foot, specially regarding stability and flexibility. The University of Aveiro humanoid platform[4,13–15] features the articulated foot shown in Fig. 1, that is divided in two sections. The main

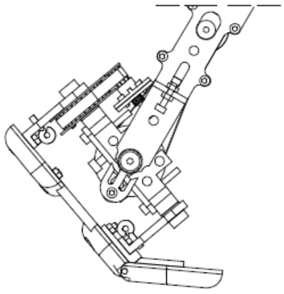

Figure 1. Articulated foot detail from University of Aveiro humanoid platform

section, which supports the weight of the robot, is partitioned in two parts in order to increase the foot's flexibility and increase the area of contact between the foot and ground. The front section intends to mimic human toes and is connected to the main section by compliant sheets, that provides a stable contact while the back foot is lifting from the ground and an impulsive mechanism for the foot liftoff. The humanoid robot Myon,[16] from the Neurorobotics Research Laboratory in Humboldt University, Berlin, also has passive toes in order to improve the stability of the walking gaits.

3.4. *Knee Return Springs*

It is easy to take notice of the parities between robotic biped locomotion and human locomotion and the proposed structures so far. If we see the frame of the robot as the skeleton and the motors as the muscles, we should ask ourselves if there are more features we should be inspired by. The ligaments have a very important role in animal locomotion, since they connect the bones to form joints, constricting some movements, stabilizing the joints and helping the muscles. In human knees for example, the ligaments provide support when a person is standing and stop the knee from bending forward and sideways.

Using springs

3.5. *Compliant Actuation*

Myon servos should be here or in the next section?

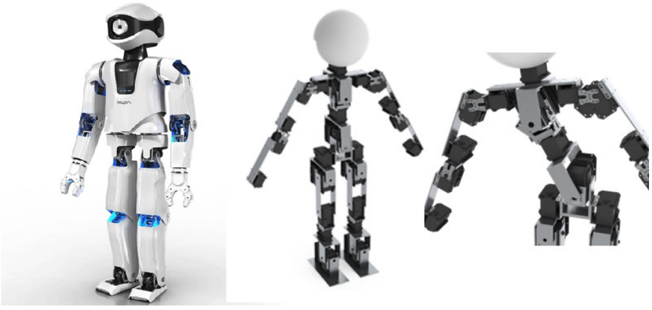

Figure 2. Myon with the exoskeleton (left) and Acroban (middle and right)

3.6. *Body Compliance*

The human body's compliance is not limited to the locomotor system and joints, but the whole body is compliant: arms, fingers, neck, torso and even skin. Acroban[17,18] is a lightweight humanoid robot featuring a compliant vertebral column with 5 degrees of freedom (DoF). The structure of the robot has many passive elements like springs and elastics and even the motors' torque can be limited in order to add compliance. This system separates the upper and lower body, which means that external disturbances won't propagate to the rest of the body (foot-ground impacts, bumping into objects, objects thrown at the robot), and has a very fast response time to external forces, making the robot very robust while standing. Another important feature of this robot is the positive emotional response from those that interact with it, in spite of its raw appearance. The robot also allows manipulation has a form of input, making it possible to drive the robot by the hand, which is a highly attractive feature for children.

Myon and the exoskeleton

-Sistemas de molas no tornozelo que absorve no heel strike e libertam a seguir -Falar sobre o movimento harmonico e a necessidade de definir o k de um actuador de acordo com a velocidade de andamento.

3.7. *Hybrid Humanoid Platform*

A humanoid platform has been developed in University of Aveiro in the past years[13–15] that features modularity, distributed control, low cost materials and possibility of adding sensors. Recently, a new version of this humanoid is being developed in order to accommodate active and passive actuation, with the goal of reducing power consumption, reducing wearing of the servos and improving the response times of the platform.[4]

Among other changes, detailed in Section 5, a passive element was introduced in the knee. This joint requires the most torque since it is supporting most of the weight of the robot, either when the robot is upright or performing a gait or a task, and using elements that are able to store and release potential energy are crucial for this joint. Using multiple fixation points and multiple bending points for linear elastic rubber bands, they are able to experiment different elastic bands and to create a torque that is quasi-linearly dependent of the knee angle - which is not the same as the elongation of the band.

3.8. *Myon*

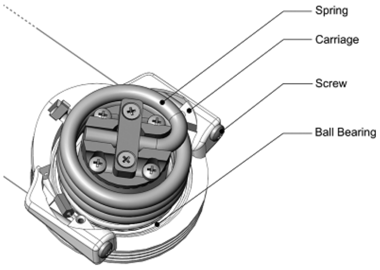

Figure 3. Myon's Actuator

Myon is a humanoid robot designed as a research platform at Neurorobotics Research Laboratory in Humboldt University, Berlin.[16] The numerous limbs of the robot are fully independent, meaning that the robot can have multiple configurations, it will continue working even if a part malfunctions and any limb can continue working even if detached from the body. In order to withstand high impact forces, all motors have a torsion spring, has shown in Fig. 3, to provide complacency. Some of the more torque demanding joints (like the knee) are driven by more than one actuator, connected by wire ropes that pass through the carriages, providing not only torque but also an antagonistic setup, where motors can work in different directions in order to control stiffness and total torque of the joint.

3.9. *Acroban*

Acroban[17,18] is a lightweight humanoid robot featuring a compliant vertebral column with 5 degrees of freedom (DoF). The structure of the robot has many passive elements like springs and elastics and even the motors' torque can be limited in order to add compliance. This system separates the upper and lower body, which means that external disturbances won't propagate to the rest of the body (foot-ground impacts, bumping into objects, objects thrown at the robot), and has a very fast response time to external forces, making the robot very robust while standing. Another important feature of this robot is the positive emotional response from those that interact with it, in spite of its raw appearance. The robot also allows manipulation has a form of input, making it possible to drive the robot by the hand, which is a highly attractive feature for children.

3.10. *Springs in Feet and Ankles*

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4. Compliant Actuators

In Section 3, the advantages of using passive elements in robots frames and joints were discussed and some examples were provided. For the same reasons, several research groups started developing compliant actuators, using a wide range of methods, in order to further improve how the compliance is used. The possibility of adjusting the compliance values, either while moving or not, to independently control the equilibrium position and the compliance of the actuator has added a whole new array of possibilities for humanoid locomotion and other human-interacting robots.

PAM - Pneumatic Artificial Muscles

Pneumatic artificial muscles (PAM)[19] are lightweight and compliant actuators, consisting on a cylindrical membrane that is operated by gas pressure and that is connected to a load at both ends. As the membrane is inflated and it bulges outward, the extremities of the actuator are pulled together, which contracts the actuator. When the membrane is deflated, it squeezes and no longer applies force to the extremities, which extends the actuator. The static force applied by the actuator depends on the current pressure, the volume-to-length characteristic of the membrane and the difference between the current length of the actuator and the equilibrium position. The

Figure 4. PAM in different contraction levels

compressibility of the gas and the force-to-contraction curve of the muscle grant compliance to the actuator, which can be controlled by the current pressure, since both terms depend on it.

For energetic reasons, these muscles are usually controlled only by inflation, which means that they are unidirectional. In order to control the position of a load, an antagonistic setup is required, where one of the muscles contracts to pull the load and the other one is used as a brake. While the muscles are lightweight, the compressed air generator, connection tubes and electric valves are cumbersome and heavy, which might be a reason for why these actuators are not more generally used. The compressibility of the gas also adds latency to the control system.

PAM can be sorted by their design and actuation methods (pneumatic or hydraulic, over or underpressure actuation, type of membrane...). Some of the current designs include the McKibben Muscle,[20] a form of braided muscle used in the Rubbertuator,[21] and the Pleated PAM,[22,23] a pleated muscle where inflation does not cause strain to the membrane. Lucy[24] uses the PPAM with a pressure, position and stiffness control.

SEA - Series Elastic Actuator

In,[25] a combination of stiff actuators and elastic elements is proposed in order to improve force control, which is hard to achieve using typical high torque actuators. By adding a spring, the force control is transformed into a position control problem, since the displacement or twist of the spring determines its output force. The force control feedback is made by a sensor that measures the elongation of the spring and the actuator's compliance is

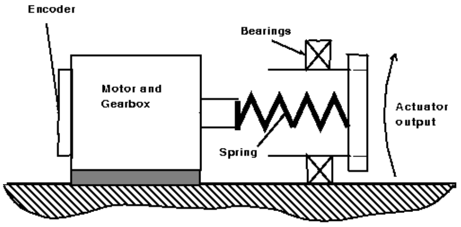

Figure 5. Series Elastic Actuator schematic

fixed during operation. A single Series Elastic Actuator (SEA) is proposed, a controller is discussed and experimental results show that the force control is improved and the stability of the SEA when dealing with high frequency vibrations is also improved when compared to the actuator without the spring. This actuator is used by Meta,[26] a semi-passive walking robot that has force controlled hip actuation, and by one of the walking robots from Cornell University.[11]

VSA - Variable Stiffness Actuator

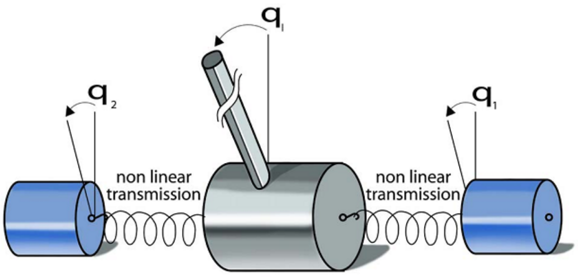

Figure 6. VSA-II schematic

The VSA[27] is a compliant controller based on an antagonistic setup, where two springs with a non-linear stiffness work against each other, actuated by two stiff servomotors. This montage allows the user to control not only the equilibrium position of the actuator but also the overall stiffness of the device. This is an important feature since it may be necessary to use different stiffness values if the external conditions change or if the task at hand requires more or less compliance. Since walking at a certain speed is a periodic movement, stiffness plays an important role on energy consumption and optimal values for a given speed must be found. The VSA consists on a mechanism with three pulleys set in a triangle shape, where two of them are actuated and the third is connected to the arm. A belt connects the three pulleys and between them there are three spring mechanisms that apply tension on the belt. The two mechanisms adjacent to the arm pulley are the non-linear springs, controlling both position and compliance of the servo. The third mechanism exists only to ensure the belt is maintained under tension. This design is being improved,[28] the schematic can be seen in Fig. 6 and the new version allows higher torque capacity and handles impacts better than the original design.

AMASC - Actuator with Mechanically Adjustable Series Compliance

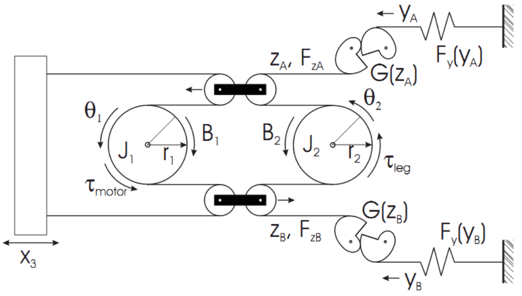

Figure 7. AMASC schematic

The stiffness and equilibrium position in this actuator are controlled independently, thanks to a system of pulleys and springs, also based on an antagonistic setup. The schematic in Fig. 7 depicts how the actuator works. The pulley J1 is controlled by a servo, which dictates the position of the floating pulleys Z_A and Z_B, which in turn sets the equilibrium position of J2 pulley, where the leg is attached. The compliance of the system is controlled by the position of X3, that pulls both Z_A and Z_B pulleys to left, which in turn elongates the springs Y_A and Y_B, increasing the stiffness of the actuator. Since the control of position and compliance is independent, it is possible to design different actuators, using different servo motors and springs, in accordance with our needs. The main disadvantage of this system is its complexity.

SCS - Structure Controlled Stiffness

This family of actuators follows the principle that the stiffness of a spring like system can be changed by manipulating its structure. For instance, in[29] a beam is added inside a helical spring and the stiffness of the system is controlled by the axial rotation of the beam. Another way to increase the inertia is by grouping layers of sheets and controlling the friction between them. When an external force is applied to the system, the sheets will only be able to be displaced if the friction force is low. If vacuum or electrostatic methods are used to keep the sheets together,[30,31] the stiffness will increase. Instead of changing the inertia, it is also possible to change the effective length of a compliant sheet, as in the Mechanical Impedance Adjuster.[32,33] In this mechanism, a slider is controlled by a motor that moves along the compliant sheet, that is connected to the moving joint. In order to reduce the compliance of the actuator, the slider is used to reduce the effective length of the compliant sheet. Once again, the compliance and the equilibrium position can be controlled independently. Using a similar idea, if the passive element is a helical spring it is possible to control the compliance by changing the number of active coils. The Jack Spring actuator,[34] represented in Fig. 8, uses a shaft to rotate the spring and set the number of active coils on the left side of the datum, thus changing the compliance of the system. By using actuators it is possible not only to change the compliance but also the equilibrium position of this actuator. The main

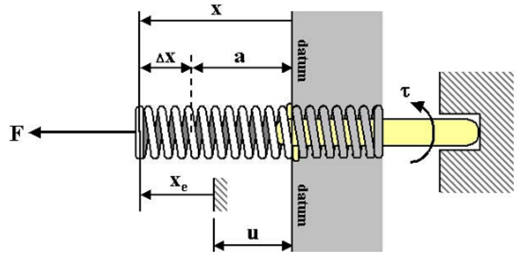

Figure 8. The Jack Spring working principle

advantages of this system are that it is small and easy to implement.

Lever Arm Length Adjustment

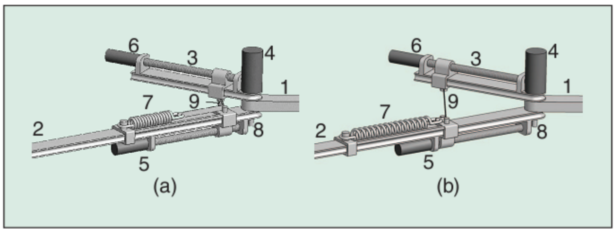

Figure 9. Lever Arm Length Adjustment

The Lever Arm Length Adjustment takes a mechanically controlled stiffness approach, in which the compliance of the system is adjusted by controlling the pretension of a passive element, in this case of a spring. As it is shown in Fig.9, this systems consist on three arms connected by a rotational axis - the grounded arm 1, the movable arm 2 and the lever arm 3 - and three servos - servo 4 controls the position of the lever arm and servos 5 and 6 control the spindles, which determine the length of the lever arm and the position of the spring. The torque generated by the spring will force the movable arm to line up with the lever arm. Therefore, to obtain a compliant system it is necessary to reduce the lever arm, as it is shown in Fig.9(a), while increasing the lever arm, as it is shown in Fig.9(b), will result in a more stiff actuator.

In spite of offering a new approach to compliant actuators, this design requires using three servos and the torque-angle characteristic is nonlinear - for small angles the nonlinearity is caused by the connection points that cannot overlap and for larger angles the nonlinearity comes from the fact the the cable does not go around the rotation axis but instead connects the two arms in a straight line. In addition to these problems, the friction of the cable causes hysteresis.

MACCEPA - Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator

The MACCEPA[35] is a compliant actuator where the compliance and equilibrium position are controllable using two independent electric servos, fol-

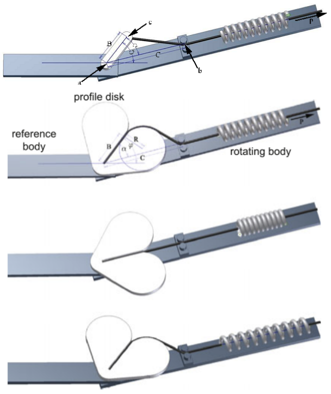

Figure 10. MACCEPA with different profile disks

lowing the mechanically controlled stiffness approach used in the Lever Arm Length Adjustment design. As can be seen in Fig. 10, there are three main parts on this actuator: the fixed bar on the left, the freely rotating bar on the right and the profile disk or bar, white on the figure, which is actuated. The profile disk, which was added in MACCEPA 2,[36] is actuated in order to set the equilibrium position, since the deviation between it and the arm will create an elongation on the spring. The shape of the disk determines the stiffness-deviation curves - the bar sets a linear dependency, while using the round disk the actuator has greater stiffness for greater displacements. The pretension of the spring is also actuated, allowing the user to change the compliance of the system online. This actuator has been used in a biped robot[37] and simulations have shown that a hopping robot with MACCEPA 2.0 is able to jump higher than with the initial design.

Conclusions

Compliant actuators will be necessary in the near future in order to develop energy-efficient, human-interacting robots. While compliance can also be achieved by adjusting the torque curves of a stiff actuator, its high bandwidth behaviour is obvious when there is foot-ground shocks and the energy consumption remains high. Compliance can come from gas compressibility, linear or non-linear spring behaviour, structure stiffness or even new materials,[38] and the ability to adapt compliance for the task at hand is crucial for energy efficiency. Another surveys on compliant actuators can be found in.[39,40]

5. Other Methodologies

Energy[41] Compliance determines walking speed Using kalman to balance, or Cognitive Sensorimotor Loops from Myon

5.1. *Hybrid Humanoid Platform*

A humanoid platform has been developed in University of Aveiro in the past years[13–15] that features modularity, distributed control, low cost materials and possibility of adding sensors. Recently, a new version of this humanoid is being developed in order to accommodate active and passive actuation, with the goal of reducing power consumption, reducing wearing of the servos and improving the response times of the platform.[4]

The foot of the new platform is divided in three parts - two sections for the main part of the foot and one front section that imitates toes of a human foot. The sections are connected using compliant materials, which not only allows for a greater support time while walking but also adds a rising impulsion mechanism for the foot. The ankle and hips joints now have a cross axe assembly, allowing two degrees of freedom and reducing the motion inertia. Both the knee and hips also include a passive system with springs to reduce motor load when the robot is in upright position and to minimize the required torque to move the servos.

6. Conclusions

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