Bio-Inspired Biped Robotic Locomotion

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Abstract: Bio-inspired robotics has become immensely popular in the last two decades. Attempts to mimic biological principles observed in animals have resulted in technological advances that have revolutionised man-made robots.

Bipedal locomotion is a daily activity of humans. In contrast, in engineering field, agile and robust locomotion for biped robots in real world applications is still a challenging task. Studying and replicating the concepts of biological locomotors, the control and feedback mechanism, to robots with suitable changes, can enhance the performance and elevate the robot applications in daily life. Successful designs of biped robots have been achieved. However, major limitations like high-energy costs, dynamic instability on uneven terrain along with lack of compliance properties still prevail.

This research paper aims to provide a detailed study of the development of biped robots focusing on the design, stability and limitations of these robots in real environments, compared to human locomotion. It also includes the study of the latest biology inspired solution, the variable stiffness actuator (VSA), which has enhanced the efficiency of biped locomotion.

Index Terms: Biped locomotion, human compliance, zero moment point concept, passive walking, series elastic actuators, variable stiffness actuators

INTRODUCTION: THE CONCEPT OF BIO-INSPIRED BIPED-ROBOT

Creating biped-robots which replicate animal locomotion with great efficiency has been a challenge before engineers since long in robotic research. The robotic locomotion prior to the development of biped robot was mainly based on tracks or wheels. The main drawback of using wheels is locomotion over uneven terrain or a path full of obstacles. Legged locomotion provides advantages of discontinuous contact with the ground, allowing avoiding obstacles or even climbing stairs [1]. Although this led to the creation of the bipedal locomotion, the efficiency was far from that observed in humans. The main aspects of human locomotion which makes it so versatile and energy efficient are dynamic stability and the intrinsic compliant properties of human joints and muscles. Due to these properties, humans can adapt to natural environments and uneven terrains providing safe and stable locomotion.

Over the last few decades, many designs for biped-robots have been proposed and implemented, which try to replicate the properties of human locomotion. Although the current biped robots based on these designs, fulfill the requirements of locomotion on flat terrains, their performance decreases on uneven terrains with unnatural surroundings. They contain joints with stiff actuators that lack the property of compliance. Due to this, the robots cannot adjust and adapt to unpredictable environments [2].

The aim of this paper is to chronologically summarize the development of biped robot locomotion putting forth the comparison between human and bipedal locomotion. It also presents the various concepts and designs of successful bipedal robots along with their advantages and disadvantages. It also includes the latest technology used in the biped robot 'Binocchio' which is the variable stiffness actuator (VSA). The study focuses on the mechanics of human locomotion. It highlights the important aspects of human locomotion which make it so versatile and energy efficient even in unstructured environments.

I. HUMAN LOCOMOTION

Human locomotion emerges as a result of neural, mechanical and morphological aspects. This helps achieve robust, versatile and energy efficient locomotion in a vast range of conditions. Compliance, which is the flexibility of physical structures in response to an external force, is an important property of human locomotion. It is achieved by the visco-elastic properties of muscles (agonists and antagonists) and joints, and series-elastic tendon structures [2]. Compliance helps the muscle-joints to vary the stiffness in accordance to the external conditions. It provides fast storage and release of energy when required by the muscles. Compliance also facilitates proper reaction to sudden impacts without losing dynamic stability.

1.1 MECHANICS OF HUMAN LOCOMOTION

Human leg stiffness is independent of speed and gravity. It depends on the inherent musculoskeletal properties. The muscles, tendons and ligaments behave as a single linear spring and mass system with the mass equivalent to the human's mass [3]. Human locomotion takes place on a wide variety of terrains; flat, uneven, smooth or filled with obstacles. The magnitude of the reaction force provided, depends on the compression factor of these terrains. Human locomotion on these surfaces can be viewed as the leg spring in series with the surface spring. The adjustable stiffness of this spring-mass system helps to achieve speed and agility in human locomotion.

1.2 CONTROL AND FEEDBACK IN HUMAN LOCOMOTION

The neuromuscular mechanism is responsible for control and feedback. It mainly consists of 'afferent nerves', which receive information (feedback) from our sensory organs and transmit it to the central nervous system, and 'efferent nerves', which send impulses (control) from the central nervous system to the limbs and organs. The neural activity controls the mechanical output of muscles that is the visco-elastic and series-elastic properties. The muscles further interact with the external environment which provides compliant human locomotion.

The human locomotion can be viewed as a combination of neural and muscular activities. Compared to humans, robotic locomotion is far from efficient. The main problem with the current biped-robots is their inability to achieve good performance in real world environments, as the joints in these robots lack the property to self adjust depending on external factors. The study presents the successful attempts to replicate the science behind human locomotion in robots trying to overcome the major drawbacks faced in robotic locomotion. It aims to provide up to date knowledge about the progress of biped robots and understand the major work done in this area in the past few decades.

II. LITERATURE SURVEY: DEVELOPMENTS IN DESIGN OF BIPED ROBOTS

Many researchers have invented and demonstrated various design concepts for efficient biped-robot locomotion. The literature describing the development of biped-robot locomotion, till the development of the solution to the current problem has been discussed in this chapter.

One of the important aspects of human locomotion is 'dynamic balance' or 'dynamic stability'. The human leg has a natural tendency to balance itself over all kinds of surfaces avoiding the body to tumble over. After studying the dynamics of human leg and foot, the 'Zero Moment Point' concept was put forth by Vukobratovic. Considering the foot as a system, the forces and moments which act on it are as follows.

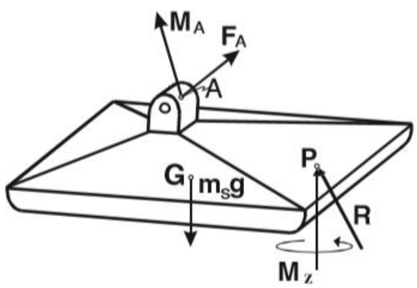

Fig. 1 FBD of foot in locomotion [4]

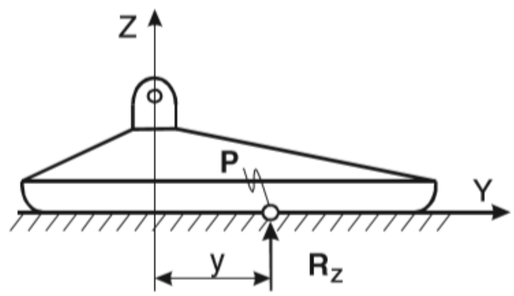

Fig. 2 ZMP concept [4]

In Fig. 1, point A represents the link between foot and ankle.
F_A and M_A represent the force and moment acting on the foot due to the mechanism of the leg above the ankle. G is the centre of gravity, $m_s g$ is weight of the foot and R is the normal reaction of the ground on the foot at a point P.
R is divided into 3 components; R_x, R_y and R_z. R_x and R_y are the horizontal components of force R which balance the horizontal component of force F_A.
Also, moment M_Z balances the vertical component of force F_A and moment M_A.
From Fig.2, the two unbalanced components on the foot are the horizontal component of moment M_A (M_{Ax}) and vertical component of force R (R_Z).
For dynamic equilibrium, the reaction of the ground on the foot can be replaced by only vertical component of R (R_Z) and M_Z at a point P and this point is called 'Zero Moment Point'. There are certain limitations to the ZMP concept, as it only talks about the dynamic stability of locomotion but fails to consider the compliance property (adjustable joint stiffness) and high energetic costs of walking [4].

Ichiro Kato, (1984) put forth the first practical demonstration of Zero Moment Point concept (ZMP) in Japan in 1984, at Waseda University, laboratory of Ichiro Kato, in the first dynamically balanced robot WL-10RD of the robotic family WABOT. However, ZMP concept did not clarify the high energy costs and reduced performance on uneven terrains for the biped robot [4].
ZMP concept provided detailed analysis of dynamic stability of locomotion. However it neglected the high energetic costs of walking. A probable solution to this was provided in the concept of passive dynamic walking. The concept stated that, gravity and inertia alone generate the locomotion pattern which is called as 'passive walking'. This concept provided mechanical simplicity, relatively high efficiency and easy control of speed and direction of locomotion.

Tad McGeer, (1990) stated that, there exists a class of two-legged machines, for which walking is a natural dynamic mode. He talked about 'passive dynamic walking' which had low energy costs and once started on a shallow slope could continue its gait cycle without energy input. He also conducted experiments to verify that passive walking can be readily exploited in real environments [5]. This study put forth a solution for the high energy costs of locomotion. However, it did not explain why the performance of the robots decreased with uneven terrains.

The inefficiency to respond to uneven terrains or unpredictable environments was the major drawback of robotic bipedal locomotion. However in contrast the humans adjusted well in similar circumstances. **Farley and Gonzales, (1996)** presented the idea, that when humans and other mammals run, the body's complex system of muscle, tendon and ligament behaves like a single linear spring ('leg spring'). They concluded from their study, the stiffness of the leg spring remains nearly the same at all speeds and that the spring-mass system is adjusted for higher speeds by increasing the angle swept by the leg spring [6]. This provided first input to the physics behind efficient human locomotion.

Furthering the research in human locomotion, **Ferris, Louie and Farley (1998)** in their study presented that, a running animal coordinates the actions of many muscles, tendons, and ligaments in its leg. They found that human runners adjust their leg stiffness to accommodate changes in surface stiffness, allowing them to maintain similar running mechanics on different surfaces [7]. These results provided important insight into the mechanics and control of animal locomotion and suggested that incorporating adjustable leg stiffness or 'compliance' in the design of hopping and running robots is important if they are to match the agility and speed of animals on varied terrain.

Trying to incorporate compliance into robotic bipedal locomotion, **Pratt and Williamson** introduced SEAs (Series Elastic Actuators).

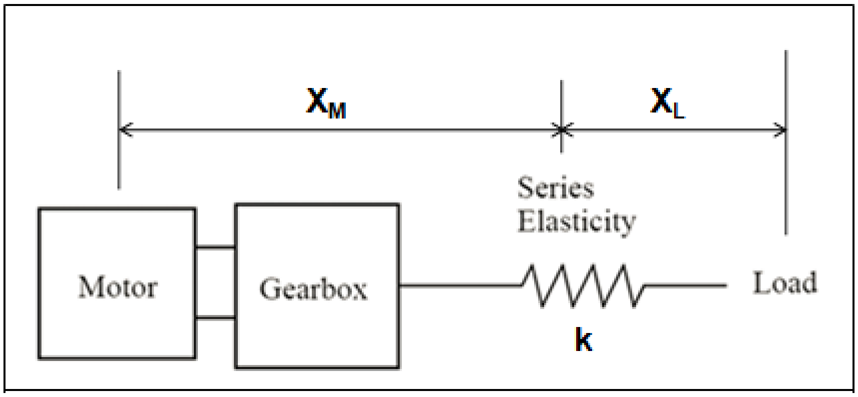

Fig.3: Block Diagram of SEA

It was the first concept to take into consideration the compliance properties of locomotion. SEA consists of an elastic element in series with the mechanical energy source. It introduced compliance to biped-robots, resulting in force control, increased shock tolerance and greater efficiency in non-structured environments. It works on force control by Hooke's law as shown in Fig. 3.
F (out) = k * (X_M – X_L). Where, F(out) is the output force, X_M and X_L are positions of motor and load, and k is the stiffness of the spring. X_M and X_L can be controlled using a position controller, thereby controlling the output force and in turn the stiffness of the joint.
The major drawback of using SEAs is that modulation of joint stiffness needs to be achieved using impedance control.

The main drawback of SEAs was impedance control as stated earlier. This drawback was removed by the research on adaptable compliance. **Vanderborght, *et al,* [8]** presented a rotational actuator with a novel concept of adaptable compliance. It was based on the MACCEPA (Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator). In the MACCEPA concept the compliance can be controlled separately from the equilibrium position. The actuator can be viewed as a torsion spring. One motor sets the stiffness of the torsion spring and another motor sets its equilibrium position. The torque is a linear function of the compliance and the angle between the equilibrium position and actual position [8]. Detailed design and working of the MACCEPA were put forth in this research.
In **2008** they presented overview of 'Lucy' project. They proposed a new concept of dynamic stabilization of a biped robot powered by pneumatic artificial muscles. In the setup of such muscles, both torque and compliance were controllable [9]. However the disadvantages of the pneumatic actuators were low efficiency compared to other actuators due to pressure losses and air compressibility.

Huang, *et al,* (2013) [8] created VERONICA (Variable joint Elasticity Robot with a Neuro-Inspired Control Approach). It was the first biped robot with MACCEPA actuator. In passive walkers, the natural frequency of limbs is fixed in design and cannot be changed. Thus, these passive walkers have one preset speed during walking. VERONICA walked using controlled passive walking where the natural frequency of the limbs was controlled by using actuators with adaptable compliance [8].

One of the optimum solutions to the problems faced in the design of biped robots was Variable Stiffness Actuator. **Rodriguez-Cianca, Weckx, *et al,* (2019) [10]** proposed, achieving human-like locomotion often requires the use of variable stiffness actuators (VSAs) in multi-degree-of-freedom robotic joints. They presented the design of the VSA module, including its mechanical design and its implementation in the biped robot 'Binocchio'. Experiments validated the VSA module to accurately estimate the output torque and stiffness of the biped robot Binocchio with only an error of around 6%.

The VSA was designed for two main purposes.
1. Actuation of the robotic joint to get required output torque and speed.
2. To provide adaptable joint stiffness to the biped robot so that the robot could perform with efficiency even in unstructured environments.
The design of the VSA is such that it fulfils both the above two purposes. The design consists of two main mechanisms.

1. Driving Mechanism to serve the first purpose, that is actuation of robotic joint.
2. Stiffening Mechanism for the second purpose, to adjust the compliance at the output.

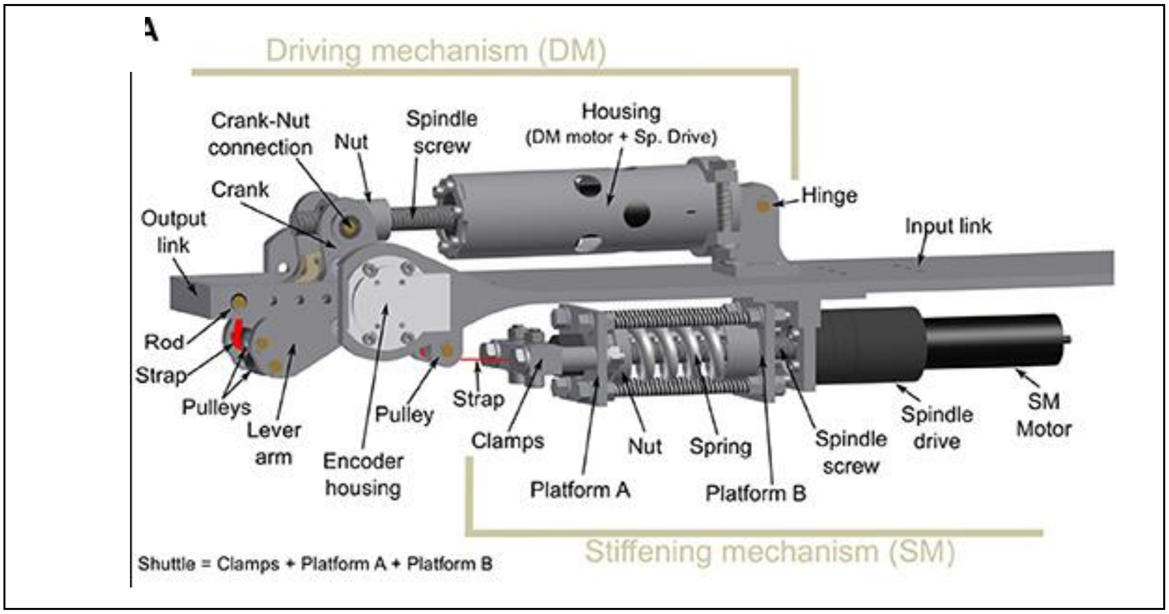

Fig. 4 The two mechanism of VSA [10]

2.1 WORKING OF VSA

2.1.1 DRIVING MECHANISM OF VSA

The driving mechanism of the VSA is as simple as a slider-crank mechanism.

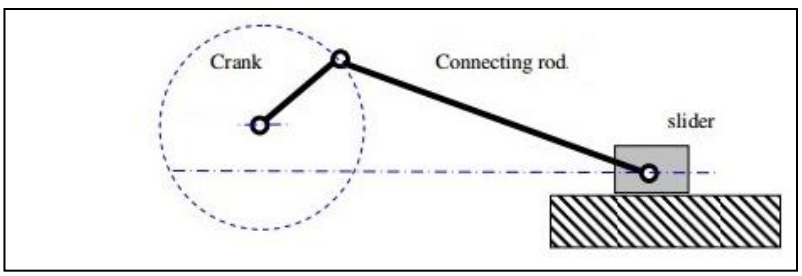

Fig. 5 Slider-crank mechanism for driving mechanism of VSA

The slider-crank mechanism consists of four main parts. Crank, Connecting rod, Slider and Frame. Analogous to this in VSA (Fig. 4) these four parts are Crank, Crank-Nut connection, Nut and the Driving Mechanism frame of VSA.
The spindle drive rotates and the rotational motion of the motor is converted to the translational motion of the nut. As the position of the crank-nut connection changes, the length of the slider changes resulting in rotation of the crank. This in turn alters the angular position of the lever arm. Thus, the lever arm receives a torque due to which the initial zero angle between Lever Arm and Output Link changes to some angle. The driving mechanism thus provides a degree of freedom to the actuated joint and can rotate the Output Link and Lever Arm to desired position.
The free end of the Output Link is attached to a strap, which has high heat resistance and strength. This strap enters the Lever Arm through a pair of pulleys and is guided by another set of pulleys through the joint's axis of rotation. The strap then enters the input link and is in contacted with the Stiffening Mechanism of the VSA [10].

2.1.2 STIFFENING MECHANISM OF VSA

The stiffening mechanism of a VSA consists of a system which transforms the angle α between Output Link and Lever Arm into a deformation of the spring.
It consists of a motor and a spindle drive attached to the input link. The position of the spindle screw can be varied using the motor and the drive.
The Stiffening mechanism consists of a shuttle which has clamp with two platforms, Platform A and Platform B as shown in Fig.4. The strap is attached at Platform A and the spring to Platform B. The shuttle can also perform linear motion along the spindle.

As the crank of the driving mechanism rotates, the angle between the Output Link and Lever Arm, which initially was zero, changes to some angle α, as discussed in the previous section. Due to this, the strap pulls the shuttle and in turn compresses the spring. The force exerted by the strap (which depends on the spring stiffness, 'k') is not aligned with the OL. This creates a torque at the axis if rotation of the joint which tries to re-align Output Link and Lever Arm.
If the pre-compression of the spring is controlled, the amount if torque is controlled which in turn controls the stiffness of the joint at the output link. The pre-compression of the spring can be controlled by changing the position of the spindle screw using the motor and the spindle drive. As the screw is directed away from the motor, a force parallel to the screw acts on the spindle which produces pre-compression in the spring.

Binocchio is a biped robot with the latest technology of variable stiffness actuators (VSA) along with series elastic actuators (SEA) implemented in it. Experiments were conducted to test whether the proposed theoretical values of output torque and stiffness (which depend on angle,α) matched with the actual values measured during the experimental analysis. The experiment validated that it is possible to control the stiffness of robot joints using variable stiffness actuators with only 6% error [10].

VSAs provide a novel solution to the traditional robot joint designs which lack compliant properties. VSAs thus provide dynamically stable, efficient and compliant joint actuation.

III. CONCLUSION

The whole research was done by extensive survey of bio-inspired biped-robots. This work emphasized on the evolution of the biped-robot design from the humble Zero Moment Point (ZMP) concept to the latest Variable Stiffness Actuators (VSA) which has revolutionized the robotic locomotion field.

The research reflects that the classic zero moment point (ZMP) concept paved the way for the modern biped-robots. The only limitation in ZMP notion was the high energy costs and low performance in unnatural surroundings. This work further revealed the theory of 'passive dynamic walking' which lowered the energy costs of locomotion of the robots. The research study further focused on human locomotion and the concept of 'spring-mass system of leg' which introduced the inherent compliant properties in humans which is the foundation of the modern biped-robot designs.

This work presented the study of a novel solution to the problems, like dynamic instability and lack of compliant properties, faced by the traditional designs. It also provides the mechanical design and mathematics behind the VSA. The research also summarizes the experiment results of VSAs to validate that VSA can control the output torque and stiffness with only 6% error. The variable stiffness actuator has a great potential to revolutionize the field of biped robots.

IV. FUTURE SCOPE

Bio-inspired biped robots are becoming technologically advanced to show good performance even in unstructured dynamically changing surroundings. These robots with VSAs and compliant joint properties show great abilities to be used in environments which are dangerous for human locomotion. Be it bomb defusing squad or mining operation, these advanced biped robots can replace humans to perform dangerous tasks. Due to their ability of adjusting joint stiffness the robots can also be used in future for medical surgeries or as prosthetics which involves intricate, accurate work.

The attempts to replicate animal motion have been successful so far, however, engineers are yet to completely understand and apply the various biological principles behind animal locomotion. For example, looking at human locomotion, on the superficial side, it is an animal that walks on the ground using its legs. However, on deeper level one can study the fundamental macroscopic principles that can be transferred from muscles and skeleton to conventional motors and mechanical linkages.

Thus there is still a scope of immense improvement in design of biped-robots inspired from biological principles.

V. REFERENCES

[1]. Carlos André Dias Bezerra , Douglas Eduardo Zampieri. Biped robots: the state of art.
https://link.springer.com/chapter/10.1007/1-4020-2204-2_29

[2]. Torricelli, D., et al. (2016). Human-like compliant locomotion: state of the art of robotic implementations. *Bioinspir. Biomimet.* 11:051002. doi: 10.1088/1748-3190/11/5/051002
https://iopscience.iop.org/article/10.1088/1748-3190/11/5/051002/meta

[3]. Farley, C., and Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. *J. Biomech.* 29, 181–186.
https://www.sciencedirect.com/science/article/abs/pii/0021929095000291

[4]. Vukobratović, M., and Borovac, B. (2004). Zero-moment point-thirty five years of its life. Int. J. Human. Robot. 1, 157–173.
https://www.researchgate.net/profile/Branislav_Borovac/publication/220065796_Zero-Moment_Point_-_Thirty_Five_Years_of_its_Life/links/02e7e538ec4fecdb4d000000.pdf

[5]. McGeer, T. (1990). Passive dynamic walking. I. J. Robotic Res. 9, 62–82.
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.97.3265&rep=rep1&type=pdf

[6]. Farley, C., and Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. J. Biomech. 29, 181–186.
https://www.sciencedirect.com/science/article/abs/pii/0021929095000291

[7]. Ferris, D., Louie, M., and Farley, C. (1998). Running in the real world: Adjusting leg stiffness for different surfaces. Proc. R. Soc. Lond B Bio. Sci. 265:989–994.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1689165/pdf/9675909.pdf

[8]. Vrije Universiteit Brussel, MACCEPA: The Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator
http://mech.vub.ac.be/multibody/topics/maccepa.htm

[9]. Vanderborght, B., *et al* (2008). Overview of the lucy project: dynamic stabilization of a biped powered by pneumatic artificial muscles. *Adv. Robot.* 22, 1027–1051. doi: 10.1163/156855308X324749
https://www.tandfonline.com/doi/abs/10.1163/156855308X324749

[10]. Rodriguez-Cianca *et al* A Variable Stiffness Actuator Module With Favorable Mass Distribution for a Bio-inspired Biped Robot
https://www.frontiersin.org/articles/10.3389/fnbot.2019.00020/full#B5