EXPERIMENTAL DEVELOPMENT OF STIFFNESS-VARIABLE FOOT SOLE MECHANISM FOR BIPEDAL ROBOTS

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ABSTRACT

This research aims to develop a novel foot sole mechanism which utilizes the jamming transition effect of granular material enclosed in an air tight bag, for use by bipedal robot walking on uneven ground. Zero Moment Point control based robots depends heavily on the accuracy of the modeling of the walking environment, making it weak towards outer disturbances such as uneven walking grounds. The purpose for the development of the foot sole mechanism is to increase the robustness of the Zero Moment Point control based bipedal robots against uneven ground surface irregularities. The mechanism is designed to make the foot sole be soft and compliant to adapt to the surface of an uneven terrain, and be stiff when the robot is in the support phase of the walking gait. Stiffness-variable property of the mechanism according to the internal air pressure of the bag is investigated. The stiffness that could be achieved by the proposed stiffness-variable mechanism is concluded to be enough to support a 60[kg] robot. To measure the effectiveness of the proposed mechanism when placed on an uneven ground, an experiment using a single robot leg to simulate the change in Zero Moment Point when a bipedal robot is in a single leg support gait cycle had been performed. From the measured ZMP position trajectory, when the proposed foot sole mechanism is used, the robot is able to maintain the same ZMP trajectory as when the robot is moving on a flat ground using a rigid sole, even when obstacles is randomly placed under the foot sole. It is concluded that the proposed stiffness-variable foot sole mechanism allows better ZMP measurement and control on uneven ground.

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1.1 Bipedal Robot

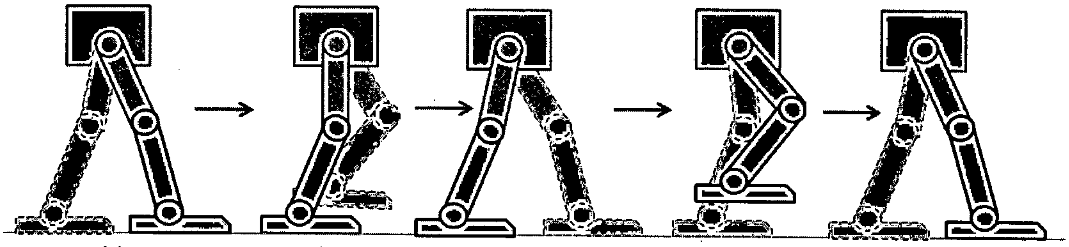

Figure 1. Gait cycle for a bipedal walking robot

One of the main challenges of bipedal robot is maintaining a stable posture when walking. If compared to robots with more than two legs, a bipedal robot is at a large disadvantage due to the limited size of support polygon that it could create from using two feet, which is reduced to the size of the foot sole of the robot when the foot is in a single-leg support phase during a gait cycle. The gait cycle of a bipedal robot (Fig. 1) consists of repetition of a dual-leg support phase, which is when both of the feet touches the ground, followed by single-leg support phase, when only one of the foot provides support to the whole robot body while the other is transferred from the back to the front.

The foot sole of a bipedal robot is important, as it is the only part of the robot mechanics that interacts directly with the environment when walking. The success of walking relies heavily on the condition of the contact between the foot and the ground, as an improper control of the foot will cause the entire robot position relative to the environment to be out of control and ultimately cause the robot to fall down. Since the contact behavior of the foot with the ground could not be controlled directly, most of the current research on bipedal robots focused on the control of the whole robot body, for example by utilizing the Zero Moment Point (ZMP) control, which is the control by gait synthesis of the point where all the moments of active forces acting on the supporting foot is equal to zero, or the limit cycle approach which treats the walking system as a non-linear periodic motion [1,2].

Walking on an unknown uneven terrain is a great challenge for a bipedal robot, due to various effects that the ground could apply to the foot of the robot. The most common problem is bumps on the ground, which will reduce the number of contact points and also move its position away from the expected position. For a biped robot that utilizes the ZMP control, the number and position of the contact points need to be accurately measured as the size of the support polygon during single-leg support is determined by the position of the outermost contact points (the convex hull of the points) of the foot sole with the ground. If a robot programmed to walk with a support polygon with set position and size ends up walking with a different real support polygon, when its Center of Pressure (COP) is at the edge of the real support polygon, the robot will experience a rotation centered at the point on the real support polygon's edge and cause the robot to rock back or forth or worse, stumble on the ground. For a bipedal robot to be able to operate in ordinary human workspace (disregarding rough outdoor terrains), we considered that it should be able to walk on bumps with 20mm in height. It should also be considered that a "bump" on the ground could also be made out of objects that are not static or rigid, such as a rock pebble or a rubber mat. For a bipedal robot to be able to operate safely in human workspace, it should be robust enough to walk on surfaces with bumps and other moving obstructions.

Humans when walking will only use their sight to detect large obstacles or bumps that they will have to adapt to by planning the appropriate leg movement, and if the bumps or obstacles is too small or trivial to be seen by the eye, humans will adapt to the bumps passively by using their multi-articulated foot that could arch, soften and stiffen accordingly. Humans could adapt to the irregularities on the ground even while wearing hard-sole shoes because of their ability to utilize their touch of sense and reflexes to swiftly and accurately control the torque and angle of the ankle joint in real time while walking. For a bipedal robot with a rigid flat sole however, it is extremely difficult to imitate the walking on uneven ground by humans.

1.1.1 Zero Moment Point

The locomotion mechanism of a bipedal robot during walking carries the task of not only to realize the set motion of all the joints and links on the mechanism, but also to maintain the dynamic balance of the robot during movement. The dynamic balance could be achieved by maintaining the whole foot sole to be in contact with the ground. The whole mechanism of the bipedal robot is in contact with the environment through the foot sole area which experiences friction force and vertical force from the ground's reaction force.

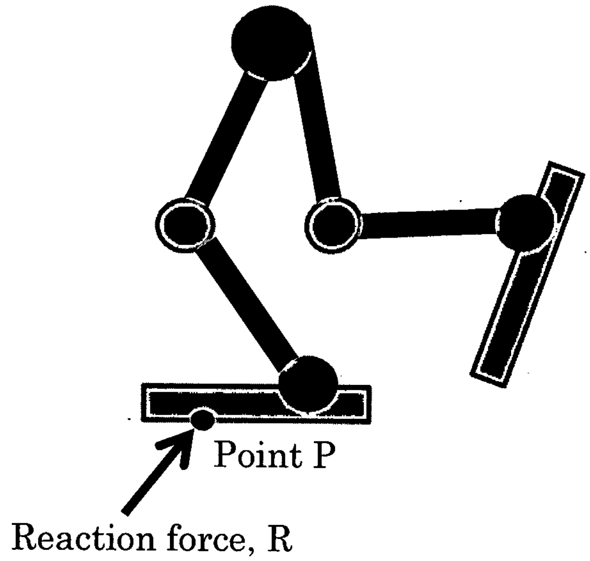

Figure 2. Bipedal robot in single leg support

When the walking mechanism is in the single support phase as shown in Figure 2, which is when only one foot is wholly on the ground, we can replace all of the influence by the mechanism above the ankle (point A) by the force F_A and moment M_A, with the weight of the foot itself at its gravity center (point G) (Fig. 3). To keep the whole mechanism in equilibrium, the foot also needs to be affected by ground reaction force at point P.

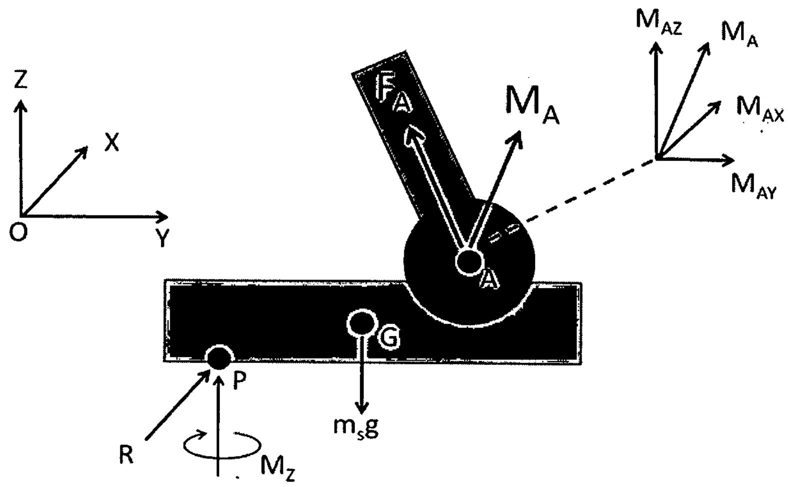

Figure 3. Force and moment working at the foot

In general, the total ground reaction force consists of force R (R_x,R_y,R_Z) and moment M (M_x,M_y,M_z). For the foot to be stationary related to the ground, the horizontal components of force R and moment M needs to be balanced by friction. This means, the horizontal component of the force F_A is balanced by friction force that is represented by the horizontal reaction force (R_x, R_y) and the vertical component of the moment M_A and the moment induced by the force F_A is balanced by the vertical reaction moment (M_Z). To put it simply, when the foot sole is not sliding on the ground, the horizontal reaction force (R_x, R_y) and vertical reaction moment (M_Z) is balanced by the static friction with the ground.

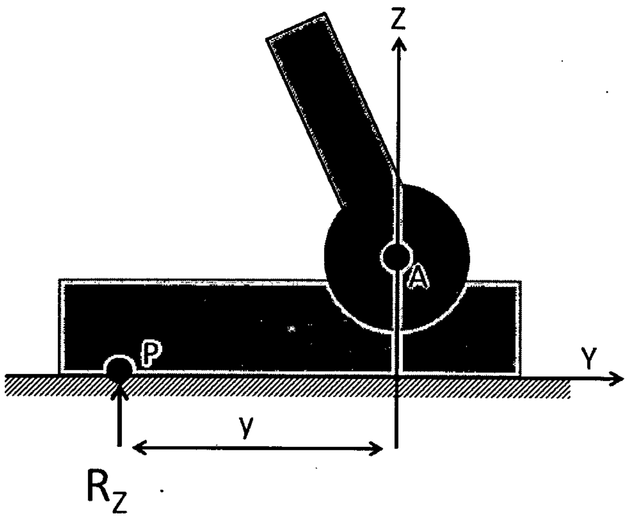

Figure 4. Reaction force R position shift according to horizontal component of moment M_A

The vertical reaction force R_Z is the ground reaction force that is balancing the vertical forces, and is represented as the reaction force R located inside the foot sole. The horizontal component of the moment M_A will shift the reaction force to balance the additional load, as illustrated in a simple x-z plane in Figure 4. The moment M_{Ay} is always balanced by the change of position of the reaction point R_Z, meaning that the horizontal component of the moments M_x and M_y does not exist.

When the area of the foot sole is not wide enough to contain the change in position of the force R when balancing the action of external moments, the reaction force R will act at the foot edge and the unbalanced part of the horizontal component of the reaction moment will cause the mechanism's rotation about the foot edge, causing the mechanism to fall. The available area for the reaction force R to move is called the "**Support Polygon**" and it is the area of the foot sole when the robot is in the single leg support, and the area of the both of the foot soles plus the area in between of the foot soles when the robot is in the double leg support (convex hull of both feet area in contact with ground).

We can conclude that the necessary and sufficient condition for the mechanism to be in dynamic stability is that for the point P on the sole where the ground force is acting,

$$M_x = 0,$$

$$M_y = 0 \tag{1}$$

The name of the point P is "**Zero-Moment Point**" as both the components relevant to the dynamic stability are equal to zero. Explaining it in another way, if the reaction force caused by the foot resting on the ground can be reduced to force R and vertical component of the moment M_z, the point P where the reaction force is acting is the ZMP.

When given a certain dynamics of the robot's mechanism, the ZMP position that will ensure the dynamic equilibrium can be calculated. For a robot resting on the ground only through the foot, the foot needs to be fully rested on the ground as a prerequisite. The static equilibrium equation for the supporting foot resting on the ground is:

$$\mathbf{R} + \mathbf{F_A} + \mathbf{m_s g} = 0, \tag{2}$$

$$\overrightarrow{\mathbf{OP}} \times \vec{\mathbf{R}} + \overrightarrow{\mathbf{OG}} \times \mathbf{m_s g} + \mathbf{M_A} + M_Z + \overrightarrow{\mathbf{OA}} \times \mathbf{F_A} = 0, \tag{3}$$

Where $\overrightarrow{\mathbf{OP}}, \overrightarrow{\mathbf{OG}}$ and $\overrightarrow{\mathbf{OA}}$ are radius vectors from the origin of the coordinate system *Oxyz* to the ground reaction force acting point P, foot mass center G, and ankle joint A, with the foot mass m_s.

If we place the origin of the coordinate system at the point P and project Eq. (3) on the z-axiz, then the vertical component of the ground reaction moment will be

$$M_Z = M_{fr} = -(M_A^Z + (\overrightarrow{OA} \times F_A)^Z).$$

Where the moment is not zero and can only be reduced to zero by the dynamics of the overall mechanism.

However, if we project the Eq. (3) onto the **horizontal plane**,

$$(\overrightarrow{\mathbf{OP}} \times \vec{\mathbf{R}})^H + \overrightarrow{\mathbf{OG}} \times \mathbf{m_s g} + \mathbf{M_A}^H + (\overrightarrow{\mathbf{OA}} \times \mathbf{F_A})^H = 0, \tag{4}$$

Which gives the equation for computing the ground reaction force acting point (P), which is the ZMP.

The position of the ZMP can be obtained by measuring forces acting between the foot sole and the ground, by using force sensors placed on the sole. The correct measurement can only be performed if all of the force sensors are in contact with the ground, as if only part of the sensor is measuring the reaction force, the measurement will most probably cause the robot to rotate along the foot edge. [20]

1.2 *Problem Statement*

When utilizing the Zero Moment Point in the gait synthesis and control of a bipedal robot, great care have to be taken to make sure that the mechanics and dynamics of the robot guarantees the force sensors attached to the foot is able to carry out accurate measurements in order for the robot to maintain walking stability. The ZMP notion is defined with a few rules which is; the whole area of the foot sole of the robot needs to be in contact with the ground, and the angle of the ground needs to be parallel to the feet. Although by measuring the angle of the ground relative to the predefined target ankle joint angle, recalculating the desired motion of the robot is in theory possible, the control algorithm during walking will be undesirably complex and might affect the reaction time of the robot against ground surface irregularities. Also, when walking on an uneven surface, a rigid foot sole will be unable to maintain full contact of its whole foot sole area with the ground because of its surface irregularities. This will cause a change in the predefined support polygon area and position, as during the case when the measurement of ZMP is done by using force sensors, the force sensors will unable to accurately detect the change in surface contact positions of the foot sole with the ground. We believe that a mechanical solution is the best approach to this problem, by developing a foot sole mechanism that is able to reduce the surface contact position and relative angle to the feet regularities.

The foot sole of a bipedal robot carries the task of providing a landing surface condition that is as close to ideal as possible for every step when walking on surface with irregularities. An ideal landing surface condition is defined as:

(A) A landing surface that provides enough friction

(B) A soft and compliant foot sole that could adapt to the uneven ground's surface

(C) A rigid sole that could prevent the shift in angle relative to the ground during the stance/support phase of walking

It is more clearly explained below.

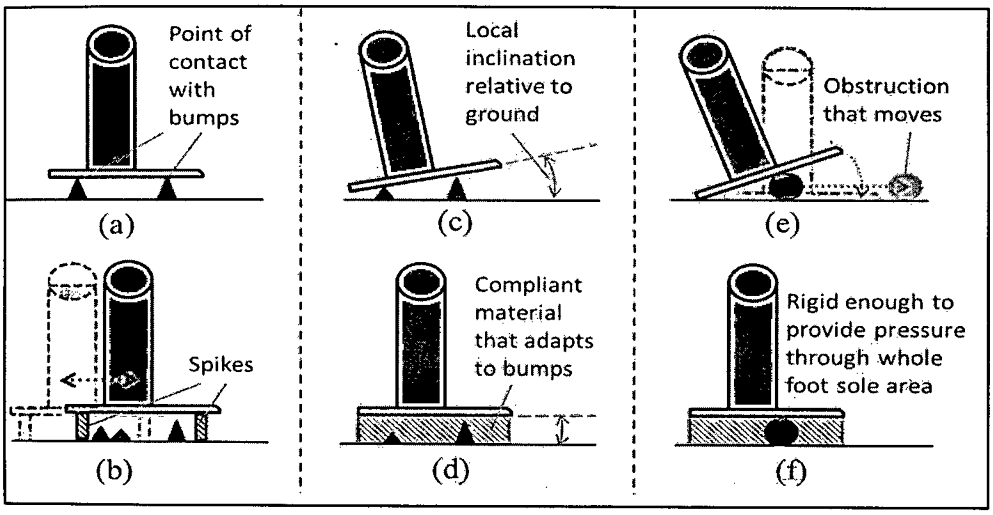

Figure 5. Walking on uneven ground

(A) Friction between the feet and the ground is crucial for bipedal walking, as the horizontal friction forces between the foot sole and the ground should be enough to balance the inertial, coriolis, centrifugal and also gravitational (when walking on a slope) forces generated by the robot body in motion.

Walking on uneven ground will generally reduce the area of contact between the foot sole and the ground (Fig. 5 (a)). The smaller the area of contact, the larger the friction coefficient of the foot sole needs to be to provide enough friction force for the robot to walk. A friction coefficient that is too large combined with a heavy body however will cause wear to the foot sole that needs to be replaced after it is exhausted. The effects of friction might be negligible when walking on flat ground at low speeds, but for example when walking on a slope, the large gravitational force of the robot will cause the robot to slip.

The use of spikes that is higher than the anticipated bump height will help in maintaining a constant number of contact points on an irregular ground surface (Fig. 5 (b)), at the cost of reduced surface contact with the ground to only a few points that could lead to slippage. However, when the spike landed on an obstacle, it will increase the danger of slippage. Ideally, the foot sole should be able to adapt to the shapes of the bumps while maintain a large contact area to the ground for friction (Fig 5 (d)).

(B) This paper will refer to the inclination of the ground, or slope itself as the "global inclination", while inclination of the foot sole relative to the ground caused by the surface irregularities on the ground surface is referred as "local inclination". The angle of local inclination depends on the height and position of the bumps on the ground that comes into contact with the sole of the robot. The higher the height and the closer the space between the contact points, the bigger the local inclination will be (Fig. 5 (c)).

Although numerous previous works have been done on bipedal walking on sloped terrain (terrain with global inclination) [5,16,17], the solution is difficult to apply for inclination of the foot sole caused by bumps (terrain with local inclination) as the bumps will not only cause inclination on both the roll and pitch direction, it will also reduce the number of contact points and reduce the size of support polygon for the bipedal robot. An ideal foot sole should be able to eliminate extreme height differences caused by the bumps by adapting to the surface irregularities, which will result in a much more predictable landing condition for the foot (Fig. 5 (d)).

(C) An ideal foot sole landing position would be that the whole surface of the rigid foot sole to be in contact with a rigid ground, which will provide the widest support polygon for the robot during single-leg support. A rigid ground guarantees that the leg and ankle joint angles relative to the ground follows the designed/calculated values.

For a bipedal robot to not "rock" or shift contact points during single-leg support, the center of pressure (COP) of the robot need to be maintained inside the support polygon. The size of the support polygon during single-leg support is determined by the position of the outermost contact points (the convex hull of the points) on the foot sole, where the contact point positions need to be measured accurately either by using sensors or by limiting the number of contact points mechanically [14,15].

Even if the size of the support polygon is accurately measured and the COP is able to be maintained in the support polygon, there is also the danger of the surface of the contact point itself to move, or change shape depending on the environment. For example in the case of using rigid foot sole, when walking on ground with rock pebbles, there is a high risk that the rock pebbles will shift position, either during contact, or when the COP is shifted across the foot sole (Fig. 5 (e)). This will cause an unpredictable sudden change in posture for the robot, which will affect the dynamics of the walking motion, and will ultimately result in the robot falling. An ideal foot sole should be able to provide the widest support polygon possible even when on uneven ground. It should also prevent any sudden change in feet angle relative to the ground caused by moving obstructions, by applying a near-uniform pressure across the foot plate area (Fig. 5 (f)).

This research aims to develop a new foot sole mechanism that will provide bipedal robots a more stable foothold on unknown uneven ground by utilizing the stiffness-variable property of the jamming transition effect. To demonstrate how the mechanism is designed to work, as shown in Fig. 6, the foot sole's stiffness is set to soft when the feet is off the ground. While the foot is lowered, using the force sensor attached to foot plate, contact with the ground is detected. When estimated sufficient contact is achieved, the foot sole's stiffness is increased until it is enough to support the pressure applied by the robot body during the stance phase.

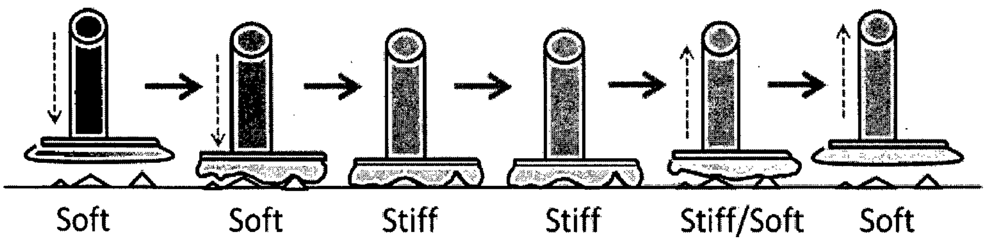

Figure 6. Demonstration of foot sole operation

1.3 Literature Review

There were numerous researches done on "blind" walking on uneven terrain, but ultimately the effectiveness and energy efficiency of the method is limited by the mechanics of the robot's feet [3-7]. There is also large number of previous works on optimizing the COP/ZMP control for uneven ground walking [8-12]. However, it is difficult for a bipedal robot with rigid, flat foot soles to maintain a constant and large support polygon due to the effects of irregularities of a real and unknown uneven ground.

Most researches done on bipedal robot walking on uneven ground is focused on the software aspect of the walking control, but we believe a hardware solution is also as important for a robot to be able to walk on uneven ground with improved stability. A hardware solution will help improve the probability of walking success if it could help reduce the effects of irregularities of the environment to the robot as a whole. Using this approach, Yamaguchi et al. [13] have developed a biped foot system WAF-2 that uses a soft shock-absorbing material sandwiched between two foot plates, and had shown to decrease vibration and increase dynamic walking success probability.

A number of researches have been done on the foot sole mechanism of the robot itself to increase adaptability to an uneven surface. Kang et al. [14] had proposed a foot mechanism that could detect, using four spikes attached to optical sensors, which side of the foot is in contact with a bump first and create a three or four point support polygon using a novel algorithm. Hashimoto et al. [15] had also proposed a novel foot mechanism that utilizes four cam-slider locking spikes mechanism to maintain a 4-point contact with convex and concave ground surface. Both of these works uses rigid spikes to reduce contact with an uneven ground which limits the condition of uneven ground that could be adapted to.

2.0 STIFFNESS ADJUSTABLE FOOT SOLE MECHANISM

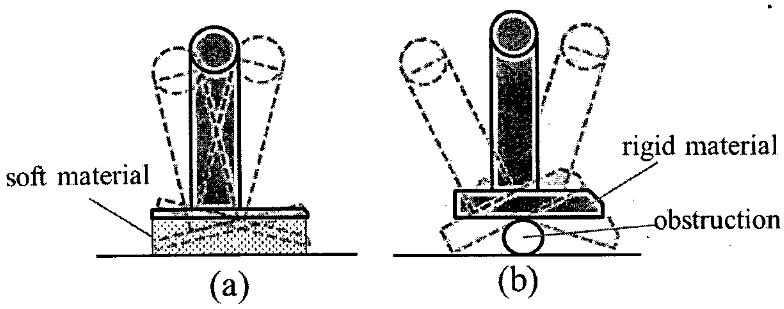

Figure 7. Foot sole (a) using soft material and (b) using rigid material

A soft and compliant foot sole will allow adaption to the unevenness with the ground. However it is difficult to adapt to the uneven terrain by simply using a soft material, because the shape of the soft material cannot be retained when the robot is in the stance/support phase of the walking gait (Fig. 7(a)). As such, an ideal foot system should be able to adapt to the unevenness and while keeping its shape when in the stance phase.

In this paper, we propose a new foot sole mechanism that is aimed to reduce the effects of ground surface irregularities by utilizing the stiffness adjustable property of the jamming transition effect.

2.1 *Jamming Transition Effect*

Granular materials with size of about 1mm in diameter in an air-tight bag will flow freely when air is inserted (density inside the bag is lowered); conversely when air is removed (density inside the bag is higher than a certain point), the bag will stiffen. This change in stiffness according to the density of the granular material and air is called jamming transition effect. By removing and inserting air into an air tight bag with granular material inside, the stiffness of the bag could be adjusted. The air-tight bag containing the granular material will hereby referred to as the jamming bag. The jamming transition effect had gained attention recently due to the research on utilizing the jamming transition effect for use as a robot hand manipulator [18,19].

2.2 *Stiffness Adjustable Foot Sole Mechanism*

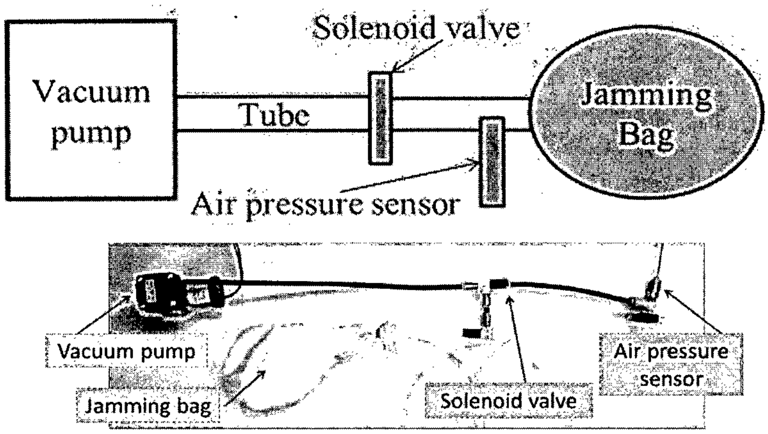

Figure 8. The stiffness variable mechanism

The stiffness-variable mechanism consists of the jamming bag, and an air flow control system (Fig. 8). The airtight jamming bag is made out of a large size balloon with couscous (a tiny granule made from wheat powder) filled inside. The air flow control system consists of air tubes that connect the jamming bag to a small-size vacuum pump, with solenoid valves to control air flow direction and air pressure sensors to measure the air pressure inside the jamming bag.

2.3 *Stiffness-changing Property of Jamming Bag*

One of the critical requirements for the mechanism for use as a foot sole is the ability to withstand the pressure applied by the bipedal robot body during the single-leg support phase. To investigate if the mechanism is capable to fulfill the requirement, we have acquired the stress-strain curve of the jamming bag by doing a compression test on the jamming bag with varying internal pressure.

2.3.1 Compression Test

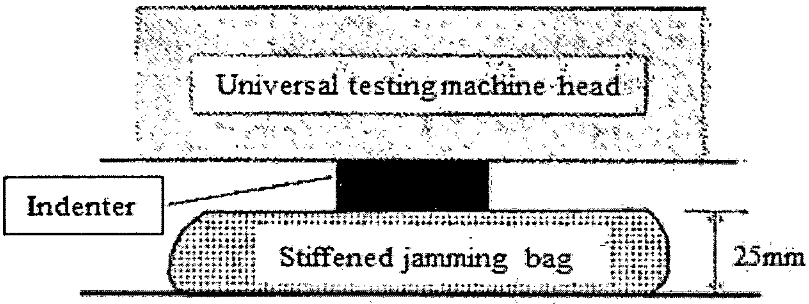

Figure 9. Compression test of jamming bag with varying internal air pressure

Couscous (a granular wheat pasta) is used as the content of the jamming bag during the compression test (Fig. 9). The jamming bag is filled with the granular material, and the air inside the bag is removed while pressed between two plates of metal to shape the stiffened bag to have uniform shape during every test. To simplify the calculation of stress, the pressure applied to the bag is done through an indenter with diameter 30mm. The volume of couscous inserted in the bag is 250ml. The thickness of the tested stiffened bag is 25mm. The compression maximum depth is set to 2.5mm (stress 10%).

The test and stress-strain measurements are carried out using Instron 5500R Material Testing System, fitted with a 2-ton maximum load cell. An air pressure sensor is used to measure the internal air pressure of the jamming bag.

2.4 *Result and Discussion*

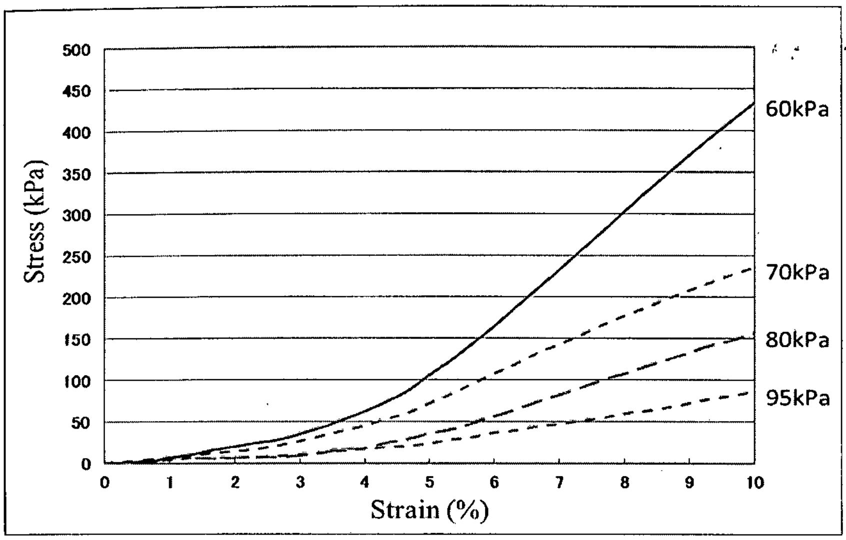

Figure 10. Stress-strain curve for internal air pressures 95 to 60kPa (atmospheric pressure assumed to be 100kPa)

The result is as shown in Fig. 10. From the result, it is observed that the stiffness of the bag increases when the internal air pressure of the bag is lowered. It is also observed that for between 5 and 10% strain from the initial thickness of the bag which is 25mm, the change of the stress-strain curve is linear, meaning that the jamming bag possesses elasticity when the strain is between 5 to 10%. To evaluate if the stiffness of the bag at internal air pressure 60kPa is enough to support a bipedal robot during single-leg support phase, we calculate the amount of strain the bag experiences when used by a 60kg robot.

For internal air pressure 60 kPa, if we assume the bipedal robot to be 60 kg and the foot sole area to be 200cm2(10cm x 20cm), when the pressure of the weight is distributed evenly, it will produce stress of about 29.4kPa for a 3% strain (0.75mm). Due to the