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THE EFFECTS OF AN ORTHOTIC DEVICE ON THE WALKING OF A HUMANOID ROBOT

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An actuator or a support structure of a humanoid robot can be damaged in the same way that a human has musculoskeletal injuries. When an actuator is damaged or risked of being fatally damage, the robot may lack of some abilities to perform fundamental tasks such as walking. In this paper, we have applied an orthotic device which is a brace or a cast to support the damaged knee joint of a humanoid robot. By applying a brace to the knee joint, the walking parameters of the robot need to be adjusted to accommodate the motion constraint introduced by the brace. The limping gait was tested and compared with the normal walking gait. The experimental results showed that the limping gait resulted in slower walk and increased the energy consumption by 30% compared to the normal walking gait. However, a humanoid robot is able to walk despite of its damaged knee joint with the proposed orthotic device.

1. Introduction

The bipedal walk is considered as one of the most difficult tasks learned by human beings [1]. For a robot, bipedal locomotion provides some major advantages over wheeled locomotion when a robot needs to perform a task in an unstructured environment. Bipedal locomotion has more dexterity and has the ability to step over an uneven surface. Nowadays, number of robots have been developed around the world with the ability to walk, run and even jump. However, bipedal walking is still one of the critical challenges for robotic researchers. Most bipedal walking methods, including ZMP (Zero Moment Point)-based control, require not only fast sensor feedback but also fast and precise control of actuators. For this reason, only a small number of research groups have the ability to create a full sized humanoid robot that can walk and run [2].

Generally, a humanoid robot has two legs with the total of 6 degrees freedom in each leg. A humanoid robot is a bipedal robot that needs balancing and control in order to walk effectively. When a motor in its leg is damaged or fails to operate properly, the robot may fall. In a human, when the musculoskeletal injury occurs and the pain is perceived, a human will try to compensate his/her walking gait automatically by limping instead of walking normally. In order to reduce pain, a human may also wear an orthotic device such as a brace, a splint and a cast to support the injured body parts.

There are some previous studies which addressed the concept of damage recovery and walking assistive device in a robot. Tam and Kottege[3] introduced the use of walking stick to help a bipedal robot to avoid and to recover itself from falling. Cully [4] proposed an intelligent algorithm which allows a six legged robot to adapt itself to wide variety of injuries in the same way as animals. Their proposed an algorithm that used the self-sensing ability to diagnose and anticipate failure modes and provide a pre-programmed contingency plan for each type of potential damage. Semwal[5] introduced the push recovery controller to help a humanoid robot to maintain balance during walking.

In this paper, the idea of applying an orthotic device to a humanoid robot is explored. An orthotic device or a brace is designed to modify the structural and functional characteristic of the humanoid robot's leg. When a brace is applied to the robot's joint, it locks the joint into a constrained position, the walking gait of the robot will have to be adapted to the reduced degree of freedom introduced by the brace.

2. System overview

The humanoid robot in this study uses a servo motor as an actuator. These motors are controlled by the STM-NECLEO-L432KC board. The Inertial Measurement Unit (IMU) sensor connects to the main controller board and is used for sensing and balancing control as shown in figure 1. During each step, the swing foot of the robot is controlled to be parallel to the floor at all times as shown in figure 2. The robot walking controller uses Zero Moment Point (ZMP), Center of Mass (CM) and Center of Gravity (CG), angular velocity and angular acceleration of the robot to calculate the walking control input in real time. The low level controller will calculate a trajectory of each leg based on the predefined walking parameters and the balancing compensation signal from the gyro sensor feedback.

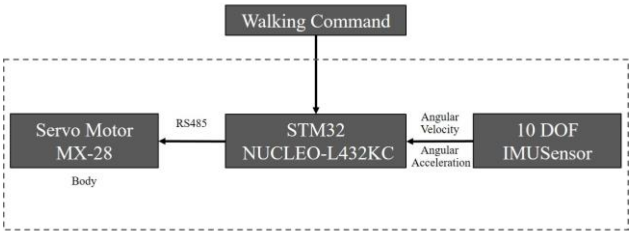

Figure 1. System diagram of the humanoid robot.

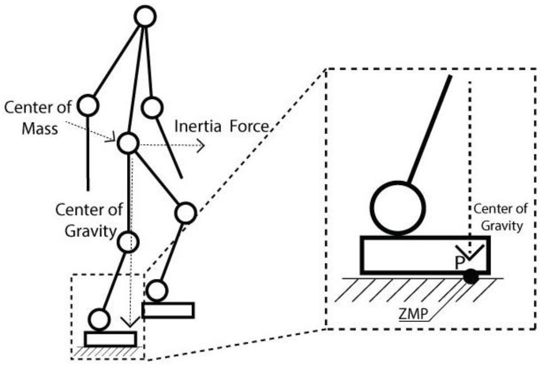

Figure 2. Calculated parameters for the robot walking controller such as ZMP, CM and CG.

The ZMP is calculated from the point (P) that the total moment caused by the force of gravity acting on the center of gravity (CG) is zero as shown in equation 1.

$$M_p = \sum_{i=1}^{n}\{m_i(r_i - P) \times (-\acute{r}_i + g) - I_i a_i - \alpha_i \times I\alpha_i\} \quad (1)$$

mi: concentrated mass at the center of mass of link i
ri: position vector of the center of mass of link i
P : zero moment point
g : acceleration of gravity
Ii: moment of inertia
ai : angular acceleration of link i
αi : angular velocity of link i
Mz: the z component of the moment at point P

2.1. *Design of an orthotic device*

When a human is injured, an orthotic device such as a cast, a splint or a brace is worn to prevent the injured limb from moving. The purpose of an orthotic device is to prevent the injured muscle from moving in order to allow the human body to naturally recover and repair itself. In a humanoid robot, when a joint or a structure of the leg is damaged, a robot may lost its ability to move or to hold position entirely. In this case, an orthotic device is designed to lock or hold the damage joint in a specific position and to provide sufficient support until the robot can be properly repaired. In our humanoid robot, each leg has 6 DOF which are shown in figure 3. When a joint is damaged, one degree of freedom is lost in that leg. In the case of knee joint damage, the pitch angle of the knee cannot be rotated. As a result, the foot step height is reduced and the foot trajectory cannot restricted to the XZ plane. Thus the foot trajectory has to compensated in the Y-axis.

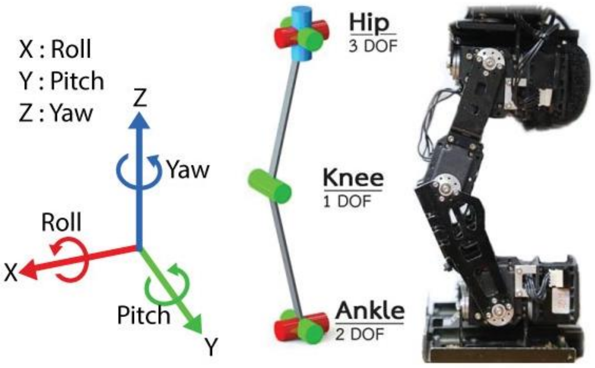

Figure 3. Motor Position and Rotation of Humanoid Robot leg

An orthotic device is designed to constrain the angular position of the damaged knee joint. In this case, the right knee joint is damaged. A brace is designed to attached to the upper and lower leg of a humanoid at an adjustable angle as shown in figure 4. The brace is made of ABS plastic using a 3D printer. The brace is designed to be lightweight. The brace can be adjusted for constraining the leg bending angle between 142 and 180 degrees. At 180 degrees, the distance between the hip joint and ankle joint is 196 mm. At 142 degrees, the distance between the hip joint and ankle joint is 183 mm. The actual brace when attached to the humanoid's knee joint is shown in figure5.

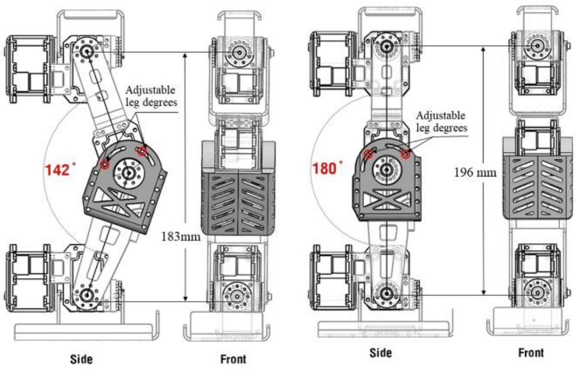

Figure 4. The brace is designed with an adjustable bending angle between 142-180 degrees.

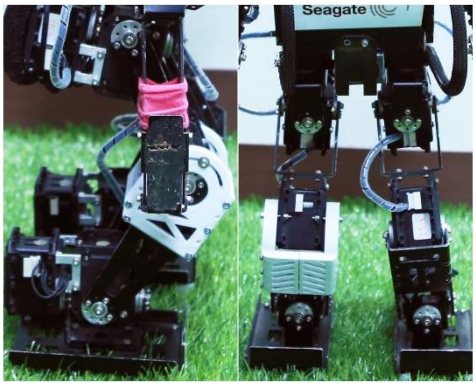

Figure 5. The brace is installed at the right knee of a humanoid robot

2.2. *Walking parameters for a limping gait*

In the normal walking gait of a humanoid robot, there are 19 parameters such as the leg, knee, him and arm positions to be specified in the walking controller program. These walking parameters are manually tuned for each robot based on the weight and dimension of the robot so that the robot is well balance.

However, the important parameters that will be considered here for the limping gait are the Cartesian target position of the left and right feet and the leg angle at the hip around z axis.

X is the distance of the foot to forward or backward in millimeter unit with the direction of Forward (+) and Backward (-)).

Y is the distance of the foot to move left or right in millimeter unit with the direction of Left (+) and Right (-).

Z is the distance of the feet up down in millimeter unit with the direction of Up (+) and Down (-).

θ is the angle of the legs, rotation of clockwise and counterclockwise in degrees with the direction of clockwise (-) and counterclockwise (+).

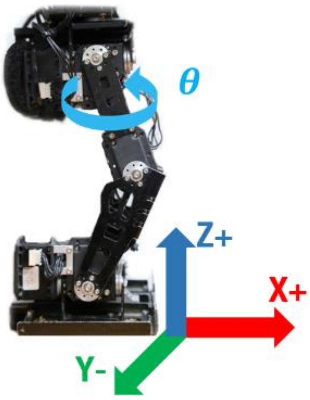

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Figure 6. Reference axes for the walking parameters

Table 1. The walking parameters of the normal walking gait and the limping gait.

Normal Walking Parameter

Motion Step		Left leg				Right leg				Time of frame
		X	Y	Z	θ	X	Y	Z	θ	
Left Walk step	Frame 1	**30**	0	**30**	0	0	0	0	0	0.15
	Frame 2	0	0	0	0	**-30**	0	0	0	0.15
Right Walk step	Frame 3	0	0	0	0	**30**	0	**30**	0	0.15
	Frame 4	**-30**	0	0	0	0	0	0	0	0.15

Limping Parameter

Motion Step		Left leg				Right leg				Time of frame
		X	Y	Z	θ	X	Y	Z	θ	
Left Walk step	Frame 1	**20**	0	**40**	0	0	0	0	0	0.15
	Frame 2	0	0	0	0	**-20**	0	0	0	0.15
Right Walk step	Frame 3	0	0	0	0	**20**	**-10**	**40**	0	0.15
	Frame 4	**-20**	0	0	0	0	0	0	0	0.15

Table 1 shows the walking gait parameters for the normal gait and the limping gait. When the knee joint is damaged, the brace is designed to lock the knee joint at 142 degrees. Therefore, the distance between the hip and ankle of the robot will be reduced from the straight leg configuration at 196 mm to 183 mm. When the right knee is locked, the degree of freedom on the XZ plane of the leg is reduced from 3 DOF to 2 DOF. The robot cannot follow the trajectory of the normal walking gait. Therefore, the target position of the right foot in the Y axis has to be compensated so that the feet can lift toward the side during the leg swing phase. The target Y position of the right foot in the limping gait becomes -10 mm instead of 0 mm as in the normal walking gait. Due to the reduced effective leg length, the step length also decreases from 30 to 20 mm. The step height in Z direction also increase to 40 cm. The walking parameters in the normal walking gait versus the limping gait.

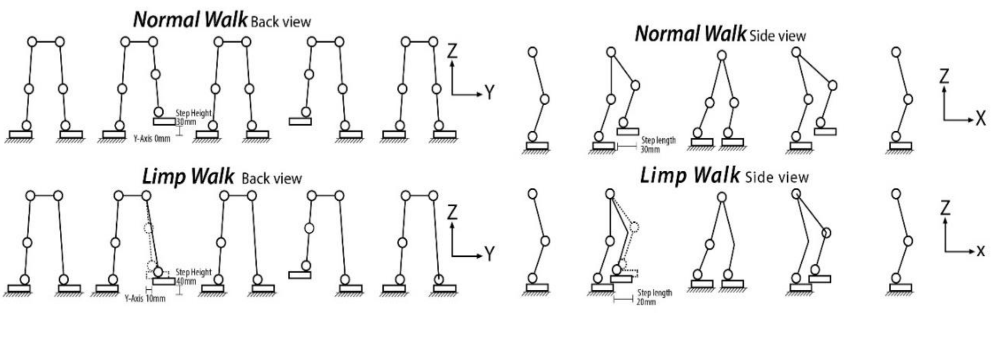

Figure 7. Rear view and Side view of the normal walking and the limping gait

3. Experiment and Results

After the brace was designed and the walking parameters were adjusted for the limping gait, the proposed limping gait were tested on the real humanoid robot. In the experiment, IMU sensors were used to record acceleration and angular velocity during the normal walk without a brace and the walk with a limp when the brace was attached to the right knee. The energy consumption of the robot was also measured from the input current and voltage accumulated over time during the experiment. The walk experiment was performed for 5 trials on an artificial grass mat with the thickness of 0.8cm. The input supply voltage of the humanoid robot was 12.6V.

1) Normal Walking

The experiment for the normal walking gait was performed with 5 steps in each trial. The normal walking gait has the step length of 30mm in X-Axis, the step height of 30mm in Z-Axis. The normal walking gait is shown in figure 8.

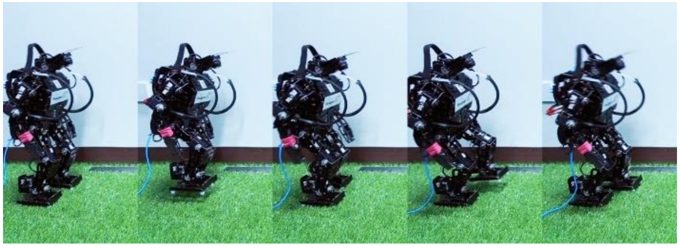

Figure 8. The normal walking gait

2) Limp Walking

In the limping gait experiment, the brace was installed at the right knee of the robot at the fixed bending angle of 142 degrees. The limping gait has lower step height compared to the normal walking gait due to the constraint introduced by the brace as discussed in the previous section. The walking parameters for the limping gait in this experiment were shown in Table 1. Figure 9 shows the limping gait experiment. The robot was commanded to walk for 5 steps with the limping gait in each trial.

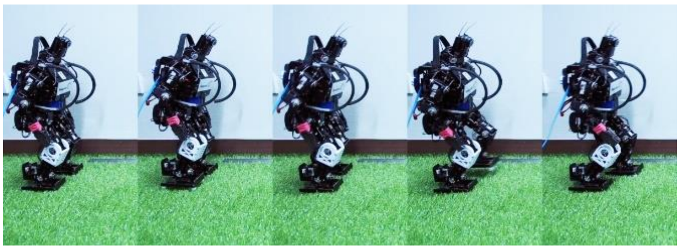

Figure 9. The limping gait

Figure 10 and 11 shows the measured linear acceleration and the angular velocity of the humanoid robot during the walking experiment. When the robot walked with the limping gait, there was a higher angular velocity around X axis (Roll) compared to the normal walking gait. This could result from the fact that in the limping gait, the lift foot has to swing toward the side (the foot target during the swing phase is set in the Y axis). Thus the robot was rocking from side to side at higher amplitude with the limping gait. However, the linear acceleration was not different between walking with the normal walking gait and the limping gait. The limping gait didn’t introduced any additional perceived impact force during the walk.

Figure 10. The measurement of acceleration and angular velocity during the normal walking gait experiment

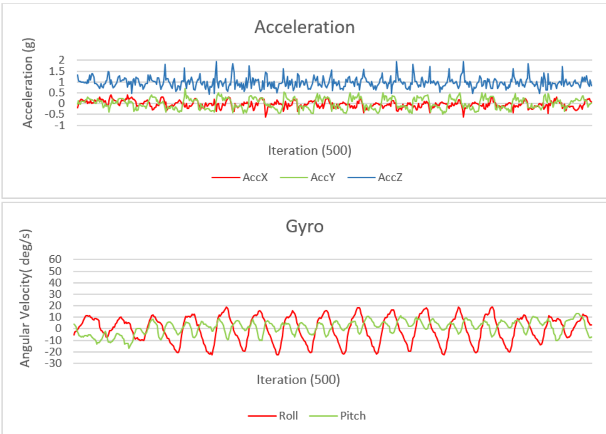

Figure 11. The measurement of acceleration and angular velocity during the limping gait experiment

Table 2. Walking speed and energy consumption of the normal walking gait and the limp walking gait.

Time of	1		2		3		4		5		**Average**	
Walk	Normal	Limp	Normal	Limp	Normal	Limp	Normal	Limp	Normal	Limp	**Normal**	**Limp**
Time (s/m)	5.98	6.44	5.3	7.42	6.53	7.79	6.14	7.12	5.9	6.28	**5.97**	**7.01**
Speed (m/s)	0.17	0.16	0.02	0.14	0.15	0.13	0.16	0.14	0.17	0.16	**0.17**	**0.14**
Current (A)	2.44	3.34	2.59	3.15	2.64	3.07	2.55	3.13	2.61	3.02	**2.57**	**3.14**
Watt (W)	29.65	40.51	31.44	38.21	32.05	37.24	30.96	37.94	31.66	36.6	**31.15**	**38.1**
Joule (J)	177.28	260.91	166.65	283.51	209.28	290.09	190.08	270.1	186.79	229.86	**186.02**	**266.9**

Table 2 shows the walking speed and the energy consumption from the experiment. Limping gait resulted in slower walking speed and higher energy consumption compared to the normal walking gait. When the robot is limping, the higher angular velocity around X axis caused higher kinetic energy for each step. The limping gait also affects the walking speed because the step length is shorter compared to the normal walking gait

4. CONCLUSION

In this work, the orthotic device was installed at the humanoid robot's knee joint to enable the robot to walk when its knee joint actuator is damaged or failed. The proposed orthotic device is a brace made of ABS plastic with an adjustable bending angle between 142-180 degrees. With the orthotic device attachment, the robot needs to adjust its walking gait to cope with the lost degree of freedom in the knee. The limping gait was proposed by compensating the foot target in the swing phase by swaying to the side. In the limping gait, the lift foot needs to be swung toward the Y axis, and the step height and the step length is shorter than the normal walking gait. The experiment shows that the limping gait resulted in slower walking speed and more energy consumption than the normal walking gait at about 30%. However, the orthotic brace and the limping gait enable the humanoid robot to walk even with the damaged knee joint. In the near future, more orthotic device will be designed and studied for different types of joint failure in the humanoid robot.

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