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Development of a Lower Extremity Exoskeleton - Preliminary Study for Dynamic Walking

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Abstract

Exoskeletons for human performance augmentation are controlled and wearable devices and machines that can increase the speed, strength, and endurance of the operator. So far most researchers focus on the upper limb exoskeletons. To help those who need to travel long distances by feet with heavy loads such as infantry soldiers, this paper presents a control principle of a lower extremity exoskeleton. An exoskeleton foot is designed to measure the human and the exoskeleton's ZMP. Using the measured human ZMP as the reference, the exoskeleton's ZMP is modified by torso control and ground reaction force control so that the exoskeleton can walk stably. Test prototypes, initial experiment results, and preliminary dynamic analysis are also presented.

1 Introduction

While research on humanoid robots has begun since many years ago, so far there are no robots can perform tasks in a wide range of fuzzy conditions preserving the same quality of performance as humans. Compared to human naturally developed algorithms with complex and highly specialized control methods, the artificial control algorithms that govern robots miss the flexibility. On the other hand, robots can easily perform some tasks those human cannot do due to their physical limits such as lifting a heavy object. It seems therefore that combining these two entities, the human and the robot into one integrated system under the control of the human, may lead to a solution which will benefit from the advantages offered by each subsystem. Exoskeletons are such systems based on this principle.

Exoskeletons for human performance enhancement are controlled and wearable devices and machines that can increase the speed, strength, and endurance of the operator. The human provides control signals for the exoskeleton, while the exoskeleton actuators provide most of the power necessary for performing the task. The human applies a scaled-down force compared with the load carried by the exoskeleton.

Hardiman [1], developed by General Electric Corporation in the 1960's, was the first attempt at a man-amplifying exoskeleton. It was a 1,500-pound, 30-DOF, hydraulic and electric full body suit and was solved as a master-slave follower system. It was designed for amplification ratio of 25:1. It was bulky, unstable, and unsafe for the operator. Unsupported walking was not achieved. Later, Kazerooni [2], [3] developed an arm extender utilizing the direct contact forces between the human and the machine measured by force sensors as the main command signal to the exoskeleton. Rosen *et al.*[4] synthesized the processed myoelectricity (EMG) signals as command signals with external-load/human-arm moment feedback to control an exoskeletal arm. Besides these, there are several other kinds of upper limb exoskeletons such as those in [5] and [6]. On lower extremity exoskeletons, there are several assist systems for rehabilitation of disabled people such as Hybrid Assistive Leg (HAL) series [7], [8]. HAL can provide external torque for the user's hip and knee joints according to the EMG signals and the ground reaction force measured from the user feet.

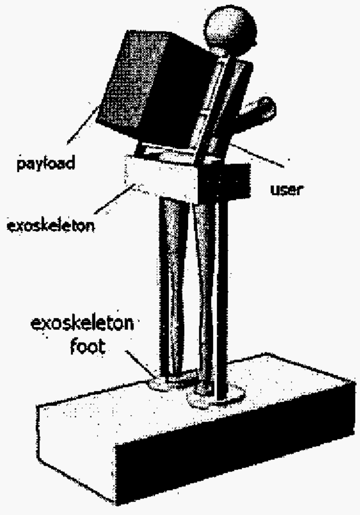


Figure 1: Conceptual design of the exoskelton

To help those who need to travel long distances by feet with heavy loads such as infantry soldiers, we are developing a lower extremity exoskeleton (see Figure 1). With the help of the exoskeleton, the user can carry more payloads and feel little or no extra burden compared to those walking without the proposed exoskeleton system. The exoskeleton will enable the soldiers carry more heavy armors and more powerful weapons to increase their surviving chance in the battlefield. Besides soldiers, fire fighters, postmen, deliverers and so on also can benefit from the exoskeleton.

Next section will present the principle of the control of the exoskeleton. A lower extremity exoskeleton test fixture, some initial experiment results and preliminary dynamic study will be introduced in Section III. At last the conclusions are presented.

2 Principle of the Control

2.1 Support Phases

Biped gait can be divided into two phases: *single support phase* and *double support phase* [9]. When one leg is moving through the air, and the other leg is in contact with the ground it is called *single support phase*. When both feet are on the ground it is called *double support phase*.

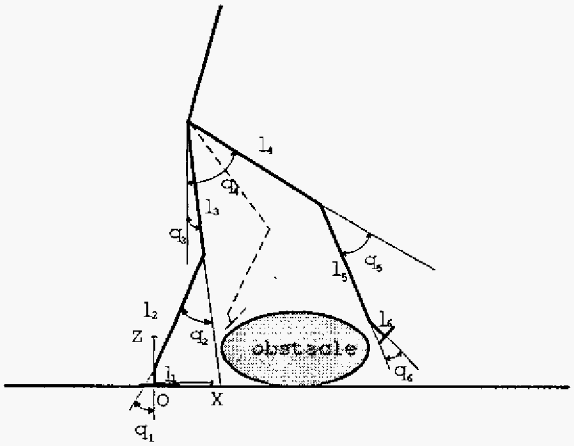


Figure 2: Human in single support phase

2.2 Leg Trajectory Control

During the single support phase, the trajectory of the swinging foot determines the gait parameters such as step length, step height. To make sure that the exoskeleton and the user can walk together, the trajectory of the exoskeleton's swing foot should trace that of the user in time. In the sagittal plane, the trajectory of the swinging foot can be described by

$$P_h(t) = \begin{bmatrix} x_h(t) \\ z_h(t) \end{bmatrix} = f(l_1, l_2, ..., l_6; q_1(t), q_2(t), ..., q_6(t)) \tag{1}$$

where l_i is the length of link i, and $q_i(t)$ is the trajectory of joint i. The lengths of the user's leg can be measured, and the angles of joints can be recorded by sensors such as encoders. Thus, the position of the user's swing foot at each time interval can be calculated online to command the exoskeleton's swinging foot.

2.3 ZMP Control

The Zero Moment Point (ZMP) [10] is defined as the point on the ground at which the net moment of the inertial forces and the gravity forces has no component along the horizontal axes.

Another concept is the Ground Contact Point (GCP) [11], defined as the point on the foot through which a resultant reaction force and a reaction moment, orthogonal to the ground surface, acts.

The gait is balanced when and only when the ZMP trajectory remains within the support area. In the single support phase, the support polygon is identical to the foot surface. In the double support phase, the support area is defined by the convex hulls of the two supporting feet.

In a stable gait, during the single support phase, the GCP of the supporting foot is also the ZMP of the whole biped. As for the double support phase, the relationship between the ZMP and the GCP is described by

$$X_p = \frac{f_{Lz}X_L + f_{Rz}X_R}{f_{Lz} + f_{Rz}}, \quad Y_p = \frac{f_{Lz}Y_L + f_{Rz}Y_R}{f_{Lz} + f_{Rz}} \tag{2}$$

where

- ZMP$= (X_p, Y_p, Z_p)$: ZMP of the whole biped.
- $GCP_L = (X_L, Y_L, Z_L)$: GCP of the left foot.
- $GCP_R = (X_R, Y_R, Z_R)$: GCP of the right foot.
- $f_L = (f_{Lx}, f_{Ly}, f_{Lz})$: ground reaction force at GCP_L.
- $f_R = (f_{Rx}, f_{Ry}, f_{Rz})$: ground reaction force at GCP_R.

If the ZMP of the exoskeleton can remain within the support area, that means the exoskeleton can keep the stability only using the ground reaction force and added force from the user is no need. In other words, the user will not feel the extra burden from the exoskeleton.

As can be concluded from the above discussion, the exoskeleton should be controlled to satisfy the two requirements:

- The swing foot of the exoskeleton should closely trace that of the user in time;

- The ZMP of the exoskeleton should remain in support area.

2.4 Foot Design

To control the ZMP of the exoskeleton, a footpad is designed as shown in Figure 3. The human foot will be on the upper plate, and the exoskeleton leg will be connected to the middle plate. There are four force sensors between the upper plate and middle plate, the middle plate and lower plate, respectively. Those sensors are distributed as shown in Figure 4.

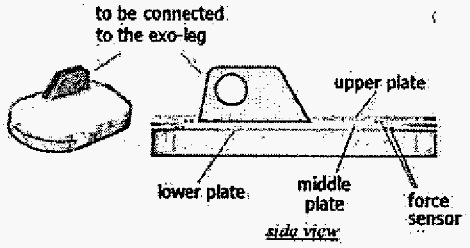


Figure 3: Design of the exoskeleton foot

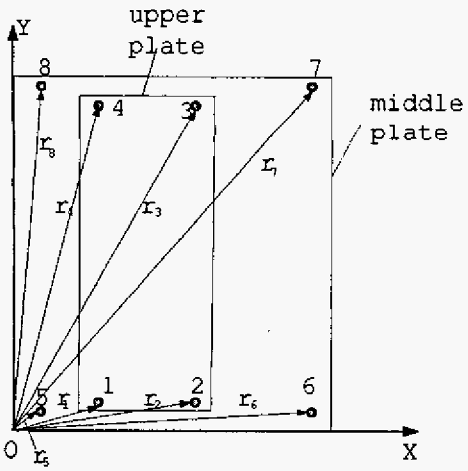


Figure 4: Distribution of the sensors

During the single support phase, sensors 1-4 measure the ground reaction force under the human foot, and the ZMP coordinates of the human in the local foot coordinate frame can be calculated according to

$$ZMP_h = \frac{\sum_{i=1}^{4} F_i r_i}{\sum_{i=1}^{4} F_i} \tag{3}$$

where F_i is the force measured by sensor i at the distance from O, r_i, as defined in Figure 4. Sensors 5-8 measure the ground reaction force under the whole system (the human plus the exoskeleton). Similarly, the ZMP of the whole system can be calculated by

$$ZMP_w = \frac{\sum_{j=5}^{8} F_j r_j}{\sum_{j=5}^{8} F_j} \tag{4}$$

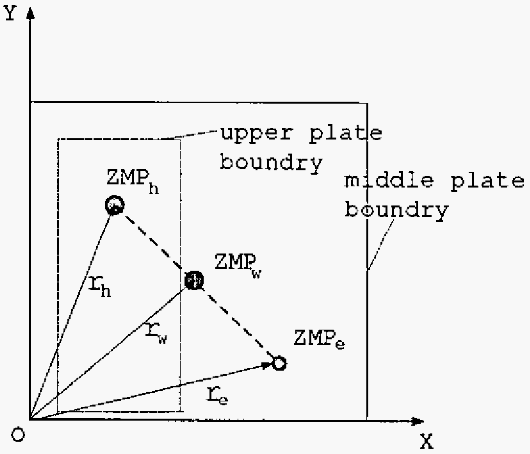


Figure 5: Relationship between the human ZMP and the exoskeleton's ZMP

The ZMP of the exoskeleton is on the radial from the human ZMP to the whole system's ZMP, and its position can be obtained from the equation given by

$$ZMP_e = \frac{\sum_{i=1}^{4} F_i (r_w - r_h)}{\sum_{j=5}^{8} F_j - \sum_{i=1}^{4} F_i} + r_w \tag{5}$$

in which r_h and r_w, as shown in Figure 5, are the coordinates of the human ZMP and the ZMP of the whole system, respectively.

During the double support phase, instead of the ZMPs, GCPs of each foot are obtained from Eqs. (3)-(5). By substituting those GCPs of the human and the exoskeleton into Eq. (2), respectively, ZMP of the human and that of the exoskeleton can be obtained accordingly.

Using the measured human ZMP as the reference, the desired ZMP of the exoskeleton can be chosen according to the following criterions:

- During the single support phase, the desired ZMP of the exoskeleton should be in the support foot area.

- During the double support phase, the human ZMP shifts from the hind foot to the former foot, the desired ZMP of the exoskeleton could be in the area between the two feet, but not too far from the measured human ZMP.

- At the end of the double support phase, when the human ZMP enters his/her former foot area, the desired ZMP of the exoskeleton should also enter the exoskeleton's former foot area.

Once the ZMP is determined, the torso movements of the exoskeleton can be calculated and controlled to satisfy the ZMP law requirements.

2.5 Ground Reaction Force Control

In ideal situation, the actual ZMP of the exoskeleton and the desired ZMP will be at the same point. In reality, however, they may differ from each other due to some reasons such as the terrain is irregular. The *ground reaction force control* [12] shifts the actual (measured) ZMP to an appropriate position by adjusting each foot's desired position and posture.

During the single support phase, when the actual ZMP is behind the desired one, the exoskeleton lowers the front (toe) section of the supporting foot. When the actual ZMP lies in front of the desired one, the exoskeleton lowers the real (heel) of the supporting foot to shift the actual ZMP rearward.

As for the double support phase, when the actual ZMP is behind the desired one, the exoskeleton lifts its hind foot and lowers its former foot. When the actual ZMP lies in front of the desired one, the exoskeleton lifts its former foot and lowers its hind foot.

3 Test Fixtures and Preliminary Results

3.1 Exoskeleton Foot

The fabricated exoskeleton foot is shown in Figure 6. Besides the three plates and sensors described above, foam is added under the lower plate to reduce the transmission of impact forces. Furthermore, it acts as a mechanical lowpass filter that prevents the vibration [13]. The sensors employed are Flexiforce sensor [14] and their coordinates in the foot coordinate frame are listed in Table 1.

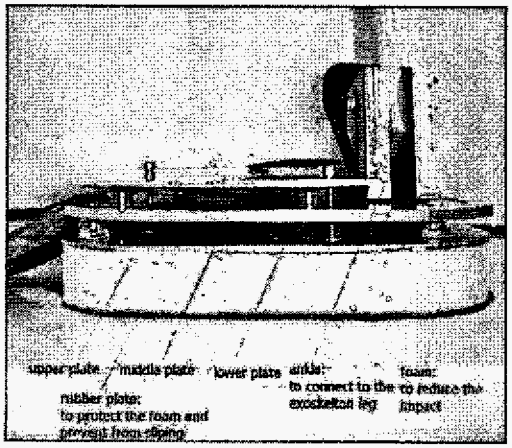


Figure 6: The exoskeleton foot

(X, Y) (mm)	Sensor 1	Sensor 2	Sensor 3	Sensor 4
	(0, 0)	(80, 0)	(80, 200)	(0, 200)
	Sensor 5	Sensor 6	Sensor 7	Sensor 8
	(-11, -11)	(131, -11)	(131, 210)	(-11, 210)

Table 1: Coordinates of the sensors

3.2 Test Fixtures

As shown in Figure 7, test fixtures have been fabricated to provide information that will be used to build a formal wearable lower body exoskeleton.

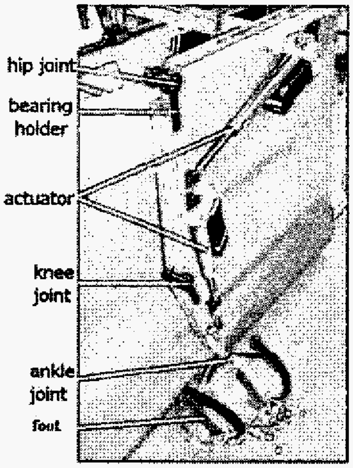


Figure 7: The test fixture

Standard industrial components such as shaft supports, aluminum profiles, etc. are used to minimize machining. To suit different human leg lengths, the length between the hip joint and knee joint as well as that between the knee joint and the ankle joint are changeable by adjusting the position of the bearing holder on the aluminum profile.

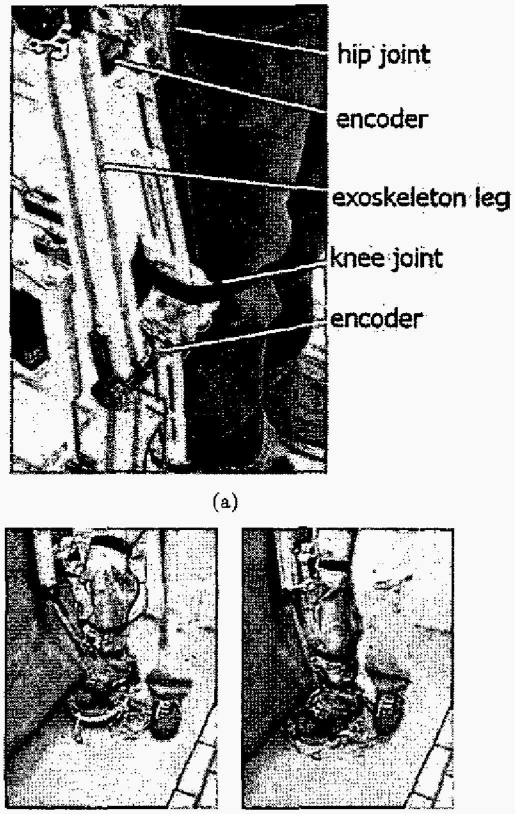
3.3 Initial Experiments

Experiments of controlling the exoskeleton's leg using the position signals measured from human leg have been performed. As shown in Figure 8(a), encoders are attached to the human joints to measure the human leg movements and the exoskeleton leg is controlled to perform the similar movements. Figures 8(b) and 8(c) are two snaps of the gait. Figure 8(b) shows the exoskeleton leg in swinging phase while Figure 8(c) shows its support phase.

During the leg movement experiment, the ground reaction force under the foot and the ZMP trajectories are recorded (see Figure 9).

3.4 Simulation Results

The data recorded during the experiments are used to establish a numerical model to analyze the torso motion of the exoskeleton. Figure 10 shows the measured angular trajectories of a human over a gait cycle. The desired ZMP law is to transform the ZMP from the heel to the toe of the supporting foot. Based on these leg trajectories and the ZMP law, the torso motion of the exoskeleton model is calculated. Figure 11 shows the stick diagram of an evaluated model over one step, where '*' represents the mass centers of the links and 'o' represents the joints. Figure 12 shows the joint angle of the torso and Figure 13 shows its angular acceleration.



(a)

(b) (c)

Figure 8: Initial experiments

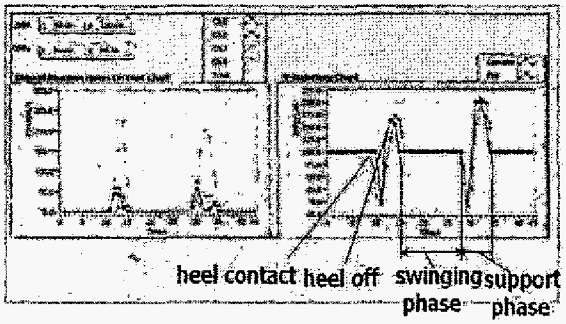


Figure 9: Recorded ground reaction force and ZMP

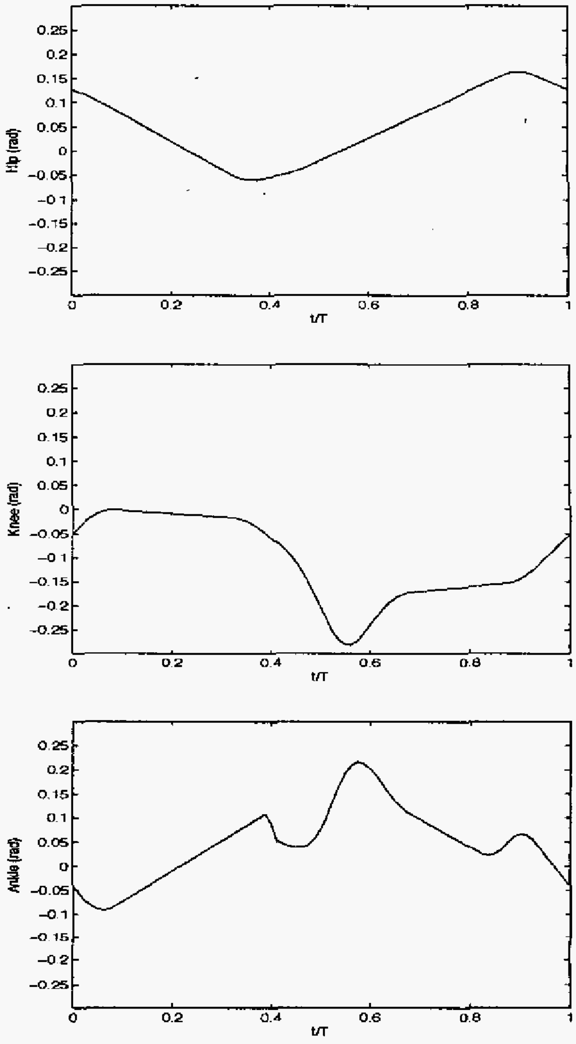


Figure 10: Angular trajectories over a gait cycle

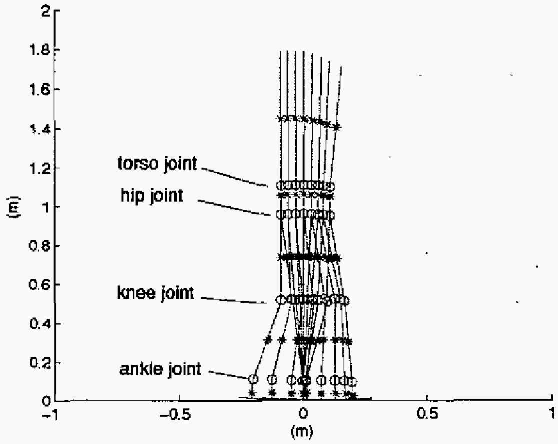


Figure 11: Torso control over one step

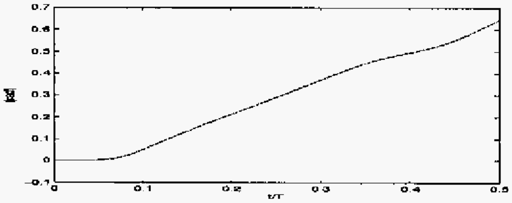


Figure 12: Joint angle of torso over one step

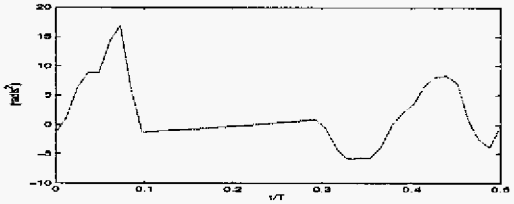


Figure 13: Angular acceleration of torso joint over one step

4 Conclusions

This paper has presented a work of a lower extremity exoskeleton, which is developed to help those who need to travel long distances by feet with heavy loads. The leg trajectories of the exoskeleton are determined by position signals measured from the human legs. The ZMP of the exoskeleton is controlled to keep the stability. Test prototypes, initial experiments and preliminary dynamics study have been discussed. The full version of the exoskeleton is being constructed and further experiments will be performed.

Acknowledgements

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