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Development and Preliminary Study of the NTU Lower Extremity Exoskeleton

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Abstract— **Exoskeletons for human performance augmentation are controlled and wearable devices that can increase the speed, strength, and endurance of the operator. 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 for human performance enhancement at the Nanyang Technological University (NTU). Together with the exoskeleton linkages, an exoskeleton foot is designed to measure the human and the exoskeleton's ZMP. By using the measured human ZMP and the human leg position signals, the exoskeleton's ZMP can be modified by trunk compensation. Simulation results are demonstrated and the prototype being developed is introduced.**

I. 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 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 that will benefit from the advantages offered by each sub system. 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, most researchers paid their attention to developing walking aid systems for gait disorder persons or aged people. One of those systems is HAL (Hybrid Assistive Leg) [7], [8]. HAL can provide assist torques for the user's hip and knee joints according to the user's intention by using EMG signal as the primary command signal.

Different from HAL, the exoskeleton we are developing is to help those who need to travel long distances by feet with heavy loads such as infantry soldiers. Fig. 1 shows a conceptual design. The exoskeleton affords the payload and keeps stability by the ground reaction force. Because the structure of the exoskeleton could be much firmer than human legs, it can carry heavy loads that a person cannot afford. With the help

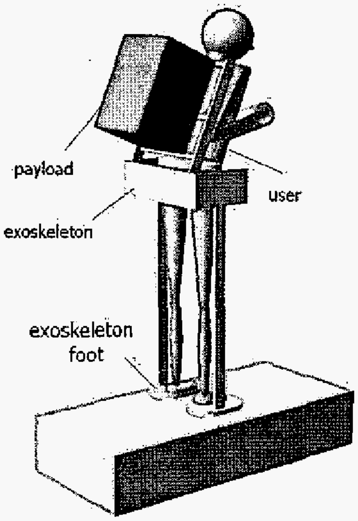

Fig. 1. Conceptual design of the exoskeleton

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of the exoskeleton, the user can carry more loads and walk longer before feeling tired if compared to those without the exoskeleton system. The system might provide soldiers, fire fighters, disaster relief workers, and other emergency personnel the ability to carry major loads such as food, weaponry, rescue equipment, and communications gear with minimal effort over any type of terrain for extended periods of time.

Next section will present the principle of the control of the exoskeleton. Simulation results will be demonstrated in Section III. Section IV introduces the prototype being developed. The last section is the conclusion.

II. PRINCIPLE OF THE CONTROL

The control algorithm consists of two parts, namely *control of the leg trajectory* and *control of ZMP.*

A. Control of the leg trajectory

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*. During the single support phase, the trajectory of the swinging foot determines the gait parameters such as step length, step height, etc. 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, as shown in Fig. 2.

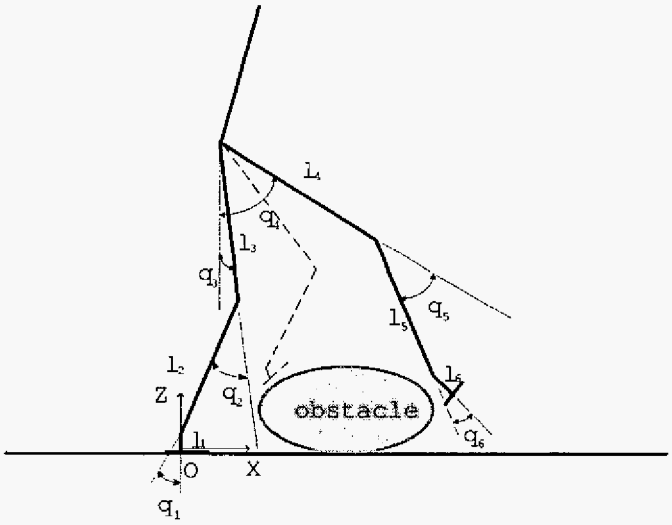


Fig. 2. Human in single support phase

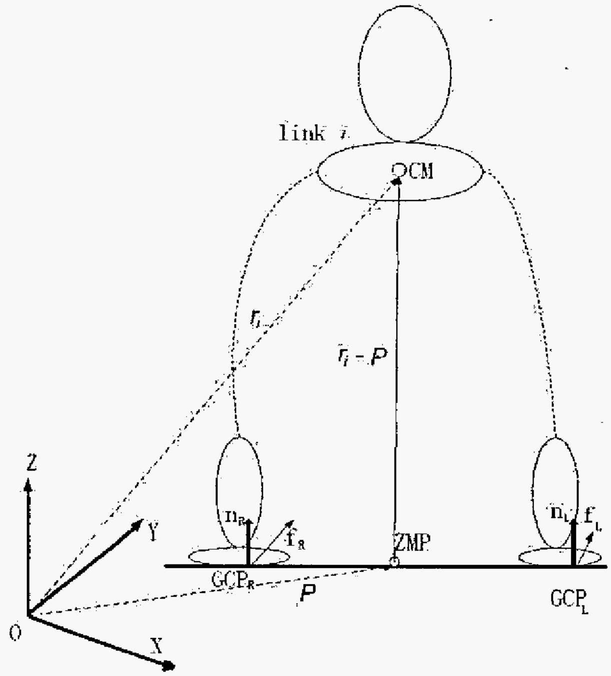
The lengths of the user's leg can be measured, and the angle of joints can be recorded by sensors such as encoders. Thus the position of the user's swing foot at each time interval can be calculated online to command the exoskeleton's swinging foot. To simplify the control, the length of the exoskeleton's leg will be designed to be adjustable. When the user wears the exoskeleton, the length will be adjusted to be the same as the user leg, then only the angles need to be controlled during the walking.

B. Control of ZMP

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. For the kinematic chain shown in Fig. 3, the ZMP condition can be represented as:

$$\sum_{i=1}^{n}[m_i(\mathbf{r}_i-\mathbf{P})\times(-\ddot{\mathbf{r}}_i+\mathbf{g})-\mathbf{I}_i\alpha_i-\omega_i\times\mathbf{I}_i\omega_i] = (0,0,M_z) \tag{2}$$

where $\mathbf{r}_i$ and $\mathbf{P}$ are as defined in Fig. 3, n is the number of links in the chain, m_i and $\mathbf{I}_i$ are respectively, the mass and moment of inertia of link i, ω_i and α_i are, respectively, the angular velocity and angular acceleration of link i, and g is the acceleration due to gravity. Also, M_z is the z component of the moment at ZMP (its value is immaterial for the computation of the ZMP). The coordinates of the ZMP can be obtained by solving this equation for the x and y components of $\mathbf{P}$.



CM stands for center of mass of link i

Fig. 3. Definition of ZMP for a kinematic chain.

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

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; during the double support phase, the relationship between the ZMP and the GCP is described by

$$X_p = \frac{f_{Lz}X_L + f_{Rz}X_R}{f_{Lz} + f_{Rz}}, \quad Y_p = \frac{f_{Lz}Y_L + f_{Rz}Y_R}{f_{Lz} + f_{Rz}} \tag{3}$$

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, it means that the exoskeleton can keep the stability only by using the ground reaction force without adding any force to the user. In other words, the user will not feel any extra burden from the exoskeleton.

1) Measurement of ZMP: To control the ZMP of the exoskeleton, a footpad is designed as shown in Fig. 4. 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. The sensors are distributed as shown in Fig. 5.

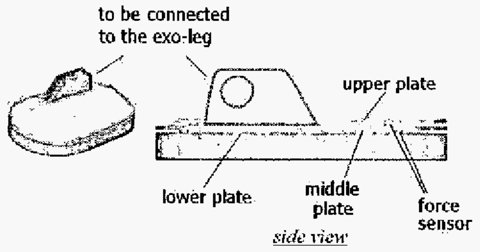


Fig. 4. Design of the exoskeleton foot

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 foot local coordinate frame can be calculated according to

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

where F_i is the force measured by sensor i at the distance from O, r_i, as defined in Fig. 5. 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

$$ZMP_w = \frac{\sum_{i=5}^{8} F_i r_i}{\sum_{i=5}^{8} F_i} \tag{5}$$

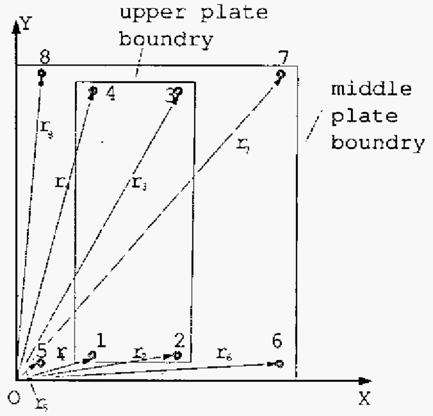


Fig. 5. Distribution of the sensors

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

$$ZMP_e = \frac{\sum_{i=1}^{4} F_i (r_w - r_h)}{\sum_{i=5}^{8} F_i - \sum_{i=1}^{4} F_i} + r_w \tag{6}$$

in which r_h and r_w, as shown in Fig. 6, are the coordinates of the human ZMP and the ZMP of the whole system, respectively.

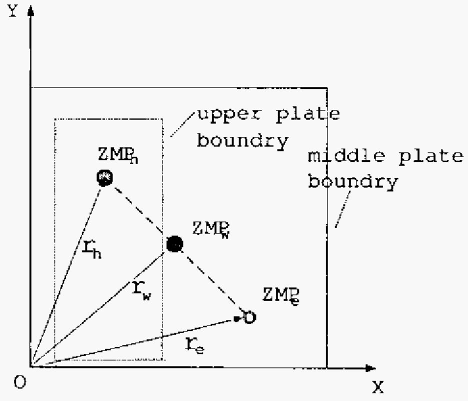


Fig. 6. Relationship between the human ZMP and the exoskeleton's ZMP

During the double support phase, instead of the ZMPs, GCPs of each foot are obtained from (4)-(6). By substituting those GCPs of the human and the exoskeleton into Eq. (3), respectively, ZMP of the human and that of the exoskeleton can be obtained accordingly.

2) Management of ZMP: 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.

If the actual (measured) ZMP of the exoskeleton differs from the desired ZMP, trunk compensation will be applied to shift the actual ZMP to an appropriate position.

By introducing the known leg trajectories and desired ZMP into (2) one can obtain exoskeleton's trunk movements needed to shift the ZMP. It is intuitively clear that the exoskeleton's trunk movements should not exceed a certain value, limited in advance, otherwise the user's trunk will be interfered. If the calculated movements exceed the limit, the desired ZMP should be reselected. Repeat this procedure until find the suitable ZMP and trunk movements.

III. SIMULATION RESULTS

A numerical model is established to analyze the torso motion of the exoskeleton. Table I shows the parameters of the model. The lengths of the exoskeleton model's legs are the same as those of a user's legs. Encoders were attached to his joints to measure the angular trajectories when he was in walking phase. Figs. 7-9 show the recorded angular trajectories over a gait cycle.

TABLE I

PARAMETERS OF THE MODEL

	Foot	Shank	Thigh	Waist	Torso
Height (cm)	10	42	44	10	68
Mass (Kg)	1.5	3.2	8.4	7	30

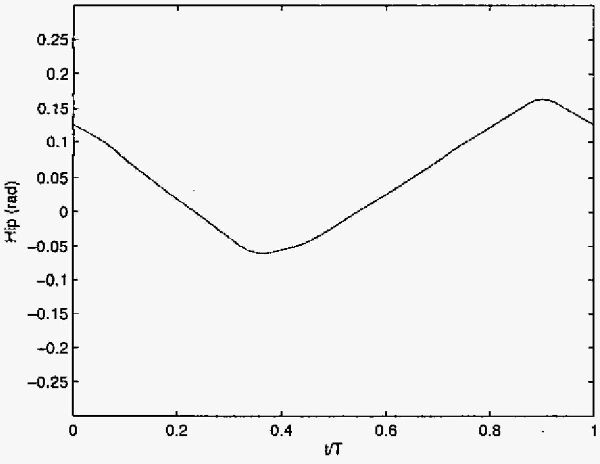


Fig. 7. Angular trajectory of hip joint over a gait cycle

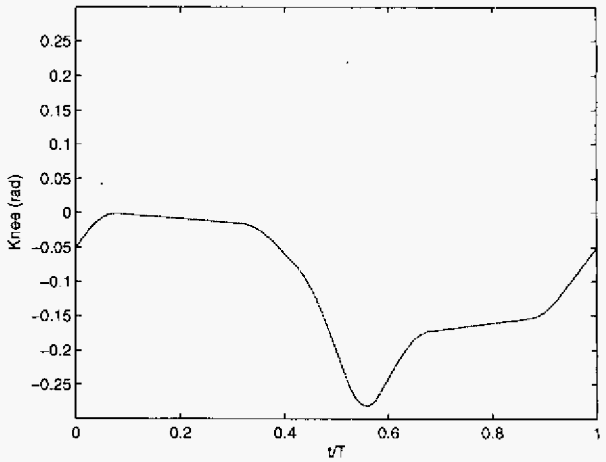


Fig. 8. Angular trajectory of knee joint over a gait cycle

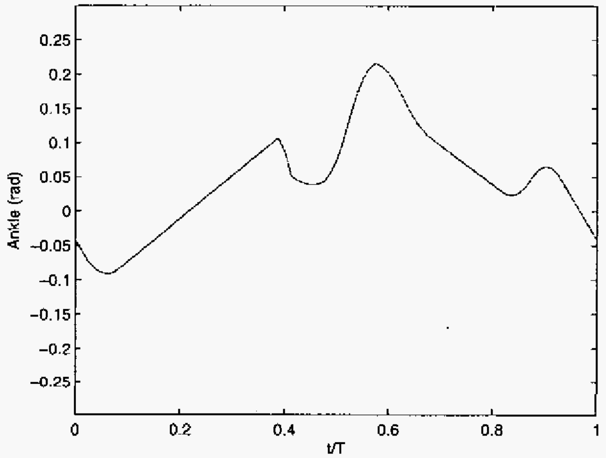


Fig. 9. Angular trajectory of ankle joint over a gait cycle

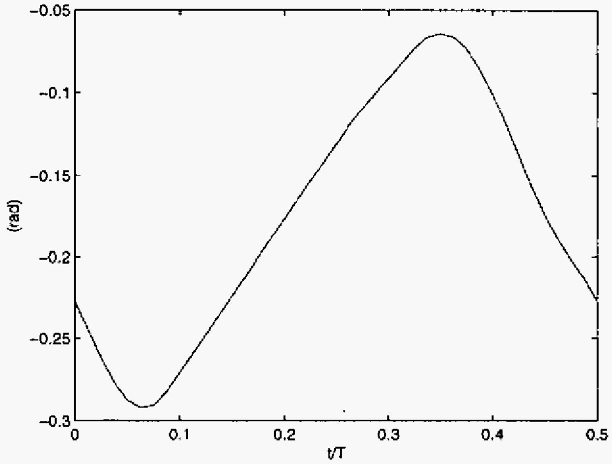


Fig. 10. Joint angle of torso over one step

The model's hip, knee and ankle joints will be driven to follow the same trajectories. The desired ZMP law is to transform the ZMP from the heel to the toe of the supporting foot. Based on the leg trajectory and the ZMP law, the torso motion of the exoskeleton model is calculated, as shown in Fig. 10. Fig. 11 shows the stick diagram of the evaluated model over one step, where '*' represents the mass centers of the links and 'o' represents the joints.

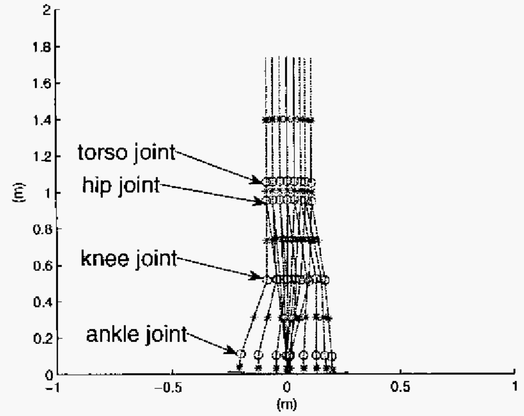


Fig. 11. Torso control over one step

IV. PROTOTYPE BEING DEVELOPED

A prototype as shown in Fig. 12 is being developed. By observing typical human joints' trajectory it is noted that the motion range in sagittal plane is much greater than the range in other planes [12]. Also, during the walking phase most movements happen in the sagittal plane. Hence, at the first stage, only the degrees of freedoms (DOFs) in the sagittal plane are actuated (each one at the torso, hip, knee and ankle, respectively). The motor with a 190:1 gearbox can provide a high torque up to 118 Nm. There are stoppers at joints to limit the motions to be larger than those of the human while walking, and smaller than the physical limit of the human joints. This is to ensure sufficient flexibility for walking, while maintaining the safety of the user. In order to suit different human legs, the shank and thigh are designed to have adjustable sections. The exoskeleton will be connected compliantly together with the user at both the waist and feet.

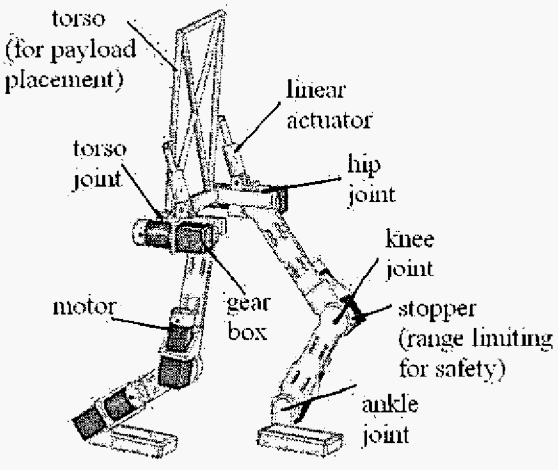


Fig. 12. Structure of the prototype being constructed

V. CONCLUSIONS

This paper gives an introduction of the NTU lower extremity exoskeleton, which is being developed to help those who need to travel long distances by feet with heavy loads. The principle of locomotion has been presented. Simulation results have also been demonstrated. The prototype of the exoskeleton is being constructed and further experiments will be performed.

ACKNOWLEDGEMENTS

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