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Development of NTU Wearable Exoskeleton System for Assistive Technologies

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Abstract— **This paper presents a wearable lower extremity exoskeleton (LEE) developed as a platform for research works on enhancement and assistive the ability of human's walking and load carrying. The whole process of the first prototype design is introduced together with the sub-systems, inner/outer exoskeleton, the attached flexible waist and footpad with sensors. Simulation model and feedback control with the ZMP method were established using Adams and Matlab. The ultimate goal of the current research work is to design and control a power assisted system, which integrates human's intellect as the control system for manipulating the wearable power-aided device. The feasibility and initial performance of the designed system are also discussed.**

I. Introduction

Current artificial control algorithms that govern robots still cannot achieve the comparable performance to naturally developed sensing and strength control methods possessed by human. Therefore, by 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. This is the underlying principle in the design of exoskeleton systems. It is also a system offering multiple opportunities for creating assistive technologies that can be used in biomedical, industrial, and aerospace applications.

An exoskeleton is one of such integrated mechanisms, which is also a wearable device attached to the human body. The physical contact between the operator and the exoskeleton allows direct transfer of mechanical power and information signals. Useful exoskeletons are controllable and wearable devices that can enhance the strength, speed, and endurance of the operator. The human provides control signals for the exoskeleton, whereas the exoskeleton actuators provide most of the power necessary to perform a task. The machine is anthropomorphic and is attached at several points along the operator's hands, legs and torso such that the geometry of the human and the machine approximately match one another.

Rosen *et al.* [1] 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 [2] and [3]. A team in Stelarc [4] presented a conceptual design on an exoskeleton system, which used smart technology to extend the body with a manipulator and to transfer the motion of the arms to the six-legged walking machine in a series of insect-like movements.

In last decades, several exoskeleton leg systems have been developed and studied. The works can mainly be used for two different applications, which can be categorized into two types: (1) walking strength *enhancement* over a long distance or load *augmentation* to carry heavy load repetitively, and (2) walking *aids* for gait disorder persons or aged people.

HardiMan [5], 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. Unsupported walking was not possible due to the huge size. The project was finally abandoned for lack of interest by potential users.

Kazerooni's group [6], [7], [8] 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. In November 2003, the first completely functional prototype experimental exoskeleton was demonstrated.

With funding from the U.S. Department of Defense, Jacobsen's Salt Lake City-based company, Sarcos, has developed another version of exoskeleton suit [9]. A person wearing the designed powered exoskeleton on his or her legs can carry massive loads without getting tired. Exoskeletons could enable soldiers to haul heavier equipment over longer distances and allow rescue workers to carry survivors more safely.

On lower extremity exoskeletons, another group of researchers paid their attention to developing walking aid systems for gait disorder persons or aged people. People with gait disorder and elderly people who are unable to walk without assistance may lose muscular strength in their legs and become bedridden. They can only move around by a wheelchair or by using a wheeled walker. Unfortunately, barriers such as bumps and steps restrict the area that these people have access to. It is hoped that the lower exoskeleton attached to the legs can enhance their muscular strength and enable them walk as normal people.

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A walking aid device for gait disorder persons, the Hybrid Assistive Leg (HAL), has been developed by Sankai et al. [10], [11]. HAL can provide assist torques for the user's hip and knee joints according to the user's intention by using EMG (ElectroMyogram) signal as the primary command signal. With all of the motor drivers, measurement system, computer, wireless LAN (local area network), and power supply built in the backpack, HAL works as a completely wearable system. With the aid of the exoskeleton, the user can carry more 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 loads such as food, weaponry, rescue equipment, and communications gear with minimal effort over any type of terrain for extended periods of time. Another intention of these powered structures was, in fact, to enable normal man to perform overloaded tasks, especially in military applications.

A group at Hokkaido University has developed wearable power assist device for a human's lower back [12], [13], [14]. Assuming that the lower back is the area most vulnerable to injury when carrying heavy loads due to the resulting compressive force applied to lower back. The group's power device assists flexion and extension of the lower back, reduces compressive force, and generates negative force to assist lifting.

In collaboration with the national defense organisation since 1999, a team in NTU has constructed the first lower extremity exoskeleton (LEE) system in Singapore [15], [16], [17], [18], [19], [20]. The system serves a useful platform for research works on augmentation and assistive technologies. The human provides control signals to the exoskeleton, while the exoskeleton actuators provide most of the power necessary for carrying the payload. There is no joystick, keyboard or steering wheel and the load carrier becomes part of the exoskeleton. 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. In the following sections, the related background and features of the LEE are introduced, together with the developed exoskeleton system and the simulation models.

II. Background

A. Structure Design

We design the structure of the lower exoskeleton with a backpack-frame according to the following issues: (1) The exoskeleton should be anthropomorphic and ergonomic, not only in shape but also in function. On the one hand, it should be analogous to the human lower limb in the case of joint positions and distribution of degree-of-freedoms (DoFs); on the other hand, the actuators in the exoskeleton leg should be allocated in the corresponding position to the representative muscles in human leg, in order to simulate the function of the muscles during the process of human walking. However, the number of actuators and sensors should be limited as much as possible to reduce the cost of the leg. Hopefully, one can then establish the premise on which the expected exoskeleton can move in concert with the operator with minimal interaction force between the two. In short, our ultimate aim is to achieve most functions of human leg through the simplified exoskeleton leg. (2) The exoskeleton structure should be length and size adaptable. That is to say, both the upper and lower parts of the exoskeleton leg can be adjusted in a broad range of length and width, thereby accommodating average people with different physical figures to strap on. (3) The exoskeleton should be firm and lightweight. As our design objective is to construct a self-contained device, which means it has to carry its own energy supply and controller other than various regular equipments, the entire exoskeleton should be as light as possible. On the other hand, the structure of the exoskeleton has to support heavy loads mounted on its backpack-like frame. So, stiffness of the structure is required to ensure the safety and reliability. (4) Springs or cushioning should be considered at the connecting and contact points to absorb any impact and vibration. This is important especially for the comfort of load carriers.

B. Control and Implementation

While there are several important aspects in successfully developing an exoskeleton, efficient control strategy and actuation scheme are critical. An important feature of a human-operated exoskeleton is the participation role of human in the process of control and decision-making. As stated previously, the design of exoskeleton is grounded in the notion that combining the skills of the human and the exoskeleton, and allowing each one to perform the tasks with the simplified design and the improving exoskeleton's effectiveness.

Some basic requirements of the control strategy are stated as follows: (1) Number of actuators and sensors should be optimized and the control scheme should be as simple as possible. (2) Learning ability might be required to accommodate the changing loading, terrain, and external conditions. This is particularly important, if the control system should possess the ability of being trained to master the operator's gait trait and feedback it to the controller to instruct the device. (3) The exoskeleton is worn by the operator through several mechanical interface points. Similar to the structure design, the proposed control algorithm should ensure that a minimum disturbance is exerted on the operator for the user comfort, while performing a smoothly and swiftly walking.

To assist in the control strategy, one should first plan the whole walking task. It involves the trajectory generation of the legs by considering any obstacle avoiding and crossing. (Note that the walking task can be studied, if required, by the virtual training by computer or the walking steps by an operator.) The gait synthesis can then be performed to simulate the required walking path and speed, by coordinating the motion of joints. Finally, the corresponding motion of each motor joint is controlled to fulfill the required gait.

C. Biped Gait with ZMP

The concept of zero moment point (ZMP) [22], which 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, has been used. The gait is balanced when and only when the ZMP trajectory remains within the support area. In this case, the system dynamics is perfectly balanced by the ground reaction force and overturning will not occur. In the single-support phase, the support polygon is identical to the foot surface. In the double support phase, however, the size of the support polygon is defined by the size of the foot surface and by the distance between them (the convex hulls of the two supporting feet). The ZMP concept provides a useful dynamic criterion for the analysis and synthesis of biped locomotion. The ZMP indicates gait balance during the entire gait cycle and provides a quantitative measure for the unbalanced moment about the support foot and for the robustness (balancing margin) of the dynamic gait equilibrium.

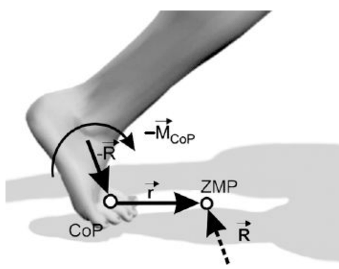


Fig. 1. ZMP and CoP do not coincide [23]

Another term is the center of pressure (CoP) [23], which is commonly used in biped gait analysis based on force platform or pressure mat measurements. CoP represents the point on the support foot polygon at which the resultant of distributed foot ground reaction force acts. According to their definitions, it is obviously that in the considered single-support phase and for balanced dynamic gait equilibrium, the ZMP coincides with the CoP. However, in the dynamically unbalanced single-support situation that is characterized by a moment about CoP that could not be balanced by the sole reaction forces, as shown in Figure 1, the CoP and the ZMP do not coincide. the ZMP location outside the support area (determined by the vector $\vec{r}$ in Figure 1) provides very useful information for gait balancing.

D. Models Developed

1) Model of the Exoskeleton: The exoskeleton composed of the trunk, the pelvis, two shanks, two thighs and two feet, will be considered. The trunk affords the payload and the payload can be seen as a part of the trunk. As shown in Figure 2, the vertical *Z*-axis and horizontal *X*-axis lie in the sagittal plane. By observing typical human joints' trajectories it can be noted that the motion range is much greater in sagittal plane than in other planes [24] and during walking most movements happen in the sagittal plane. Hence, at the first stage, only the joints rotating around the *Y*-axis are actuated and movements in the sagittal plane are studied.

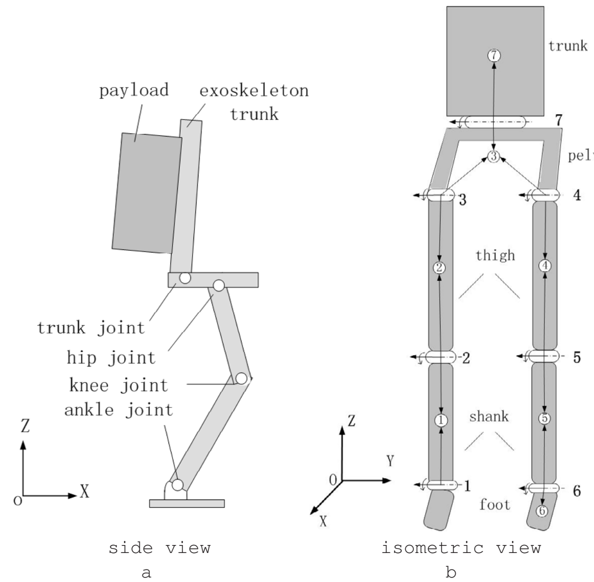


Fig. 2. The model of the exoskeleton

2) Exoskeleton's Dynamics: The dynamical equation which describes the movement of a biped, i.e. the exoskeleton, has the following form:

$$M(\vec{q})\ddot{\vec{q}} = f(\vec{q}, \dot{\vec{q}}) + \vec{Q} \tag{1}$$

where $\vec{q} = (q_1, ..., q_7)^T$ is the vector of generalized coordinates, which are the joint angles. The matrix function $M(\vec{q})$ takes into account the mass distribution, and the vector function $f(\vec{q}, \dot{\vec{q}})$ describes the influence of both inertial forces and gravity. The elements of the vector $\vec{Q}$ are generalized force applied to the system, while the dots denote the time derivatives.

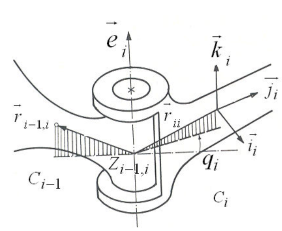


Fig. 3. Joint coordinate of a revolute kinematic pair $\{C_{i-1}, C_i\}$

The exoskeleton's structure is a set of rigid bodies interconnected by the revolute joints. Two adjacent links $\{C_i, C_k\}$ interconnected by a joint at point Z_{ik} is called a kinematic pair. Figure 3 shows a kinematic pair whose joint angle is q_i, where $[\vec{i}_i \quad \vec{j}_i \quad \vec{k}_i]$ is the local orthogonal coordinate frame attached to the center of mass of link i, $\vec{e}_i$ is the unit vector of the axes of joint i, $\vec{r}_{ik}$ is the position vector from point Z_{ik} to the center of mass of link i. The kinematic pairs compose of kinematic chains. Taking the supporting foot as the C_0, which is connected to the ground, the exoskeleton has two simple chains $\{C_1, C_2, C_3, C_4, C_5, C_6\}$ and $\{C_1, C_2, C_3, C_7\}$, as shown in Figure 2b. Without losing the generality, only the first chain is explained here and the second chain can be solved in the similar way. When all joint coordinates are equal zero, $q_i = 0$, i.e., all links are at their home positions. And for $R_i^o = [\,\vec{q}_{i1}^o \quad \vec{q}_{i2}^o \quad \vec{q}_{i3}^o\,]$, which represents the transformation matrix of the i-th link coordinate frame into the global frame, there exists

$$R_i^o = [\,\vec{e}_i^o \quad \vec{a}_i^o \quad \vec{e}_i^o \times \vec{a}_i^o\,]\,[\,\vec{\tilde{e}}_i \quad \vec{\tilde{a}}_i \quad \vec{\tilde{e}}_i \times \vec{\tilde{a}}_i\,]^T \tag{2}$$

where

$$\vec{a}_i^o = \frac{\vec{e}_i^o \times (\vec{r}_{i-1,i}^o \times \vec{e}_i^o)}{|\vec{e}_i^o \times (\vec{r}_{i-1,i}^o \times \vec{e}_i^o)|} \tag{3}$$

$$\vec{\tilde{a}}_i = \frac{\vec{\tilde{e}}_i \times (\vec{\tilde{r}}_{ii} \times \vec{\tilde{e}}_i)}{|\vec{\tilde{e}}_i \times (\vec{\tilde{r}}_{ii} \times \vec{\tilde{e}}_i)|} \tag{4}$$

$$\vec{r}_{i,i+1}^o = R_i^o \vec{\tilde{r}}_{i,i+1} \tag{5}$$

$$\vec{e}_{i+1}^o = R_i^o \vec{\tilde{e}}_{i+1} \tag{6}$$

where $\tilde{(.)}$ represents (.) with respect to the local coordinate frame. By virtue of the recursive computation according to Eqs. (2-6), R_i^o can be obtained. Next, applying the theorem of finite rotations (Rodrigue's formula) for the revolute joints one obtains

$$\vec{q}_{ij} = [\,\vec{e}_i \times (\vec{q}_{ij}^o \times \vec{e}_i) \quad \vec{e}_i \times \vec{q}_{ij}^o \quad (\vec{e}_i.\vec{q}_{ij}^o)\vec{e}_i\,] \begin{bmatrix} \cos q_i \\ \sin q_i \\ 1 \end{bmatrix}, \quad j = 1, 2, 3 \tag{7}$$

thus the matrix $R_i = [\,\vec{q}_{i1} \quad \vec{q}_{i2} \quad \vec{q}_{i3}\,]$, which represents transformation matrix from the i-th link coordinate system into the global system, is determined, where $\vec{e}_{i+1} = R_i \vec{\tilde{e}}_{i+1}$ and $\vec{e}_1$ is known. Hence, the position vectors with respect to the global system are obtained:

$$\begin{aligned} \vec{r}_{ii} &= R_i \vec{\tilde{r}}_{ii} \\ \vec{r}_{i,i+1} &= R_i \vec{\tilde{r}}_{i,i+1} \end{aligned} \tag{8}$$

Applying the basic theorems of rigid body kinematics, one obtains the following recursive equations:

$$\begin{aligned} \vec{\omega}_i &= \vec{\omega}_{i-1} + \dot{q}_i \vec{e}_i \\ \vec{v}_i &= \vec{v}_{i-1} + \vec{\omega}_{i-1} \times \vec{r}_{i-1,i} + \vec{\omega}_i \times \vec{r}_{ii} \\ \vec{\alpha}_i &= \vec{\alpha}_{i-1} + \dot{q}_i \vec{\omega}_{i-1} \times \vec{e}_i + \ddot{q}_i \vec{e}_i \\ \vec{a}_i &= \vec{a}_{i-1} + \vec{\alpha}_{i-1} \times \vec{r}_{i-1,i} + \vec{\omega}_{i-1} \times (\vec{\omega}_{i-1} \times \vec{r}_{i-1,i}) \\ &\quad + \vec{\alpha}_i \times \vec{r}_{i,i} + \vec{\omega}_i \times (\vec{\omega}_i \times \vec{r}_{i,i}) \end{aligned} \tag{9}$$

where $\vec{\omega}_i$, $\vec{v}_i$, $\vec{\alpha}_i$ and $\vec{a}_i$ are the angular velocity, linear velocity of the center of mass, angular acceleration and linear acceleration of the center of mass of the i-th link, respectively. The inertial force of the center of mass of the i-th link $\vec{F}_i$ and moment of the i-th link $\vec{M}_i$ can then be obtained by using Newton-Euler's equations, respectively:

$$\begin{aligned} \vec{F}_i &= m_i \vec{a}_i \\ \vec{M}_i &= I_i \vec{\alpha}_i \end{aligned} \tag{10}$$

with

$$\begin{aligned} I_i &= \textstyle\sum_{l=1}^{3} R_{il} J_{il} \\ R_{il} &= [\,q_{il}^1 \vec{q}_{il} \quad q_{il}^2 \vec{q}_{il} \quad q_{il}^3 \vec{q}_{il}\,] \end{aligned} \tag{11}$$

where m_i is the mass of link i, q_{il}^j (j = 1, 2, 3) denotes the j-th component of vector $\vec{q}_{il}$ and J_{il} is the principle moment of inertia of link i.

E. Gait Control

According to the features of the biped gait described above, the control of the LEE is divided into two parts, namely *leg control* and *ZMP control*.

1) Leg Control: 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. To do that, a mechanical linkage named *inner exoskeleton* is attached to the human operator, as shown in Figure 4. Accordingly, the exoskeleton which is controlled and carrying a payload is named *outer exoskeleton*. The inner exoskeleton equipped with encoders is merely to capture the joint information of the pilot and feedback to the outer skeleton. it consists of several units, which each attached to a human joint. Note that no linkage or connection is required between the units. The length of the linkages of the outer exoskeleton is designed and adjustable so that the linkages are kinematically similar to the pilot's legs. Such a design makes the control of the outer exoskeleton's leg easy - directly forward mapping the angle to the exoskeleton, and the human operator can control the exoskeleton's leg intuitively.

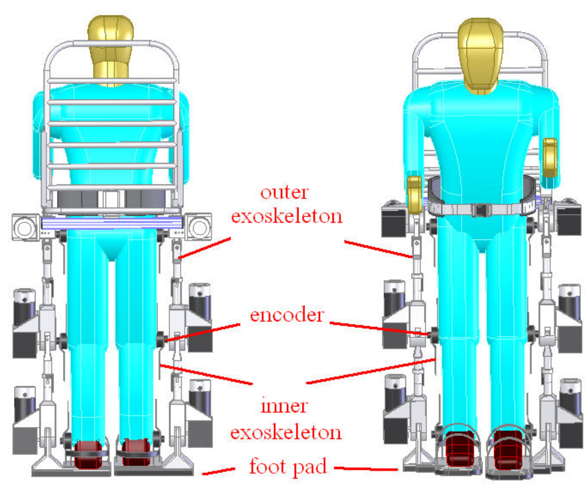


Fig. 4. The inner and outer exoskeleton

2) ZMP Control: From the definition of the ZMP, we have

$$(\vec{M}_G + \vec{M}_F).\vec{e}_X = 0 \tag{12}$$

$$(\vec{M}_G + \vec{M}_F).\vec{e}_Y = 0 \tag{13}$$

where $\vec{M}_G$ is the total movement of gravity forces with respect to ZMP, $\vec{M}_F$ is the total moment of inertial forces of all the links with respect to ZMP, while $\vec{e}_X$ and $\vec{e}_Y$ denote unit vectors of the X and Y axes of the absolute coordinate frame. Eq. (13) can be further replaced with

$$\sum_{i=1}^{7}[(\vec{p}_i \quad \vec{p}_z) \times (G_i + \vec{F}_i) + \vec{M}_i].\vec{e}_Y = 0 \tag{14}$$

where $\vec{p}_z$ is the ZMP coordinates in the global coordinate frame, $\vec{p}_i$ is the position vector of the center of mass of the i-th link,

$$\vec{p}_i = \vec{p}^* + \sum_{j=1}^{i-1}(\vec{r}_{jj} \quad \vec{r}_{j,j+1}) + \vec{r}_{ii} \tag{15}$$

where $G_i = m_i g$ is the gravity force of link i, $\vec{p}^*$ is the position vector of joint 1 with respect to the global coordinate system. Substitute Eqs. (9, 10, 11, 15) into Eq. (14), one can obtain

$$\sum_{i=1}^{7} a_i.\ddot{q}_i + \sum_{i=1}^{7}\sum_{j=1}^{7} b_{ij}.\dot{q}_i\dot{q}_j + \sum_{i=1}^{7} c_i G_i = 0 \tag{16}$$

where the coefficients a_i, b_{ij} and c_i are the functions of the generalized coordinates q_i. The trajectories of q_1 to q_6 are determined by the signals measured from the pilot's legs, as mentioned in the previous section, while q_7 is determined according to Eq. (16) in such a way to adjust the ZMP to the desired position. Such a way to adjust the ZMP by controlling the trunk movements is named trunk compensation.

A footpad (or exoskeleton foot) that can online measure the ZMP of the exoskeleton and that of the pilot is designed. Using the measured human ZMP as the reference, the desired ZMP of the exoskeleton can be selected. If the actual ZMP of the exoskeleton differs from the selected (desired) ZMP, trunk compensation will be applied to shift the actual ZMP to an appropriate position. Details of the footpad via ZMP control can be found in [17], [18], [19], [20].

III. Simulation Model

By using Adams [25], an exoskeleton model is added to the human model, as shown in Figure 5. The density, mass distribution and moment of inertia all can be modified on-line. During walking, the lower limb joints of the exoskeleton have the same angular trajectories as those of the human model joints. The flow chart for the simulation is shown in Figure 6, where the block of exoskeleton's parameters represents the length, mass and moment of inertial of each part of the exoskeleton model. At each time interval of the simulations, the angular positions, velocities and accelerations of the exoskeleton's joints are sent to Matlab, a trunk compensation module will calculate the torque needed at the trunk joint and such a torque will be applied in Adams so that the exoskeleton model can walk stably. Figure 7 shows some snapshots of the models walking in a simulation, while Figure 8 shows the torque applied to the exoskeleton's trunk joint for the changing masses of the load (5 kg and 20 kg).

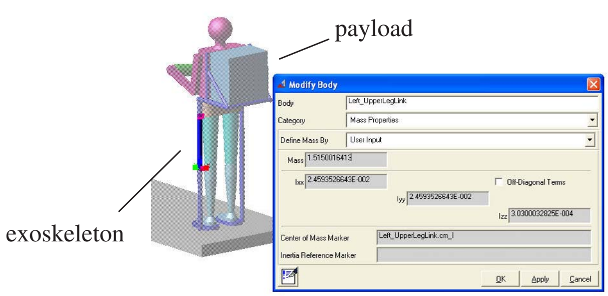


Fig. 5. Modifying the parameters of the exoskeleton

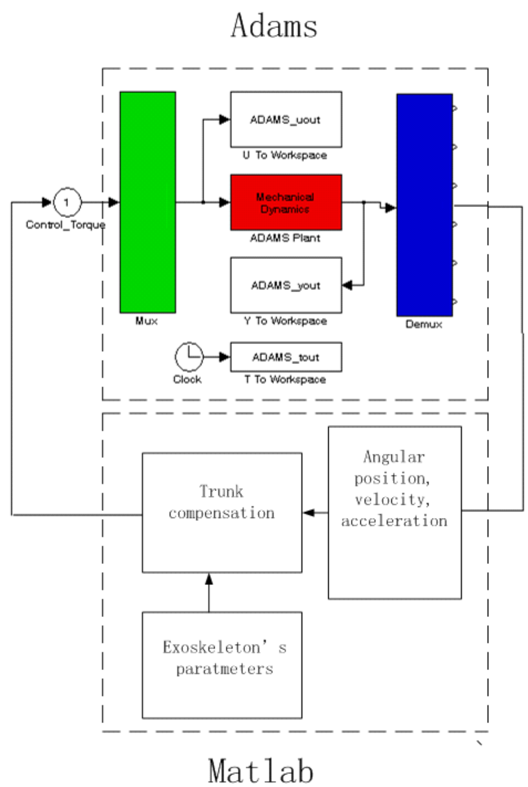


Fig. 6. The flow chart of the simulation

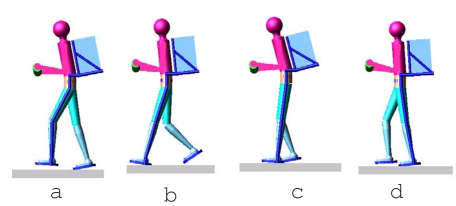
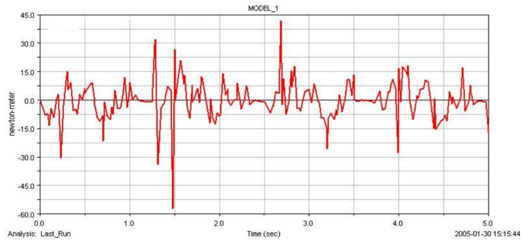


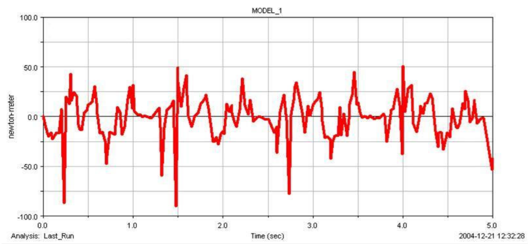
Fig. 7. The snapshots of the models walking

IV. Inner Exoskeleton

As shown in Figure 4, the inner exoskeleton is a data acquisition system used for the acquiring of angular positions of the lower extremities of the user. It should be modular in nature hence allowing compatibility in size of a larger percentile population. The usage environment requires it to be of



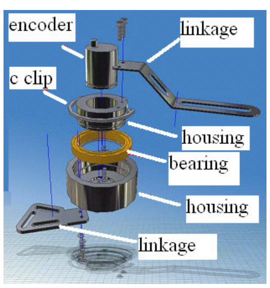
mass of load = 5kg



mass of load = 20kg

Fig. 8. Torque at the trunk joint

a rugged nature with minimal restrictions to the user in terms of mobility. The inner exoskeleton includes a rotary encoder bracket system, a harness system and a data acquisition board.



(a)

(b)

Fig. 9. The encoder bracket

As shown in Figure 9a, a minimum protrusion is achieved by designing the brackets to allow the tip of the encoder spindle to actually touch the surface of the user. This feat was achieved by the use of a larger but extra thin bearing which allows the rotary encoder to reside within the bearing itself. Figure 9b shows the encoder housing with the encoder mounted. In this design, linkages are separated from the encoder housing. This modular concept of the housing allows the same housing unit to be repeated for the hip unit, the knee unit and the ankle unit. Figure 10 shows the user wearing the inner exoskeleton.

V. Outer Exoskeleton

In order to achieve an ideal performance, the outer exoskeleton should satisfy the following criteria.

- High safety: The outer exoskeleton must be able to operate safely and not cause any injuries or pose any hazards to the user and the environment.

a: side view b: back view c: kneel down

Fig. 10. The inner exoskeleton

- Easy to wear: The user should be able to wear and subsequently disengage from the exoskeleton whenever needed in an easy, transparent and quick method.
- High aesthetic satisfaction: The exoskeleton must look sleek, compact and at the same time, must ”feel” sturdy and reliable. Also, it is preferred that the exoskeleton will resemble the actual human lower limbs.
- Length adaptable: The length of shank and thigh of the exoskeleton can be adjusted in a broad range in order to accommodate average people with different physical figures to strap on.

A. Joints and DoFs

As mentioned above, the outer exoskeleton is actuated only at the trunk, hips, knees and ankles to allow flexion and extension of the trunk joint, hip joints and knee joints as well as dorsiflexion and plantarflexion of the ankle joints. Besides, to increase the stability and flexility of the exoskeleton, there is a passive joint to allow abduction and adduction at each hip joint and ankle joint. Those non-actuated degrees of movements are spring loaded to a default standing posture. There are mechanical stoppers at each joint to limit the moment range of the exoskeleton's linkages according to the human anatomy of the lower limbs in case the exoskeleton would damage the user in some emergencies. The allowable range of each joint is listed in Table I.

TABLE I

Critical Angles of the Joint Movements

Joints	Movements	Maximum Angles
Hips	Flexion	60^o
	Extension	-20^o
Knees	Flexion	120^o
	Extension	0^o
Ankles	Dorsiflexion	20^o
	Plantarflexion	-30^o

B. Waist Assembly

The waist connecting the inner and outer exoskeleton is an important component for the successful execution of the exoskeleton system. The main functions of the waist assembly is shown in Figure 11.

Human knee joints are complex joints with a changing instantaneous center of rotation, with motion characteristics that are extremely variable between individuals. However the exoskeleton's knee joints are pin joints and the linkages are

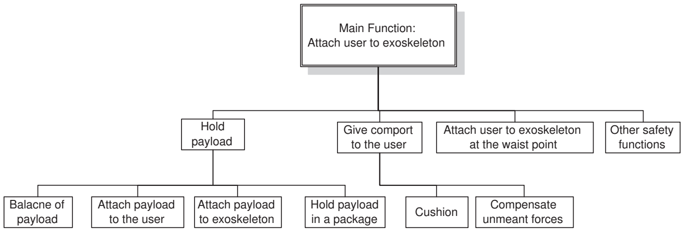


Fig. 11. Main functions of waist assembly

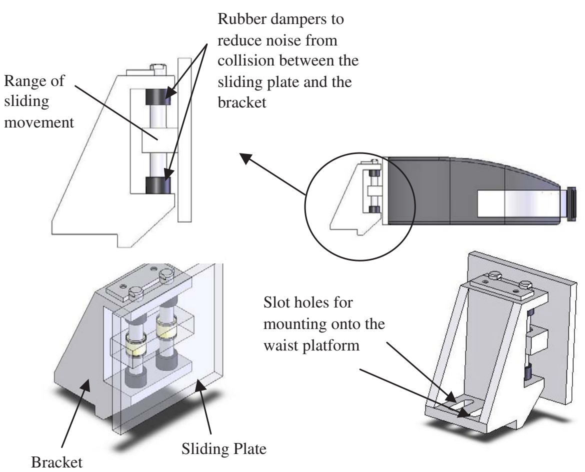


Fig. 12. The sliding attachment at the waist

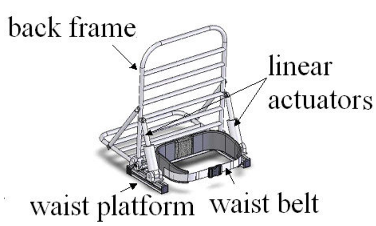


Fig. 13. The design of waist

solid. To cater for the difference, a sliding attachment is designed and attached to the waist belt to the waist platform, This sliding attachment allows the waist belt to slide up and down for a small range and thus, giving the user some free play when wearing the waist belt. The embodiment design of this sliding attachment can be seen in Figure 12. The sliding plate can slide along the support shafts for a small range. A bracket, holding the support shafts, is also used to attach the whole sliding attachment to the waist platform. The waist belt will be attached to the sliding plate. For wearing of the waist belt, a standard plastic buckle is used to fasten the belt to the user's waist. Such a design makes the user be able to wear and subsequently disengage from the exoskeleton whenever needed in an easy, transparent and quick method. Figure 13 shows the overall embodiment design of the waist assembly.

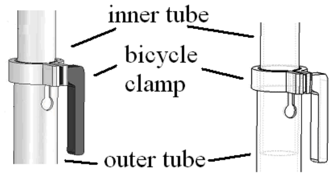


Fig. 14. Clamp method to adjust length of exoskeleton limbs

C. Limb-Length Adjusting and Foot Design

The design of the limbs must fit the sizes of different users. Using the a clamp method shown in Figure 14, the limbs can be adjusted accordingly to the user's height. The outer diameter of the inner tube is slide-fit to the inner diameter of the outer tube when the clamp is released. When the clamp ledge is tightened, the outer tube will clamp the inner tube tightly such that the two tubes will not slide even under large vertical forces. Such a method can ensure the continually adjusting and is able to adjust a full range of lengths, thus accurate match to the user's anthropometrics.

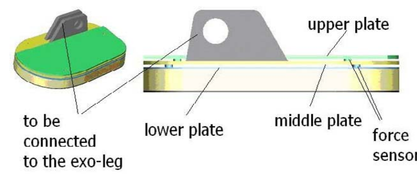


Fig. 15. Design of the exoskeleton foot

To control the ZMP of the exoskeleton, a footpad is designed as shown in Figure 15. The human foot will be sit 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. Figure 16 shows the fabricated feet with the sensors. The discussion of ZMP control associated to the sensors can be found in [20].

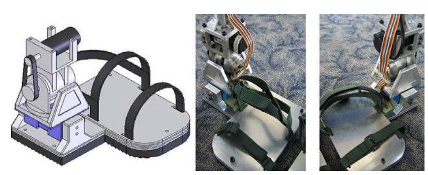


Fig. 16. The feet with sensors

D. Prototype

A prototype of the outer exoskeleton has been constructed. as shown in Figure 17. The figure also shows the user with the whole exoskeleton system. Control implementation of the exoskeleton is being developed and the walking experiment will then performed.

VI. Conclusion and Future Works

This paper has presented a wearable lower exoskeleton system developed for augmentation of human walking ability,

Fig. 17. User resting with the exoskeleton system

which incorporates human as the integral part of the control system and can relieve human's physical fatigue caused by excessive walking or heavy payload. The methodology of designing an anthropomorphic and adaptable exoskeleton system is discussed. Prototype of exoskeleton has been constructed and further experiments will be performed. Future work should focus on designing a more lightweight, compact, comfortable and flexible exoskeleton, and improving the control algorithm to be more robust and adaptable to various conditions. Future efforts should also include the development of lighter devices, speed controls, and more exoskeleton's degrees of freedom to better match the real human model. With respect to the controller system, a real-time learning method, by which the device adapts itself to the person wearing it, and a portable and independent embedded controller should be built into the assist device to enable it for practical use. Future applications can be wearable exoskeleton system helping the user to climb over steep and rough slope/hill while carrying loads. An untethered, fieldable, and mountable power generation subsystem remains a more challenging issue for implementation. In fact, the research work of exoskeleton is still in its initial development stage. There is still a long way to go before one will see a reliable and useful exoskeleton that can effectively enhance human's strength and endurance, as defined by DARPA, USA.

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