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Implementation of Lower-Limb Rehabilitation System Using Attraction Motors with a Treadmill

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Abstract**—**This paper proposes a prototype of a lower-limb rehabilitation system for recovering and strengthening patients' injured lower limbs. The system is composed of traction motors for each leg position, a treadmill as a walking base, tension sensors, microcontrollers controlling motor functions and a main system with graphic user interface. For derivation of reference or normal velocity profiles of the body segment point, kinematic method is applied based on the humanoid robot model using the reference joint angle data of normal walking.

Keywords**—**Rehabilitation, lower limb, treadmill, humanoid robot.

I. INTRODUCTION

REHABILITATION is acknowledged more and more significant as medical technology prolongs human's life time, and urban dwellers are more prone to suffer from various disasters and accidents. Among various fields of rehabilitation, the present paper deals with the system to help the lower-limb paralytic patient to recover their muscular strength.

To this end, an exoskeletal robotic limb system such as HAL [1] had been commercialized with good reliability and performance. Despite the high feasibility of HAL, it is expensive to purchase in hospitals or fitness centers. Treadmill has been employed as a moving base to the robotic limb system such as Lokomat [2], since walking area is confined to narrow space in hospital. If traction motors are installed at the front and end parts of the treadmill rotating simultaneously according to the treadmill speed, system cost will be much lowered with more robust mechanic structure.

The present work develops a lower-limb rehabilitation system using a treadmill, controllers, ac servomotors, load cell sensors, and user-interface display. Two motors are assigned to each segment point and collaborate by rotating in clockwise and counterclockwise directions to guide the patient to walk according to the patient's injury condition. Since treadmill speed can be changed, the angular velocity of motors should be synchronized with it.

This rehabilitation system is equipped with traction motors pulling their connected leg point forward and backward in a synchronous way, which helps and guides the patient walk alone and steadily. For this type of operation, the motors should be provided with velocity profile running in velocity control mode. In general, the velocity profile at some point of a human body is difficult to measure without expensive acceleration sensors or motion capture systems. The present work newly adopts a three-dimensional full-body humanoid robot model to derive velocity profile of any position in a human body during walking when joint angle trajectories of normal walking are given [3].

II. HUMANOID ROBOT MODEL

Human body is made up of 206 bones, 300 joints, and 640 muscles on average. Humanoid robot is the one that has similar joint-link structure to act human-like motions. In this paper, the robot is modeled with 18 joints, and the resultant 20 link coordinates are mathematically described with Denavit -Hartenberg (DH) convention. For DH convention, four parameters are required for adjacent coordinates: joint angle(δ), link twist(α), link offset(d), link length(a), which are defined in Fig. 1. Homogenous transformation matrix for DH convention is described with the four DH parameters as below:

$$B_i\left(\delta_i, d_i, a_i, \alpha_i\right) = \begin{bmatrix} C_i^\delta & -S_i^\alpha C_i^\alpha & S_i^\delta S_i^\alpha & a_i C_i^\delta \\ S_i^\delta & C_i^\delta C_i^\alpha & -C_i^\delta S_i^\alpha & a_i S_i^\delta \\ 0 & S_i^\alpha & C_i^\alpha & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

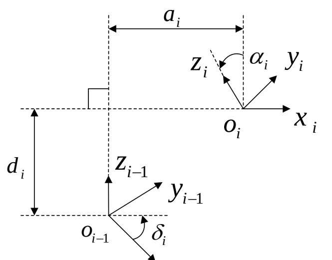

Fig. 1 Definition of four DH parameters in adjacent coordinates

Figure 2 shows a lower extremity model of the humanoid robot with 12 link coordinates. Table I summarizes 12 DH

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parameter sets for the lower extremity when a humanoid robot stands with the left foot.

When the robot stands with the right foot, the origin of reference coordinate $x_0y_0z_0$ must be located at the right leg's ankle, which leads to overall coordinate exchange. Owing to symmetry of human's leg structure, parameter changes occur only in B_6 and B_7 : from $-\psi_1$ to $-\psi_1+\pi$ for B_6 and $-\pi/2$ to $\pi/2$ for B_7. In more detail, additional coordinate change is required at both hip joints by multiplying each transformation matrix.

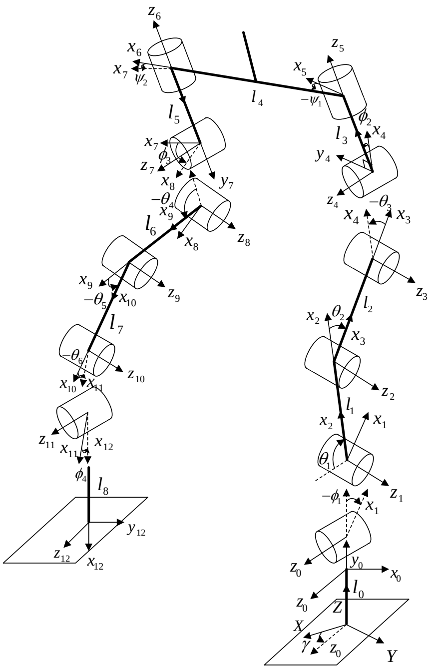

Fig. 2 Lower extremity of the humanoid robot

Figure 3 shows humanoid robot's upper extremity model made of 8 link coordinates, and Table II describes DH parameters for the upper body coordinate transformation. Since hip joint coordinates, i.e. $x_5y_5z_5$ and $x_6y_6z_6$, are interchanged as the supporting foot changes during walking, homogeneous transformation matrices from the hip joint coordinate of the supporting leg $(x_5y_5z_5)$ to left shoulder joint coordinate $(x_{13}y_{13}z_{13})$ are slightly different from each other. In standing on the left leg, homogeneous transformation matrix is like the following:

$$T_{13}^{6}=\begin{bmatrix} x_{13}\cdot x_6 & y_{13}\cdot x_6 & z_{13}\cdot x_6 & -\frac{l_4}{2}+\frac{l_{sh}}{2} \\ x_{13}\cdot y_6 & y_{13}\cdot y_6 & z_{13}\cdot y_6 & 0 \\ x_{13}\cdot z_6 & y_{13}\cdot z_6 & z_{13}\cdot z_6 & l_{tr} \\ 0 & 0 & 0 & 1 \end{bmatrix}=\begin{bmatrix} 0 & 0 & 1 & -\frac{l_4}{2}+\frac{l_{sh}}{2} \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & l_{tr} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

On the contrary, in right-leg supporting, the transformation matrix is slightly modified as

TABLE II
DH PARAMETERS FOR THE ROBOT'S UPPER EXTREMITY

DH parameters	δ_i	d_i	d_i	d_i
B_{14}	$-\theta_7$	0.025	0.014	$\frac{\pi}{2}$
B_{15}	$\phi_5-\frac{\pi}{2}$	0	l_9	0
B_{16}	ϕ_6	0	l_{10}	0
B_{18}	$-\theta_8$	-0.025	0.014	$\frac{\pi}{2}$
B_{19}	$\phi_7-\pi$	0	l_{11}	0
B_{20}	ϕ_8	0	l_{12}	0

B_8	ϕ_3	0	0	2 $-\frac{\pi}{2}$
B_9	$-\theta_4+\pi$	0	l_6	0
B_{10}	$-\theta_5$	0	l_7	0
B_{11}	$-\theta_6$	0	0	$\frac{\pi}{2}$
B_{12}	ϕ_4	0	l_8	0

$$T_{13}^{6}=\begin{bmatrix} 0 & 0 & 1 & -\frac{l_4}{2}+\frac{l_{sh}}{2} \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & l_{tr} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

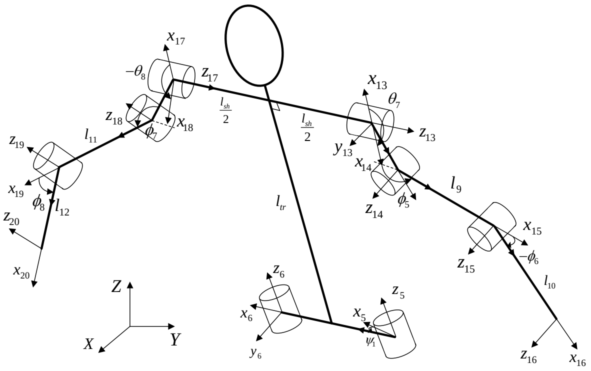

Fig. 3 Upper extremity of the humanoid robot

III. SYSTEM SETUP

The proposed treadmill walking guidance system is composed of a main computer, microcontrollers, a treadmill system, coupled traction motors and tension sensors as shown in Fig. 4.

The main computer takes user's commands with GUI, analyzes them, sends an appropriate motor velocity profile to microcontrollers, manages database information of registered patients with Intel Pentium 3.40GHz, 2GB DDR2, Intel i945p, Gefroce 6200. GUI windows are programmed with MicroSoft C# as shown in Fig. 5.

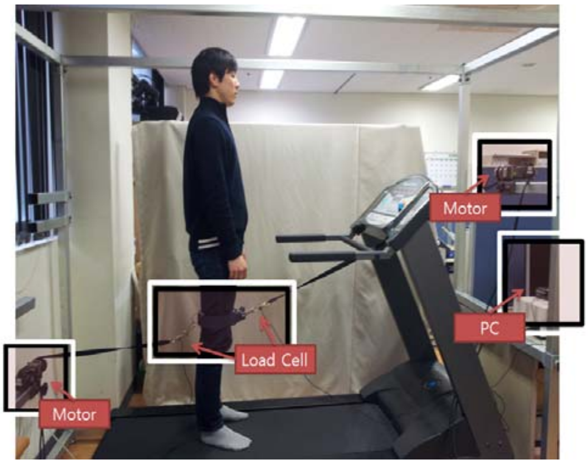

Fig. 4 Components of the proposed system

ATmega128 is selected as a microcontroller which controls traction motors in velocity control mode according to the given reference velocity profile sent from the main computer. Mitsubish AC servomotor HF-kp43 is employed as traction motors, and load cells sum-100K made by SENSTECH is used as tension sensors.

Fig. 5 GUI in system running

As shown in Fig. 4, the patient is tied with the belt connected to the coupled traction motors and slowly walks on the treadmill with guidance of the motors. He may keep walking half an hour. The two traction motors are controlled to rotate synchronously by ATmega128 microcontrollers in order to maintain belt tension for normal walking. For a complete guidance with a heavily injured patient, eight motors will be installed on the system with four leg points.

IV. EXPERIMENT RESULT

For obtaining reference velocity profile of a thigh point, reference joint angle data are applied to the proposed kinematic method for a humanoid robot. Fig. 6 shows a snapshot of Matlab simulation where the foremost circle represents the traction motor.

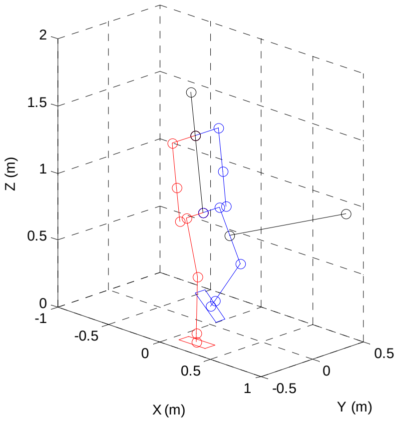

Fig. 6 Components of the proposed system

Fig. 7 demonstrates walking on the proposed rehabilitation system. The character LCD displays analog voltages for the traction motors, which is commanded by ATmega128 microcontroller. Although the system has not been completed yet, technological fundamentals have been verified through simulation and experiment.

Fig. 7 Demonstration of walking on the proposed rehabilitation system

V. CONCLUSION

This paper proposes an inexpensive and efficient lower-limb rehabilitation system using treadmill and traction motors. In this system, reference angular velocity profile of traction motors is significant for training. Using reference joint angle trajectories tabulized in [3] and kinematics of the three-dimensional full-body humanoid robot, the velocity profile can be estimated and applied to the treadmill system. Adjusting the velocity profile under variation of injury status and body specification is future work along with completion of system development.

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