Different Methods of Robotic Motion Planning for Assisting and Training Paralyzed Person

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This paper addresses methods to assist and train walking of a paralyzed person using a robot attached to the pelvis. A leg swing motion has been created by moving the hips without contact with the legs. Motion capture data was compared with the results obtained from the dynamic motion optimization. The results would indicate that it could be possible for the robot to create walking gait for assisting and training the paralyzed person.

Keywords: Hip swinging robot, Paralysed person; Dynamic motion

INTRODUCTION

In India several people experience heart attack and traumatic spinal cord injury each year. Impairment in walking ability after such neurological injuries is common. Recently, a new approach to locomotion rehabilitation called body weight supported training has shown promise in improving walking after heart attack and spinal cord injury[1]. The technique involves suspending the patient in a harness above a treadmill in order to partially relieve the weight of the body, and manually assisting the legs and hips to move in a walking pattern. Patients who receive this therapy can significantly increase their independent walking ability[2].

Clinical access to body weight supported training is currently limited because the training is labor intensive. Multiple therapists are often required to control the hips and legs. Implementing body weight supported training with robotics is attractive because it could improve experimental control over the training, thus providing a means to better understand and optimize its effects[3]. A difficulty in automating body weight supported training is that the required patterns of forces at the hips and legs are unknown. One approach towards determining the required forces is to instrument the therapist hands with force and position transducers. However, therapists are relatively limited in the forces that they can apply compared to robots, and there is no guarantee that any given therapist has selected an optimal solution.

This paper explores different methods of robotic motion employed for assisting and training neurologically paralyzed patients. The objective is to optimize dynamic motion that assisting in hip motion can theoretically generate repetitive walking of the paralyzed patie

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HUMAN MODEL

The human model used for studying the motion of the legs as shown in Figure.1 is simplified with the following assumptions:

- The head, torso, pelvis, and arms are combined into a single rigid body
- The mass of the lower leg, foot, and toes are also combined.
- The walking cycle is assumed to be bilaterally symmetric; that is, the left side stance and swing phases are assumed to be identical to the right-side stance and swing phases, respectively. Based on this assumption only one-half of the gait cycle is simulated.

The joints on the side of the stance phase are called the stance joints and the joints on the side of the swing phase are called the

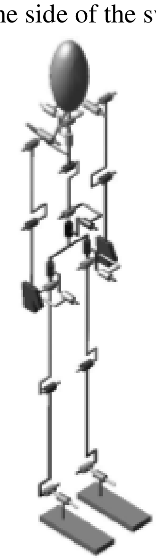

Figure 1 Human model

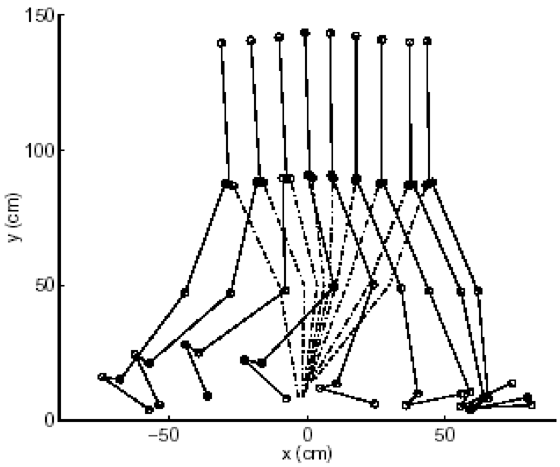

Figure 2 One half of the gait cycle – one step

swing joints. For simplicity both the stance and swing hips are modeled as 2-degrees of freedom universal joints. The stance hip is allowed to rotate about axes oriented in the x- and y-directions. These are the degrees of freedom (dof) assumed to be controlled by the hip swinging robot as shown in Figure.2. The torso is assumed to remain at a fixed angle about the z- axis. The swing hip is assumed to rotate only about axes in the x- (i.e. leg adduction/abduction) and z- (i.e. hip flexion/extension). Rotation about the y- axis (i.e. leg internal/external rotation) is not included in the simulation. The knee is modeled as a 1-dof hinge joint about the z- axis (knee flexion/extension). Motion captures data of key body segments for an unimpaired subject is obtained using a video-based system. Inverse kinematics is performed on the collected kinematic data in order to determine the joint positions and orientations.

ROBOTIC MOTION PLANNING AND CONTROL

The repetitive stepping is given to a paralyzed patient by moving the hip along some trajectory without explicitly controlling the legs. This problem can be addressed mathematically as an optimal control problem for an underactuated system. This is used to obtain a normal swing phase of the flaccid leg by shifting the hip. The motion of the stance hip found from the video capture data of the unimpaired subject is used as an input to the underactuated human model. The swing motion is considered to be an optimal control problem as follows:

$$\text{Minimize,}\quad J_c = \frac{1}{2}\int_0^{t_f}\sum_{i=4}^{10} w_e \tau_i^2 \, dt \tag{1}$$

subject to

$$H(q)\ddot{q} + h(q, \dot{q}) = \tau \tag{2}$$

$$q(0) = q_0, \dot{q}(0) = \dot{q}_0 \tag{3}$$

$$q(t_f) = q_f, \dot{q}(t_f) = \dot{q}_f \tag{4}$$

where τ_1, τ_2, and τ_3 are the generalized forces associated with the translation of the stance hip (and are not included in the cost function since the position of the stance hip was specified by the motion capture data); τ_4 and τ_5 are the moments corresponding to the two rotations of the stance hip (controlled by the hip-swinging robot); τ_6, τ_7 and τ_8 are the swing hip moments (corresponding to abduction/adduction and flexion/extension, external/internal rotation respectively); τ_9 and τ_{10} correspond to knee and ankle rotation moments respectively; and w_{ei} are weighting coefficients. $\tau_6 \sim \tau_{10}$ are assumed zero for the impaired leg. $\tau_{msd4} \sim \tau_{msd10}$ are modeled as nonlinear spring-damper muscle systems while $\tau_{msd1} \sim \tau_{msd3}$ are zero since no muscular force is needed for the linear translation of the stance hip. Equation (2) represents the dynamics for the human model with the joint coordinates $q \in R^{10}$, the joint forces or torques $\tau \in R^{10}$ and the muscular forces or torques $\tau_{msd} \in R^{10}$, where H(q) is the generalized mass matrix and $h(q, \dot{q})$ contains the centrifugal, Coriolis and gravitational forces and the joint friction. In addition, it is necessary to avoid the collision of the swing leg with the stance leg and the ground. This is achieved by introducing two penalty functions into the cost function that penalizes the penetration of the swing leg with the stance leg and the ground. Therefore, the penalty functions J_{p1} and Jp2 are used to represent the collision and are added to the cost function:

$$J_{p1} = \sum_{i=0}^{n_t} w_{p1} \left\{ \begin{array}{l} \left(y_{ground} - y_{heel}\left(\frac{i}{n_t} t_f\right) \right)^2 \\ + \left(y_{ground} - y_{toe}\left(\frac{i}{n_t} t_f\right) \right)^2 \end{array} \right\} \tag{5}$$

$$J_{p2} = \sum_{i=0}^{n_t} w_{p2} \left\{ \left(\begin{array}{l} z_1\left(\frac{i}{n_t} t_f\right) \\ -z_{knee}\left(\frac{i}{n_t} t_f\right) \end{array} \right)^2 + \left(\begin{array}{l} z_2\left(\frac{i}{n_t} t_f\right) \\ -z_{heel}\left(\frac{i}{n_t} t_f\right) \end{array} \right)^2 \right\} \tag{6}$$

where $n_t > 0$ is the number of time instances when the collision is checked; w_{p1} and w_{p2} are positive weighting coefficients; $(x, y, z)_{knee}$, $(x, y, z)_{heel}$, $(x, y, z)_{toe}$ are the Cartesian coordinates of the knee, heel and foot respectively which can be computed by forward kinematics. Y_{ground} is the height of the ground in the y-direction. z_1 and z_2 are selected to constrain the movement of the swing leg in the z-direction to avoid excessive out of plane motion.

The following cost function is used to drive the passive joints of the swing leg to the desired final configuration:

$$\begin{aligned} J_{p3} = \frac{1}{2}\sum_{i_p} w_{p31}\left(q_{ip}(t_f) - q_{fip}\right)^2 \\ + w_{p32}\left(\dot{q}_{ip}(t_f) - \dot{q}_{fip}\right)^2 \end{aligned} \tag{7}$$

where ip is the passive joint index; q_{fip} and $\dot{q}_{fip}$ are the final joint position and velocity respectively; and w_{p31} and w_{p32} are the weighting coefficients.

OPTIMIZATION OF DYNAMIC MOTION

In order to formulate the optimal control problem for a numerical solution, the joint trajectories were interpolated by uniform, C^4 continuous quintic B-spline polynomials over the knot space of an ordered time sequence.

The joint trajectories $q \in R^n$, are written as

$$q(t,p) = \sum_{j=0}^{m} p_j B_{j,6}(t) \tag{8}$$

where n is the number of actuated joints; $P = [p_0, \ldots\ldots, p_m]$ with $p_j \in R^n$ is the set of the control points and $B_{j,6}$ is a B-spline basis function.

For the simulation of the paralyzed patient the system is modeled as an underactuated one with active and passive joints. In order to perform the optimization, an initial trajectory is required. The trajectory identified from motion capture as the initial trajectory and defined it with the parameter set P such that q = q (t, P).

The optimal control problem (1) is then transformed into the following discrete parameter optimization:

$$\text{Minimum}\, j_{cp} = J_c + J_{p1} + J_{p2} + J_{p3} \tag{9}$$

subject to

$$H(q)\ddot{q} + h(q,\dot{q}) = \tau + \tau_{msd} \tag{10}$$

$$\begin{aligned} p_0 &- q_0 \\ p_1 &= q_0 + \frac{1}{5}\dot{q}_0 \Delta t \end{aligned} \tag{11}$$

$$\begin{aligned} p_m &= q_f \\ p_{m-1} &= q_f - \frac{1}{5}\dot{q}_f \Delta t \end{aligned} \tag{12}$$

The trajectory of the stance hip (q_1, q_2, q_3) is approximated as a B-spline curve based on the motion capture data. Equations (11) and (12) are used to meet the initial and final conditions (3) and (4), respectively. The actual variable parameters are P, excluding the fixed p_0, p_1, p_{m-1} and p_m; and the total number of variable parameters is n (m -3).

The optimization of dynamic motion is carried out with different weighting coefficients for different methods. In each method, 8 variable parameters (m=11) are used for each of the active joints. The joint torques is computed for the human model based on the estimated dynamic properties and the B-Spline joint trajectories.

RESULTS AND DISCUSSION

Using the optimization of dynamic motion, four different methods are studied:

- Unimpaired swing leg with effort minimization of all joints.
- Paralyzed swing leg with effort minimization of the stance hip toques.

Method-1

A fully actuated human model with active hip and knee joints in the swing leg is studied to test the optimization technique. 56 parameters (8 for each joint) are used in the optimization. The parameters that set the limits on allowable out of plane motion of the legs, z_1 and z_2 in the penalty function J_{p2} are chosen as

$$z_1(t) = z_{\text{stance hip}}(t) + l_{\text{hip}} - 0.005 \tag{13}$$

$$z_2(t) = z_{\text{stance hip}}(t) + l_{\text{hip}} - 0.033 \tag{14}$$

where l_{hip}-0.005 and l_{hip}-0.033 are the smallest distances between the swing knee and the stance hip and between the swing heel and the stance hip respectively identified from motion capture. The weighing coefficients are listed in Table-1 and are chosen heuristically based on many simulations. The optimization is obtained in 3 hours with a Pentium IV – 1000 MHz PC.

Table-1: Weighting coefficients for model-1

$w_{e4},\ldots, w_{e8}$	w_{e9}	w_{e10}	w_{p1}	w_{p2}
0.05	0.1	2.5	$5\text{x}10^5$	$5\text{x}10^4$

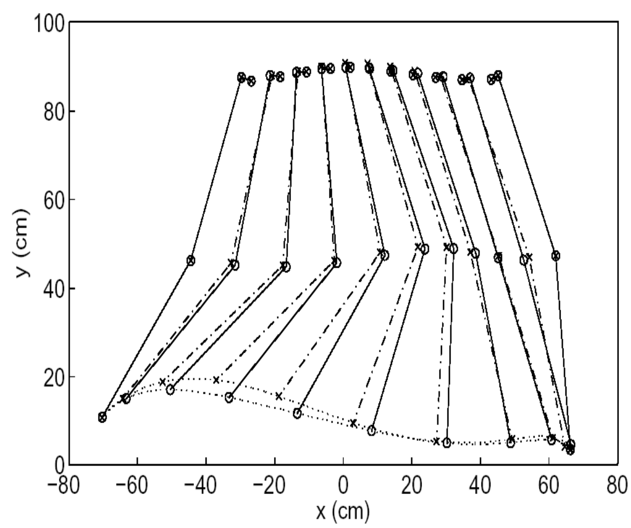

Figure.3 Unimpaired swing leg with effort minimization of all joints

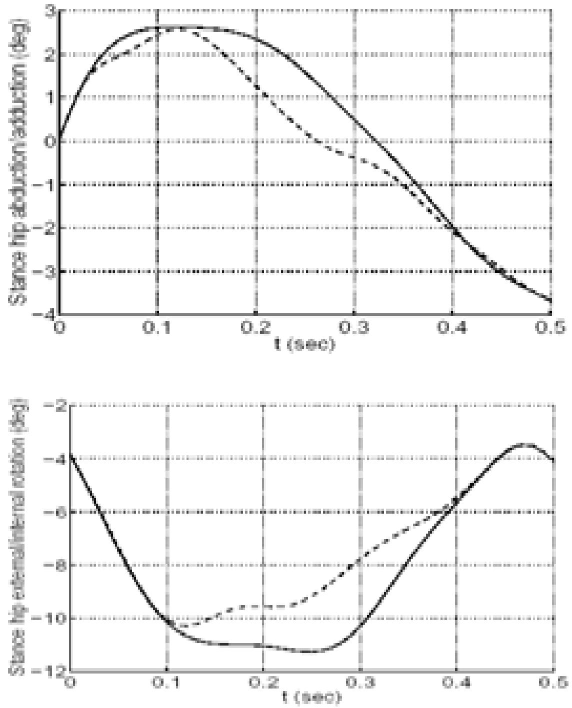

Figure 4 The resulting joint motions of method-1

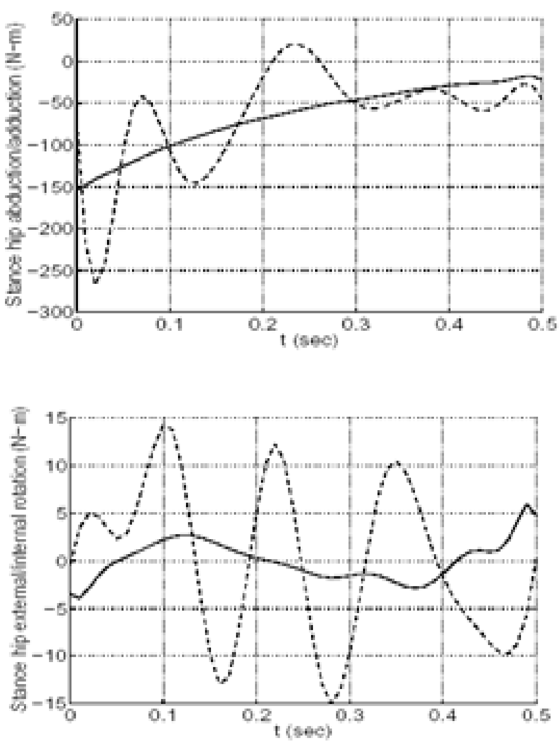

Figure 5. The resulting joint torques of method-1

Figure.3 shows the resulting gait. The optimization results are represented as solid lines, and the actual human data as dashed lines for comparison. The correspondence between the optimized and actual joint motions suggests that the simulation adequately predicts what a normative trajectory would be, given only the limb dynamics and desired final configuration of the leg. The joint angles and torques of the stance hip are shown in Figure 4 and 5, respectively. The optimization has resulted smooth joint torques.

.2 Method-2

To simulate a paralyzed person, the swing hip, knee and ankle joints were made passive. 16 parameters (8 for each active joint) were used in the optimization. Although less parameters are used in this case than in the model-1, the computation load for integration of the dynamics motion is actually higher. This is because the dynamics are hybrid with both active and passive joints, which the previous case had only active joints. The optimization took approximately 3 hours to complete.

Table-2: Weighting coefficients for model-2

w_{e4}	w_{e9}	w_{p1}	w_{p2}	w_{p31}	w_{p32}
10^{-4}	10^{-4}	10^{5}	10^{4}	10^{3}	10^{2}

The positions z_1 and z_2 in the penalty function J_{p2} were chosen as

$$z_1(t) = z_2(t) = z_{stance\ \ hip}(t) + \frac{2}{3} l_{hip}$$

which allows more hip adduction than the previous case. The weighting coefficients are listed in Table-2. The resulting motion for the method-2 is shown in Figure.6 and its corresponding stance hip angles and torques are shown in Figure.7 and 8. The optimization has lifted the swing hip to avoid the collision between the legs and between the swing leg and the ground. At the same time, it twisted the pelvis to pump energy into the paralyzed leg and moved the leg close to the desired final configuration. Thus the optimization is able to determine a strategy that can achieve repetitive stepping by shifting the pelvis alone. From figure.7 and 8 it is understood that the large stance hip torques are required to achieve the desired motion.

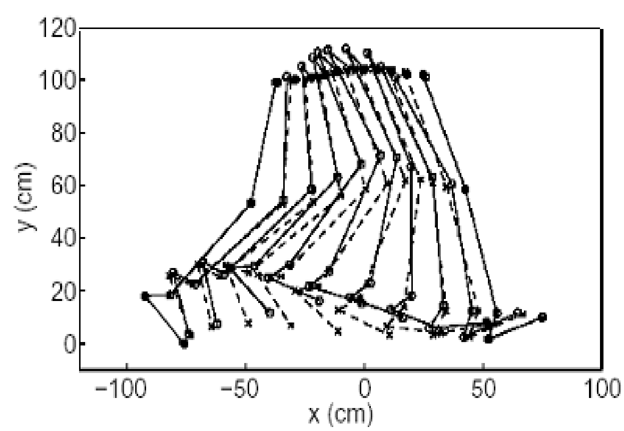

Figure 6 Paralyzed swing leg with effort minimization of the stance hip toques

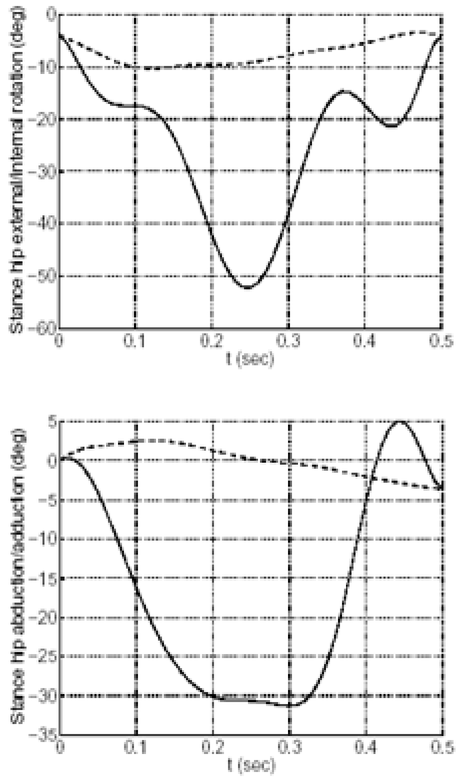

Figure 7. The resulting joint motions of method-2

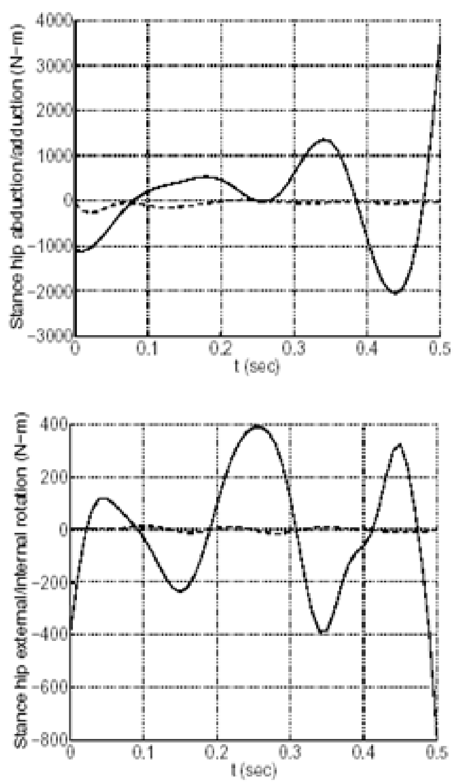

Figure 8. The resulting joint torques of method-2

CONCLUSION

This paper proposes a hip-swinging robot for assisting and training the locomotion of the paralyzed person. Although it may not be possible to fully control swing from the hip, a considerable amount of control is possible, and the level of control appears sufficient for achieving repetitive stepping by a paralyzed person. A hip swinging robot could also be useful for loading the stance leg by pressing downward on the stance hip, thus providing load-related sensory input required for stepping at the same time as assisting in swing. Dynamic motion optimization can be used to automatically generate strategies on a patient-by-patient basis.

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