Robotic Configuration for Paralyzed Swing Leg with Motion Captured Stance Hip Orientation

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Abstract—This research work explores an alternate approach toward generating strategies for developing dynamic motion planning for walking and training the paralyzed leg with a robot attached to the pelvis. The dynamic properties considered in this work are mass, center of gravity, moments of inertia of each link and the friction at each joint. The B-spline curves were used for the dynamic motion planning. The least square method is used to identify the dynamic properties after exciting the robot and collecting the data of joint positions, velocities, accelerations and applied forces. The joint trajectories are defined by B-spline polynomials along with a time-scale factor. A robot attached to the pelvis is employed to control the stepping motion of a paralyzed person suspended on a treadmill.

Index Terms— Robot, paralyzed leg, pelvis, trademill, walking motion.

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1 INTRODUCTION

HUMAN walking is a smooth, highly coordinated, rhythmical movement by which the body moves step by step in the desired direction. Numerous studies from various fields, such as biomechanics, robotics, and ergonomics, have provided a rich database on normal straight-walking gait patterns. The human beings experience heart attack and spinal cord injury. Mutilation in walking ability after such neurological injuries is general. The clinical stepping motion training is inadequate because the training is labor concentrated. Many therapists are mandatory to control the pelvis and legs. A locomotion rehabilitation called body weight supported (BWS) training has shown warranty in enhancing locomotion after spinal cord injury [1]. The technique involves suspending the patient above a treadmill to partly relieve the body weight, and physically supporting the legs and pelvis while moving in a walking pattern. Patients who be given this therapy can considerably increase their independent walking ability [2, 3]. This technique works by force, position, and touch sensors in the legs during stepping in a repetitive manner, and that the circuits in the nervous system learn from this sensor input to generate locomotion.
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The BWS training with robotics is an attractive as it improves the training. A difficulty in automating BWS training is that the required amount of forces at the pelvis and legs are unknown.

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This article explores an alternate approach toward generating strategy for developing dynamic motion planning for walking and training the paralyzed leg with a robot attached to the pelvis. The robotic configuration used is paralyzed swing leg with motion captured stance hip orientation. This configuration is studied to control the swing leg by applying a normative pelvis trajectory.

2 REHABILITATION ROBOT CONFIGURATION

Human walking requires the simultaneous involvement of all lower limb joints in a complex pattern of movement. Basically, all normal people walk in the same way. From human gait observations [4], the differences in gait between one person and another occur mainly in movements in the coronal and transverse planes. Throughout the whole body, those joint movements that occur in the sagittal plane are very similar between individuals, and if the upper limbs are unencumbered, they actually demonstrate a stereotyped pattern of reciprocal movement in phase with the lower limbs. The word configuration is taken from the human gait terminology.

While walking, the position and orientation of legs change as shown in figure 1. The robot used to assist the paralyzed leg should simulate the walking pattern of the normal leg. Thus, the rehabilitation robot configuration is defined [5]. The rehabilitation robot is described kinematically by giving the values of link length, link twist, joint distance and joint angle. The rehabilitation robot transformation matrices are very vital for the dynamic analysis.
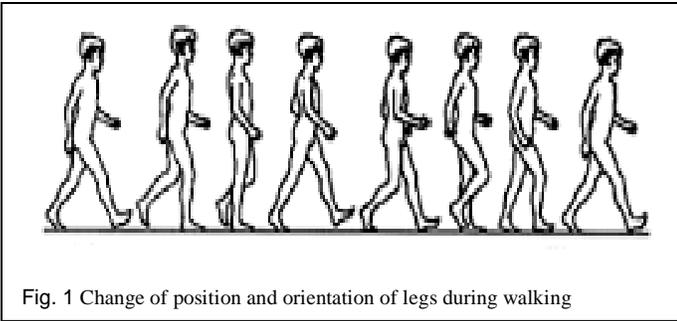
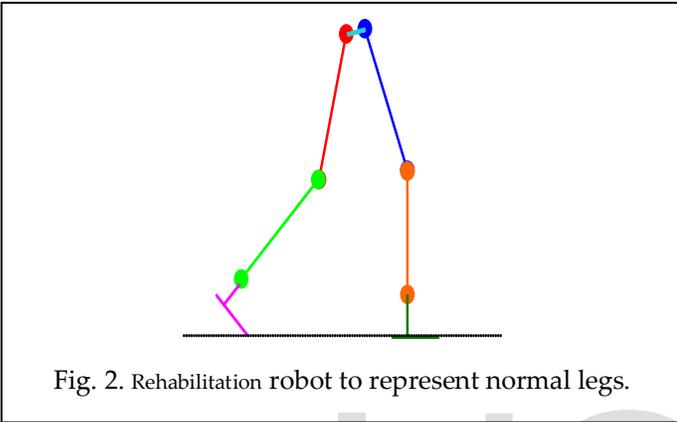Fig. 1 Change of position and orientation of legs during walking

Fig. 2. Rehabilitation robot to represent normal legs.

4   METHODOLOGY

The position and orientation of frame i relative to that of frame (i–1) is given by

$$T_{0,n}(q_1, q_2, \ldots q_n) = T_{0,1}(q_1)T_{1,2}(q_2) \ldots T_{n-1,n}(q_n) \tag{1}$$

where q_i is the joint variable for link i.

The mapping between the joint velocities and the end-effector velocities is defined by the differential kinematics equation

$$V_e = \begin{bmatrix} \omega_e \\ v_e \end{bmatrix} = J_e(q)\dot{q} \tag{2}$$

where V_e is the spatial velocity of the end-effector; we and ve the angular and linear velocities of the end-effector, respectively; $\dot{q}$ the generalized velocity of the robot manipulator; and Je the Jacobian matrix. The Jacobian can be expressed entirely in terms of the joint screws mapped into the base frame. Each column of $J_e^s(q)$ depends only on q1, q2, . . . qi-1. In other words, the contribution of the ith joint velocity to the end-effector velocity is independent of the configuration in the manipulator.

The dynamic equations of open-chained robot manipulators can be expressed in the general form

$$H(q)\ddot{q} + h(q,\dot{q}) = \tau \tag{3}$$

which relates the applied joint forces τ to the joint positions q and their time derivatives $\dot{q}$ and $\ddot{q}$. H(q) is the mass or inertia matrix and $h(q,\dot{q})$ contains the centrifugal, Coriolis,

gravitational and frictional forces.

The Newton-Euler recursive algorithm of the inverse dynamics is as follows:

• Initialization

$$V_0, \dot{V}_0, F_{n+1} \tag{4}$$

• Forward recursion: i = 1 to n

$$V_i = Ad_{T_{i-1,i}^{-1}} V_{i-1} + S_i \dot{q}_i \tag{5}$$

$$\dot{V}_i = Ad_{T_{i-1,i}^{-1}} \dot{V}_{i-1} + S_i \ddot{q}_i + ad_{v_i} S_i \dot{q}_i \tag{6}$$

• Backward recursion: i = n to 1

$$F_i = Ad^*_{T_{i-1,i}^{-1}} F_{i+1} + J_i \dot{V}_i - ad^*_{v_i} + J_i \dot{V}_i - ad^*_{v_i} J_i V_i \tag{7}$$

$$\tau_i = S_i^T F_i + f_{ci} \operatorname{sgn}(\dot{q}_i) + f_{vi} \dot{q}_i \tag{8}$$

In the algorithm, the index i represents the ith link frame counted from the base frame (i = 0). The joint screw, spatial velocity, spatial acceleration and spatial force are written as S, V , $\dot{V}$ and $F \in se(3)$, respectively. Particularly, V_0 and $\dot{V}_0$ represent the spatial velocity and acceleration of the base, respectively, while Fn+1 represents the external spatial force on the last link or end-effector. $T_{i-1,i} \in SE(3)$ denotes the transformation from the (i – 1)th link frame to the ith link frame. The joint velocity, acceleration, force and the Coulomb and viscous frictions are written as $\dot{q}$, $\ddot{q}$, τ , f_c and $f_v \in$, respectively. And J is the spatial inertia matrix

$$J_i = \begin{bmatrix} I_i - m_i \hat{r}_i^2 & m_i \hat{r}_i \\ -m_i \hat{r}_i & m_i \bullet 1 \end{bmatrix} \tag{9}$$

where mi and Ii are the mass and inertia of the ith link, respectively; ri is a vector from the origin of the ith link frame to the center of mass of ith link; $\hat{r}_i$ is the skew symmetric matrix formed by ri using the notation from the last chapter; and 1 is an identity matrix. The spatial velocity and force are

$$V_i = \begin{bmatrix} w_i \\ v_i \end{bmatrix}$$

$$F_i = \begin{bmatrix} m_{ti} \\ f_{ti} \end{bmatrix} \tag{10}$$

where w, v, mt and ft are the angular velocity, linear velocity, moment and force, respectively. This recursive formulation shows how the spatial velocity and acceleration propagate forwards from the base to the end-effector and how the spatial force propagates backwards from the end-effector to the base.

The B-spline curve is used to the joint trajectories [6]. The B-spline curve, $q \in \Re$ is written as

$$q(t, p) = \sum_{j=0}^{m} p_j B_{j,k}(t) \tag{11}$$

where $p = \{p_0, ... p_m\}$, with , are the control points and $B_{j,k}$ is the B-spline basis function. The index k defines the order of the basis polynomial, e.g. k = 4 for a cubic one or k = 6 for a quintic one. The semi-infinite constraints are transformed into a set of linear inequalities by exploiting the convex hull property [7].
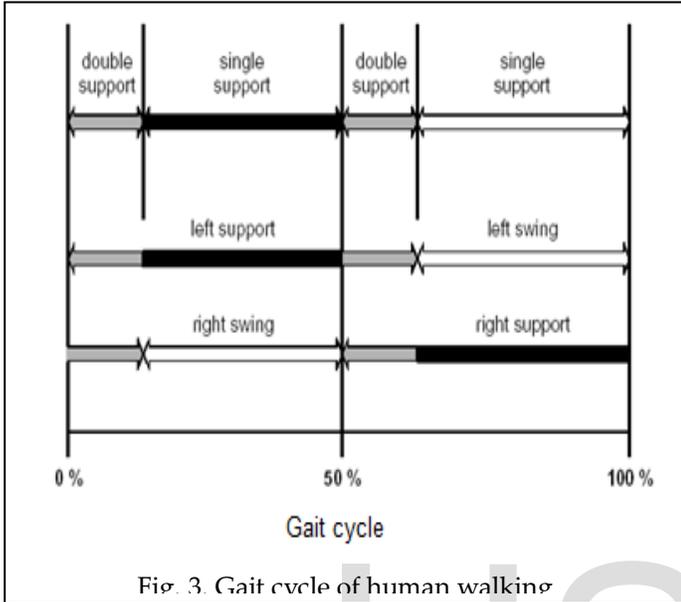

Fig. 3. Gait cycle of human walking

4 HUMAN MODEL AND WALKING MOTION

For studying the motion of the legs, the head, torso, pelvis, and arms were combined into a single rigid body (upper trunk). The walking gait cycle (figure 3) was assumed to be bilaterally symmetric [7]. The left-side stance and swing phases were assumed to be identical to the right-side stance and swing phases, respectively. Thus, only one-half of the gait cycle was simulated in this study. The stance hip was modeled as a two degrees-of-freedom (DOF) universal joint rotating about the x- and y-directions. The upper trunk was fixed about the z-axis. The swing hip was modeled as a 3 DOF ball joint rotating about axes in the x-, y-, and z- directions. The knee and ankle were modeled as 1 DOF hinge joints about the z-axis.

Motion capture data of major body segments for an unimpaired person during treadmill walking was obtained using a video-based system at FESTO Pvt.Ltd, Bangalore. The frequency of motion capture was 50 Hz. External markers were attached to the body at the antero-superior iliac spines (ASISs), knees, ankles, tops of the toes, and backs of the heels [8, 9]. The link lengths and joint orientations are shown in Table 1. The human subject was 1.95 m tall and weighed 70 kg.

TABLE 1
Link Lengths

l_{hip}	$l_{upper\,leg}$	$l_{lower\,leg}$	l_{foot}	l_{toe}	l_{heel}
0.15 m	0.47 m	0.49 m	0.08	0.18 m	0.07 m

Passive torque-angle properties of the hip, knee, and ankle joints were measured for the subject with a Biodex active dynamometer. The dynamometer imposed slow iso-velocity movements at the joints and measured applied torques and resulting joint angles. Joints were measured in a gravity-eliminated configuration. The dynamic properties of the human model is given in Table 2.

TABLE 2
Dynamic Properties of Human Model

Link	Mass, Kg	Inertia, Kg-m²	Center of Mass, m
Upper Trunk	46.05	$\begin{bmatrix} 3.23 & 0 & 0 \\ 0 & 0.78 & 0 \\ 0 & 0 & 2.76 \end{bmatrix}$	$\begin{Bmatrix} -0.001 \\ 0.360 \\ 0 \end{Bmatrix}$
Upper Leg	9.54	$\begin{bmatrix} 30.16 & 0 & 0 \\ 0 & 0.035 & 0 \\ 0 & 0 & 1.15 \end{bmatrix}$	$\begin{Bmatrix} -0.025 \\ -0.170 \\ 0.007 \end{Bmatrix}$
Lower Leg	3.56	$\begin{bmatrix} 0.064 & 0 & 0 \\ 0 & 0.006 & 0 \\ 0 & 0 & 0.062 \end{bmatrix}$	$\begin{Bmatrix} -0.005 \\ -0.207 \\ 0.019 \end{Bmatrix}$
Foot	1.44	$\begin{bmatrix} 0.003 & 0 & 0 \\ 0 & 0.009 & 0 \\ 0 & 0 & 0.007 \end{bmatrix}$	$\begin{Bmatrix} 0.044 \\ -0.040 \\ 0.010 \end{Bmatrix}$

The joints were modeled as nonlinear springs in which the joint torque was a polynomial function of the joint angle. A least squares method was used to best-fit polynomials. Third order polynomial function was used for the torque-angle property of each joint. A polynomial of order 7 is used to the ankle joint data. The resulting polynomial equations for curves are mentioned as follows:

Hip external/internal rotation $\left(-60^0, 60^0\right)$

$$\tau_m = -0.6837 - 0.7621q + 0.9772q^2 - 2.2620q^3 \tag{12}$$

Hip abduction/adduction $\left(-50^0, 30^0\right)$

$$\tau_m = -0.0542 - 0.8266q - 6.0205q^2 - 29.0271q^3 \tag{13}$$

Hip extension/flexion $\left(-35^0, 70^0\right)$

$$\tau_m = 1.0863 + 1.5721q + 6.3488q^2 - 23.0405q^3 \tag{14}$$

Knee flexion/extension $\left(-140^0, 0^0\right)$

$$\tau_m = -24.9343 - 53.1584q - 37.5211q^2 - 9.8685q^3 \qquad (15)$$

Ankle plantar/dorsal flexion $\left(-52^0, 46^0\right)$

$$\tau_m = 0.1305 - 3.99564q + 1.5596q^2 - 4.7881q^3 + 2.4229q^4$$
$$+ 6.2372q^5 - 5.6802q^6 - 19.5304q^7 \qquad (16)$$

In addition to the polynomial function, a nonlinear spring-damper system was used to place a hard limit on joint movement when it is close to its upper and lower bounds.

$$\tau_{sd} = \begin{cases} -\beta\left(10^4(q-q_2) + 5x10^2\dot{q}\right) & \text{if } q \geq q_2 \\ -\beta\left(10^4(q-q_1) + 5x10^2\dot{q}\right) & \text{if } q \leq q_1 \\ 0 & \text{otherwise} \end{cases} \qquad (17)$$

where

$$\beta = \begin{cases} 6x10^5(q-q_2)^5 - 1.5x10^5(q-q_2)^4 + 10^4(q-q_2)^3 & \text{if } q_2 + 0.1 \geq q \geq q_2 \\ -6x10^5(q-q_1)^5 - 1.5x10^5(q-q_1)^4 + 10^4(q-q_1)^3 & \text{if } q_1 - 0.1 \geq q \geq q_1 \\ 1 & \text{otherwise} \end{cases}$$

The function τ_{sd} is C2 continuous in order to be used in the computation of the analytical gradient in the dynamic motion optimization. Four steps at three different treadmill walking speeds (1.75, 1.25 and 0.75 m/sec) were obtained from motion capture.

5 RESULTS AND DISCUSSION

The swing hip, knee and ankle joints were set to be passive while the stance hip joint followed the trajectory identified from motion capture. Assuming no ground contact, the equations of motion were solved. Figure 4 shows that the swing leg moves at its natural frequency. Solid lines represent the simulated data. The dashed lines signify experimental data. However, there would be a collision between the leg and the ground at about x = 0 (mid-stride) if the ground were not neglected. The leg is internally rotated away from the desired configuration at the end of swing as shown in figure 5.
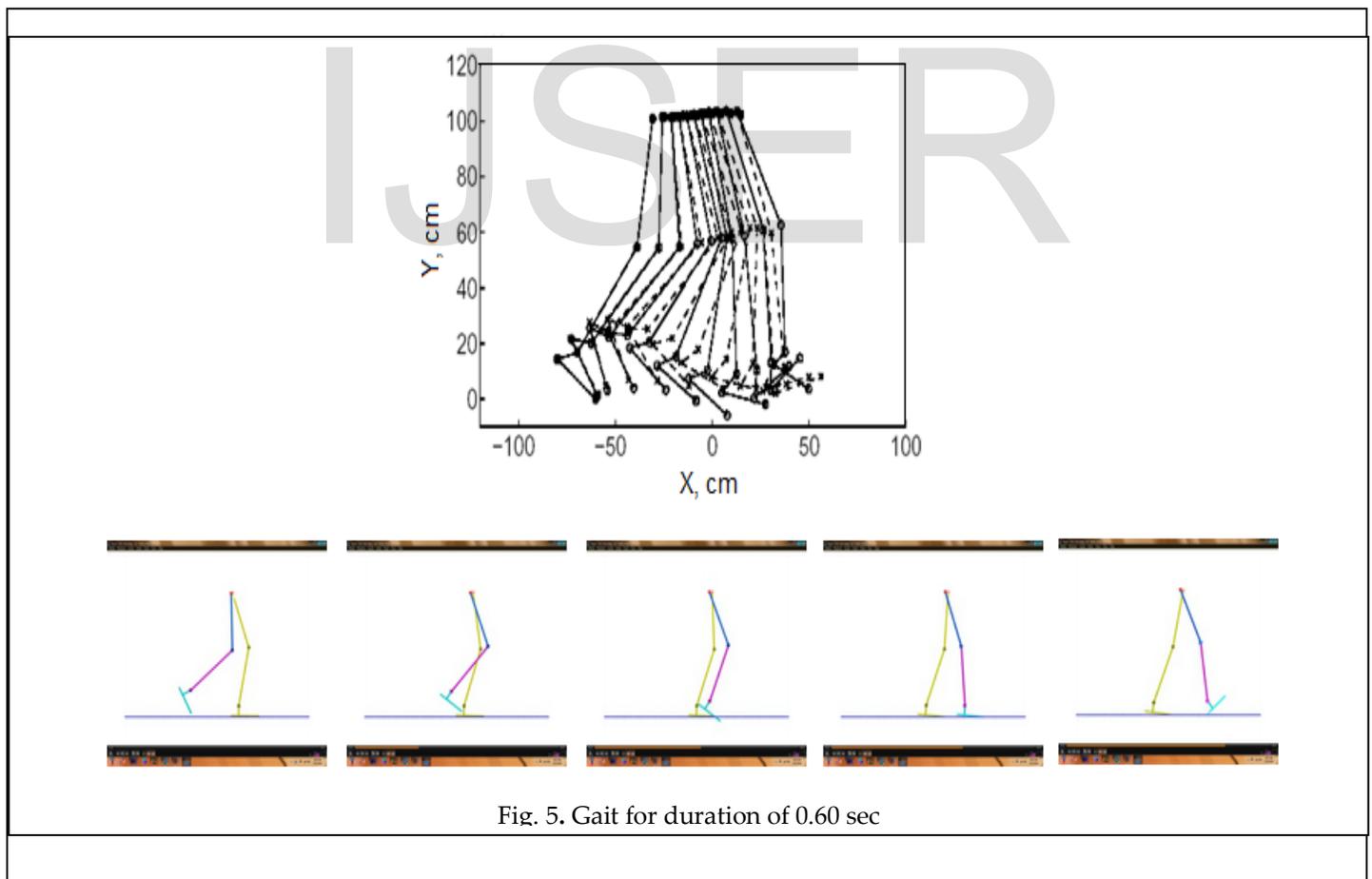

Fig. 5. Gait for duration of 0.60 sec

The applied effort for two gait durations is shown in figure 6. The effort required for step duration of 0.60 seconds is higher than that required for 0.45 seconds. This shows that
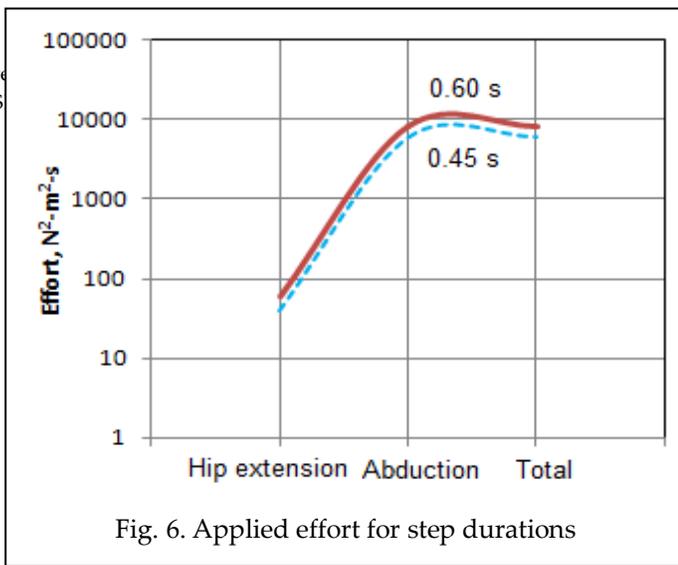
Fig. 6. Applied effort for step durations

most of the effort goes into tilting the pelvis, i.e. abducting the stance hip, due to working against gravity.

6 CONCLUSIONS

Walking motion was generated for a robot attached to the pelvis of a paralyzed person suspended on a treadmill. A leg swing motion was created by moving the pelvis. Although it may not be possible to fully control swing by manipulating the pelvis, a surprising amount of control is possible, and the level of control appears sufficient for achieving repetitive stepping for a paralyzed person. The dynamic motion planning can also generate leg swing motions similar to the human gait during the swing phase.

7 FUTURE SCOPE OF WORK

The prospective work is divided into the following interesting areas:

- Build a robot for body weight supported training. The resulting motions found with the dynamic motion planner can be tested on the robot. That would provide useful information to modify the current motion planner and improve the design of the robot.

- Generate a complete walking gait. In this work, the stepping motion has been generated only during the swing phase of a gait. However, the effort applied to the stance leg is not taken into account in this work. This has to be done in order to generate a complete gait.

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