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Gravity Balancing of a Human Leg using an External Orthosis

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Abstract— **Gravity balancing is often used in industrial machines to decrease the required actuator efforts during motion. In this paper, we present a new design for gravity balancing of the human leg using an external orthosis. This external orthosis is connected to the human leg on the shank and its other end is fixed to a walking frame. The major issues addressed in this paper are: (i) Design for gravity balancing of the human leg and the orthosis, (ii) Kinematic compatibility of the human leg and the external orthosis during walking, (iii) Comparison of the joint torque trajectories of the human leg with and without external orthosis, and (iv) Effects of variation of the link lengths and masses of the human leg on the inertia of the external orthosis. We illustrate feasible 2D and 3D designs of the external orthosis through computer simulations. Fabrication of this design will be the subject of future work.**

I. INTRODUCTION

In recent years, passive gravity balancing orthoses have been proposed for the upper arm ([1], [2], [3]). However, orthoses for the lower extremity are typically powered. The authors have proposed a design of an exoskeleton for full or partial gravity-balancing of a human leg during motion ([4],[5]). The device is worn by the user and segments of the exoskeleton are strapped to the corresponding segments of the human leg. However, there are some issues with the existing exoskeletons ([6], [7], [8], [9]) which motivate us to look at alternative designs. One such issue is the alignment of the human leg and exoskeleton segments. Also, it is hard to get full extension of the knee due to singular configuration of the exoskeleton. Robotic devices are developed to assist patients with lower extremity using alternate designs [10], [11], [12]). Aoyagi et al. developed a robotic device, PAM(Pelvic Assist Manipulator), that assists the pelvic motion during gait training on a treadmill [10]. PAM consists of a pair of 3 DOF pneumatic robots. Galvez et al. proposed a sensorized orthosis that measured shank kinematics and therapist forces during locomotor training [11]. The orthosis is attached to one of the legs. Surdilovic et al. developed the String-Man, a tension controlled wire-drive system which stabilizes the torso of a subject during stepping on a treadmill [12].

In this paper, we present a new design for gravity balancing of the human leg using an external orthosis. The key contribution of this paper is the design of an external orthosis to avoid issues with the existing exoskeletons, such as joint and segment misalignment. This orthosis is designed for a two degree-of-freedom (DOF) motion of the human leg in the sagittal plane, i.e., flexion and extension at the hip and knee during walking and hip abduction/adduction motion. The foot is considered as a point mass at the end of the shank segment. The external orthosis connected at the shank, together with the human leg, creates a kinematic closed loop. The kinematic loop constraint can be satisfied during walking by choosing appropriate link lengths for the external orthosis. Gravity balancing of the human leg and the external orthosis is achieved by making the potential energy of the combined system, human and the machine, to be configuration invariant. First, the potential energy of the system is written in terms of the joint angles of the human leg and the external orthosis. Loop constraint equations are then substituted in the potential energy to express dependent joint angles in terms of independent ones. Finally, the coefficients of joint angle dependent terms in this expression are made to vanish to make the potential energy invariant, thereby achieve a gravity balanced system. These conditions are satisfied by choosing appropriate inertia parameters of the segments of the orthosis and addition of proper springs.

The main advantages of the design of human leg with external orthosis as compared to the existing exoskeletons are as follows: (i) This design has a better alignment between the human leg and the orthosis. (ii) We can also get the full extension of the knee with this design. (iii) it is required less hardware such as force-torque sensors between human leg and orthosis to compute the joint torques. However, there are also some drawbacks for this design such as: (a) It increases the inertia of the system, which may be a drawback during fast walking. (b) Modeling of the human leg with the external orthois, which makes a kinematic closed loop, is more complicated than the modeling of the existing exoskeletons, namely, open loop system.

The organization of this paper is as follows: Section II describes the kinematic compatibility of the human leg and the external orthosis during walking. Gravity balancing of the human leg and the external orthosis is described in Section III. Some feasible designs are then presented in Section IV. Joint torque computation is studied in Section V followed by sensitivity analysis of the results described in Section VI.

II. KINEMATIC COMPATIBILITY

The external orthosis is designed for three DOF motion of the human leg, namely, two DOF motion in the sagittal plane, i.e., flexion and extension at the hip and knee and one DOF for hip abduction/adduction (See Fig. 1). The human leg has

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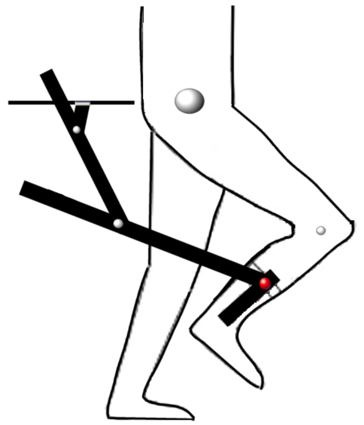

Fig. 1. A schematic of a 3 DOF human leg and external orthosis

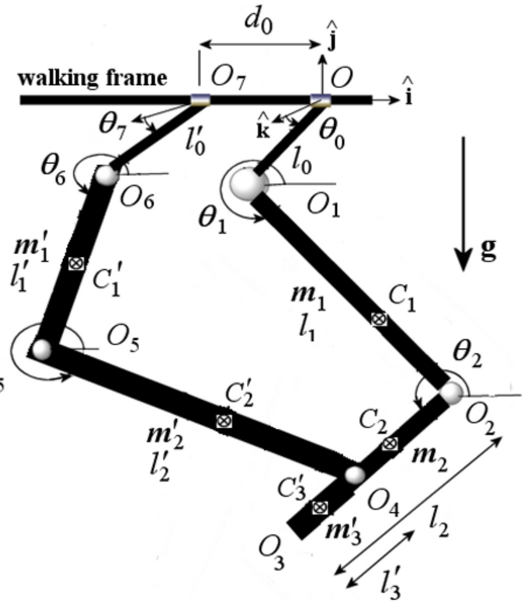

Fig. 2. Geometric and inertia parameters of the human leg and external orthosis

one DOF for the hip abduction at point O, i.e., θ_0, and two DOF for the flexion/extension at points O_1 and O_2, namely, θ_1 and θ_2. Also the external orthosis has one DOF at point O_7, i.e., θ_7, and two DOF at points O_5 and O_6, i.e., θ_5, θ_6 as shown in Fig. 2. The axes of rotation of θ_0 and θ_7 are along $\hat{\mathbf{i}}$. The human leg is connected to the external orthosis through a spherical joint at point O_4. The human leg and external orthosis are fixed to the walking frame at points O and O_7, respectively. Therefore, this system creates a kinematic closed loop mechanism with three DOF, as shown in Fig. 2.

Kinematic compatibility of the human leg and the external orthosis during walking is achieved by satisfying the kinematic loop constraint equations. Using Fig. 2, the loop constraint equation for the system is written as

$$\overrightarrow{OO_1} + \overrightarrow{O_1O_2} + \overrightarrow{O_2O_3} + \overrightarrow{O_3O_4} + \overrightarrow{O_4O_5} + \overrightarrow{O_5O_6} + \overrightarrow{O_6O_7} + \overrightarrow{O_7O} = 0 \quad (1)$$

This equation can be written in terms of its components along $\hat{\mathbf{i}}$, $\hat{\mathbf{j}}$ and $\hat{\mathbf{k}}$ as

$$l_1c_1 + (l_2 - l'_3)c_2 - l'_2c_5 - l'_1c_6 + d_0 = 0 \quad (2)$$
$$l_0s_0 + l_1s_1c_0 + (l_2 - l'_3)s_2c_0 - l'_2s_5c_7 - l'_1s_6c_7 - l'_0s_7 = 0 \quad (3)$$
$$l_0c_0 - l_1s_1s_0 - (l_2 - l'_3)s_2s_0 + l'_2s_5s_7 + l'_1s_6s_7 - l'_0c_7 = 0 \quad (4)$$

where s_i and c_i stand for $\sin\theta_i$, $\cos\theta_i$, respectively. Here, l_0 is the offset of the hip abduction and hip flexion joint axes, l_1 and l_2 are link lengths of the thigh and the shank segments of the human leg, and l'_0, l'_1 and l'_2 are the link lengths of external orthosis. Furthermore, l'_3 locates the distance between O_3 and O_4.

Equations (2)-(4) are three nonlinear equations to be solved numerically to express dependent joint angles [θ_5, θ_6, θ_7] in terms of independent ones [θ_0, θ_1, θ_2]. The link lengths of external orthosis are chosen such that above equations are satisfied during walking.

III. Gravity Balancing of the Human Leg and External Orthosis

The objective is to design an external orthosis with appropriate geometry and inertia, and springs such that the combined system of human leg and the external orthosis becomes gravity balanced. The potential energy of the human leg and external orthosis can be written as

$$V_g = -\sum_{i=1}^{2} m_i\mathbf{g}\cdot\mathbf{r}_{OC_i} - \sum_{i=1}^{3} m'_i\mathbf{g}\cdot\mathbf{r}_{OC'_i} \quad (5)$$

where m_i is the mass of link i of the human leg, $\mathbf{r}_{OC_i}$ is the location of center of mass of link i from origin O. Also m'_i is the mass of link i of the external orthosis, $\mathbf{r}_{OC'_i}$ is the location of center of mass of link i from origin O and $\mathbf{g}$ is the gravity vector. Upon substitution of $\mathbf{g} = -\hat{\mathbf{j}}g$ and

$$\begin{aligned}
\mathbf{r}_{OC_1} &= l_{1c}c_1\hat{\mathbf{i}} + (l_0s_0 + l_{1c}s_1c_0)\hat{\mathbf{j}} + (l_0c_0 - l_{1c}s_1s_0)\hat{\mathbf{k}} \\
\mathbf{r}_{OC_2} &= (l_1c_1 + l_{2c}c_2)\hat{\mathbf{i}} + (l_0s_0 + l_1s_1c_0 + l_{2c}s_2c_0)\hat{\mathbf{j}} + \\
&\quad (l_0c_0 - l_{1c}s_1s_0 - l_{2c}s_2s_0)\hat{\mathbf{k}} \\
\mathbf{r}_{OC'_3} &= (l_1c_1 + l_2c_2 - l'_{3c}c_2)\hat{\mathbf{i}} + \\
&\quad (l_0s_0 + l_1s_1c_0 + l_2s_2c_0 - l'_{3c}s_2c_0)\hat{\mathbf{j}} + \\
&\quad (l_0c_0 - l_{1c}s_1s_0 - l_2s_2s_0 + l'_{3c}s_2s_0)\hat{\mathbf{k}} \\
\mathbf{r}_{OC'_1} &= (-d_0 + l'_{1c}c_6)\hat{\mathbf{i}} + (l'_0s_7 + l'_{1c}s_6c_7)\hat{\mathbf{j}} + \\
&\quad (l'_0c_7 + l'_{1c}s_6s_7)\hat{\mathbf{k}} \\
\mathbf{r}_{OC'_2} &= (-d_0 + l'_1c_6 + l'_{2c}c_5)\hat{\mathbf{i}} + (l'_0s_7 + l'_1s_6c_7 + \\
&\quad l'_{2c}s_5c_7)\hat{\mathbf{j}} + (l'_0c_7 + l'_1s_6s_7 + l'_{2c}s_5s_7)\hat{\mathbf{k}} \quad (6)
\end{aligned}$$

into (5), the total potential energy V_g can be written in terms of joint angles as

$$V_g = m_1g(l_0s_0 + l_{1c}s_1c_0) + m_2g(l_0s_0 + l_1s_1c_0 + l_{2c}s_2c_0) + m'_3g(l_0s_0 + l_1s_1c_0 + l_2s_2c_0 - l'_{3c}s_2c_0) + \quad (7)$$

$$m_1'g(l_0's_7 + l_{1c}'s_6c_7) + m_2'g(l_0's_7 + l_1's_6c_7 + l_{2c}'s_5c_7),$$

All parameters and symbols are shown in Fig. 2. Here, $l_{1c} = O_1C_1$, $l_{2c} = O_2C_2$, $l_{3c}' = O_3C_3'$, $l_{1c}' = O_6C_1'$ and $l_{2c}' = O_5C_2'$ are locations of COM of the links from their origins. Also, $d_0 = O_7O$ is a fixed distance between points O and O_7.

The loop constraint equations can be used to express dependent joint angles in terms of independent ones. There are 3 constraint equations. Ideally, we should express θ_5, θ_6, θ_7 in terms θ_0, θ_1, θ_2. However, the potential energy expression is in terms of Sin of the all joint angles and the Cos of θ_0 and θ_7. Should we want to use all three constraint equations, the loop constraint equation in terms of Cos of the joint angles, i.e., (2), should be expressed in terms of Sin of them. This is a nonlinear equation and the final form of V_g becomes very cumbersome to satisfy the conditions. Hence, we use only the loop constraint equation which is in terms of Sin of joint angles to eliminate one of the independent joint angles. Here, we should apply extra conditions. Hence, using the second loop constraint equation, i.e., (3), one obtains,

$$s_6c_7 = \frac{l_0s_0 + l_1s_1c_0 + (l_2 - l_3')s_2c_0 - l_2's_5c_7 - l_0's_7}{l_1'} \quad (8)$$

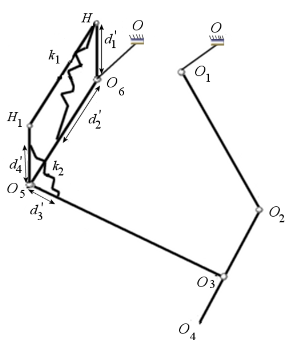

Fig. 3. Springs attachment to the external orthosis

Upon substitution of (8) into (7), the expression for the potential energy can be written in terms of joint angle variables as

$$V_g = K_0s_0 + K_1s_1c_0 + K_2s_2c_0 + K_3s_5c_7 + K_4s_7 \quad (9)$$

where

$$\begin{aligned} K_0 &= (m_1 + m_2 + m_3' + m_1'l_{1c}'/l_1')l_0g \\ K_1 &= (m_1l_{1c} + m_2l_1 + m_3'l_1 + m_1'l_{1c}'l_1/l_1' + m_2'l_1)g \\ K_2 &= (m_2l_{2c} + m_3'(l_2 - l_{3c}') + m_1'l_{1c}'(l_2 - l_3')/l_1' + \\ &\quad m_2'(l_2 - l_3'))g \qquad (10) \\ K_3 &= (-m_1'l_{1c}'l_2'/l_1' + m_2'(-l_2' + l_{2c}'))g \\ K_4 &= (m_1' - m_1'l_{1c}'/l_1')l_0'g \end{aligned}$$

With further analysis, one can show that two springs need to be added to the external orthosis to compensate for the gravitational potential energy of the system, as shown in Fig. 3. First spring is connected to link l_1' at one end and fixed to point H on an axis parallel to gravity vector at the other end. The second spring is connected to link l_2' and fixed to point H_1 on an axis parallel to gravity vector at the other end. The vertical axis for the second spring is acquired by using a parallelogram shown in Fig. 3. The total potential energy due to the gravity and springs is given by

$$V = V_g + V_s, \quad (11)$$

where V_g is as defined in (9) and

$$V_s = \sum_{i=1}^{2} \frac{1}{2}k_ix_i^2. \quad (12)$$

Here, k_i and x_i are stiffness and extension of the i^{th} spring.

In this work, it is assumed that the undeformed length of the spring is zero. In other words, the spring force is zero when the deformation of the spring is zero. In the physical implementation of zero free length, nonzero free length spring can be used behind the pulley where the spring force can be transmitted through a wire [13].

The extension of the springs are written as

$$\begin{aligned} x_1^2 &= {d_1'}^2 + {d_2'}^2 - 2d_1'd_2's_6c_7 \\ x_2^2 &= {d_3'}^2 + {d_4'}^2 - 2d_3'd_4's_5c_7 \qquad (13) \end{aligned}$$

where d_i', $i = 1, \cdots, 4$ are the connection points of the springs. Upon substitution of V_g from (9) and inserting (8) and (12) into (11), one obtains

$$\begin{aligned} V &= C_0l_0s_0 + C_1s_1c_0 + C_2s_2c_0 + C_3s_5c_7 + \\ &\quad C_4l_0's_7 + C_5, \qquad (14) \end{aligned}$$

where

$$\begin{aligned} C_0 &= K_0 - k_1d_1'd_2'l_0/l_1', \\ C_1 &= K_1 - k_1d_1'd_2'l_1/l_1', \\ C_2 &= K_2 - k_1d_1'd_2'(l_2 - l_3')/l_1', \qquad (15) \\ C_3 &= K_3 + k_1d_1'd_2'l_2'/l_1' - k_2d_3'd_4', \\ C_4 &= K_4 - k_1d_1'd_2'l_0'/l_1', \\ C_5 &= \frac{1}{2}k_1({d_1'}^2 + {d_2'}^2) + \frac{1}{2}k_2({d_3'}^2 + {d_4'}^2). \end{aligned}$$

The coefficients C_i, for $i = 0, \cdots, 4$, namely,

$$\begin{aligned} C_0 &= C_0(m_1', m_3', l_1', l_{1c}', k_1), \\ C_1 &= C_1(m_1', m_2', m_3', l_1', l_{1c}', k_1), \\ C_2 &= C_2(m_1', m_2', m_3', l_1', l_{1c}', l_3', l_{3c}', k_1), \qquad (16) \\ C_3 &= C_3(m_1', m_2', l_1', l_{1c}', l_2', l_{2c}', k_1, k_2), \\ C_4 &= C_4(m_1', l_1', l_{1c}', k_1), \end{aligned}$$

should be made to be zero to make the total potential energy configuration independent.

The design variables are the mass and location of the center of mass of each link of external orthosis as well as the stiffness of the springs. Here, we have an under-determined system with less number of equations than variables. Therefore, we have free parameters left after satisfying all conditions. The link masses of external orthosis, m_i',

$i = 1, 2, 3$ and the stiffness of the springs are considered to be the primary variables. The other design variables are considered to be auxiliary variables. The auxiliary variables are chosen such that the link masses m'_i become minimum to obtain a lighter external orthosis.

IV. Feasible Designs

As an example, the inertia and geometric parameters of the human leg are considered for a normal healthy subject [14], as shown in Table I.

TABLE I

GEOMETRIC AND INERTIA PARAMETERS OF THE HUMAN LEG FOR A NORMAL USER

	Mass, Kg	Length, m	COM, m
OO_1, hip		$l_0 = 0.15$	
O_1O_2, thigh	$m_1 = 7.39$	$l_1 = 0.4322$	$l_{1c} = 0.41 l_1$
O_2O_3, shank	$m_2 = 4.08$	$l_2 = 0.4210$	$l_{2c} = 0.44 l_2$

The link lengths of external orthosis are derived such that loop constraint equations, i.e., (2)- (4) are satisfied during the walking. Their expressions are $l'_0 = 0.30$ m, $l'_1 = 0.4332$ m, $l'_2 = 0.4634$ m and $l'_3 = 0.2316$ m. Snapshots of animation of the human leg and external orthosis during the walking are shown in Fig. 4.

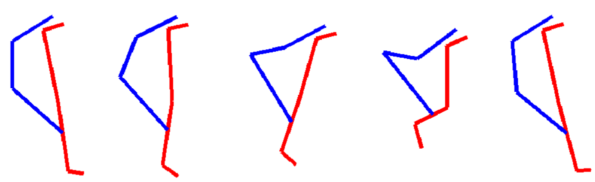

Fig. 4. snapshots of animation of the human leg (red) and external orthosis (blue) during the normal walking

Two types of designs are considered here. Section IV-A presents 3D design in which the gravity balancing is given for the hip abduction/adduction, hip flexion and knee flexion. Here, the gravity balancing is not only considered for the sagittal plane motion, but also consider for the hip abduction/adduction motion. However, in Section IV-B, the gravity balancing is considered only in sagittal plane for the hip and knee flexion in which the coefficients C_1, C_2 and C_3 in 15 should be zero to make the total potential energy configuration independent.

A. A Feasible Design: 3D case

In this design, the gravity balancing is given for the hip abduction/adduction, hip flexion and knee flexion. Using the geometric and inertia parameters of the human leg from Table I and satisfying the conditions as mentioned in (16), the geometric and inertia parameters of the external orthosis are derived and listed in Table II. In this design, two springs are attached to external orthosis: one spring is attached to link O_6O_5 and another one is attached to link O_5O_4 as shown in Fig. 3. The stiffness of the required springs are $k_1 = 1164$ N/m and $k_2 = 639$ N/m. It may be noted that COM of the links of the external orthosis are located at appropriate positions using counterweights.

TABLE II

GEOMETRIC AND INERTIA PARAMETERS OF THE EXTERNAL ORTHOSIS WITH TWO SPRINGS

	Mass, Kg	Length, m	COM, m
O_6O_5	$m'_1 = 8.92$	$l'_1 = 0.4322$	$l'_{1c} = -0.23 l'_1$
O_5O_4	$m'_2 = 4.36$	$l'_2 = 0.4634$	$l'_{2c} = -0.70 l'_2$
O_4O_3	$m'_3 = 1.56$	$l'_3 = 0.2316$	$l'_{3c} = 0$

B. A Feasible Design: 2D case

In this design, the gravity balancing is applied only to the hip flexion and knee flexion. Two cases are considered: (I) using only one spring and (II) using two springs.

1) A Feasible 2D Design with one Spring: Using the geometric and inertia parameters of the human leg from Table I and making the coefficients C_1, C_2 and C_3 in (16) to be zero, the geometric and inertia parameters of the external orthosis are derived and listed in Table III. Here, we have used only one spring which is attached to link O_6O_5 of the external orthosis as shown in Fig. 5. The symbols are shown in Fig. 5(b). The stiffness of the required spring is $k_1 = 2150$ N/m.

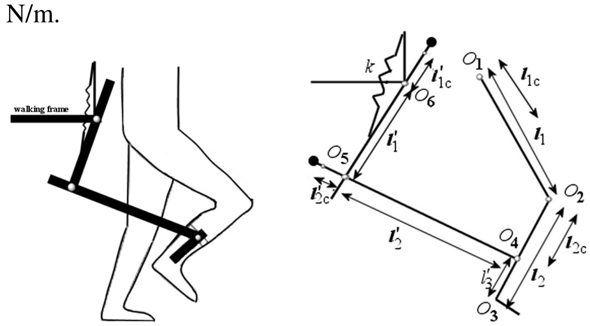

Fig. 5. A 2 DOF human leg and external orthosis with one spring: (a) A schematic design, (b) Geometric and inertia parameters

TABLE III

GEOMETRIC AND INERTIA PARAMETERS OF THE EXTERNAL ORTHOSIS WITH ONE SPRING

	Mass, Kg	Length, m	COM, m
O_6O_5	$m'_1 = 3.41$	$l'_1 = 0.4322$	$l'_{1c} = -0.23 l'_1$
O_5O_4	$m'_2 = 12.4$	$l'_2 = 0.4634$	$l'_{2c} = -0.70 l'_2$
O_4O_3	$m'_3 = 1.56$	$l'_3 = 0.2316$	$l'_{3c} = 0$

2) A Feasible 2D Design with two Springs: In this design, two springs are attached to external orthosis: one spring is attached to link O_6O_5 and another one is attached to link O_5O_4 as shown in Fig. 6(b). Using the geometric and inertia parameters of the human leg from Table I and making the coefficients C_1, C_2 and C_3 in (16) to be zero, the geometric and inertia parameters of the external orthosis with two springs are derived and listed in Table IV. The symbols are shown in Fig. 6(b). The stiffness of the required springs are $k_1 = 1250$ N/m and $k_2 = 700$ N/m.

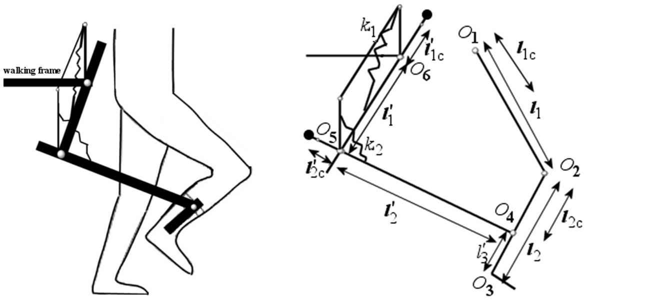

Fig. 6. A 2 DOF human leg and external orthosis with two springs: (a) A schematic design, (b) Geometric and inertia parameters

TABLE IV
GEOMETRIC AND INERTIA PARAMETERS OF THE EXTERNAL ORTHOSIS WITH TWO SPRINGS

	Mass, Kg	Length, m	COM, m
O_6O_5	$m'_1 = 2.07$	$l'_1 = 0.4322$	$l'_{1c} = -0.23l'_1$
O_5O_4	$m'_2 = 3.6$	$l'_2 = 0.4634$	$l'_{2c} = -0.70l'_2$
O_4O_3	$m'_3 = 1.56$	$l'_3 = 0.2316$	$l'_{3c} = 0$

As shown in Tables II and IV, the inertia of the external orthosis with two springs for the 3D design is much higher than the inertia for the 2D design because of gravity compensation for the hip abduction motion. Therefore, it is better to use the 2D deisgn where the effect of hip abduction is not as important as hip and knee flexion.

Upon comparison of the results of 2D designs with one spring and two springs, one can infer that using two springs decreases the inertia of the external orthosis. On the other hand, this adds to the complexity of the design.

C. Orthosis-only Balanced Design

To compare the performance of the gravity balancing of the human leg using external orthosis and the nominal case without using gravity balancing, it is desirable to have orthosis-only balanced design. The feasible 2D and 3D designs presented in previous section can be modified easily by removing the springs and reducing the masses of counterweights to have orthosis-only balanced design.

V. Joint Torque Computation

Joint torques are not needed to keep the human leg in equilibrium at any configuration of the leg using external orthosis design. However, joint torques are needed during the walking. To this end, the torque trajectories of the human leg during walking are computed and compared for the following two cases: (I) Human leg and the external orthosis design, (II) human leg without external orthosis. Case (I) is a closed loop system while case (II) is an open loop system. Given the hip and knee joint trajectories and their time derivatives during walking, the joint torques of the human leg for case (I) are computed as follows: The dependent joint angles and their time derivatives are derived in terms of independent joint ones using the loop constraint equations and their time derivatives. Next, the joint torques at the hip and knee joints are derived using inverse dynamics of closed loop system [15]. Also, given the hip and knee joint trajectories and their time derivatives during walking, the joint torques of the human leg for case (II) are computed using inverse dynamics of open loop system.

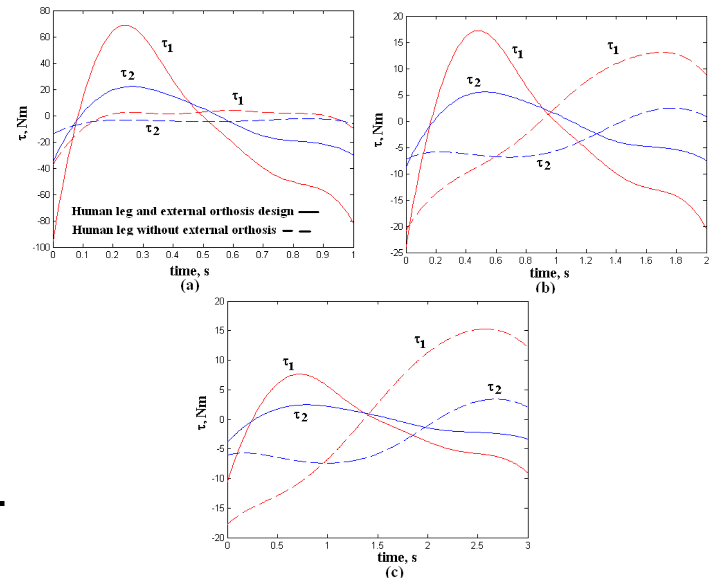

Fig. 7. Joint torque trajectories at the hip (τ_1) and the knee (τ_2) for the design with one spring (2D case) at different walking speeds: (a) 0.8432 m/s, (b) 0.4170 m/s and (c) 0.278 m/s

As an example, consider the geometric and inertia parameters of the human leg and the external orthosis designs with one spring and two springs (2D cases) given in Tables I, III and IV, respectively. Also, the hip and knee joint trajectories during normal walking are given in [16]. Using these data, the joint torques trajectories of the human leg at the hip and knee are computed for the human leg and the external orthosis design with one and two springs as well as for the human leg only. The results are shown for the design with one spring at different walking speeds of 0.8432 m/s, 0.4170 m/s and 0.278 m/s in Figs. 7(a),(b) and (c). The results for both designs with one and two springs at a specific walking speed of 0.4170 m/s are depicted in Fig. 8(a) and (b), respectively. It can be concluded from these figures that higher joint torques are required at fast walking because of the inertia of the external orthosis. Also, the joint torques in design with two springs are less than the joint torques in the design with one spring. Therefore, the design with one spring which has less complexity can be used at slow walking.

VI. Sensitivity Analysis

Effect of segment masses of the human leg on the link masses of the external orthosis can be determined by varying

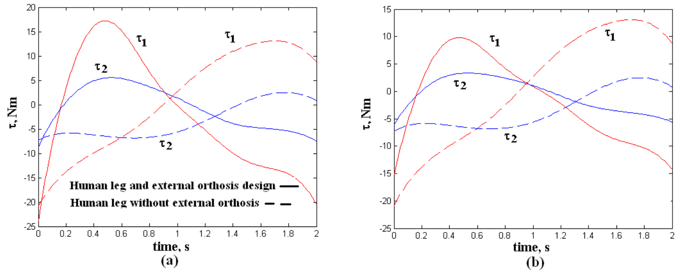

Fig. 8. Joint torque trajectories at the hip (τ_1) and the knee (τ_2) at a walking speed of 0.4170 m/s: (a) design with one spring, (b) design with two springs

the segment masses of the human leg on the coefficients of total potential energy of the system given in (10). As an example, by varying the human leg masses presented in Table I by 10%, the variation of masses of external orthosis are derived and shown in Fig. 9.

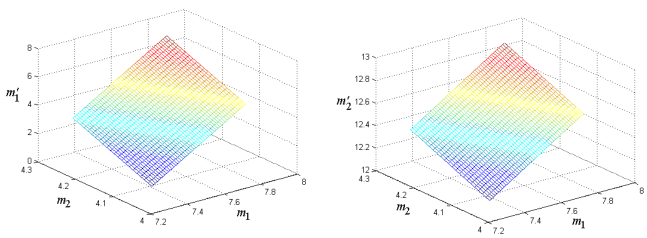

Fig. 9. Masses of external orthosis with one spring design versus masses of the human leg: (a) variation of m_1', mass of the first link, (b) variation of m_2', mass of the second link

Moreover, the variation of segment lengths of the human leg are derived and presented in Fig. 10.

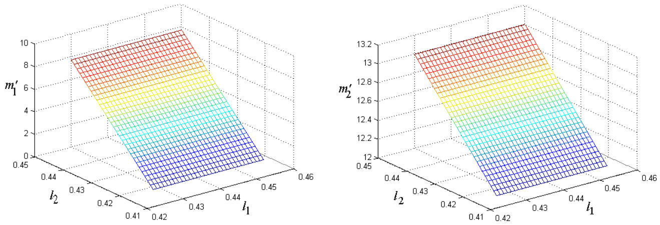

Fig. 10. Masses of external orthosis with one spring design versus link lengths of the human leg: (a) variation of m_1', mass of the first link, (b) variation of m_2', mass of the second link

As shown from the results, mass of the first link of the external orthosis is very sensitive to the variation of masses and segment lengths of the human leg.

VII. Conclusion

The paper provided the design of an external orthosis to remove gravity load on the joints of a human leg during walking. This design connects to the human leg at a single point and thus does not have the issue of joint alignment between the human leg and the device. However, it increases the inertia of the system, which may be a drawback during fast walking. The results showed that the 3D design has larger inertia with respect to 2D design. In 2D design, the joint torque computation showed that the design with two springs is more desirable at fast walking. It is also concluded that the mass of the first link of external orthosis is very sensitive to the variations of link masses and lengths of the human leg. We believe that the gravity balancing devices will provide insight into the human locomotion under reduced gravity. Fabrication of this design will be the subject of future work.

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