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下肢癱瘓病患交替旋進助行矯具之設計

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Design of a Reciprocal Swivel Gait Orthosis for Paraplegics
下肢癱瘓病患交替旋進助行矯具之設計

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Abstract

Swivel walkers enable paraplegic and quadriplegic patients to ambulate without use of their hands. Patients move side to side to lift one footplate and to produce a side thrust, which rolls the swivel walker. Since each footplate is instrumented with a yawing mechanism, the lifting footplate makes the body structure of the walker free to pivot about the other foot bearing axis of the yawing mechanism. Given the situation that the center of mass of the body structure lies anteriorly to the bearing axis, the pivoting moment is attributed to rolling inertial, yawing inertial and the gravitational force. The major disadvantages include slow ambulation, comparative metabolic inefficiency, awkwardness of doffing and donning, and inability to walk on uneven terrain. The purpose of this research is to design a new orthosis, Reciprocating Swivel Gait Orthosis (RSGO), which allows swivel and reciprocating walking at the same time such that the current function of the swivel walker can be ameliorated. The biomechanical analysis of the new orthosis was performed based on a mathematical model. This report contains the mathematical model and design criteria derived from the results of the biomechanical analysis. The biomechanical analysis will lay a solid foundation for the design of the RSGO system, where a rigorous, systematic design can be carried out.

中文摘要

擺盪式(swing through)與交替式(reciprocal)助行矯具為兩種最常提供下肢癱瘓病人助行的復健器材。其不僅滿足治療上的需求，也提供病人更多的自主性。然而病人在體能上的消耗卻是使用此類行走輔具最大的限制。現有的研究不斷尋求不同之機電方式做為解決方案。旋進機制(swivel mechanism)的優點，主要為將側向擺動的機械能，轉化為前進的動力。本研究深入探討旋進機制，希冀有效地利用機械動力降低病人行走時的能量消耗。

本研究提出一新式的個人化交替旋進助行矯具(Reciprocating Swivel Gait Orthosis, RSGO)。此新式矯具之上層結構結合定製的膝踝足矯具(KAFO)與一迫使髖關節成為旋轉中心之機構。其下層結構則包括踏板(shoe plate)和接地板(ground plate)構成之旋轉機構。預期交替旋進助行矯具將同時改善旋進助行器之速度，以及交替式助行器耗能高的問題。設計上需透過數學模型的建立、動力學分析、以及電腦模擬等步驟來達成。本報告提出一個數學模型並由動態分析推導設計基準，為要鋪陳一個堅實的學理基礎，好為RSGO從事嚴謹之系統化設計。

Background

The concept of swivel walking was introduced in 1960s and the swivel walkers [1-13] enable paraplegic and quadriplegic patients to ambulate in an upright position without use of their hands and walking aids such as walkers or crutches. The basic structure of swivel walkers is composed of a standing frame and a swivel base (Figure 1). The swivel base contains a pair of parallel footplates, each of which is associated with a swivel joint.

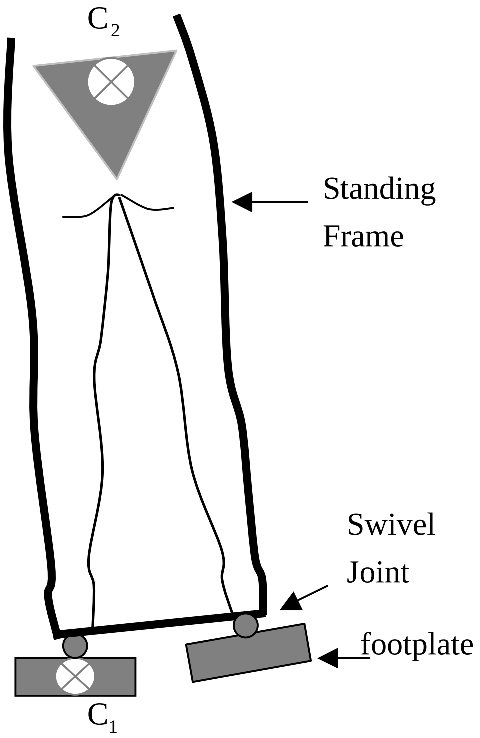

Figure 1 A Swivel Walker

The center mass of the standing frame and the patient is placed anterior to the swivel joint. When patients roll side to side, the rolling inertia and the gravity produce a swivel moment, which leads to a forward propulsion. The patient can further increase the walking speed by swing his arms and by rotating his trunk. The clinical applications of swivel walkers have mostly been to children with myelomeningocele, spinal cord injury or muscular dystrophy [14-17]. The patients enjoy the physiological and psychological benefits being able to stand and walk independently in school. However, swivel walkers are most criticized for its low walking speed and for its inability to ambulate on an uneven surface. In a comparison of the gait efficiency [17-18], swivel walkers were found superior to parapodium in swing gait but inferior to knee-ankle-foot orthoses in swing gait. In spite of slower walking velocity, swivel walkers apparently have considerably lower metabolic costs in order to keep higher efficiency than parapodiums. It can be concluded that the swivel motion should be a key factor that reduces the energy expenditure.

In our research, a new gait orthosis, Reciprocating swivel gait orthosis (RSGO), is being developed, which applies the swivel concept to a simple reciprocal gait orthosis. When a patient wears the new orthosis, the swivel motion that compensates the lack of the pelvic rotation together with a guided hip motion simulates the human reciprocal gait. A patient walking with the new orthosis on and mimicking the human walking presents with a smoother gait. In this report, a conceptual design and biomechanical analysis are presented. The biomechanical analysis was based on a mathematical model of the orthosis and some design criteria was derived from the results of the analysis.

Reciprocating Swivel Gait Orthsis (RSGO)

The idea of the new orthosis has been the application of the swivel motion to a reciprocal gait in order that the rotary motion in transverse plane can be introduced and the gait efficiency can be improved. The RSGO in a broad sense could be a swivel base plus any type of the reciprocal gait orthoses. The RSGO system represents a patient wearing a RSGO. In this research, we are aiming at the development of the new concept and the RSGO in this report (Figure 2) strictly means two swivel units for two legs mounted on a simple, low-profile reciprocal gait orthosis. The swivel unit has a footplate with a swivel joint on the top of the footplate. The low-profile reciprocal gait orthosis is simply a pair of KAFO’s interconnected with an infraperineum bridge. The bridge with the function of hip adduction control allows the hip motion in sagittal plane but restricts motions in other planes. Like the swivel walker design, the footplates in the RSGO also require built-in dihedral angles with the ground surface such that the side-to-side rolling (lateral coronal) movements can be produced.

The RSGO system in our model includes three motion types, namely, rolling, yawing and pitching. The system rolls about the medial edge of the footplate in stance. The swivel joint is responsible for the yawing and the hip joint is for the pitching. The three motions cover a full spectrum of rotary motion like an aircraft in the air or a ship on the water, which would allow the patient orient himself in any direction.

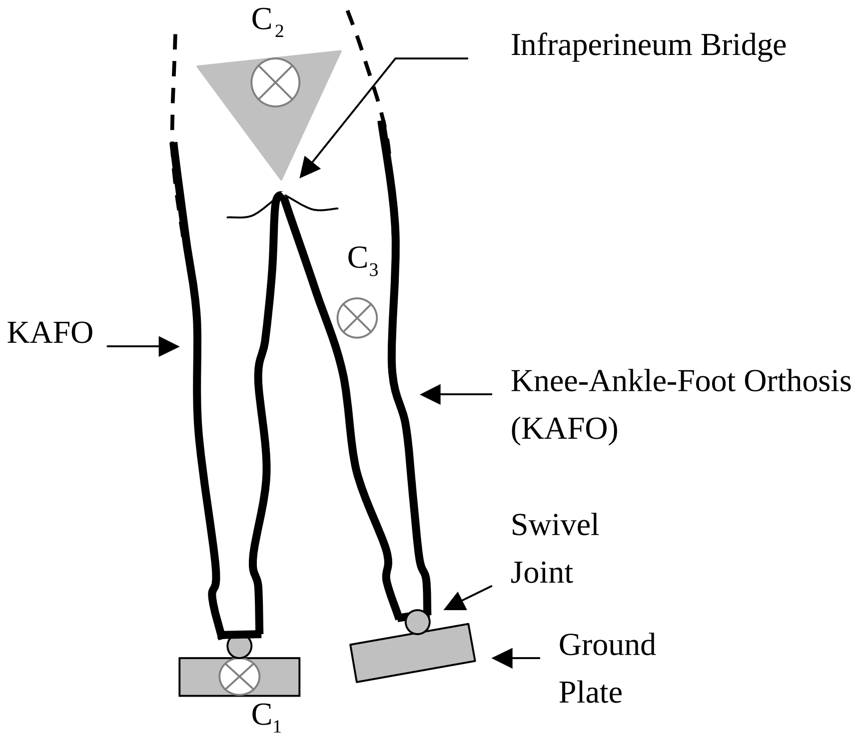

Figure 2 A Reciprocal Swivel Gait Orthosis

Mathematical Model

The RSGO system is rather a complex system and it is necessary to make simplifications on a mathematical model so that the key behavior of the system can be analyzed. A simplified model was developed based on the following general assumptions:

1. The system components are rigid bodies and only rigid-body dynamics were carried out.
2. Patient movements are considered to be low-speed and all the centripetal and Coriolis forces are neglected.

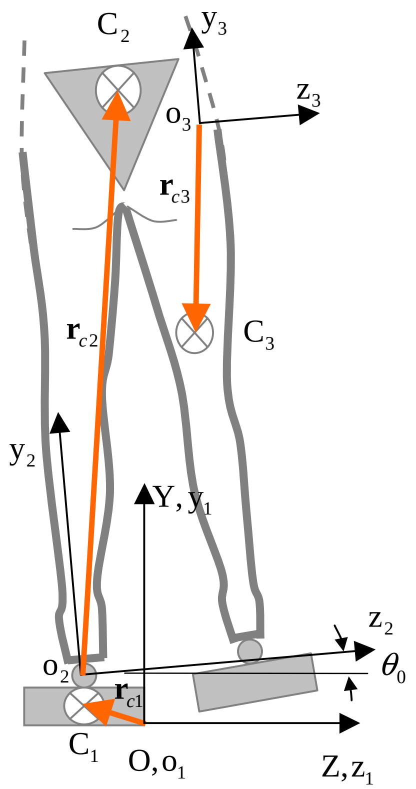

Figure 3　The simplified model of the RSGO system

Figure 3 depicts a posterior view of our simplified model of the RSGO system where the left footplate is laid flat on the ground and the right leg is lifted off the ground. The first rigid body is the left swivel unit, the mass center of which is marked C_1. The patient's whole left leg, pelvis plus the trunk compose the second rigid body where the controlled trunk and the left hip motions are assumed. The third rigid body includes the whole right leg and the right swivel unit. C_2 and C_3 are the mass centers of the second and the third rigid bodies. These three rigid bodies are interconnected with the left swivel joint and the right hip joint. The left footplate is assumed planted on the ground and only the coronal plane rotation is allowed. In addition to the global coordinates (X,Y,Z), three body-fixed coordinate systems are assigned, i.e., (x_1, y_1, z_1), (x_2, y_2, z_2), and (x_3, y_3, z_3). The body-fixed coordinates are local coordinates and move with the rigid bodies. The benefits of having the local moving coordinates are two folds:

(1) The dynamics of the system can be made structurally systematic.

(2) The dynamic parameters, such as the location of the center mass and the moment of inertia, can remain constant in reference to the local coordinates.

The origins of the global coordinates and the first body-fixed coordinates coincides and the location is marked by O and o_1. The origins of the second and the third body-fixed coordinates are located at the left swivel joint (o_2) and the right hip joint

(o_3), respectively. The location of each origin is also represented by a local position vector. The location of o_1 is represented by a local vector $\mathbf{o_2} - \mathbf{o_1}$, i.e., $[l_{02} \quad h_{02} \quad -b_{02}]^T$, where l_{02}, h_{02}, and b_{02} are distances measured from o_1 to o_2 in x_1, y_1, and $-z_1$ directions, respectively. Accordingly, a local vector $[l_{03} \quad h_{03} \quad b_{03}]^T$ in coordinates (x_2, y_2, z_2) represents the location of o_3.

The zero positions and orientations of the coordinate system are shown in Figure 3. The first local coordinates are parallel to the global coordinates. The second coordinates are rotated $-\theta_0$ about the x-axis of the first coordinates and the third coordinates are parallel to the second.

The system has three degrees of freedom representing the aforementioned three motions. The roll angle is represented by θ_1, a rotation about the x-axis of the first local coordinates. The system rolls medially when θ_1 increases. θ_2 represents the yaw angle, a rotation about the y-axis of the second local coordinates. When θ_2 increases, the pelvic and the swing leg rotate medially. Finally, the pitch angle θ_3 is a rotation about the z-axis of the third local moving coordinates. When θ_3 increases, the hip on the swing side flexes.

The dynamic properties such as masses, mass centers, and moments of inertia should also be specified before a biomechanical analysis can be performed. m_1, m_2 and m_3 are the three masses of the first, second, and third rigid bodies. $\mathbf{r}_{c1}$, $\mathbf{r}_{c2}$ and $\mathbf{r}_{c3}$ are local position vectors representing the locations of three mass centers with respect to their own body-fixed coordinates, where

$$\mathbf{r}_{c1} = [l_{c1} \quad h_{c1} \quad -b_{c1}]^T, \ \mathbf{r}_{c2} = [l_{c2} \quad h_{c2} \quad b_{c2}]^T \text{ and } \mathrm{r}_{c3} = [l_{c3} \quad -h_{c3} \quad b_{c3}]^T$$

The moments of inertia with respect to mass centers of the three rigid bodies are defined in their local coordinates as follows,

$$\mathbf{I}_1 = \begin{bmatrix} I_{1xx} & -I_{1xy} & -I_{1xz} \\ -I_{1xy} & I_{1yy} & -I_{1yz} \\ -I_{1xz} & -I_{1yz} & I_{1zz} \end{bmatrix},$$

$$\mathbf{I}_2 = \begin{bmatrix} I_{2xx} & -I_{2xy} & -I_{2xz} \\ -I_{2xy} & I_{2yy} & -I_{2yz} \\ -I_{2xz} & -I_{2yz} & I_{2zz} \end{bmatrix},$$

$$\text{and } \mathbf{I}_3 = \begin{bmatrix} I_{3xx} & -I_{3xy} & -I_{3xz} \\ -I_{3xy} & I_{3yy} & -I_{3yz} \\ -I_{3xz} & -I_{3yz} & I_{3zz} \end{bmatrix}$$

The equations of motion were derived by the Newton-Euler's method. In our research, we investigate the dynamics that concern the propulsion and the stability of the RSGO system. Two equations of motion and the system potential energy were derived.

The dynamics of the swing leg can be described by the equation of the hip motion, which was expressed by a second-order differential equation of θ with respect to time as

$$\begin{aligned}\left(I_{3zz} + m_3({l_{c3}}^2 + {h_{c3}}^2)\right)\ddot{\theta}_3 &= -\mu_1\ddot{\theta}_1 - \mu_2\ddot{\theta}_2 \\ &\quad - m_3 g l_{c3}\left(\cos(\theta_0 - \theta_1)\cos\theta_3 + \sin(\theta_0 - \theta_1)\sin\theta_2\sin\theta_3\right) \qquad (1) \\ &\quad - m_3 g h_{c3}\left(\cos(\theta_0 - \theta_1)\sin\theta_3 - \sin(\theta_0 - \theta_1)\sin\theta_2\cos\theta_3\right) + M_h\end{aligned}$$

where

$\theta_1 < \theta_0$

$$\begin{aligned}\mu_1 &= I_{3zz}\cos\theta_2(\cos\theta_0\sin\theta_2 - \cos\theta_0\sin\theta_2\cos\theta_3 - \sin\theta_0\sin\theta_3) \\ &\quad - I_{3xz}(\cos^2\theta_2\cos\theta_3 + \sin^2\theta_2) - I_{3yz}\cos\theta_2(\sin\theta_0\sin\theta_2 - \sin\theta_0\sin\theta_2\cos\theta_3 + \cos\theta_0\sin\theta_3) \\ &\quad + m_3 l_{c3} h_{02}(\cos\theta_0\sin\theta_2\sin\theta_3 - \sin\theta_0\cos\theta_3) + m_3 l_{c3} b_{02}(\sin\theta_0\sin\theta_2\sin\theta_3 + \cos\theta_0\cos\theta_3 - \cos\theta_2\cos\theta_3) \\ &\quad + m_3 l_{c3} h_{03}\sin\theta_2\sin\theta_3 + m_3 l_{c3} l_{03}\sin\theta_2\cos\theta_3 + m_3 {l_{c3}}^2\cos\theta_2\left(\cos\theta_0\sin\theta_2(1 - \cos\theta_3) - \sin\theta_0\sin\theta_3\right) \\ &\quad - m_3 l_{c3} b_{c3}(\cos^2\theta_2\cos\theta_3 + \sin^2\theta_2) + m_3 h_{c3} b_{02}(\cos\theta_0\sin\theta_3 - \sin\theta_0\sin\theta_2\cos\theta_3) \\ &\quad - m_3 h_{c3} h_{02}(\sin\theta_0\sin\theta_3 + \cos\theta_0\sin\theta_2\cos\theta_3) + m_3 h_{c3} l_{03}\sin\theta_2\sin\theta_3 - m_3 h_{c3} b_{03}\cos\theta_2\sin\theta_3 \\ &\quad - m_3 h_{c3} h_{03}\sin\theta_2\cos\theta_3 + m_3 h_{c3} b_{c3}\cos\theta_2(\sin\theta_0\sin\theta_2 - \sin\theta_0\sin\theta_2\cos\theta_3 + \cos\theta_0\sin\theta_3) \\ &\quad + m_3 {h_{c3}}^2\cos\theta_2(\cos\theta_0\sin\theta_2 - \cos\theta_0\sin\theta_2\cos\theta_3 - \sin\theta_0\sin\theta_3)\end{aligned}$$

$$\begin{aligned}\mu_2 &= I_{3zz}(\cos\theta_0\sin\theta_2\sin\theta_3 - \sin\theta_0\cos\theta_3) + I_{3xz}\cos\theta_2\sin\theta_3 - I_{3yz}(\sin\theta_0\sin\theta_2\sin\theta_3 + \cos\theta_0\cos\theta_3) \\ &\quad - m_3 l_{c3} b_{03}\sin\theta_3 + m_3 l_{c3} b_{c3}\cos\theta_2\sin\theta_3 + m_3 {l_{c3}}^2(\cos\theta_0\sin\theta_2\sin\theta_3 - \sin\theta_0\cos\theta_3) \\ &\quad + m_3 h_{c3} b_{c3}(\sin\theta_0\sin\theta_2\sin\theta_3 + \cos\theta_0\cos\theta_3) + m_3 h_{c3} b_{03}\cos\theta_3 \\ &\quad + m_3 {h_{c3}}^2(\cos\theta_0\sin\theta_2\sin\theta_3 - \sin\theta_0\cos\theta_3)\end{aligned}$$

and $M_h = \text{physiological residual moment or moment provided by an artificial control}$.

The swivel-joint dynamics can be represented by the equation of yawing motion. The equation was derived based on a further simplification by assuming the hip motion is a quasi-static motion and the effect to the swivel joint is negligible. Therefore, the second rigid body and the third one are treated as one rigid body, the dynamic parameters of which such as mass center and moment of inertia are redefined as

$$\mathbf{r}_{c2'} = \begin{bmatrix} l'_{c2} & h'_{c2} & b'_{c2} \end{bmatrix}^T \text{ and } \mathbf{I}_{2'} = \begin{bmatrix} I'_{2xx} & -I'_{2xy} & -I'_{2xz} \\ -I'_{2xy} & I'_{2yy} & -I'_{2yz} \\ -I'_{2xz} & -I'_{2yz} & I'_{2zz} \end{bmatrix}$$

The equation of the yawing was derived as

$$\begin{aligned}
&\left((m_2+m_3)({b'_{c2}}^2+{l'_{c2}}^2)+I'_{2yy}\right)\ddot{\theta}_2 \\
&=\begin{pmatrix}(m_2+m_3)(h'_{c2}+b_{02}\sin\theta_0+h_{02}\cos\theta_0)(b'_{c2}\sin\theta_2+l'_{c2}\cos\theta_2) \\ +(I'_{2xy}\cos\theta_2+I'_{2yz}\sin\theta_2)\end{pmatrix}\ddot{\theta}_1 \\
&+(m_2+m_3)g\sin(\theta_0-\theta_1)(b'_{c2}\sin\theta_2+l'_{c2}\cos\theta_2)+M_s
\end{aligned} \tag{2}$$

where $M_s = \text{Moment provided by an artificial control}$.

In addition, the system potential energy was derived as

$$\begin{aligned}
PE &= \left(m_1h_{c1}+(m_2+m_3)h_{02}\right)g\cos\theta_1+\left((m_2+m_3)b_{02}-m_1b_{c1}\right)g\sin\theta_1 \\
&+\left\{\left(m_2b_{c2}+m_3(b_{03}+b_{c3})\right)\cos\theta_2-(m_2l_{c2}+m_3l_{03})\sin\theta_2\right\}g\sin(\theta_0-\theta_1) \\
&+(m_2h_{c2}+m_3h_{03})g\cos(\theta_0-\theta_1) \\
&+(l_{c3}\sin\theta_3-h_{c3}\cos\theta_3)m_3g\cos(\theta_0-\theta_1) \\
&-(l_{c3}\cos\theta_3+h_{c3}\sin\theta_3)m_3g\sin\theta_2\sin(\theta_0-\theta_1)
\end{aligned} \tag{3}$$

Biomechanical Analysis

The gait efficiency is measured upon the energy consumption and the walking speed. The cadence and the step length determine the speed. The energy expenditure of the patients walking with the swivel walkers has been experimentally proved superior to that of the swing gait when using the parapodium. In this report, we study the dynamics of hip motion and swiveling and analyze the system speed by looking into the their dynamic equations. We investigate the propulsion forces for each motion in particular in order that the system behavior may be studied and the design criteria may be derived. We made further assumptions that all three motions are small (less than 10^{o}) and the following simplifications were applied to the system equations, i.e.,

$$0\approx\sin\theta_i\sin\theta_j<<\sin\theta_i\approx\theta_i<<\cos\theta_i \quad \text{for } i=1,2,3,4 \text{ and } j=1,2,3,4$$

$$\cos\theta_i\cos\theta_j\approx\cos\theta_i\approx1 \quad \text{for } i=1,2,3,4 \text{ and } j=1,2,3,4$$

where $\theta_4=\theta_0-\theta_1$.

Equation (1) can then be simplified and rewritten as

$$\left(I_{3zz}+m_3({l_{c3}}^2+{h_{c3}}^2)\right)\ddot{\theta}_3+m_3gh_{c3}\theta_3=-\mu_1\ddot{\theta}_1-\mu_2\ddot{\theta}_2-m_3gl_{c3}+M_h \tag{4}$$

where

$$\begin{aligned}\mu_1 = &-I_{3xz} - I_{3yz}\theta_3 \\ &- m_3 l_{c3} h_{02}\theta_0 + m_3 l_{c3} l_{03}\theta_2 - m_3 l_{c3} b_{c3} + m_3 h_{c3} b_{02}\theta_3 \\ &- m_3 h_{c3} h_{02}\theta_2 - m_3 h_{c3} b_{03}\theta_3 - m_3 h_{c3} h_{03}\theta_2 + m_3 h_{c3} b_{c3}\theta_3\end{aligned}$$

and

$$\begin{aligned}\mu_2 = &-I_{3zz}\theta_0 + I_{3xz}\theta_3 - I_{3yz} \\ &- m_3 l_{c3} b_{03}\theta_3 + m_3 l_{c3} b_{c3}\theta_3 - m_3 l_{c3}{}^2\theta_0 + m_3 h_{c3} b_{c3} + m_3 h_{c3} b_{03}\theta_3 + m_3 h_{c3}{}^2\theta_0\end{aligned}$$

In most cases, $\mu_1 < 0$ and $\mu_2 > 0$ because from the geometrical configuration, the following conditions are usually true, i.e.,

$$I_{3xz} + I_{3yz}\theta_3 + m_3 l_{c3}(h_{02}\theta_0 + b_{c3}) + m_3 h_{c3}(h_{02}\theta_2 + b_{03}\theta_3 + h_{03}\theta_2) > m_3 l_{c3} l_{03}\theta_2 + m_3 h_{c3}\theta_3(b_{02} + b_{c3})$$

and

$$I_{3zz}\theta_0 + I_{3yz} + m_3 l_{c3} b_{03}\theta_3 + m_3 l_{c3}{}^2\theta_0 < I_{3xz}\theta_3 + m_3 l_{c3} b_{c3}\theta_3 + m_3 h_{c3} b_{c3} + m_3 h_{c3} b_{03}\theta_3 + m_3 h_{c3}{}^2\theta_0$$

Let the propulsion force $f_3 = -\mu_1\ddot{\theta}_1 - \mu_2\ddot{\theta}_2 - m_3 g l_{c3} + M_h$. The hip motion is governed by a shorter form as

$$\left(I_{3zz} + m_3(l_{c3}{}^2 + h_{c3}{}^2)\right)\ddot{\theta}_3 + m_3 g h_{c3}\theta_3 = f_3 \tag{5}$$

The natural frequency of the hip motion is thus derived as

$$\omega_{3n} = \sqrt{\frac{m_3 g h_{c3}}{I_{3zz} + m_3(l_{c3}{}^2 + h_{c3}{}^2)}} \tag{6}$$

For a 60kg patient, let m_3 be 10 kg, I_{3zz} be 0.83 $\mathrm{kg \cdot m^2}$, h_{c3} be 0.5 m, l_{c3} be -0.1 m. The natural frequency of his hip motion is 0.6 Hz, i.e., 36.1 cycles per minute.

The swing motion can be actively controlled using feedback control technique to achieve desired cadence and step length. The design criterion for the hip motion can therefore be set as

$$f_3 = -\mu_1\ddot{\theta}_1 - \mu_2\ddot{\theta}_2 - m_3 g l_{c3} + M_h = -\beta_3\dot{\theta}_3 - \gamma_3\theta_3 + A_3\sin\omega_3 t$$

where β_3, γ_3, A_3 and ω_3 are design parameters to be determined.

The control moment can therefore be computed according to the following formula:

$$M_h = -\beta_3\dot{\theta}_3 - \gamma_3\theta_3 + A_3\sin\omega_3 t + \mu_1\ddot{\theta}_1 + \mu_2\ddot{\theta}_2 + m_3 g l_{c3} \tag{7}$$

Equation (2) can also be rewritten as

$$\begin{aligned}&\left((m_2+m_3)(b'^{\,2}_{c2}+l'^{\,2}_{c2})+I'_{2yy}\right)\ddot{\theta}_2\\&=\left((m_2+m_3)(h'_{c2}+h_{02})b'_{c2}\theta_2+(m_2+m_3)(h'_{c2}+b_{02}\theta_0+h_{02})l'_{c2}+(I'_{2xy}+I'_{2yz}\theta_2)\right)\ddot{\theta}_1\\&\quad+(m_2+m_3)g(\theta_0-\theta_1)l'_{c2}+M_s\end{aligned} \qquad (8)$$

The swivel motion is a non-oscillatory motion since there is no restoration force to draw the motion toward an equilibrium point. The propulsion forces include an inertial force and a gravitational force, which are produced by the lateral coronal plane movements. Again, let the total propulsion force be

$$\begin{aligned}f_2&=\left((m_2+m_3)(h'_{c2}+h_{02})b'_{c2}\theta_2+(m_2+m_3)(h'_{c2}+b_{02}\theta_0+h_{02})l'_{c2}+(I'_{2xy}+I'_{2yz}\theta_2)\right)\ddot{\theta}_1\\&\quad+(m_2+m_3)g(\theta_0-\theta_1)l'_{c2}+M_s\end{aligned}$$

Equation (8) can be put in a shorter form as

$$\left((m_2+m_3)(b'^{\,2}_{c2}+l'^{\,2}_{c2})+I'_{2yy}\right)\ddot{\theta}_2=f_2 \qquad (9)$$

The swivel motion can also be actively controlled utilizing feedback control technique, and the design criterion can be set as

$$f_2=-\beta_2\dot{\theta}_2-\gamma_2\theta_2+A_2\sin\omega_2 t$$

where β_2, γ_2, A_2 and ω_2 are design parameters to be determined. The control moment of the swivel mechanism can be designed as follows,

$$\begin{aligned}M_s&=-\beta_2\dot{\theta}_2-\gamma_2\theta_2+A_2\sin\omega_2 t\\&\quad-\left((m_2+m_3)(h'_{c2}+h_{02})b'_{c2}\theta_2+(m_2+m_3)(h'_{c2}+b_{02}\theta_0+h_{02})l'_{c2}+(I'_{2xy}+I'_{2yz}\theta_2)\right)\ddot{\theta}_1\\&\quad-(m_2+m_3)g(\theta_0-\theta_1)l'_{c2}\end{aligned} \qquad (10)$$

The system potential energy can be analyzed to derive the stability design criteria. The gravity provides a restoration force to the side-to-side rolling movement. The gravitational potential energy converts into the kinetic energy of hip and swivel motions as the RSGO system rolls medially. When the system continues to roll medially, the pelvic and the swing leg rotates medially due to the swivel motion dynamics and hip on the swing side flexes due to the hip motion dynamics. The potential energy must decrease in the course of medial rolling. In a mathematical language, the first derivative of the potential energy with respect to each motion has to be less than zero, i.e., $\frac{\partial PE}{\partial\theta_i}<0$ at $\theta_i=0$ for $i=1,2,3$.

By applying the small motion assumptions, the following stability design criteria can be derived,

$$\begin{aligned}\frac{\partial PE}{\partial \theta_1} &= -\left(m_1 h_{c1} + (m_2 + m_3) h_{02}\right) g \theta_1 + \left((m_2 + m_3) b_{02} - m_1 b_{c1}\right) g \\ &\quad - \left\{\left(m_2 b_{c2} + m_3 (b_{03} + b_{c3})\right) - (m_2 l_{c2} + m_3 l_{03}) \theta_2 \right\} g \\ &\quad + (m_2 h_{c2} + m_3 h_{03}) g (\theta_0 - \theta_1) - h_{c3} m_3 g (\theta_0 - \theta_1) + l_{c3} m_3 g \theta_2 \\ &\quad < 0\end{aligned} \tag{11}$$

$$\frac{\partial PE}{\partial \theta_2} = -(m_2 l_{c2} + m_3 l_{03}) g (\theta_0 - \theta_1) - l_{c3} m_3 g (\theta_0 - \theta_1) < 0 \tag{12}$$

$$\frac{\partial PE}{\partial \theta_3} = (l_{c3} + h_{c3} \theta_3) m_3 g < 0 \tag{13}$$

Discussion

The mathematical model provides a research tool that allowed us to perform biomechanical analysis and derived several design criteria. The results of the biomechanical analysis give us certain directions to develop a sound RSGO system in a mathematically rigorous way. We tackled two of the most challenging problems, namely, the gait efficiency and the stability of the system.

Equation (8) tells us that the swivel motion was driven by the side-to-side rolling induced inertial force and gravity. In other words, the swivel motion solely relies on the lateral coronal plane movement. In order the swivel walking be effective, the side-to-side rolling is essential. To enhance the swivel motion, the dynamic parameters in the equation can be designed. The swivel motion can also be controlled to achieve desired cadence and step length using active feedback control theory.

In addition to the swivel motion, the hip motion can further improve the system speed. Equation (4) allows us to design suitable dynamic parameters for an effective driving force. The driving forces include (1) inertial forces induced by the rolling and yawing and (2) the gravity induced by rolling and hip pitching. Their frequency spectrum can affect the quality of the speed performance. The placement of the mass center of the swing leg can play an important role too. By placing the mass center posterior to the hip joint, the sense of the term $-m_3 g l_{c3}$ in Equation (4) can be changed to convert the impeding force into a driving force, which can improve the amplitude of the hip movement and increase the step length. The natural frequency (Equation(6)) can be tuned by selecting the dynamic parameters, which can improve the cadence and step length as well.

The control of the hip motion can also be intervened by putting active feedback control into the system according to the design criteria of Equation (7). A hybrid system [19], that is the combination of the FES and RSGO, may present a solution to this issue. The RSGO provides a mechanical platform and the FES plays an assistant role to smoothen the gait. The mechanical power and FES stimulated muscle together provide more energy-efficient gait and increase the aerobic-anaerobic threshold of the patients in the long term [20-21]. In addition, the activity of the paralyzed muscle is maintained and the cardiovascular function can be improved in rehabilitation aspect [22]. We believe that the richness of the hybrid system for gait orthoses has not yet been explored fully and deserves to be further studied. The coordination of three motions should also be dealt when the new system is designed.

The stability consideration was given by looking into the system's potential energy and its associated terms. Equations (11)-(13) are design criteria for the system dynamic parameters and are the conditions for system stability. It was found that the posterior placement of the mass center of the swing leg is also important to the system stability.

Conclusion

The swivel mechanism has been applied to the walking orthosis since 60's; however, its advantage has not been fully explored. This research introduced a new orthosis incorporating the swivel motion into a reciprocating walking, the ultimate goal of which was to achieve a stable, smooth, and efficient gait. The RGSO is a complex dynamic system and deserves a deliberate analysis such that the system characteristics can be well understood and desired system performance can be accomplished. A mathematical model was developed to provide a foundation for biomechanical analysis. The mathematical model and biomechanical analysis allow a systematic design of the new system to be achieved on a rational basis.

The roles of the dynamic properties in the dynamic system were outlined when the system characteristics and stability were discussed. The adjustment of these dynamic properties can therefore be used to design desired system dynamic behavior. The possible active feedback controls were also described and discussed in this report, which will lead to an implementation of a new hybrid system.

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