Dynamic Modelling and Analysis of a Cane under Cane Gait

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***Abstract*—In order to develop a cane robot to be compliant with the motion habits of an elder during his walking assisted by a general cane, the motion state of an ordinary cane was analysed in this paper. Two different cane-assisted gaits were introduced and the motion state of the cane was divided by two motion phases. The relationship of the human-cane interaction force for each phase was analysed, and the dynamic model of the cane was founded individually. An experimental setup was constructed and validity of the proposed dynamic models were verified.**

***Index Terms*—dynamic model, cane gait, walking habit**

I. Introduction

Due to the aging society, disabled and semi-disabled elderly increase rapidly [1]. In 2015, the population over the age of 60 will grow from 11% to 12% to more than 25% in Asia [2]. How to solve the daily care of the elderly with a modern way is a work for researchers in the field of robots always working on. Currently, there are three kinds of robots assisting walker's function, namely the exoskeleton robot, the walking frame robot and the cane robot.

Currently, a lot of research focusing on the exoskeleton robot have been done by many scholars [3]-[6]. For example, Yoshiyuki Sankai developed an exoskeleton robot called HAL-5. The robot can help the elderly complete some action, such as walking and stairs up and down [7]-[9]. However, exoskeleton robots still have some drawbacks, such as the robot was connected with user by bundling. It causes the user's body will produce poor blood circulation and it is too unachievable for an elderly to wear the equipment independently. For the research on walking aid robot, a walking robot JARoW [10], [11] was proposed, in which a laser sensor was employed to locate the relative position of legs and the center of the walker. The robot was controlled to coincide COGs of users and the robot frame. Walk frame robots are usually with large size and restrict human motion, and it is not suitable for indoor environment.

Generally, certain motion abilities were survived for most of elderly people, the most effective walking assist equipment for them is something with smaller size and easy to use and unrestricted moving just like a general cane. Cane robots just meet the requirements mentioned above. In 2013, Toshio Fukuda developed an omnidirectional cane robot based on human walking intention. The robot recognized the intention of the direction by analyzing the interaction between man and the robot was realized to assist users walking effectively [12]-[16]. However, there are still some problems with this kind of robots. For example, the supporting stick and the moving platform are always integrated and there is no any joint connecting them together. The stick is perpendicular with floor and there is no effective support comparing with that of a general cane. Moreover, it is incompliant with the motion habits of an elder walking assisted with a cane.

In this paper, In order to develop a cane robot to be compliant with the motion habits of an elderly people during his walking assisted by a general cane, the motion state of an ordinary cane was analyzed firstly, and then two different cane-assisted gaits were introduced and the motion state of the cane was divided by two motion phases. The relationship of the human-cane interaction force for each phase was analyzed, and the dynamic model of the cane was founded individually. An experimental setup was constructed and validity of the proposed dynamic models was verified.

II. Analysis of Cane's Motion State

There are two kinds of cane gait, one is Two-point gait and the other is the Three-point gait. The Two-point gait is shown in Fig. 1(a). In this situation, a cane is on the same side with the unaffected extremity. On first step, the cane and affected extremity are stepped out simultaneously, and then the user holds the cane and supports body weight with arm power and step out the unaffected extremity after the body is stable. In the Three-point gait, as shown in Fig. 1(b), a cane is also required on the same side with an unaffected extremity before walking. At first, the user steps out the cane and then holds the cane tightly supporting his body with the arm power, then the affected extremity is stepped out when his body is stable. After that, the unaffected extremity is stepped out.

The cane motion can be divided into supporting phase and non-support phase. In the supporting phase, the cane provides support force to stabilize the body, referring to step2 in Two-point gait, and step3 in Three-point gait. In non-support phase, the cane move forward after the body is stable, which refers to step1 in Two-point gait and refers to step1 and 2 in Three-point gait.

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(a) Two-point gait

(b)Three-point gait

Figure 1. Cane gait classification

III. Dynamics Models of Cane

A. Establishment of Coordinate System

In order to accurately explain the movement state of cane under cane gait, defining the earth coordinate system and the cane coordinates as follows:

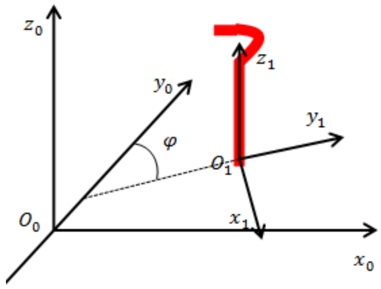
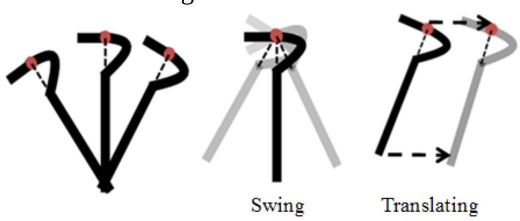


Figure 2. The definition of cane coordinate system

As shown in Fig. 2, $O_0 - x_0y_0z_0$ is the earth coordinate system, $y_0$is point toward the Geographic North Pole; x_0 is perpendicular to y_0 and point to the East; z_0 is perpendicular to the plane $x_0y_0z_0$.

$O_1 - x_1y_1z_1$ is the cane coordinate system, x_1 is perpendicular to y_1 and point to right; y_1 is the forward direction of cane along the handle.



(a)Supporting phase (b) Non-supporting phase

Figure 3. Cane's motion classification

Under these two coordinate systems, according to the analysis of Section II, we also divide the motion state of the cane into two phases, namely the Support phase and the Non-support phase. The support phase is defined as the cane's terminal remains stationary and cane provide support force, as shown in Fig. 3(a).

The Non-support phase was defined as the cane's terminal was hung up and moved from one point to another point as shown in Fig. 3(b).

The state cane does not provide support force. During Non-support phase, the cane motion is combined rotation around the handle and translation together. In support phase, the human force, the gravity and the supporting force from floor are simultaneously acted to determine the cane motion. In non-support phase, only the human force and the gravity are acted simultaneously to determine the cane motion. The acceleration in the direction of y_1 axis was defined as a_y,

$$a_y = S * ay_1 + C * ay_2$$

$$S = \begin{cases} 1 & Fz \geq 0 \\ 0 & Fz < 0 \end{cases} \quad C = \begin{cases} 0 & Fz \geq 0 \\ 1 & Fz < 0 \end{cases} \tag{1}$$

where ay_1 and ay_2 represent acceleration of support phase and the non-support phase respectively.

B. Dynamic Model in Support Phase

In this section, the acceleration of the cane on Y axis is analysed in $O_1 - x_1y_1z_1$ coordinate system during supporting phase. Illustration of the acceleration decomposition of the cane is shown in Fig. 4.

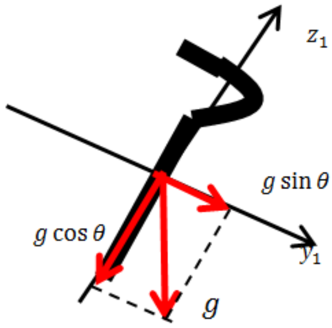


Figure 4. Decomposition of acceleration

In support phase, the cane rotates around the other end of the cane. This movement causes the cane's terminal to be almost static. Therefore, the acceleration in y_1 axis is mainly the component of the gravity acceleration without gravity compensation. The acceleration produced by other forces at y_1 axis is approximately zero, so

$$a_{Sup} = mgsin\theta = ay_1 \tag{2}$$

C. Dynamic Model of Swing in Non-support Phase

In this section we analysed acceleration of the cane on Y axis caused by swing motion. In $O_1 - x_1y_1z_1$ coordinate system, the torque exerted on cane by human and the gravity act simultaneously to determine the swing motion of the cane. The movement of cane is divided into three stages.

F_h is force exerted on cane by human. T is torque exerted on cane by human composed of F_1 and F_2, $T = F_1 * l_1 + F_2 * l_2$. When cane are perpendicular to the ground and still static, we record the status as state1as shown in Fig. 5(a). When the torque T causes the cane to do counterclockwise motion, we record the status as state2 as shown in Fig. 5(b). When the torque T and gravity cause the rotate motion of cane together, we record the status as state3 as shown in Fig. 5(c). The movement of cane change between the three states. We get the formula for swing motion

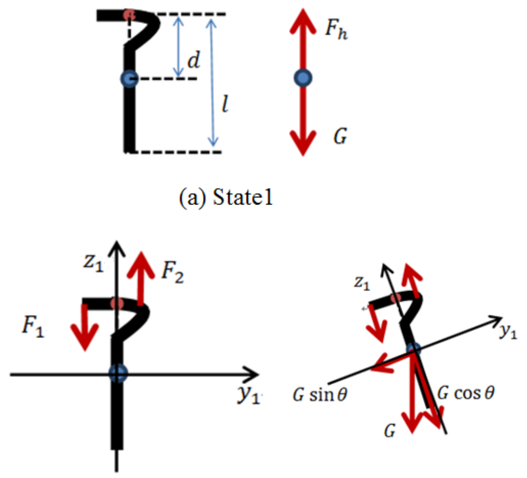
$$T - mg\ sin\theta * d = J\ddot{\theta} \tag{3}$$

where m represents quality of lower part, which consists of F/T senor and the lower part of cane. d represents the distance from the rotation point to COG of the lower part. θ represents the angle between z_0 and z_1. J represents the moment of inertia of cane, get the formula

$$\ddot{\theta} = a_{Rota}/l \tag{4}$$

where a_{Rota} represents the linear acceleration of the cane's terminal, l represents length of cane. We see the cane as a uniform thin rod and add a coefficient k to make up the error of the moment of inertia.

$$J = (1/3) * m * l^2 * k \tag{5}$$



(a) State1

(b) State2

(c) State3

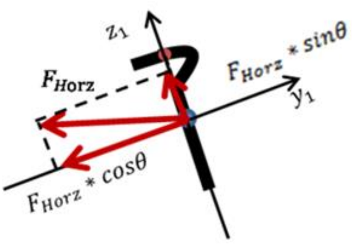
Figure 5. Static analysis of swing motion

The coefficients k are empirical values. We get a formula for calculating moment of inertia of a cane as formula(5), the linear acceleration of the cane's terminal can be obtained, get the formula

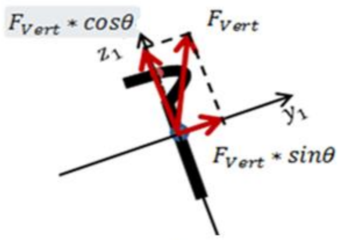
$$a_{Rota} = \frac{3(T - mgsin\theta * d)}{mlk} \tag{6}$$

D. Dynamic Model of Swing in Non-support Phase

In this section we analysed acceleration of the cane on Y axis caused by translation motion as shown in Fig. 6.



(a)



(b)

Figure 6. Static analysis of translational motion

When the translation speed of lower part and upper part of the cane is synchronized on the $z_1o_1y_1$ surface, Interaction force between them don't appear. When the speed is not synchronized, interaction force between them will appear. Horizontal force called F_{Horz}, the vertical force F_{Vert}. The acceleration produced by the translation on the Y axis is a_{Trans}.

$$a_{Trans} = (F_{Horz} * cos\theta + F_{vert} * sin\theta)/m \tag{7}$$

In the Non-Support Phase, the acceleration on the y_1 is caused by the swing and the translation, so the final acceleration should be the synthesis of the two kinds of motion called a_c,

$$a_c = a_{Rota} + a_{Trans} = ay_2 \tag{8}$$

IV. Experiment

A. Experiment Setup

In order to verify validity of the proposed model, a cane motion monitor system was designed. A F/T sensor and a gyro sensor were mounted on the cane as shown in Fig. 7.

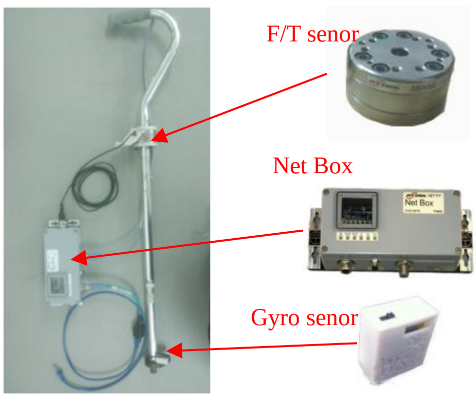


Figure 7. Cane motion monitor system

The experimental platform parameters are as follows: the quality of the lower part is 0.75kg and the length of cane is 0.87m, the distance from rotation point to COG of lower part is 0.5m. In earth coordinate system $O_0 - x_0y_0z_0$ we choose a path called $Route$, as shown in Fig. 5. α is the plane containing the Route and the z_0. The plane $z_1O_1y_1$ coincides with the plane α.

The cane is pitched in the plane α. An user walked with Three-point gait use cane motion monitor system along the $Route$ with 0.16m/s. Recording the force data from the F/T sensor and the posture and acceleration information from the gyro. The force of the cane includes the force along the z_1 axis, denoted as F_z, and the torque around the x_1 axis, denoted as T_x. These two parameters reflect force situation of cane. The cane posture is reflected by the pitch angle of the cane in α plane, denoted as *Pitch*. The cane's terminal acceleration on the y_1 axis is denoted as *Acc*, the parameter reflect the movement of the cane.

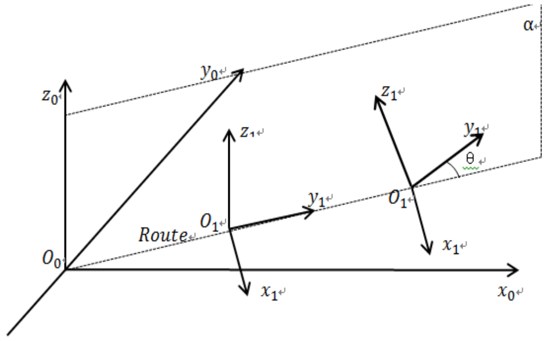


Figure 8. Experimental method description

B. Data Analysis

In Fig. 9, the blue line represents F_z (N) , the green curve represents *Pitch* (unit: degree); the red curve represents *Acc* (unit: m/s^2); the light blue curve represents T_x (unit: N·M). The black curve is zero reference line

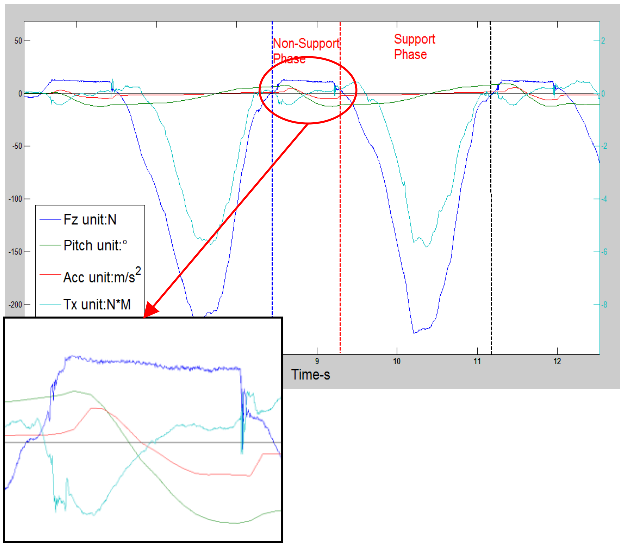


Figure 9. Variation of force, moment, angle and acceleration

It can be seen from the curve that the four parameters F_z , *Pitch*, T_x and *Acc* are cyclically changed. This characteristic is consistent with the characteristics of gait changes when a person uses a cane.

Inputting real measurements of F_z, *Pitch* and T_x into formulas and setting k as 1.3, then the acceleration of cane's terminal on y_1 axis is shown in Fig. 10. The blue and the green curves represent the acceleration measured by gyro and calculated based on the dynamic model respectively. It can be seen that the two curves match very well. The results verified the dynamic model of a cane under cane gait is correct.

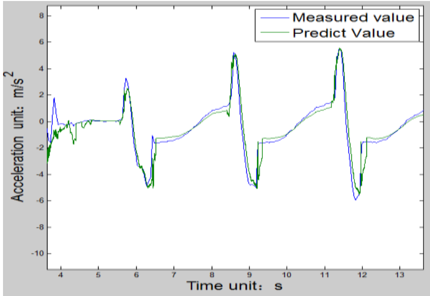


Figure 10. Variation of acceleration in Y axis

V. Conclusion

In this paper, two different cane-assisted gaits were introduced and the motion state of a general cane was divided by two motion phases. The dynamic models of the cane were founded individually and an experimental setup was constructed and validity of the proposed dynamic models were verified. The results of this paper are good for developing a cane robot to be compliant with the motion habits of an elder during assisted by a general cane.

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