Mechanism and Machine Theory 104 (2016) 31–42

Contents lists available at ScienceDirect

Mechanism and Machine Theory

journal homepage: www.elsevier.com/locate/mechmt

Conceptual design and dimensional synthesis of cam-linkage mechanisms for gait rehabilitation

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ARTICLE INFO

Article history:
Received 17 January 2016
Received in revised form 22 May 2016
Accepted 23 May 2016
Available online 2 June 2016

Keywords:
Dimensional synthesis
Cam-linkage mechanism
Gait rehabilitation

ABSTRACT

In order to overcome the drawbacks of traditional gait training methods, gait rehabilitation robotized systems have been developed to provide a consistent, labor-saving and efficient treatment. However, the high cost of these systems makes them impracticable for home healthcare. This paper deals with the conceptual design and dimensional synthesis of cam-linkage mechanisms for gait rehabilitation. First, a two degrees of freedom seven-bar crank-slider mechanism is selected as the original mechanism, of which the displacement of the slider is formulated as a function of the crank angle to achieve the target trajectory by using the inverse kinematics. A cam is then designed to reduce the mobility of the mechanism to one. Moreover, a constant speed motor is sufficient for the control of the mechanism. For the dimensional synthesis, a goal function is proposed based on the kinematic performance criteria and constraints, and the genetic algorithm is employed for global searching. Two target trajectories are used for the dimensional synthesis of the mechanism. The results show the generated trajectories match well with the desired ones, which illustrates the feasibility of the methodology.

1. Introduction

The ageing population is one of the most critical global issues. A survey from the United Nations shows that the number of population over 60 years will increase from 810 million to 2 billion between 2012 and 2050 [1,2]. Stroke is one of the leading causes of the permanent disability throughout the world, and nearly three quarters of all strokes occur in people over 65 years [2,3]. Although treatments can be applied, nearly two third of the survivors will experience paralysis or hemiplegia and have problem in performing activities of daily living (ADL), such as walking [4]. In order to help people who have difficulty in walking, many researches have been carried out. It has been proven that repetitive and intensive gait training is helpful to regain the walking ability [5]. However, the conventional rehabilitation exercises are labor intensive and expensive for most patients [6,7], which limits their pervasive application.

Since 1980s, robotized systems have been used in the domain of rehabilitation to liberate the labor of therapists, which improves the efficacy of rehabilitation and reduces the healthcare costs [8,9]. It has been shown that rehabilitation robots have significant advantages in helping patients recover from neurological disorders and walk again [10,11]. Over the last decades, many kinds of lower limb rehabilitation robots have been developed, and a few of them have been commercialized [12]. These robots can be simply classified into two types according to the rehabilitation principle [4,13,14]: (1) exoskeleton robots, e.g. Lokomat, Auto-Ambulator, LOPES, ALEX and NaTUre-gaits [13,15–17], and (2) end-effector based robots, e.g. HapticWalker, ARTHuR, GM5

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http://dx.doi.org/10.1016/j.mechmachtheory.2016.05.018
0094-114X/

and G-EO [14,18–20]. However, the high cost of these rehabilitation robots makes them impracticable for application at home. Therefore, several one degree of freedom (DOF) mechanisms have been proposed for rehabilitation training, such as the four-bar mechanisms proposed by Ji and Alves [6,21], the Stephenson II six-bar mechanism presented by Wang [22], the Stephenson III six-bar mechanism and the ten-bar linkage proposed by Tsuge [23,24]. Nevertheless, the limitation for these mechanisms is that the desired gait path can only be matched approximately. In order to overcome the limitation of linkage mechanism, Kay and Haws [25] proposed a cam-linkage mechanism combined a fixed cam and a four-bar linkage to exactly generate the desired path. Ye and Smith [26] presented an analytical method for a combined cam-linkage mechanism having an oscillating roller follower for path generation. Mundo and Liu [27] synthesized cam-linkage mechanisms having one or more cams for precise path generation. Soong [28] proposed a novel cam-geared mechanism for path generation. As for the cam design, González-Palacios and Angeles [29] provided an algorithm for various cam mechanisms. Cardona and Géradin [30] analyzed the kinematics and dynamics of cam mechanisms, and using the splines to describe the geometry of a cam. Flores [31] presented a computational approach for the dimensional optimization of cam mechanisms having offset translating roller followers. Cardona and Hidalgo-Martínez [32–34] presented methods for the optimization of the cam profile based on Bézier curves. Cardona and Zayas [35] analyzed the influence of the inclination and offset of the translating follower in a constant-breadth cam mechanism. Ji [36] used the conjugate theory and differential geometry to derive the globoidal cam surface. However, the time-sequence of the desired trajectory is barely taken into account in the literature, thus servomotors must be used to control the mechanisms, which increases the complexity of the robot control system.

In this paper, a method is proposed for the synthesis of cam-linkage mechanisms. With the aid of this method, a seven-bar crank-slider mechanism and a cam are combined together to generate a precise target path. The time-sequence of the trajectory is taken into account in the dimensional optimization in order to obtain the desired trajectory with a constant input speed. The novel lower-limb rehabilitation system is composed of a body weight support system to unload the body weight, and two cam-linkage mechanisms to generate the natural gait trajectory and guide the patient's feet.

The outline of the paper is as follows. In Section 2, the conceptual design of the cam-linkage mechanism is briefly described. Section 3 then investigates the dimensional synthesis of the proposed mechanism, including the inverse kinematic analysis of the seven-bar crank-slider mechanism, the synthesis of the cam profile, and the optimization. Two numerical examples are given at the end of this section to illustrate the feasibility of the methodology. Finally, conclusions are drawn in Section 4.

2. Conceptual design

Human gait is a complex periodic motion achieved through the synergistic movements of lower limbs, which can be determined by gait trajectory, gait phase and cycle time. In order to help people with disability of lower limb, Tsuge and Plecnik [23] proposed a Stephenson III six-bar mechanism (see Fig. 1(a)) for gait path generation. However, the generated path deviated from the natural gait path, and servomotors must be used to control the rotation of the crank in order to meet the natural gait phase. For the problem of path generation, it is well known that the coupler point of the mechanism is expected to pass through all points along a desired path. Meanwhile, each point on the given path is defined by two independent x and y coordinates, thus two independent inputs should be involved in the mechanism. By adding a slider to the Stephenson III six-bar mechanism (see Fig. 1(a)), a 2-DOF seven-bar crank-slider mechanism (see Fig. 1(b)) can be generated, where the crank angle and the displacement of the slider are driven independently, and the input parameters can be obtained from the inverse kinematics. This mechanism can be further simplified by expressing the displacement of the slider as a function of the crank angle, resulting in a 1-DOF cam-linkage mechanism with a sophisticatedly designed cam profile (see Fig. 1(c)). The merit of the proposed mechanism is that only a constant speed motor is needed to control the movement of the coupler point. For this purpose, the dimensional synthesis of the mechanism must be investigated, which will be presented in the following section.

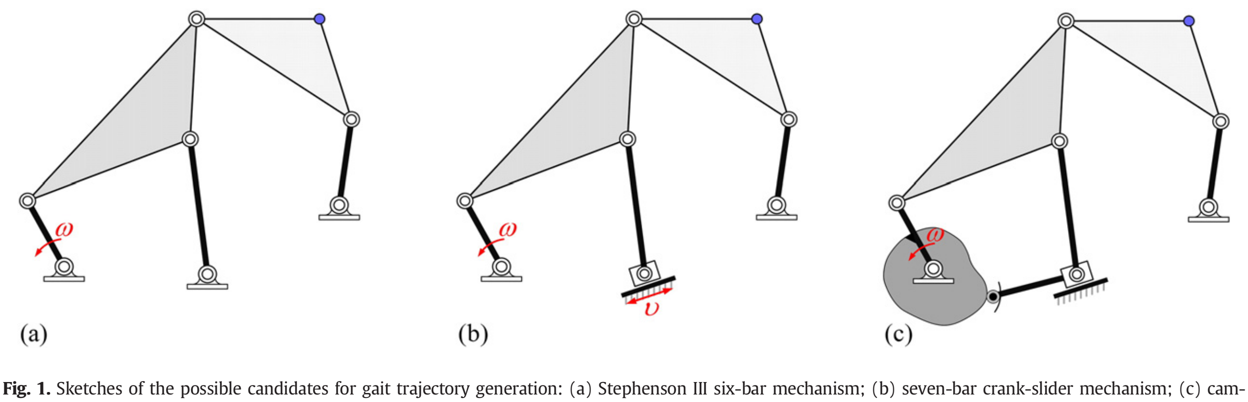

Fig. 1. Sketches of the possible candidates for gait trajectory generation: (a) Stephenson III six-bar mechanism; (b) seven-bar crank-slider mechanism; (c) cam-linkage mechanism.