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Efficiency improvement of walking assist machine using crutches based on gait-feasible region analysis

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ABSTRACT

To improve gait efficiency of a walking assist machine using crutches (WAMC), a parameter study has been carried out to introduce the gait-feasible region (GFR). GFR is the region of a set of state variables of WAMC in which safe gait can be achieved. Evaluation indices for energy consumption and ride comfort are derived. On the basis of these indices with GFR, design of suitable control input parameter to achieve efficient and comfortable gait is discussed. A foot-driving mechanism (FDM), which amplifies the actuator input to generate quick rotation of foot without an additional actuator, is introduced to improve energy consumption and ride comfort of WAMC, and its simple and practical composition is presented. On the basis of the results of several simulations and experiments using a prototype, validity and effectiveness of the proposed methodology are demonstrated.

1. Introduction

Assistance for handicapped people is an increasingly important task for mechanical engineering since developed societies are aging. Transportation presents an especially big challenge. For example, Japan has 0.63 million people who have disability issues with their lower limbs [1], and many of them use wheelchairs for their daily transportation. Although wheelchairs are safe and easy to use, they also have many considerable disadvantages, such as a restricted range of activities due to large foot print, difficulty in ascending/descending steps, lower eye level, limited reach ranges of arms, and lower visibility to other people. To solve these problems and help handicapped people to lead independent daily lives, upright walking assist machines are strongly required.

The field of walking assistance has been widely researched. Particularly popular developments include robotic exoskeletal apparatuses such as powered suit HAL [2,3], Berkeley Lower Extremity Exoskeleton (BLEEX) [4], Ekso [5], Vanderbilt Powered Orthosis [6,7] and ReWalk [8]. However, such products tend to be complicated and expensive. Although a biped-robot walking chair [9] using specially designed spatial parallel mechanisms [10], coupled planar parallel mechanisms connected by orthogonal joints [11], and cable-based manipulator type walking assist device [12] have also been developed, such mechanisms are also complicated, heavy, and expensive. To design a simple and light-weight walking assist machine for daily transportation assistance, it is worth considering the fact that many paraplegics maintain healthy upper-limb functions the same as able-bodied people. This means that the forearm crutches can be used for not only improving the stability by increasing the number of contact points but also supporting and driving the user's body more actively. From this point of view, Huang et al. developed a cane-like apparatus having omnidirectional wheels [13], but it could not support all lower limbs to assist the walking of paraplegics. Mori et al. developed powered crutches that can be used together with a lower limb orthosis [14] and was able to assist a user's sitting/

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standing motion and walking, but the apparatus was still too complicated for daily use. Ikehara et al. [15,16] and Takaiwa et al. [17] proposed simple lower-limb orthosis that employs a few actuators and flexible shafts, or pneumatic sole. Both were intended to assist specific joints such as knee and ankle joints, but these devices could not support the walking of paraplegics.

Therefore, a simple and effective mechanism and its control strategy must be figured out for establishing practical daily walking assistance for paraplegics. Subsequently, the lower-limb function artificially assisted or substituted by an apparatus should be carefully chosen but should not have to be fully covered. For walking assistance, the required lower-limb function is just to support the user's body while s/he is standing and kicking the ground and to make the user's body move forward while transiting to the swing phase [18,19]. To establish a practical and daily walking assistance for paraplegics by a simple mechanism, the authors have designed an apparatus called the walking assist machine using crutches (WAMC), illustrated in Fig. 1. This machine utilizes the user's upper limb ability to support body mass and to control gait together with the implemented actuator. This design provides many benefits such as a simple and light-weight structure, establishment of stable standing without actuation, low energy consumption, and enhancement of the user's health. In previous works [20,21], the basic composition of WAMC has been proposed, and gaits on horizontal ground as fast as those of able-bodied people and steps as high as 180 mm have been successfully achieved. However, some remaining challenges must be overcome to employ the device in daily transportation, such as quantitatively analyzing gait stability to evaluate the practical range of control input, reducing energy consumption, and improving ride comfort.

In the present paper, energy consumption and ride comfort which is evaluated by initial acceleration are quantitatively measured on the basis of kinetostatic model analysis. The relationship between design parameter of the actuator input trajectory and achievement of gait is investigated to distinguish dominant parameters to provide a simple and strategic scheme to denote actuator input, and to guarantee the stability of resulting gait. In addition, an additional mechanical component called the foot-driving mechanism (FDM) is introduced to improve ride comfort and reduce energy consumption. Finally, the proposed methodology is validated through a motion control experiment using a prototype.

2. Kinetostatic analysis of WAMC

2.1. Kinetostatic model in sagittal plane

On determination of the model, the two legs of the WAMC attached on left and right sides are assumed to be synchronously driven. On the basis of this assumption, the motion of the apparatus and the user before the swing motion is modeled as a planar four-link mechanism moving in the sagittal plane shown in Fig. 1(b). Model parameters are each link's length, L, mass, m, and moment of inertia, I. The actual value of each model parameter is listed in Table 1. Configuration of the mechanism is represented by the angles between crutch and the ground, and between lower limb and the ground, denoted by θ and ϕ, respectively.

2.2. Determination of actuator input

As explained above, control input is given to two linear actuators, represented by a prismatic joint M in Fig. 1(b). The same reference trajectory is given to the two actuators while each drives a different leg. First, swing-through crutch locomotion by an able-bodied person was measured using an optical motion capture setup to clarify the motion and desired actuator input

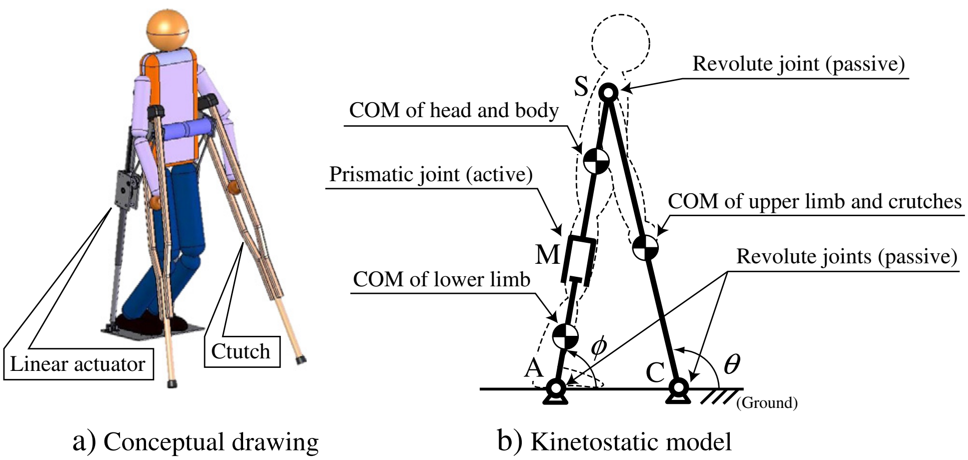

Fig. 1. 3D-CAD drawing and kinetostatic model of WAMC.