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DESIGN OF ELECTRIC CART WITH FUNCTION OF MAINTAINING/IMPROVING THE PHYSICAL STRENGTH OF THE ELDERLY

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Abstract

This paper explains the development of a three-wheeled electric cart that not only is a means of transportation, but also provides the driver with a way of getting some physical exercise.

Based on an investigation of the physiological decline accompanying aging, pedaling was chosen to implement the function of maintaining or improving physical strength; and an ergonomically designed pedal unit was mounted on a cart. An interface board that handles inputs and outputs was assembled to simplify the design of the system. Finally, a simple bilateral master-slave control system was built to test the cart. Experimental results on a fabricated cart demonstrate the effectiveness of pedaling and the usability of the system structure.

KEYWORDS: electric cart, aging, motor functions, pedaling, control system.

1. INTRODUCTION

The number of elderly people in Japan is increasing at an unprecedented rate. According to an annual report on aging from the Cabinet Office of the Government of Japan [1], the percentage of old people (over 65 years old) in the population exceeded 7% (aging society) in 1970 and 14% (aged society) in 1994, and reached 19% in 2003. As the average life span of Japanese continues to increase, there is a concomitant marked increase in the number of people who are in fragile health due to age, suffer senile dementia, or are bedridden. The medical treatment and care of old people confined to bed is a particularly onerous burden on financial and manpower resources, and is becoming a very serious social problem. The last decade has seen a rise in public concern about how to establish an environment for the elderly that will facilitate their maintaining and improving their health to ensure a useful and productive old age (i.e., to ensure mental and physical soundness); and a great deal of research and development related to the health and welfare of the elderly is now being carried out. One part of this research focuses on electric carts, a great variety of which have been developed to improve the ability of old people to get around [2, 3]. However, designers have tended to take a rather short-sighted view by emphasizing convenience and ease of use (the driver just has to push a forward or backward button and steer) while neglecting long-term health effects. That is: almost all commercially available carts were designed solely as a means of transportation, and no consideration was given to an elderly person's need for physical exercise. Unfortunately, a reliance on these carts for getting around can ultimately result in the deterioration of the user's leg and back muscles, thus contributing to, rather than helping to solve, the problem. Thus, it would be difficult to say that currently available carts truly enhance the lifestyle of the elderly by helping them to be more mobile and independent because, in the long run, they simply hasten the descent into a dependent state.

This paper first reviews measures for preventing muscular degeneration due to aging based on an investigation of the physiological deterioration that typically accompanies aging. Based on these results and on ergonomics studies, a prototype of a new-concept electric cart was designed and built. It is quite different from commercially available models in that it combines the functions of transportation and exercise. So, not only does it help the elderly get around, at the same time it also helps them maintain or improve their physical condition in a natural and enjoyable way. This actively prevents the degeneration of motor functions. As a result, it has salutary effects on both the physiology and psychology of the elderly, which is a benefit to the whole society. This type of cart can thus make a very positive contribution to the aging society.

2. MUSCULAR DEGENERATION DUE TO AGING AND ITS PREVENTION

This section concerns an analysis of muscular degeneration due to aging, and measures to prevent it.

2.1 Muscle degeneration due to aging

The human body changes with age. An analysis of the relationship between muscle volume and aging revealed the following: The muscle volume of the brachial-flexor group is 200 ~ 300 cm^3 for men and 150 ~ 200 cm^3 for women of all ages, and seems to be unaffected by aging. In contrast, the muscle volume of the femoral-extensor group reaches a maximum during a person’s twenties or thirties, and is 1700 cm^3 for men and 1200 cm^3 for women. Subsequently, the volume

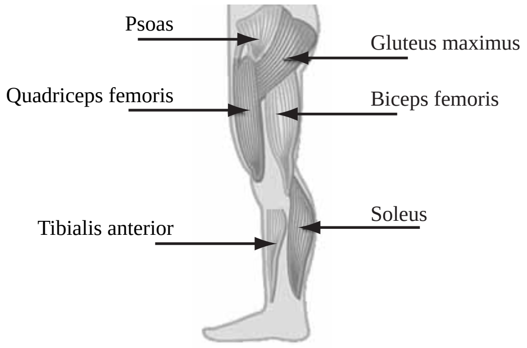


Fig. 1. Walking muscles.

gradually decreases, and drops to about 60% of the peak value for people in their seventies. Clearly, the decrease in muscle volume is more marked for lower than for upper limbs. The major cause seems to be that the activity of the arms does not decrease very much with age, whereas people tend to become more sedentary in later life, which causes the leg muscles to atrophy.

Walking is a basic action of daily life involving the use of what are called the walking muscles: loin muscle (psoas), gluteal muscle (gluteus maximus), front thigh muscle (quadriceps femoris), hamstring muscle (biceps femoris), calf muscle (soleus), shin muscle (tibialis anterior) and some others (Fig. 1). The cycle of lower limb movements (Fig. 2, [4,5]) consists of two stages: the propulsive, or retractive, stage from footfall to foot liftoff; and the recovery, or protractive, stage from foot liftoff to footfall. The propulsive stage mainly employs the gluteal, front thigh, and calf muscles; and the recovery stage mainly employs the gluteal, hamstring, front thigh, and shin muscles.

The loin, front thigh, calf, and shin muscles are the ones that tend to weaken the most with aging. The leg cannot be lifted if the front thigh and loin muscles are too weak; the heel cannot be raised if the calf muscle is too weak: and the toes cannot be raised if the shin muscle is too weak.

On the other hand, muscle tissue contains two types of fibers: slow-twitch and fast-twitch. Slow-twitch fibers provide stamina; while fast-twitch fibers contract rapidly, providing quick power. Fast-twitch fibers tend to atrophy more quickly during the aging process.

2.2 Prevention measures

To prevent the degradation of motor functions, the walking muscles that degenerate most rapidly (loin, front thigh, calf, and shin muscles) need to be exercised. Moreover, some thought needs to be given to the characteristics of the activity to ensure that fast- and slow-twitch fibers are exercised in a balanced way [6, 7]. That is: in addition to general exercise, exercise that induces an excitatory state is needed to arrest the atrophy of fast-twitch fibers. For example, it is strongly recommended that physical exercise for old people include not only jogging or walking for a relatively long time to work the slow-twitch fibers, but also some very short (dozens of seconds) strengthening exercises to work the fast-twitch fibers.

Considering the variety of activities available, cycling would seem to be almost the ideal exercise to work the muscles that are liable to degenerate due to aging [5, 8]. When the pedal moves through the downward half of the cycle, the front thigh, hamstring, and calf muscles are worked; when it moves back up, the loin, front thigh, and shin muscles are worked.

Based on these considerations, we decided to mount two foot pedals on an electric cart to provide the driver with a way of exercising the walking muscles.

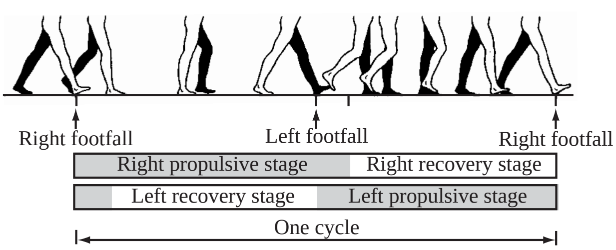


Fig. 2. Walking muscles.

Table 1. Specifications of pedal motor.

Rated output	Rated voltage	Rated speed	Rated torque	Gear ratio
25 W	24 V	2550 rpm	0.098 Nm	12.5

3. SYSTEM DESIGN

This section describes the pedal design, how the pedal load is generated, and the structure of the system.

A commercially available ready-made three-wheeled electric cart, the Everyday Type-S (Araco Corp., Japan) was selected as the foundation of the system.

3.1 Pedal load and pedal installation

Two commercially available pedals are used in the system. Since we want to focus on exercising the walking muscles, it is natural to consider adding a load to the pedals, which is the amount of additional resistance that the driver feels when the pedals are pushed. There are two types of loads that can be produced: constant and time-varying. Using a time-varying load, especially one that is responsive to the road conditions, provides the driver with a more enjoyable and more realistic driving

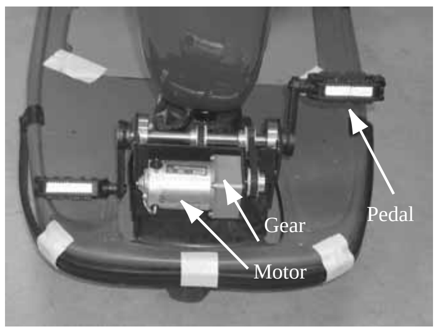


Fig. 3. Pedals and pedal motor.

Table 2. Statistics on the elderly in Japan.

Year	Height	Height of seat	Height of knee
2000	1543 mm	378 mm	450 mm
2001	1550 mm	376 mm	453 mm

experience. That makes it more suitable. Furthermore, even though a mechanical connection between the pedals and the drive wheels (as on a bicycle) was deemed to be the most appropriate for the system structure, an electrical connection was employed because it provided greater potential for further development. A geared motor connected to the pedals generates the load. The specifications of the motor are shown in Table 1. This scheme facilitates the design of a control system that can easily adjust the load, or even produce an assist for the driver as the need arises. The resulting pedal unit is shown in Fig. 3.

Some statistics on the elderly in Japan are shown in Table 2 [9], where the height of the seat means the vertical distance from the bottom of the foot to the hamstring while seated, and the height of the knee means the vertical distance from the bottom of the foot to the top of the kneecap while seated (Fig. 4). The optimal pedaling region is given by [10] (Fig. 5). Based on these data and on-the-spot adjustments, the seat was mounted 40 cm above the base of the cart; and the pedal unit was mounted 13 cm above the base and 80 cm forward from the back of the seat.

3.2 Interface design

Two optical encoders measure the rotational angles of the pedals and the cart (8000 and 2400 cycles per turn for the pedals and the cart, respectively); and an interface board handles all the inputs and outputs of the pedals and the cart (Fig. 6). To allow room for system expansion and to process information intelligently, the board has a PIC microcontroller (PIC16C74), which contains an 8-bit 20-MHz CPU, 4 KB of program memory, 2 PWM modules, SSP and USTRT serial communication ports, PSP parallel communication ports, and 8 input channels for an 8-bit A/D module. The PIC was programmed to implement the following functions: Two serial communication ports are used as two counters to collect information on rotational angle from the optical encoders of the pedal and cart, and the information is sent to the computer (the controller) over parallel connections. The computer sends the control inputs for the pedal and cart motors to the PIC over two parallel connections, and the PIC converts them to analog voltages. The 2 PWM modules function as 8-bit D/A converters. Finally, the power of the control signals is amplified by a TA7272.

Since many of the resources of the PIC remain available for the developer to use, a great variety of

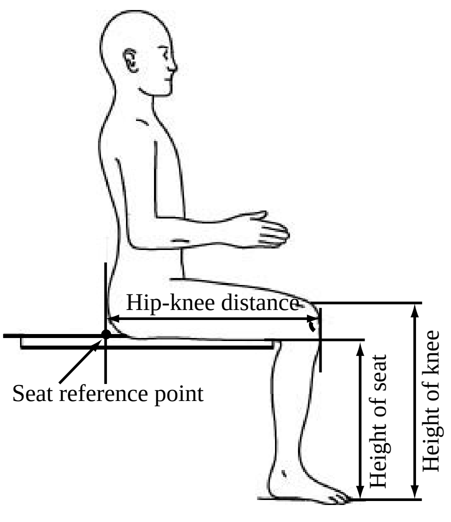


Fig. 4. Definitions [9].

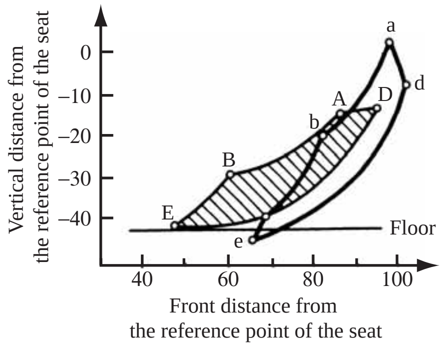
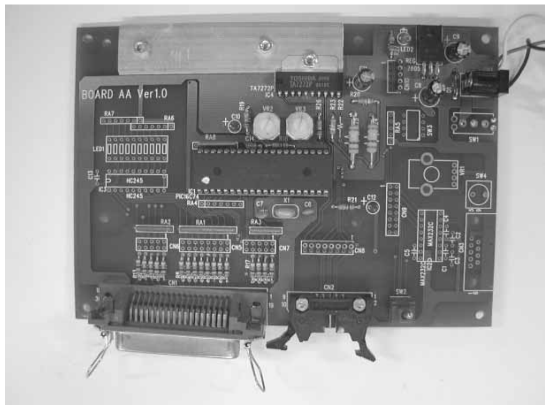
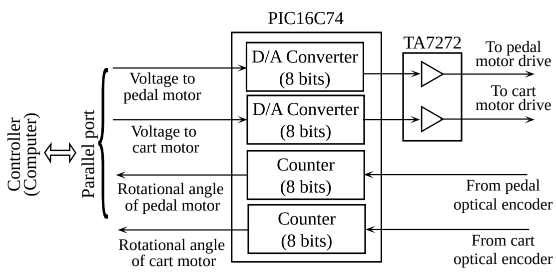


Fig. 5. Optimal pedaling region (Capital: heel position, small: toe position).



(a)



(b)

Fig. 6. Interface board: (a) Photo; (b) Block diagram.

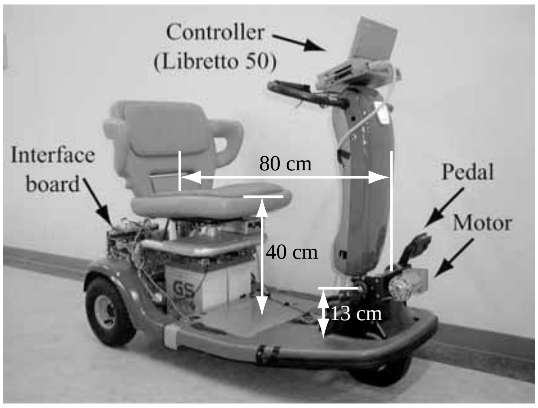


Fig. 7. Photograph of assembled electric cart.

functions can be implemented directly on the interface board. So, the board provides the developer with a test bed for system integration.

An electric cart modified as described above is shown in Fig. 7.

4. SYSTEM TEST

A simple control system for the cart was designed to test both the effectiveness of pedaling as a way of maintaining or improving physical strength, and the usability of the system structure.

4.1 Bilateral master-slave system

Instead of simply pushing forward and backward buttons to make the cart move, the driver has to push the pedals to generate a reference input for the cart. So, the whole thing is a kind of cooperative man-machine system. The system employs a master-slave configuration, with the pedals as the master and the cart as the slave. And a bilateral master-slave configuration [11] was employed in the test control system so that the road conditions could be fed back to the driver. The controlled output is the rotational angle of the cart. Pushing the pedals produces a torque that makes the pedal motor turn.

The rotational angle of the pedal motor is used as a reference angle for the cart motor. The difference between the angles of the two motors is fed back to the controller of the cart motor, which then generates a control input to make the angle of the cart motor track the angle of the pedal motor. In the bilateral scheme, the difference between the two rotational angles is also fed back to the controller of the pedal motor, which then produces a load for the pedals so that the driver can feel the road conditions and obtain a more realistic driving experience. The load for the pedals is easy to adjust by means of the controller. The configuration of the bilateral master-slave cart system is shown in Fig. 8, where $\tau(t)$ is the torque produced when the pedals are pushed, $\theta_m(t)$ and $\theta_s(t)$ are the rotational angles of the pedal and cart motors, and $u_m(t)$ and $u_s(t)$ are the control voltages

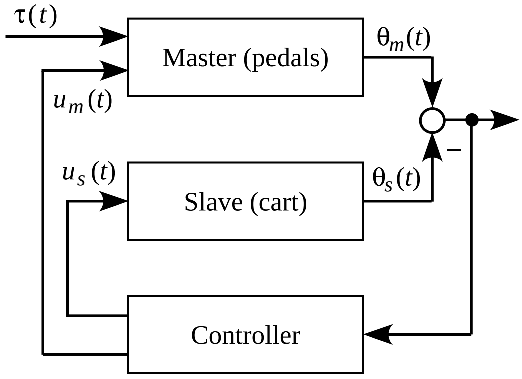


Fig. 8. Configuration of bilateral master-slave cart system.

applied to the pedal and cart motors, respectively.

For simplicity, the controllers were given the same structure:

$$\begin{cases} u_m(t) = K_{pm}\left[\theta_m(t) - \theta_s(t)\right] + K_{dm}\left[\dot{\theta}_m(t) - \dot{\theta}_s(t)\right] \\ \qquad + K_{2dm}\left[\ddot{\theta}_m(t) - \ddot{\theta}_s(t)\right], \\ u_s(t) = K_{ps}\left[\theta_m(t) - \theta_s(t)\right] + K_{ds}\left[\dot{\theta}_m(t) - \dot{\theta}_s(t)\right] \\ \qquad + K_{2ds}\left[\ddot{\theta}_m(t) - \ddot{\theta}_s(t)\right] \end{cases} \quad (1)$$

They were implemented by means of the backward difference algorithm.

In this system, the rotational angle of the pedal motor is determined by the driver's efforts, and constitutes a reference input for the cart. The designed controller makes the rotational angle of the cart motor track that reference. So, the experience is very similar to riding a bicycle.

4.2 Experimental results

The models of the master and the slave are

$$\begin{cases} \text{Master}: \quad P_m(s) = \dfrac{3.79}{s(s+0.74)}, \\ \text{Slave}: \quad P_s(s) = \dfrac{0.53}{s(s+0.25)}. \end{cases} \quad (2)$$

The parameters of the stabilizing controller in (1) were selected to be

$$\begin{cases} K_{pm} = 1.4, \quad K_{dm} = 2.7, \quad K_{2dm} = 2.5, \\ K_{ps} = 1.5, \quad K_{ds} = 2.5, \quad K_{2ds} = 2.0. \end{cases} \quad (3)$$

These controllers were implemented on a Libretto 50 notebook computer (CPU: 75-MHz Pentium; Memory: 16 MB; Toshiba). Since the control information is handled by the interface board, the implementation of the controllers is very simple. Even a low-performance computer, such as that used in the test system, is sufficient to control the system. This demonstrates the rationality of the system configuration. In fact, since the interface board can be programmed to perform various functions for system integration and many resources on the board remain available for further development, the

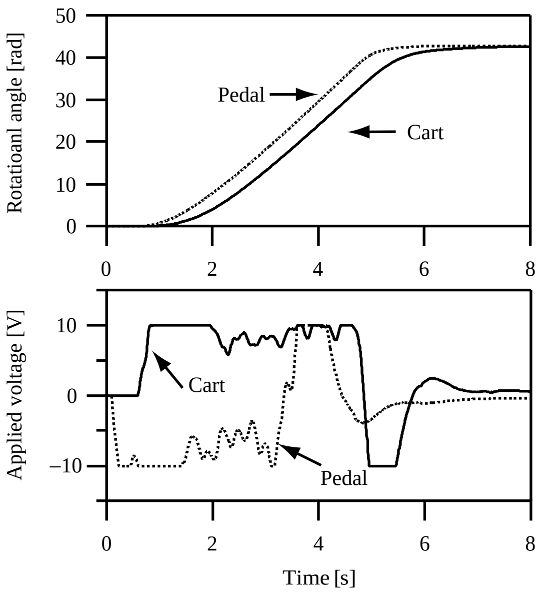


Fig. 9. Experimental results.

board can be used not only to implement complicated control schemes but also to monitor and supervise the driver's health.

Experiments were carried out on a flat road. The cart was initially at rest. The driver pushed the pedals for a while to make the cart move, and then stopped pushing. Typical experimental results are shown in Fig. 9. As expected, the rotational angle of the cart tracks that of the pedals. When the driver starts pushing the pedals, the pedal controller produces a negative voltage, which makes the pedals difficult to turn. This means that an extra load is produced for the driver. However, when the driver stops pushing, the pedal controller produces a positive voltage. This reflects the inertia of the cart and gives the driver more of a feeling of really driving, thus providing more sensory stimulation.

5. CONCLUSIONS

A new type of three-wheeled electric cart has been developed to maintain or improve the physical strength of the elderly. It features an ergonomically designed pedal unit that provides exercise for the muscles of the lower limbs, which tend to degenerate most rapidly due to aging. An electrical rather than a mechanical connection is employed between the pedals and the drive wheels to enhance the flexibility. An interface board was assembled to intelligently handle the inputs and outputs of the system and to lighten the burden on the control computer. The board includes a PIC microcontroller that allows the system to be augmented with a great variety of functions. A bilateral master-slave control system was built to test the effectiveness of the cart and the system architecture. Test results show that this system configuration is very reasonable and that the cart is useful for providing an appropriate level of physical exercise.

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