

Walking Assist Device with Stride Management System

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ABSTRACT

This paper discusses a novel walking assist device that assists users in adopting a more efficient posture, muscular usage and walk ratio. An assist method was developed that coordinates the walk ratio of users while increasing their propulsive force. This assist method was implemented through a hardware system that consists of low-profile actuators and compact electrical components. The device is light and adaptable to users of various shape and size. A long-term experiment showed that elderly subjects using the walking assist device were eventually able to walk with a wider stride, at a higher speed, and with a lower heart rate, without help from the device. Their balance of muscular usage also changed accordingly. Energy consumption increased according to the increase in the subjects' speed. This result suggests the possibility of using the walking assist device as a tool for increasing elderly peoples' physical activity, while reducing the level of stress this would normally produce.

1. Introduction

According to a survey conducted by the Ministry of Internal Affairs and Communications, the number of Japanese citizens aged 65 or over reached 28.19 million (12.03 million men and 16.16 million women) in 2008. This represents 22.1% of the total population, indicating that Japan has become a full-fledged elderly society⁽¹⁾. Many of Japan's elderly citizens are living their lives without concern for their age, and are actively involving themselves in social activities in their particular communities. The maintenance or enhancement of the individual's physical functions can be considered an important factor in the ability to live this type of active life.

The physical functions of elderly individuals decline as their physical strength declines with advancing age. This not only reduces their level of activity, but produces a vicious circle in which insecurity regarding going out and other issues lead to greater declines in physical function. Insufficient muscular strength can be considered to be the main factor in the decline of physical function among the elderly. Muscle training has been recommended for the elderly in the United States since the 1990s, and

this practice is also becoming more widespread in Japan⁽²⁾.

Extensive research has been done on compensating for this lack of muscular strength using robotic technology, and on power assist technologies that would further boost muscular strength. Devices have also been developed that measure the amount of force the individual wishes to generate using electromyographs and force sensors, and boost their strength with power assist⁽³⁾.

Meanwhile, some reports have indicated that the level of stress associated with a particular amount of exercise can be reduced simply by altering the way in which the individual moves⁽⁴⁾⁻⁽⁷⁾. Rather than exerting force constantly from the beginning to the end of a movement, concentrating force at the appropriate time and then relying on inertia reduces heart rate, blood pressure, energy consumption⁽⁴⁾⁻⁽⁷⁾.

In the case of walking also, research has commenced on a two-axis walk, which effectively uses changes in the center of gravity⁽⁷⁾. In this mode of walking, virtual axes passing through the foot making contact with the ground, the knee, the hip joint, and the shoulder blade, move forward alternately on the left and right like a pair of stilts. The center of gravity moves forward without the upper and lower bodies twisting. This two-axis walk has

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recently been used by Japanese athletes who have been said to be at a disadvantage in terms of physique and muscular strength. This technique has enabled them to supplement their muscular strength with gravity and inertia, and to achieve good results in world championships⁽⁸⁾.

Robots are also being used while patients who have been paralyzed by strokes are being retrained in how to move their shoulders and elbows, in this case not to increase muscular strength but to teach patients the correct movements⁽⁹⁾. The robot assists patients in moving their shoulders and elbows in the correct trajectory to enable them to grasp objects, generating a load if they move outside the appropriate trajectory. In this type of training process, results achieved using a robot are indicated as being superior to those achieved by normal training⁽⁹⁾.

The aim of the research discussed in this paper was to develop a system that would induce an effective mode of walking in the user without reliance on assist power, thus reducing the exercise stress associated with walking. Another aim was to attempt to help ensure that this effect was lasting, and that the user eventually became able to walk under their own power, thus establishing a positive cycle in which the amount of exercise taken by the user

would increase naturally and muscular activity would be beneficially stimulated. It was believed that by this means, it would be possible to assist elderly individuals in leading healthy and active lives.

The balance between the stride and the cadence (steps/min) is termed the walk ratio (stride/cadence). Experiments have shown that energy consumption increases unless this walk ratio is close to 0.0063⁽¹⁰⁾. Figure 1 shows the results of a verification of this phenomenon. The graph shows that energy consumption changes at the same walking speed when the walk ratio is varied. As Fig. 2 shows, among the elderly the walk ratio declines at both normal and maximum speed^{(10),(11)}. In other words, there is a tendency for energy consumption when walking to increase among the elderly. A means of inducing an appropriate walk ratio in the elderly is therefore important in inducing efficient walking. With this concept in mind, the research discussed here based itself on the two-axis walk and realized a new assist method that would assist with propulsive force to propel the body forward, and would induce a walk ratio while adjusting stride and cadence⁽¹²⁾. This paper will introduce this assist method and the assist device developed on the basis of the method, in addition to discussing the results of test verification with elderly subjects.

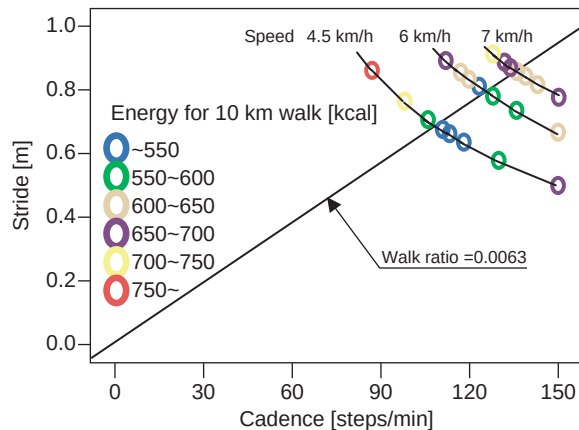


Fig. 1 Map of energy consumption by walk ratio

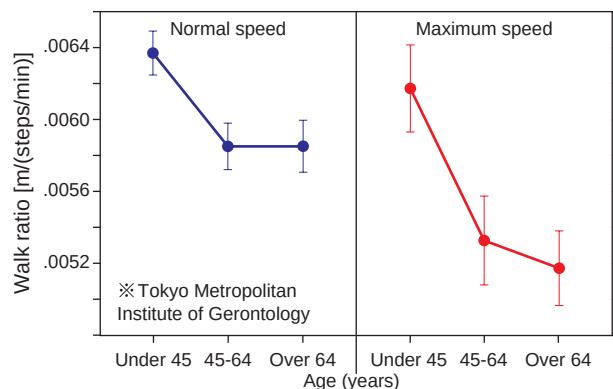


Fig. 2 Change in walk ratio with advancing age

2. Assist Method

The computer used for control of the assist device contains a rhythm pattern generator^{(13),(14)} that generates walking trajectories in response to predetermined rhythms. Assist is realized using a control flow in which the user's walking rhythm and stride, which are input to the generator, are modified (Fig. 3).

2.1. Mutual Adaptation of User and Device

When two people walk side by side, they may unconsciously adapt the cadence of their walks to each other. This is known to be a phenomenon of mutual adaptation in which the individual rhythms of the walkers mutually influence each other to create a new overall rhythm, and each individual is unconsciously entrained by this rhythm⁽¹⁵⁾. The assist method discussed here uses this phenomenon to entrain users' cadences into new rhythms that are produced as a result of mutual interaction between the user and the assistance.

Reflexive and periodic motions such as the gait of animals are believed to be controlled by rhythm pattern generators in the spine⁽¹³⁾. The rhythm pattern generator used in the assist device models these rhythm pattern generators, and generates assist patterns using reflexive, predetermined rhythms while adapting to the input user rhythm measured by the angular sensors. These rhythms synchronize with the user's walking, and change in accordance with the walk ratio control

to be discussed in the next section, enabling the device to induce a cadence in the user.

2.2. Walk Ratio Control

The rhythms generated by the rhythm pattern generator are produced by a pacemaker in the control computer. First, the walking rhythm of the user, as measured by the angular sensor, is input to the pacemaker. The pacemaker is entrained by this rhythm, and oscillates in synchrony with it. The phase difference between the rhythm produced by the pacemaker and the input rhythm is measured at this time. This phase difference is a result of mutual adaptation, and cannot be directly controlled⁽¹⁵⁾. For this reason, the phase difference is controlled by evaluating the measured phase difference and correcting the rhythm of the next step of the assist device. This corrected rhythm becomes the next rhythm of the pacemaker.

The device reads changes in the area in which the user

is walking as changes in the walk ratio. On flat ground and when climbing stairs or slopes, the phase of the device will be accelerated slightly beyond that of the user to give the user a sense of forward propulsion; when going down, the phase of the device is retarded by the application of brakes. In this way, the device induces cadences in the user. When the detected phase difference is retarded in relation to the ideal phase difference, the pacemaker will speed up the pace of the rhythm, and when the detected phase difference is advanced in relation to the ideal phase difference, it will reduce the pace of the rhythm⁽¹⁵⁾.

By establishing the appropriate phase difference, it is possible for users to excite their legs, while controlling their stride, using a minimal assist force that they are able to stop under their own power. A relatively large assist force is applied during the turn-over phase, when the leg starts moving forward or pushes off the ground, as if pushing a child on a swing. Other motions are left to inertia, reducing the amount of assist force required⁽⁴⁾⁻⁽⁶⁾.

The stride is determined by the relationship between the cadence as set by phase control and the ideal walk ratio, and is used to derive a target hip joint angle. At this time, the stride is adjusted to attempt to eliminate asymmetry between right and left. The rhythm pattern generator outputs torque to enable this hip joint angle to be realized by the thigh frame.

2.3. Assist for Supporting Leg

In order to facilitate displacement of the center of gravity by pushing the hips forward while supporting the body, the device synchronizes assist to extend the supporting leg to the rear and assist in swinging the idling leg forward. In a repeated cycle, the reaction force generated by this assist for the supporting leg advances the center of gravity^{(7),(16)}, the idling leg swings forward as if attempting to follow, and touches down on the ground.

The force generated by the assist is transmitted in sequence to the extremities, from the hip joint to the knees and ankles⁽¹⁷⁾, and indirectly assists in the flexion and extension of the knee. Tests showed that the provision of assistance to the hip joint of the supporting leg has the effect of maintaining the extension of the knee and keeping the knee from bending. Before the foot touches the ground, assist begins to increase to push the thigh to the rear, in order to help ensure that the knee is extended at the point at which the heel makes contact with the ground. After the foot touches the ground, the upper body is supported while the center of gravity is maintained in a high position with the knee extended, and the force that causes the upper body to topple forward is the propulsive force⁽¹⁸⁾. Even if the foot touches the ground with the knee bent, the extension of the knee is compensated for with assist that pushes the thigh to the rear. The main propulsive force is generated at the hip joint, where large

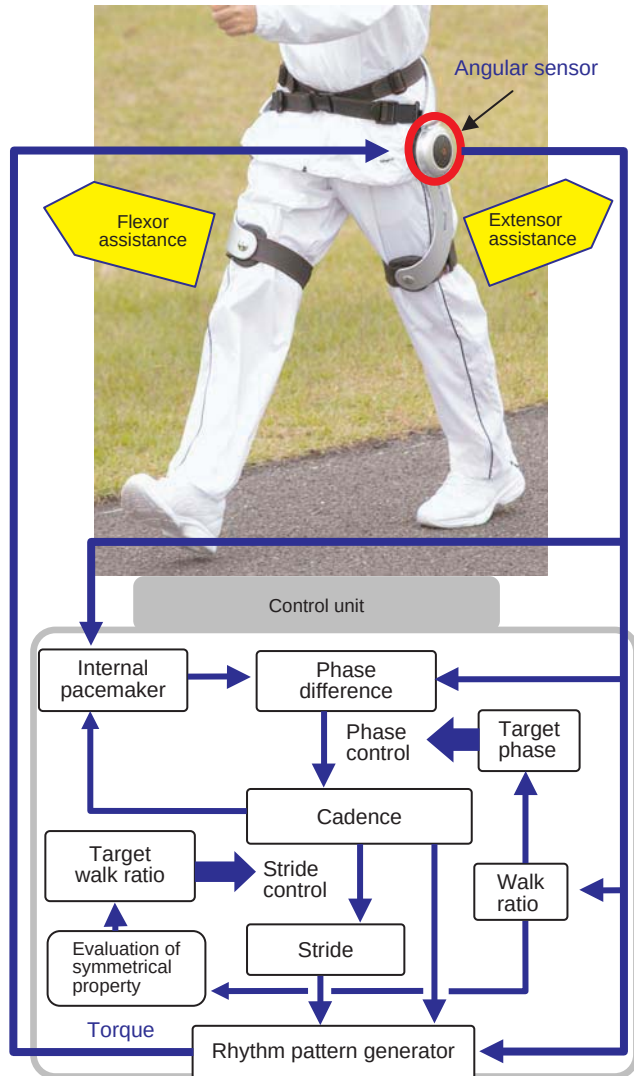


Fig. 3 Control flow for walking assist

muscles are concentrated, and is transmitted to the extremities^{(4)-(6),(17)}. The aim for this assist method was to show users this mode of walking with every form of assistance, and to enable them to learn the mode of walking through their own bodies⁽¹²⁾.

3. Assist Device

3.1. Mechanism

The assist device that implements this method of walking assist (Fig. 4) is made up of two actuators positioned on the axis of the hip joints (a), a lumbar frame that supports them (b), and a thigh frame that can be attached or disconnected with one touch (c)⁽¹⁹⁾. The actuators are connected to the lumbar frame by coupling joints that possess a degree of freedom in adduction and abduction⁽¹⁸⁾. Assist is provided for the flexion and extension of the thigh during walking by assist force transmitted from the actuators to the thigh frames.

The small, lightweight actuators (Fig. 5) are a combination of a multi-polar brushless motor and a planetary gear mechanism⁽¹⁹⁾. Low-profile actuators have been used in an attempt to ensure that they do not interfere with the wearer's arms or get caught on surrounding objects. Angular sensors in the actuators monitor the status of flexion and extension of the user's thighs⁽¹⁹⁾. Angular sensors are the only sensors employed.

The control circuits and batteries are located in the lumbar frame (Fig. 6). Table 1 shows the specifications of the device. The use of a mechanism that only assists

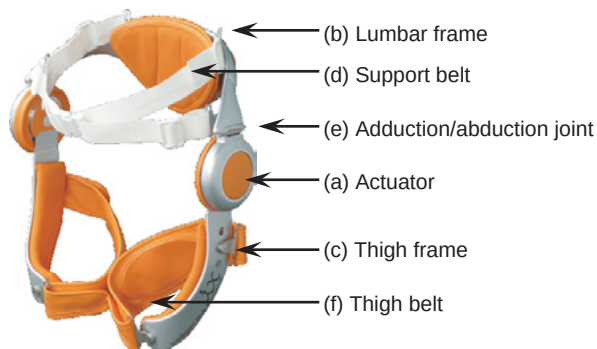


Fig. 4 Overview of walking assist device



Fig. 5 Low-profile actuator

Table 1 Key specifications of walking assist device

Size	3 sizes (small, medium, large) Distance between motors: (S) 312 mm; (M) 342 mm; (L) 372mm
Weight (kg)	2.8 (medium)
Drive system (motor/reduction ratio)	Brushless DC motor /10
Battery	Lithium-ion battery/ 22.2 V-1 Ah
Operating time per charge	2 hours (when walking at 4.5 km/hour)

the hip joint has enabled the total inertia on the legs with the device fitted to be reduced, and the weight of the device to be controlled to 2.8 kg.

3.2. Fitting

To fit the device, the lumbar frame is first fitted around the hips. The front support belt [(d) in Fig. 4] is fastened in place by a buckle at the base of the abdomen, and the thigh frames are fastened around the thighs by thigh belts [(f) in Fig. 4]. From considerations of ease of fitting and removing the device and of the possibility of the user sitting in a chair, and the like, the thigh frames only extend from the sides to the front of the thighs, and are fastened with a belt at the back of the thighs.

The upper belt passes over the pelvis, and keeps the lumbar frame from coming away from the body due to the reaction force to assist force. In order to maintain the transmission efficiency of the assist force, the lumbar frame, which supports the actuators, is highly rigid; cushioning has been used on the side that makes contact with the user's body. A front belt has been employed to ensure that the lumbar frame makes solid contact with the pelvis; the belt presses on a point 5 cm below the navel, increasing abdominal muscle pressure⁽²⁰⁾. The configuration here was modeled on the belt of a *hakama*. It has long been known that in addition to tilting the pelvis forward and stabilizing it, these belts guide the spine into the correct position, causing the weight of the upper body to ride on the pelvis, and directing it through the skeleton

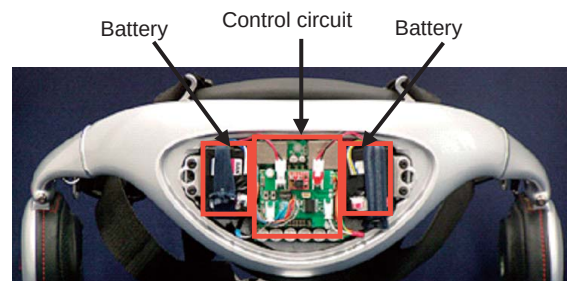


Fig. 6 Layout of control circuit and battery

to the surface of the ground. It was considered that by realizing these same functions in the harnesses of the assist device, it would be possible for assist to be provided after the user had adopted a comfortable posture in a standing position prior to going out walking.

To enable the device to be adapted to changes in the physique with advancing age and to different body types, the lumbar frames and thigh frames are available in small, medium, and large sizes; the type most suitable for the user's particular body type can therefore be selected from among nine variants. This enables the device to be used by 95% of Japanese adults⁽²¹⁾. Employing size adjustment mechanisms for each of the two frames would have made the configuration complex, and would also have added to the weight of the device. The nine variant sizes were adopted to avoid these issues.



Fig. 7 Design proposal



Fig. 8 Color variation model



Fig. 9 Walking assist device

3.3. Design

The design of the device focused on the theme of a “wearable man-machine interface,” and considered the feeling of integration between the user and the device to be the most important design factor. Use of the device in a variety of actual environments, including nursing homes and parks, was projected, and the ability of elderly users to easily fit the device themselves before going out was considered. The aim was for a simple and easy-to-understand design like a pair of headphones or a waist pouch (Figs. 7 through 9).

The basic layout employed was one in which the configuration of the buckles, waist belt and supporters enables the tightness of the lumbar frame to be adjusted at the lower abdomen⁽²⁰⁾ (Fig. 4).

People go out wearing clothes of a variety of forms and made of a variety of materials. There are also considerable differences in physique and body type between different individuals. In addition, different individuals display different levels of resistance to wearing this type of device close to their bodies. In order to minimize the discomfort experienced by these individuals and the physical and psychological lack of fit between themselves and the device, stylings were developed that would result in a greater level of harmony between the users and the use environments of the devices. Designers aimed for stylings that could be used irrespective of age or gender.

4. Verification Tests

Tests were conducted in which elderly subjects wore the assist device to enable verification of its short-term induction effects^{(11),(19),(22)} and its long-term induction effects^{(11),(19)} by studying changes in walking patterns and levels of muscle activity. These tests were approved by the Ethics Committee of the Tokyo Metropolitan Institute of Gerontology.

4.1. Verification of Short-term Effects

Ten elderly males with an average age of 76 ± 2 years were selected as test subjects. The changes in walking patterns and in muscle activity displayed by these subjects during a 50-minute period of walking on a treadmill at 4 km/h with and without the assist device were compared. Figure 10 presents a photograph of a subject wearing the assist device.

4.1.1. Verification of the device's ability to induce a walk ratio

Measurement of the test subjects' walk ratios prior to the tests revealed an average figure of approximately 0.005, and the walk ratios tended to be lower than the figure of 0.0063 discussed above. In order to verify the ability of the device to induce a walk ratio, irrespective of the differences in walk ratios between different

individuals, the initially-measured figure plus 0.0005 was made the target walk ratio for all subjects, and the walk ratio induction effect of the assist device was verified. As Fig. 11 shows, a walk ratio approaching the target ratio was achieved by 9 of the 10 test subjects.

4.1.2. Evaluation of muscle activity

In order to understand what type of effect walking assist has on muscle activity, positron emission tomography was used to measure the sugar metabolism due to muscle activity displayed by the test subjects following walking on the treadmill. This method enables the cumulative effect of muscle activity during walking to be studied even when the subject has ceased walking. The expected result here was that the walking assist would change the balance of the muscles used, and that muscle activity would increase in the muscles being assisted, the muscles close to the hip joints and around the hips.

Figure 12 shows an example of results for a representative test subject. The left and right sides of the figure respectively show visualizations of muscle activity with and without assist. The more intense the red color, the greater the level of muscle activity. Increased muscle

activity can be observed in the muscles of the buttocks, but muscle activity is reduced in the muscle group at the back of the thighs, which push the leg to the rear when it is acting as the supporting leg. It is believed that this is because the assist has reduced the burden on these muscles⁽¹¹⁾. The muscles of the buttocks have been indicated as providing support to enable the opposite side of the pelvis to the leg making contact with the ground not to sink, and it is believed that the muscle activity in these muscles increased in response to the increase in the length of the subject's stride⁽¹¹⁾.

4.2. Verification of Long-term Effects

Having verified the ability of the assist device to induce a walk ratio, 13 female test subjects with an average age of 78 ± 2 who had not taken part in the short-term study were selected for a five-month study. In this study, the test subjects would walk outside twice a week using the assist device for 30 or 40 minutes, depending on their physical condition (Fig. 13). The average walk ratio of the subjects was approximately 0.004 prior to the tests. The target walk ratio for each twice-weekly walking session was set at the initially-measured value plus 0.0005. The tests verified that there was a lasting induction effect from periodic application of the assist device.

4.2.1. Evaluation of walking

Figure 14 shows a comparison of results for stride, walking speed, and cadence measured before the commencement of the tests and after three months of regular walking using the assist device. The measurements were taken without using the assist device. Of the 13 test subjects, 11 increased their stride and 12 increased their walking speed, indicating that the assist induced lasting effects. However, because the test subjects' cadences, which should have become more relaxed with increased stride lengths, actually became faster, no increase in their walk ratios was observed. There was no major difference



Fig. 10 Experiment with elderly adult

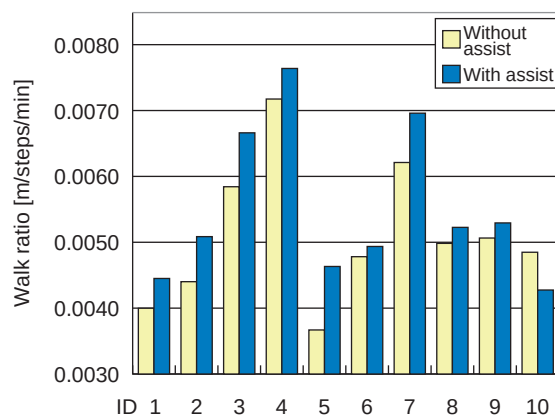


Fig. 11 Result for control of walk ratio

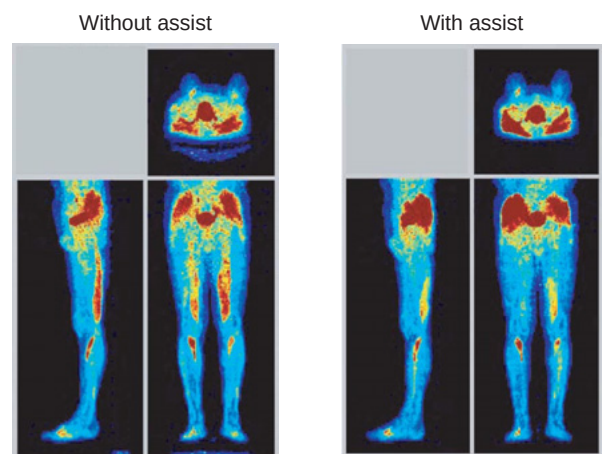


Fig. 12 Positron emission tomography muscular images



Fig. 13 Open-air long-term application for elderly subject

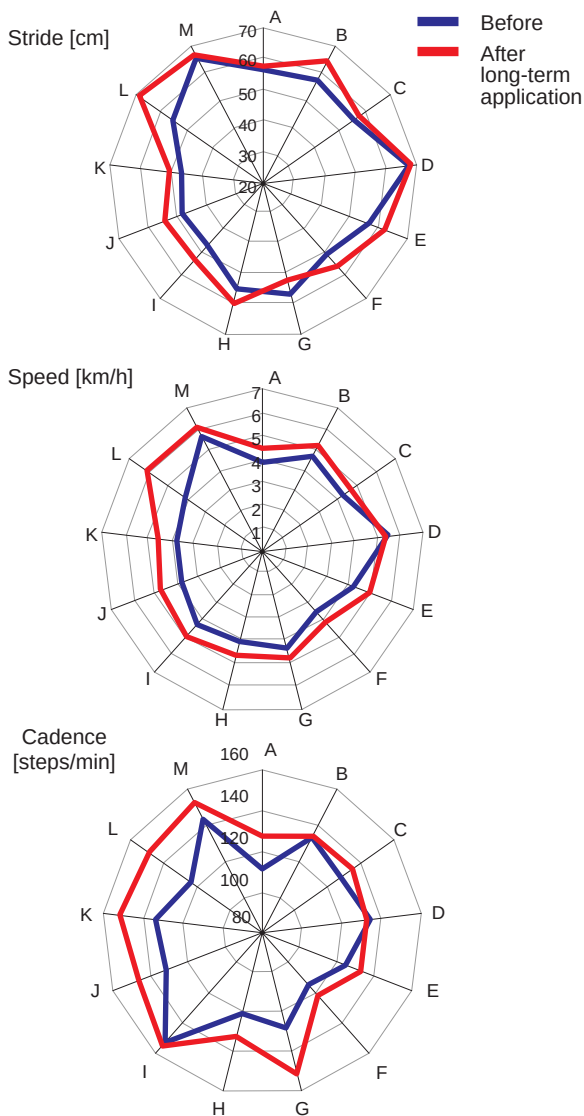


Fig. 14 Comparison of walking parameters before and after long-term application

between results after three months and results after five months⁽¹¹⁾.

Considering the changes over the course of the long-term tests, the increase in subjects' stride length was observable after only 1-2 tests, and no significant changes were observed following this⁽¹¹⁾. Considering this, the assist method can be indicated as having a nearly instantaneous effect.

4.2.2. Evaluation of muscle activity

Figure 15 shows a comparison of positron emission tomography results for a representative test subject before the commencement of the tests and after five months of regular walking using the assist device. The images of muscular activity were taken without using the assist device. It was believed that the increase in the subject's walking speed would result in an increase in activity in the muscles at the back of the thighs, which push the leg to the rear when it acts as the supporting leg, and in fact the actual results did display this tendency⁽¹¹⁾. It is thought that activity in these muscles facilitates the displacement of the center of gravity in a forward direction, and is linked to an extension of stride length and an increase in walking speed. A more detailed study of the rate of increase in activity of each muscle showed a 17% decrease in activity in the muscles at the front of the thighs that extend the knees and support the body. This is believed to be because the increased activity of the muscles at the back of the thighs reduced the burden on the knees⁽¹¹⁾. The pelvis tends to display a posterior inclination among the Japanese, and the muscular burden therefore tends to concentrate in the muscles at the front of the thighs⁽⁸⁾. These tests indicated that the assist device fulfilled its aim in enabling greater use of the muscles at the back of the thighs, and suggest that there is a possibility that it also promotes a more efficient balance of muscle activity⁽¹¹⁾.

By contrast with the results of the short-term study, activity in the muscles below the knees has increased, but this test subject walked from the beginning using these muscles. These muscles are known to be used when the area of the supporting leg below the knee moves to the rear, and the extension of the knee is maintained while

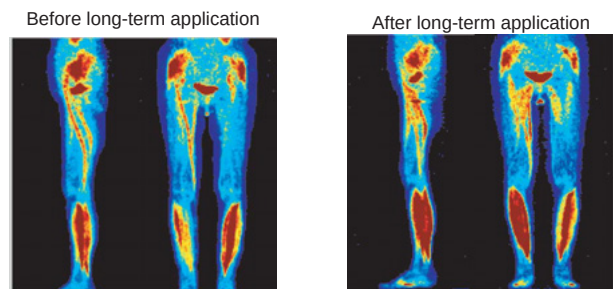


Fig. 15 PET comparison of muscular activity before and after long-term application

the thigh moves forward faster than the area below the knee⁽¹⁸⁾. It is believed that activity in these muscles for this test subject increased with increased activity in the muscles at the back of the thigh. The reduction in the activity of the muscles around the hips, which stabilize the pelvis when the leg is used as the supporting leg, is thought to be due to the length of time that each leg is used as the supporting leg becoming shorter with the increase in the subject's cadence.

4.2.3. Changes in energy consumption and heart rate per unit distance

Test subjects walked around an indoor course for 12 minutes without using the assist device to enable measurement of average energy consumption and heart rate per unit time. These figures were divided by the distance walked by the subjects to obtain average energy consumption and heart rate per unit distance. Figure 16 shows the rate of increase in average energy consumption and heart rate per unit distance from the period prior to the commencement of long-term application of the assist device. The figures were divided by the distance walked because the walking speeds of the test subjects differed before and after the long-term tests. A breathalyzer device was used to measure energy consumption.

Energy consumption naturally increased due to increased walking speed, but despite this, the subjects' average heart rate decreased by 7% after five months. Given that a reduction in the heart rate reflects a reduction in the burden on the heart, this indicates that the heart rate can be reduced despite an increase in the amount of exercise performed and the amount of energy consumed. This would enable the amount of exercise performed to be comfortably increased.

The phenomenon of a reduction in the heart rate despite an increase in the amount of exercise performed and the amount of energy consumed has already been reported⁽⁵⁾. This is believed to be because the promotion of muscle activity makes exercise easier and causes the muscles to act as secondary hearts in pumping blood, thus reducing the burden on the circulatory system⁽⁵⁾.

It has also been reported that in comparisons of the mode of exerting force during weight training, both heart rate and subjective exercise stress are lower when force

is exerted only during the turn-over phase, after which inertia is then relied on, rather than when force is exerted constantly from the beginning to the end of the exercise⁽⁴⁾⁻⁽⁶⁾. This is believed to be because when exercise is performed in this way, the duration of tonus is reduced, and the duration of relaxation is increased by the same amount⁽³⁾⁻⁽⁵⁾. The method of assist discussed here has the potential to produce the same results, and it will be necessary to conduct a more detailed study in the future using measurements of myoelectric potential, and the like.

4.2.4. Subjective comments

Test subjects commented that even when they were not wearing the assist device, "I feel more comfortable," "I feel happier," "Walking is enjoyable," "I can walk faster than before," and "I can walk for longer than I could before."

The reduction in heart rate reflects a reduction in the burden on the heart, a fact which backs up these comments. This suggests the value of the assist device as a tool to support self-reliance by enabling the amount of exercise performed to be comfortably increased and physical functions to be maintained or enhanced.

5. Conclusion

Of the various walking-related parameters, the walk ratio was selected as an indicator, and an assist method for the hip joints designed to facilitate and induce displacement of the center of gravity, along with an assist device based on this method, were developed. Short-term tests with elderly test subjects showed that when the device was worn, a walk ratio matching the target ratio was induced, and the burden on the muscles was reduced, verifying the assist effect. Tests involving periodic application of the device over a longer period confirmed that longer strides and faster walking speeds were maintained even when the device was not being worn. Activity in the muscles that move the thigh to the rear tended to be increased in these subjects, while some activity in the muscles that support the knees was reduced, indicating that the assist device also tended to enhance the balance of muscle activity. A comparison of measurements taken following the long-term tests with measurements taken at the commencement of the tests showed that subjects' heart rates had declined despite an increase in the amount of exercise performed, and this phenomenon correlated with a reduction in their level of subjective exercise stress.

6. Afterword

One of the major characteristics of the assist method discussed in this paper is the mutual adaptation of user and device, based on the human ability to learn motions. As an extension of this, the device can be expected to be

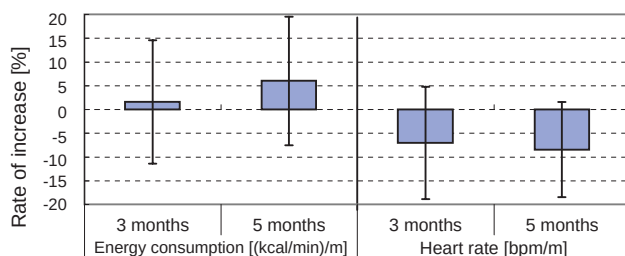


Fig. 16 Rate of increase in energy consumption and heart rate

useful in the case of patients who are experiencing difficulty in walking due to spinal cord injuries or cerebral disorders such as strokes or Parkinson's disease. At present, the value of the device in these cases is being tested in a number of rehabilitation facilities. In the future, it will be necessary to not merely study the effect of the method on muscle activity, but also on posture and on the reorganization of the brain and central nervous systems in cases of impaired walking.

The assist device was exhibited at the International Home Care & Rehabilitation Exhibition in 2007, and has been exhibited at a number of domestic exhibitions, including Barrier-Free 2008 and Welfare 2008.

Acknowledgments

Up to the present, this project has received the generous cooperation of numerous individuals, including test subjects and individuals who provided valuable comments on the device at exhibitions. The authors wish to offer all of these individuals their sincere thanks.

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References

- (1) Nemoto, I., Aoyama, M., Yanagita, M., Matsugaki, N., Yamakawa, J., Kuroda, Y., Kimura, Y., Yoshitake, Y., Higuchi, M.: Health related potential of resistance training in middle-aged men, *Journal of Exercise Science*, Vol. 4, p. 29-38 (1994)
- (2) Nakai, T.: Hyoumen Kindeni wo Mochiita Power Assist Seigy Shuhou no Kaihatsu to Hokou Shien You Power Assist Kyaku HAL-3 no Kouchiku, Master thesis, Graduate School of Systems and Information Engineering, University of Tsukuba (2002) (in Japanese)
- (3) Nakamura, N., Nemoto, I., Kuroda, Y., Koyama, Y.: The study of safety of resistance training by continuous measurement of blood pressure in middle aged-men, *Descent sports science*, Vol. 19, p. 104-115 (1998)
- (4) Nemoto, I., Nakamura, N., Koyama, Y., Daimon, Y., Suzuki, T., Iwatake, J., Kuroda, Y.: Shodoufuka Training no Kagakuteki Kiso, *Taiiku no Kagaku*, Vol. 49, p. 147-156 (1999) (in Japanese)
- (5) Ogita, F., Koyama, Y., Fujiwara, H.: Effects of the difference between two methods in weight-training on cardiovascular responses and range of motion, *Journal of Training Science*, Vol. 7, No. 2, p. 77-84 (1995)
- (6) Oda, S.: Undou Kagaku, Maruzen-shuppan, p. 225 (2003) (in Japanese)
- (7) Takano, S.: Nihonjin no Tame no 2jiku-souhou, *Ski Journal*, p. 128 (2007) (in Japanese)
- (8) Volpe, B. T., Krebs, H. I., Hogan, N., Edelman, L., Diels, C., Aisen, M.: A novel approach to stroke rehabilitation, Robot-aided sensor motor stimulation, *Neurology*, Vol. 54, p. 1938-1944 (2000)
- (9) Nagasaki, H.: Dousa no Imiron, *Kirara Shobo*, p. 281 (2004) (in Japanese)
- (10) Suzuki, T., Hirata, T., Oikawa, K., Endo, Y., Yasuhara, K., Shimada, K., Kikuchi, K., Ido, T., Naka, T., Kimura, Y., Ishiwata, K., Ishii, K., Shimizu, T., Shimada, H., Furuta, T., Isumi, O.: Koureisha ni taisuru Hokou Assist Robot no Kouka Kenshou Kenkyu, Collaboration of Tokyo Metropolitan Institute of Gerontology and Honda R & D Co., Ltd., p. 113 (2007) (in Japanese)
- (11) Yasuhara, K., Shimada, K., Hirata, T., Kikuchi, K., Miyake, Y.: Hokou Shien Robot ni yoru Hito Hokou Undou no Hattatsu, The 6th annual conference of the Japanese Society of Cognitive Therapeutic of Exercise, *Proceedings*, p. 41 (2005) (in Japanese)
- (12) Taga, G., Yamaguchi, Y., Shimizu, H.: Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment, *Biological Cybernetics*, Vol. 65, p. 147-159 (1991)
- (13) Tojima, W.: Sekizui Sonshou to Iu Ashikase kara Tokihanatareru Hi he (3) Robot Gijutsu de Rehabili wo Shien, *Medical Bio*, November issue, p. 64-69 (2007) (in Japanese)
- (14) Miyake, Y., Miyagawa, T., Tamura, Y.: Man-machine interaction as co-generation process, *The Transaction of the Society of Instrument and Control Engineers*, Vol. 37, No. 11, p. 1087-1096 (2001)
- (15) Ueda, J., Shirai, K., Oda, S., Ogasawara, T.: Moment compensation for fast dynamic walking of humanoids based on human athletes pelvis rotation, *Journal of the Robotics Society of Japan*, Vol. 23, No. 4, p. 75-83 (2005)
- (16) Suzuki, H., Fujimori, K., Yoshida, M., Koyama, Y.: Shodoufuka Training Dousa no Biomechanics to Shinkei Kin Seigy, *Biomechanics Kenkyu*, Vol. 9, No. 1, p. 26-33 (2005) (in Japanese)
- (17) Goetz-Neumann, K., Tsukisiro, K., Yamamoto, S., Ebara, Y., Bonkohara, S.: Kansatsu ni yoru Hokou Bunseki, *Igakushoin*, p. 186 (2005) (in Japanese)
- (18) Oikawa, K.: Hokou Assist, Hito to Kyozon Suru Kuruma to Robot Forum, *Proceedings*, p. 7-11 (2008) (in Japanese)
- (19) Seimei-kougaku-kougyo-gijutsu-kenkyusho: Sekkei no Tame no Jintai Sunpou Data Shu, *Tsusansho-kougyo-gijutsuin-seimei-kogaku-kenkyusho*, p. 219 (1994) (in Japanese)
- (20) Wacoal-ningen-kagaku-kenkyusho: Spiral Aging,

Wacoal PR Department, p. 98 (2000) (in Japanese)

- (21) Shimada, H., Suzuki, T., Kimura, Y., Hirata, T., Sugiura, M., Endo, Y., Yasuhara, K., Shimada, K., Kikuchi, K., Oda, K., Ishii, K., Ishiwata, K.: Effects of an automated stride assistance system on walking parameters and muscular glucose metabolism in elderly adults, *British Journal of Sports Medicine*, Vol. 42, p. 622-629 (2008)

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