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What is This?
A gait-assistive mobile robot based on a body weight support and autonomous path tracking system

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Abstract: With the rising numbers of elderly and disabled people, the demand for welfare services using a robotic system and not involving human effort is likewise increasing. This study deals with a mobile robot system combined with a body weight support (BWS) system for gait rehabilitation. The BWS system was designed via the kinematic analysis of the robot’s body-lifting characteristics and of the walking guide system that controls the total rehabilitation system integrated in the mobile robot. This mobile platform is operated by utilizing the autonomous guided vehicle driving algorithm. Especially, the method that integrates geometric path tracking and obstacle avoidance for a non-holonomic mobile robot was applied so that the system can be operated in an area where the elderly users are expected to be situated, such as in a public hospital or a rehabilitation centre. The mobile robot follows the path by moving through the turning radius supplied by the pure-pursuit method, one of the existing geometric path-tracking methods. The effectiveness of the proposed method was verified through real experiments that were conducted for path tracking with static and dynamic obstacle avoidance. Finally, through electromyography signal measurement of the subject, the performance of the proposed system in a real operation condition was evaluated.

Keywords: gait rehabilitation, service robot, body weight support system, pure-pursuit algorithm

1 INTRODUCTION

Walking is a learned activity in which the moving body is supported successively by one leg and then by the other. The dynamic regulation of the upright stance is essential for the safe and efficient performance of many activities of daily living. During single-limb support (approximately 40 percent of the gait cycle for each limb), the body is in an inherent state of instability, because the vertical projection of the centre of mass passes along the medical border of the foot [1] and not within the base of support, as suggested by Sudarsky [2]. For the swinging limb, the toe clears the ground by less than a centimetre as it travels at its highest forward velocity. The HAT (head, arm, and trunk) segment represents about two-thirds of the total body mass and has to be controlled by the hip muscle group to avoid tilting. The only period of stability is during the double-support phase, and even during this period, the two feet are not completely flat on the ground while the HAT segment travels at its maximum velocity [3]. Even if walking is performed almost unconsciously and largely automatically, several sources of information help the subject control his/her walking. Dynamic walking balance is achieved by integrating the sensory inputs from the visual, vestibular, and proprioceptive systems with adequate muscle strength, appropriate neuromuscular timing, and free passive joint mobility [4–7]. In normal ageing, degeneration of one or more of these sensory systems occurs and
may compromise the balance during walking \[8, 9\]. Elderly people, however, suffer from the mobility problem because of their musculoskeletal weakness, and they experience falls more frequently than younger people do. Falls are a major cause of morbidity in the elderly, and in most incidents, some degree of locomotion problems has been implicated \[10–15\]. In this context, the elderly have a need for a daily gait-supporting device and a practice device to assist them and to enhance their muscle strength simultaneously. Moreover, people who have not walked for a prolonged time suffer serious changes in the muscles and bones of their lower limbs, which increase the risk of injuries.

Barbeau et al. \[16\] designed and manufactured a broad range of rehabilitation devices. One involves the treadmill, which has an upper frame (adjustable by hand) that supports the patient’s weight. A robot assistant, AID-1, uses compressed air to lift the patient’s body, thereby lessening the patient’s weight. REHABOT, a device that lessens the patient’s weight through the same method as that employed by AID-1, enables the patient to walk on a circular route. In the beginning, a parallel bar is used with this equipment to allow patients who have orthopedic or central nervous system problems (which will make exercise more difficult) to use the equipment. The walking capability of healthy individuals is tested with 60 per cent or more body weight support (BWS) \[17\]. Norman et al. \[18\] redesigned the equipment so that the treadmill and the BWS device now use hydraulic power. When a patient holds on to the parallel bars to walk, the degree of support at any harness height can be adjusted, following the generated moment. Egawa et al. \[19\] is a proposed power-assisted walking support device for individual walking that does not require any other assistance. The parameter of viscous resistance is tuned for each examinee’s gait stability \[19\]. McLachlan et al. \[20\] suggested a shared multi-stage control strategy for the human-walking-assistive mobile robot system. They used a fuzzy algorithm to merge the user intent and the obstacle avoidance information. Jiang et al. \[21\] developed an omnidirectional mobile robot for lower limb rehabilitation, focusing on the centre-of-gravity shift during walking, and they applied the robust-control algorithm to the control system to secure the stability while integrating human walking with the system.

This study aimed to the development of multi-functional gait-assistive mobile robot system based on BWS. This system has manual and autonomous driving modes, and the user can switch each of those modes directly. Using this function, the user can drive the system by his/her own intent, or mobile robot can guide and train the user’s walking autonomously with the user’s body weight supporting. In this context, this article introduced the treatments for each driving mode using look-ahead distance method and tried to verify those performances for path tracking and BWS for subjects. The overall goal is to develop a gait rehabilitation system that can assist a user weighing up to 75 kg in walking.

2 MECHANICAL DESIGN

2.1 System requirements

The mechanical design of the gait rehabilitation mobile robot was established through the extensive analysis of the requirements of the motion range for the human walking including elderly, published kinematic and kinetic data from clinical gait analyses, ergonomic constraints, analysis of the control law, and extended periods of testing with the former prototypes. The preliminary design work involved planning how to support the users’ own weight while walking as well as determining the required sensors for the system control. The main requirement is functionality. Related to this is a further requirement for comfort in use: the device should not interfere with the behaviour of the user. The design of gait rehabilitation system must allow enough freedom of movement for the machine to follow the body of the user during walking. While the user walks, the natural motion of the upper body is characterized by swinging from the top to the bottom and from right to left. The right-and-left motion is mainly important for gait stability; the system incorporates the top-and-bottom motion for weight support. The revolving joint of the robot user is placed on an axis orthogonal
(right-angled) to the user’s sagittal plane (an imaginary plane that bisects the body from top to bottom). Essentially, the robot has three degrees of freedom (DOFs); the gait-assisting system has two and the BWS system has one DOF. Figure 1 shows the conceptual design of the proposed robot system. Basically, the gait parameters that were used in this research are the following: count of steps per minute (114.8 step/min), walking velocity (0.5 m/s), elapsed time for one cycle (1.06 s), elapsed time for one step (0.53 s), and elapsed time for the standing phase using two legs (0.24 s). The traveling distance of one cycle was 0.49 m and the stride length 0.26 m.

2.2 Kinematic design of the BWS system

The BWS system reduces the load of the user’s own weight while walking or lifting. Obviously, various types of mechanisms can be introduced for the body lifting system. However, the proposed system applied one-DOF type four-bar linkage because it can be operated by only one actuator which can be mounted at any point of linkage or joint. Second, four-bar linkage meets the required trajectory of up–down motion, as shown in Fig. 3. Figure 2 shows the free-body diagram for the analysis of the kinematics of the designed mechanism.

(a) position

\[ Z_{O2} + Z_2 - Z_{O1} - Z_1 = 0 \]
\[ l_{b2} + l_A e^{\theta_2} - l_A - l_1 e^{\phi_1} = 0 \]
\[ \phi = \theta_1 - \theta_2 \]
\[ k_1 = l_A - l_1 \cos \phi \]
\[ k_2 = -l_1 \sin \phi \]
\[ \therefore \theta_2 = 2 \tan^{-1} \left( \frac{k_2 + \sqrt{k_2^2 - k_1^2 + l_1^2}}{k_1 + l_1} \right) \]

(b) velocity

\[ \omega_2 = \frac{\dot{l}_1 \cos(\theta_2 + \phi) - l_1 \phi \sin(\theta_2 + \phi)}{l_1 \sin(\theta_2 + \phi) - l_A \sin \theta_2} \]
\[ \therefore v_y = (l_A + l_{k2}) \cdot \omega_2 \cdot \cos \theta_2 \]

(c) force

\[ F_A = F \sin \phi \]
\[ F_B = \frac{l_A}{l_A + l_{k2}} \cdot F \]
\[ F_y = F_B \cos \theta_2 \]

Figure 3 shows the simulation result of the allowable trajectory of the proposed BWS system. This system can serve weight supporting to users who have statures from 150 to 180 cm and it is verified by kinematic simulation of BWS. However, the users who are out of this range also can use this system by adjusting the height of the interface part which meets with the armpit. Obviously, the force for reducing the weight bearing following the walking cycle has to be consistent at all times so that the force measured by the F/T sensor is fed back and operates the actuator and it can lift it with a consistent force at all times.

2.3 User command system

The user command system (UCS) is a man–machine interface that transfers the user’s decision about walking to the robot, such as whether to continue to walk or not and whether to slow down or not. As shown in Fig. 4, difference of velocity between the robot and the user can be input as a user’s desired velocity command directly by relative motion between BWS interface and its mounting unit. User holds the grip of BWS interface and reclines the part of his/her own body’s weight. Therefore, BWS interface is combined with user and the users generate the command signal by regulating his/her walking speed and the system catches the velocity difference by linear potentiometer (Fig. 4, left) and degree of BWS is measured by F/T sensor (Fig. 4, right) Therefore, user’s horizontal and vertical movements against the mobile robot can be handled together using a UCS. The most important requirement for this mobile robot system is to prevent the robot from moving backward and to keep a safe distance between the robot and the user because the latter can fall...
backward while using this robot. The degree of sliding between the robot and the user was measured by USC and the acceptable signal range of the sensor was confirmed.

3 SYSTEM DRIVING METHODOLOGIES

3.1 Background

The proposed mobile robot has two modes of driving: manual and autonomous. The former one is to drive the system by user’s free intent directly. Users can drive the system using the UCS only. The latter one is the mode to activate the autonomous driving system. Operation modes of proposed system can be alternated by the mode change function executed by the user or the rehabilitation manager. This mode changing can be handled on the touch screen which is mounted on the proposed system.

3.2 Manual driving control

Figure 5 shows the generalized diagram of the designed gait-assistive mobile robot. The way-point shown in this figure is the virtual point that the user wants to reach. Generally, the user looks ahead at the target point then drives the system using the UCS. At this time, there is an angle difference of change in
heading (CIH) and to reduce such difference, the user moves his/her body and inputs the user command signal to the system. Through these processes, the mobile robot system is simultaneously driven forward, left, and right towards the virtual way-point. To operate the mobile robot naturally using this command, the relation between two rotations of the user’s head and torso should be considered. When the user steers the mobile robot system, the heading angle of the user’s head is one of the most important factors to consider. In the proposed system, however, the cornering of the mobile robot is performed via torso rolling (of the user’s body, which is connected to the UCS), according to the cornering direction.

\[
\int_{t_a}^{t_b} v(t) \, dt = R \theta_M
\]

\[
R = \frac{1}{2 \theta_H} \int_{t_a}^{t_b} v(d_{BH}) \, dt
\]

where \(v(d_{BH})\) is the linear velocity command of the mobile robot, which is generated by \(d_{BM}\) of the UCS and \(d_{BH}\) the user’s own intent for robot driving.

The relation of the CIH (\(\theta_H\) in Fig. 6) and mean body velocity (MBV) (\(d_{BH}\) in Fig. 6) can be connected with the trunk roll orientation (TRO) using the data of human walking along a curved path, as shown in Fig. 7, which consists of the experiment results of Courtine and Schieppati [22]. It shows the MBV map according to the variance of TRO and CIH applied in the manual driving mode. This relation is applied to the developed mobile robot system and combines the measured signal from the UCS (which catches the TRO and MBV) with the velocity of mobile robot. Using this velocity map, the user can operate the proposed system based on the human’s own natural cornering behaviour.

Finally, the input command of the cornering radius \(R\) for the mobile robot can be calculated only using the TRO (measured by the F/T sensor of the UCS), which alternates the CIH (\(\theta_H\)) and MBV (\(d_{BH}\) or \(v_M\)). By substituting the measured \(v(d_{BH})\) and calculating \(R\) in equation (4), the velocity command of each wheel can be generated. Using this approach, the manual-driving control mode can be easily realized.

### 3.3 Autonomous driving control

#### 3.3.1 Background

Figure 8 shows the kinematic model of the proposed two-wheeled mobile robot with cornering radius \(R\), angular velocity \(\omega\), and linear velocity \(v\).

In this figure, \(G_x, G_y\) means that the global coordinate belongs to the arbitrary fixed coordinate and the robot coordinate, expressed as \(R_x, R_y\), to the centre point of the moving mobile robot. The position and direction of the mobile robot are expressed as \(x_R, y_R\), and \(\theta_R\), and the geometric configuration of the mobile robot can be defined as the following vector \(q\)

\[
q = \begin{bmatrix} x_R \\ y_R \\ \theta_R \end{bmatrix}
\]
Therefore, the kinematical dynamic equation is derived as the following matrix form

\[
\dot{q} = \begin{bmatrix} \cos \theta_R & 0 \\ \sin \theta_R & 0 \end{bmatrix} u
\]

where \( u = [v \ w]^{T} \) pertains to the control input vector. Generally, from this kind of non-holonomic constraint, the kinematic model can be derived. The non-holonomic constraint is a kind of velocity constraint expressed as the following equation

\[
x_R \sin \theta_R - \dot{y}_R \cos \theta_R = 0
\]

That is, when it is assumed that the mobile robot moved slowly as much as the longitudinal force and the lateral traction force cannot overcome the maximum static friction force between the wheel and the ground, no sleep motion exists between the wheel of the mobile robot and the ground because the velocity of the \( y \)-axis component is zero, as shown in equation (4). In equation (3), although the linear and angular velocities of the mobile robot are used as control inputs, the final control input should be the linear velocity of both wheels when the wheels are directly derived by the motor. At the same time, as shown in Fig. 8, the velocity of both wheels for rotating as cornering radius \( R \) is determined by equation (5).

\[
v_L = v\left(1 - \frac{b}{2R}\right), \quad v_R = v\left(1 + \frac{b}{2R}\right)
\]

The autonomous driving control mode was driven using the pure-pursuit method. The look-ahead distance according to the human user in the manual-driving mode was moved to the point of view of the robot in this strategy. In the next section, pure pursuit for geometric path tracking is briefly introduced and a calculation method for the look-ahead distance is proposed for tuning the control system.

3.3.2 Path tracking using the pure-pursuit method

Pure pursuit is a geometric path-tracking method for generating the cornering radius to retrieve the original path \cite{23}. Figure 9 shows the pure-pursuit path-tracking method. The rotating radius can be obtained by generating the circle at the centre of the mobile robot and the look-ahead distance \( L \) from the centre of the robot to the circled point on the target trajectory in Fig. 9.

If the location of the look-ahead point is far from the \( x \)- and \( y \)-axes by as much as \( x_L \) and \( y_L \), the following equations can be derived from the geometric relation of the triangle, as shown in Fig. 9

\[
x_L^2 + y_L^2 = L^2
\]

\[
a^2 + x_L^2 = R_{\text{track}}^2
\]

and

\[
a = R_{\text{track}} - y_L
\]

If equation (8) is substituted for equation (7), equation (7) will be rearranged into the following equation

\[
x_L^2 + y_L^2 = 2y_LR_{\text{track}}
\]
If equation (6) is substituted for equation (9), the cornering radius $R_{\text{track}}$ for retrieving path will be derived as follows

$$R_{\text{track}} = \frac{L^2}{2y_L} \quad \text{(10)}$$

### 3.3.3 Selection of the look-ahead distance

The path-tracking performance of the geometric method depends on the look-ahead distance. As a car driver usually looks far ahead when driving his/her vehicle at a high speed, the look-ahead distance of the mobile robot should be controlled as the variance of the system velocity. If the look-ahead distance is long, the mobile robot starts cornering earlier; hence, the look-ahead distance should be made shorter so that it could track the reference trajectory. If the look-ahead distance is relatively short, a high angular velocity is required to track the small cornering radius. This motion will cause slippage between the robot and the ground and will influence the odometry method, calculating the position of the robot by counting the number of wheel rotations. Therefore, in this article, a look-ahead distance estimation is performed to restrict the radius of rotation. Figure 10 shows the simulation result of look-ahead distances of 1.9099, 0.9550, and 0.6366 m at 0.5 m/s, respectively.

![Fig. 9 Geometry of pure pursuit](image)

![Fig. 10 Trajectories of the mobile robot with three $L$ values](image)

![Fig. 11 Angular velocities of the mobile robot with three $L$ values](image)

Figures 10 and 11 show the angular velocities of the three cases. In these simulation results, the maximum angular velocity is shown to be inversely proportional to the look-ahead distance at a fixed linear velocity, and the look-ahead distance should be arranged to be proportional to the reference linear velocity as a pure-pursuit method. If the linear velocity is set as $v$, the look-ahead distance $L$ will be defined as follows

$$L = 2 \frac{v}{\omega_{\text{lim}}} \quad \text{(11)}$$
3.3.4 Path tracking and obstacle avoidance

As shown in Fig. 12, sensing the obstacle within the range of 180° was performed using a laser scanner on a two-dimensional ground. If the area covered by the radius of \( d_{\text{max}} \) in Fig. 12 is assumed as the possible detection area, only the obstacle contained in a half-circle area covered by the radius of \( d_1 \) will be considered.

Therefore, this area was defined as an effective obstacle area. The coordinate of the laser scanner was defined based on its centre position and was made to span \( L_X \) and \( L_Y \). The \( x \)-axis of the laser scanner is on the \( x \)-axis of the robot coordinate, but the \( y \)-axis of the laser scanner and robot coordinate has an offset of \( \alpha \). The laser scanner scanned every 0.5°; hence, the position vector is defined as \( P_{Oi} = [x_{Oi}, y_{Oi}] \) at \( i = 0°, 0.5°, \ldots, 180° \). \( L_{pOi} \), \( \ell_{pOi} \), and \( G_{pOi} \) pertain to the coordinates of the laser scanner, mobile robot, and global coordinate, respectively, and the geometric relation between these coordinates is expressed using a transformation matrix. The terms \( \ell_{pOi} \) and \( L_{pOi} \) were arranged as

\[
\begin{bmatrix}
\ell_{pOi} \\
L_{pOi}
\end{bmatrix}
= 
\begin{bmatrix}
1 & 0 & a \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\ell_{pOi} \\
L_{pOi}
\end{bmatrix}
\]

\( \ell_{pOi} \) and \( L_{pOi} \)

\[
\begin{bmatrix}
\ell_{pOi} \\
L_{pOi}
\end{bmatrix}
= 
\begin{bmatrix}
1 & 0 & a \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\ell_{pOi} \\
L_{pOi}
\end{bmatrix}
\]


\[
G_{pOi} = \begin{bmatrix}
\cos \theta_R & -\sin \theta_R & x_R \\
\sin \theta_R & \cos \theta_R & y_R \\
0 & 0 & 1
\end{bmatrix}
\]

(14)

3.3.5 Obstacle potentials

Using the defined position vector presented in the previous section, the shortest distance between the robot and the obstacle is expressed as

\[
d = \min_{i=0,0.5,\ldots,180} |R_{pOi}| \]

(15)

From distance \( d \) in equation (15), obstacle potential \( v_i \) is defined as follows

\[
v_i = \begin{cases} 
\frac{1}{d^2 + d_0^2} + \frac{d}{(d + d_0)^2} & \text{if } 0 \leq d \leq d_1 \\
\frac{1}{d^2 + d_0^2} & \text{if } d > d_1 
\end{cases}
\]

(16)

where \( d_0 \) is a constant to prevent the value of the obstacle potential from becoming infinite. Therefore, virtual force \( f_i \) is acquired by deriving a gradient of the obstacle potential.

\[
f_i = -\nabla v_i
\]

(17)

In this research, the mobile robot that has a non-holonomic constraint condition was focused on, as shown in equation (4). To consider this kind of constraint condition, a method of generating a cornering radius to avoid an obstacle was introduced in this study using the force magnitude derived by the obstacle potential. The cornering radius for obstacle avoidance is inversely proportional to the magnitude of the virtual force, and the cornering radius should be smaller when heading towards an obstacle. Therefore, the cornering radius for obstacle avoidance is defined as follows

\[
R_{\text{avoid}} = \begin{cases} 
\frac{\ell_{pOi}}{\alpha/|f|} & \text{if } \theta_R - \theta = 0 \\
\frac{\sin(\theta_R + \theta)}{\alpha/|f|} & \text{otherwise}
\end{cases}
\]

(18)

where \( \alpha \) is the gain of the arbitrary value, \( \theta_R \) the angle of position vector \( R_{pOi} \) and the \( x \)-axis of the global coordinate, and \( \epsilon \) the arbitrary small value.
3.3.6 Linear velocity deceleration according to obstacle detection

The virtual force from the obstacle induces a deceleration of linear velocity $v$ of the mobile robot as follows

$$v = v_{\text{ref}} - \beta |f|^2, \quad v > 0$$

(19)

where $v_{\text{ref}}$ is the reference velocity and $\beta$ the arbitrary gain value.

When equation (19) is substituted into equation (11) of the look-ahead distance, the look-ahead distance becomes smaller in proportion to the velocity of the mobile robot. Hence, the mobile robot can correspond not only to static obstacles but also to dynamic obstacles. As the aforementioned method of path tracking and obstacle avoidance can be expressed by calculating the cornering radius using equations (10) and (18), it can be expressed as follows

$$\omega_{\text{track}} = \frac{v}{R_{\text{track}}}$$

$$\omega_{\text{avoid}} = \frac{v}{R_{\text{avoid}}}$$

(20)

Therefore, $\omega_{\text{navi}}$ and $R_{\text{navi}}$ which perform the path tracking and obstacle avoidance is as follows

$$\omega_{\text{navi}} = \omega_{\text{track}} + \omega_{\text{avoid}} = v \left( \frac{R_{\text{track}} + R_{\text{avoid}}}{R_{\text{track}} R_{\text{avoid}}} \right)$$

(21)

$$R_{\text{navi}} = \frac{R_{\text{track}} R_{\text{avoid}}}{R_{\text{track}} + R_{\text{avoid}}}$$

(22)

Using the cornering radius in equation (22) and the derived linear velocity in equation (19), the linear velocity of both wheels of the mobile robot can be obtained.

4 CONTROL STRATEGY

In the walking performance enhancing mobile robot, unlike in the traditional mobile robots, the human user and the machine are integrated and have physical contact with each other. This couples the dynamics of the hardware involved with a control architecture. The controller of the proposed mobile robot consisted of an autonomous guided controller for the mobile robot’s gait assistance system and a weight-unloading controller of the BWS for gait rehabilitation, as shown in Fig. 13.

It is a danger that if the user falls on or is struck by the mobile robot; it can turn with a short rotation radius or go backward. Therefore, for the proposed mobile robot, the control strategy was designed using an integrated path-tracking algorithm and a user command detecting algorithm. Next, in the case of weight-unloading control, the force for reducing weight bearing following the walking cycle has to be consistent at all times with the force measured by the strength sensor, which is fed back and operates the motor for lifting. When the way-point that has to be followed by the mobile robot is supplied from the global path planner, the robot performs path tracking and obstacle avoidance. The detailed control strategy for path tracking is summarized as shown in Fig. 14.

Cornering radius $R_{\text{track}}$ for path tracking is generated by the feedback regarding the way-points, the look-ahead distance, and the position and orientation.
of the mobile robot for the pure-pursuit path-tracking method. Cornering radius $R_{\text{avoid}}$ for obstacle avoidance is generated by the position vector acquired by the laser scanner, and by the position and orientation of the mobile robot. Finally, the velocity commands of both wheels of the mobile robot are determined by the cornering radius. While the linear velocity of both wheels and the magnitude of virtual force $f_i$ increase, the linear velocity decreases. A feedback signal for the decreased look-ahead distance is executed to track the path simultaneously.

5 PERFORMANCE VERIFICATION FOR DEVELOPED SYSTEM

In this section, several experiments that were performed to verify the capability of the developed gait rehabilitation mobile robot are described. These experiments had several limitations with regard to the usage of subjects; ordinary persons were selected as the experiment subjects. Selected as study subjects were a 32, 27, 62-year-old male adults with a 172, 165, and 160 cm height respectively. (Case 1, 2, 3 in order).

5.1 Path-tracking performance in the autonomous mode

A driving test was performed according to the conditions shown in Table 1. The test place was a flat and level ground, and four way-points were applied based on the global coordinate shown in Fig. 15.

The path-tracking performance was tested first, and then an obstacle avoidance test using two objects on the path was conducted. Finally, the dynamic obstacle avoidance was tested by moving the subject (a human passing by the robot’s path). The mobile robot maintained the velocity given in Table 1 ($v_{\text{ref}} = 0.5 \text{ m/s}$) and Fig. 16 shows the tracked the trajectory.

As a follow-up test, the path-tracking performance of the mobile robot was examined in terms of obstacle avoidance. The objects were placed on two spots (5 m, 0 m) and (8 m, 5 m) in the trajectory of the mobile robot, as shown in Fig. 17. The robot avoided the two obstacles and followed its own trajectory.
An experiment on dynamic object avoidance was conducted with a human subject passing by the robot’s trajectory. As shown in Fig. 18, the operation time of the laser scanner was about 14 s, and the robot was able to detect and avoid the subject.

In the afore-mentioned three experiments, the change in the look-ahead distance of mobile robot according to the time is shown in Fig. 19. Only in the case of trajectory following, the robot did not meet the obstacle; hence, the look-ahead distance was maintained at $L = 1.146\, \text{m}$. In the case of moving-trajectory avoidance, however, the robot avoided the two objects, and the look-ahead distance was decreased. Finally, in the case of dynamic object avoidance, as the subject approached the mobile robot, the look-ahead distance was sharply decreased. Therefore, the look-ahead distance and the magnitude of the target velocity of the mobile robot decreased simultaneously, and the robot moved along the small cornering radius while maintaining its low angular velocity.

5.2 Performance of BWS

For the details of the experiment, a comparison was done of whether the force lifted from the BWS system was consistently maintained and the electromyography (EMG) measurement following each BWS system level was done. A test was performed on the three BWS level cases (full body weight [FBW] and 20 and 40 per cent body weight supported [BWS]), where the walking velocity was 0.2 m/s. To evaluate the performance of musculoskeletal gait assistance, as shown in Fig. 20, surface electrodes were placed over the following muscles on the subjects’ dominant sides: the quadriceps femoris, medial hamstrings, gastrocnemius, and tibialis anterior. Prior to the application of the surface electrodes, the subjects’ skins were shaved and cleaned with alcohol. Two electrodes were placed over each muscle, with an interelectrode distance of approximately 1 cm. During the testing session, the subjects walked at a rate of 0.5 m/s, with a 0 per cent level during each of the following harness-supported ambulation situations: FWB and 20 and 40 per cent BWS. Five-second EMG data
(1024 Hz) were recorded for each condition. The raw EMG data were collected using the Myosoft™ software (Noraxon USA®, Scottsdale, AZ®), which was also used to record an analogue signal.

Figure 21 lists the average muscle activity for each muscle group expressed as a percentage of the FWB amplitude for each case of subject. In the case where the subject was 32 years old, the average amplitude for the quadriceps on 40 per cent BWS decreased to 72.8 per cent of the FWB value. In the cases of other two subjects, the average EMG activity did not change significantly for any of the muscle groups when FWB was compared to 20 per cent and 40 per cent BWS ambulation. The results suggest that muscle activation can be preserved while possibly decreasing the load at the joint of the lower extremities. Figure 22 lists the percentage MVIC of each muscle activity for each subject. As shown in the figure, essential characteristics of muscle activation for each subject exist but there is no proof that these results mean the muscle activation characteristic of each age group for BWS. This result, however, shows the dominant tendency. First, 20 per cent BWS is better than 40 per cent BWS for all subjects in common. Though in case where the subject was 32 years old there is a different effect at the hamstring muscle on 20 per cent and 40 per cent BWS but other groups of muscles of all subjects show the better effect on 20 per cent BWS.
than 40 per cent BWS. Second, with the results of Fig. 21, all subjects show that they still perform his walking using most dominant muscles while reducing the user’s own weight from 20 per cent to 40 per cent. This means that this system can be utilized by the users who need to reduce the load of his/her own body weight during the rehabilitation while training the most of dominant muscles for lower extremities activation.

6 CONCLUSIONS AND CONSIDERATIONS

In this study, the gait rehabilitation mobile robot was developed using the mobile robot platform. The mechanism of BWS and changeable driving modes were designed for the consideration and analysis of the human gait. Moreover, the robot motion was determined by the information regarding the environment and the distance between the user and the robot, which were measured using a laser range finder and a linear potentiometer. Obstacle recognition for guidance was applied and experimentally evaluated. The results of the experiments show that the mobile robot tracks the reference path properly using a laser range finder. Conceptually, the combination of the manual and autonomous driving modes integrated the look-ahead distance characteristic of human nature while cornering with pure-pursuit method for geometric path tracking of mobile robot which uses the calculation method of ‘the look-ahead distance’.

The conclusions of this study are as follows:

1. A UCS was proposed as a man–machine interface that transfers the user’s decision about walking to the mobile robot.
2. Gait velocity was selected as an ergonomic design parameter of the mobile robot and human walking characteristics based on the investigation of the human gait data.
3. The weight-unloading force measured based on the load cell was controlled in the BWS system, and a four-bar linkage was applied to the of the BWS system. From the experimental results, the performance of BWS is verified that user who needs the walking rehabilitation can utilize this system to train the normal walking while reducing his/her own body weight from 20 per cent to 40 per cent.

This system, however, has several limitations; solution for balancing control problem against the sub-jects who have an excessive off-balanced walking and more experimental details for much more crowded environments will be handled in the future work.

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