A New Control Approach for a Robotic Walking Support System in Adapting User Characteristics

Oscar Chuy, Jr., *Student Member, IEEE*, Yasuhisa Hirata, *Member, IEEE*, and Kazuhiro Kosuge, *Fellow, IEEE*

***Abstract*—This paper proposes a new control approach for a robotic walking support system to adapt a user's controlling characteristic. The control approach will be implemented by changing the kinematic structure of the robotic walking support system based on a variable center of rotation. This new control approach aims to help users who have difficulties in controlling their walking support system. In this study, we have a training stage to evaluate and adapt user's controlling characteristics. This will be implemented by allowing the user to follow some training paths. In the event a large path error occurs, a learning algorithm will vary the center of rotation of the support system until the user can successfully follow the training path. The relationship between the user intent in the form of applied force/torque and the new center of rotation will be taken by considering several training paths. This relationship will be used in actual control of the robotic walking support system. Experimentation and evaluation are presented to show the validity of the proposed control algorithm.**

***Index Terms*—Robotic walking support system, variable center of rotation.**

I. Introduction

THE population of elderly people is rapidly increasing. In Japan, the current population of people aged 65 and above is about 20%, and it is estimated that it will continue to increase to 35% by 2050 [1]. The increase in the elderly population and lack of caregivers open the opportunity for robotic applications to address elderly problems. Robotic applications such as assisting the elderly in their daily activities to regain independence and increase the quality of life will be developed.

A conventional walker is normally used to address the elderly mobility problem [2]. This device provides walking stability and weight support to the user. It is considered a passive device that depends on the user's decision-making and moves only when force/torque is applied to the system. A conventional walker requires the user to have sufficient cognitive function, good vision, judgment, and endurance. These requirements are difficult to satisfy for the elderly, whose controlling characteristics degrade due to aging. A walking support system that will address this mobility problem and can adapt the changing controlling characteristics of a user will be of great interest.

Robotic technology can be introduced to a conventional walker. This will enhance the walker's functions such as providing guidance to disoriented users, giving reminders like when to take medicine to users who suffer from memory loss, monitoring their physical conditions, etc. These functions are very important to increase the quality of life of an elderly. It is also possible that with robotic technology, the idea of adapting a user's characteristic functions can be implemented and the requirements of using a conventional walker are reduced.

The elderly can also suffer from other problems aside from mobility. These problems are memory loss, disorientation, etc. It is possible to integrate the solutions of the aforementioned problems into a single device. As an example, visual information about the user's location can be integrated to a conventional walker, and this addresses the mobility and disorientation problems [3], [4]. Another research approach that incorporates solutions to several elderly people's problems is discussed in [5]. This new concept of integrating solutions to mobility and other problems of the elderly leads to the development of a robotic walking support system [5]–[8].

A robotic walking support system can be classified into passive and active type. A passive type of robotic walking support system depends on the applied force/torque of the user, and this leads to the walking support system's inherent safety feature [9], [10]. The basic disadvantage of the passive type is the load problem. The user handles the weight of the support system, and this leads to limited high-level functions. An example of a passive-type robotic walking support system is described in [10]. This system uses brakes to change its maneuverability. It also has a human adaptive motion control algorithm, which is important in addressing human–robotic walker interaction.

The active type of robotic walking support system has motors to drive the system [5], [6], [11], and this solves the load issue from which the passive type suffers. The active type can be augmented with many functions since the mobile base handles the weight issue of the system. The basic design issue of an active type of robotic walking support system is the human–robotic walker interaction. This issue is how we can make the user feel as if they are controlling a conventional walker that is safe and stable. This aforementioned design issue will be addressed in designing the proposed control algorithm.

The current research on robotic walking support systems focuses on augmenting the high-level functions such as obstacle avoidance, guidance, and health monitoring. These high-level functions are meaningless if the user cannot properly control the walking support system. Although several studies have been reported on robotic walking support systems [5], [6], studies in adapting user characteristics have not been reported. This paper proposes a new control approach that will try to adapt the user's controlling characteristics. The proposed control approach will change the kinematic structure of the system, and

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O. Chuy is with the Department of Bioengineering and Robotics, Tohoku University, Sendai 980-8579, Japan.

Y. Hirata and K. Kosuge are with the Department of Bioengineering and Robotics, Tohoku University, Sendai 980-8579, Japan.

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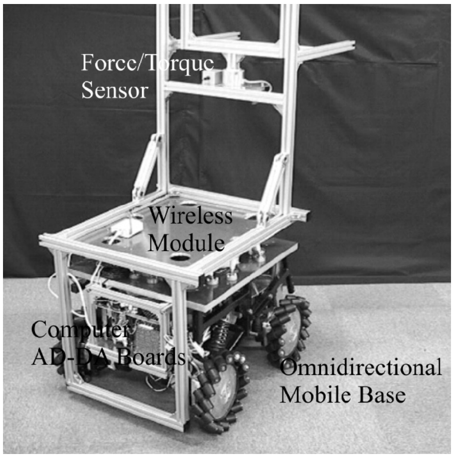


Fig. 1. Robotic walking support system "Walking Helper."

this will be implemented by varying the center of rotation of the robotic walking support system. The control approach aims to help users who have difficulties in controlling their walker.

The advantage of varying the center of rotation to adapt the user's controlling characteristic is that the maneuverability of the system will only change when there is an applied force/torque. Another possible solution to aid users who cannot properly control their walker is to add force/torque to the equation of motion. The alternative solution will not ensure the safety of the user. It is possible that the system moves without any applied force/torque since an active type of robotic walking support system is being used in this study.

Section II discusses the hardware and the system description of the robotic walking support system "Walking Helper." Section III describes the motion control algorithm based on imposed apparent dynamics. Section V discusses the determination of the new center of rotation based on training. Section VI presents the experimentation and evaluation to illustrate the validity of the proposed control algorithm.

II. System Description of the Robotic Walking Support System

A robotic walking support system referred to as "Walking Helper" is used to implement the proposed control algorithm. It has an omnidirectional mobile base, support frames, computer system, analog-to-digital and digital-to-analog converters, and a wireless Ethernet module (Fig. 1). This robotic walking support system is also installed with a force/torque sensor, which is used to measure the user's intentions in the form of applied force/torque. The force/torque sensor data are used to derive the command signals to the robotic walking support system's motion controller.

The omnidirectional mobile base is implemented using four Mecanum wheels driven by a dc motor with an encoder. The kinematic equation of the mobile base is derived in [12] based on an arbitrary point called the center of rotation. The motion characteristics of the mobile base can be changed by relocating the center of rotation, and this is possible through software implementation.

III. Fundamental Motion Control Algorithm Based on Apparent Dynamics

An omnidirectional active type of robotic walking support system is used in this study. This type of robotic walking support system suffers from one control issue, that is, human–robotic walker interaction [13], [14]. This issue is how we make the user feel as if they are controlling a conventional walker without imposing a physical load on the user. One possible solution to this issue is to introduce an apparent dynamics to the system such that the user's applied force/torque is used to generate the desired velocity. This approach will emulate the motion characteristic of a passive system. The governing equation of the aforementioned concept is

$$\boldsymbol{M}\ddot{x} + \boldsymbol{D}\dot{x} = \boldsymbol{F}_{\text{applied}}. \tag{1}$$

The state-space representation of (1) is given by

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & I \\ 0 & -\boldsymbol{M}^{-1}D \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} F_{\text{applied}} \tag{2}$$

$$y = [0 \quad I] \begin{bmatrix} x \\ \dot{x} \end{bmatrix} \tag{3}$$

where $\boldsymbol{M}$ and $\boldsymbol{D} \in R^{3\times3}$. $\boldsymbol{M}$ and $\boldsymbol{D}$ are inertia and damping matrices, respectively. $\boldsymbol{F}_{\text{applied}} \in R^{3\times1}$, and it is the applied force/torque to the robotic walking support system. The parameters of $\boldsymbol{M}$ and $\boldsymbol{D}$ can be determined by asking the user how they feel with the specified values (e.g., is it heavy?). This approach is also used in [5]. An experimental approach for determining the apparent dynamics parameters is also described in [14]. $\boldsymbol{M}, \boldsymbol{D}$, and $\boldsymbol{F}_{\text{applied}}$ are given in (4)–(6), respectively. The states of the system are the velocity and position along the X and the Y axes and the angular velocity and position with respect to Z axis.

$$\boldsymbol{M} = \begin{bmatrix} M_x & 0 & 0 \\ 0 & M_y & 0 \\ 0 & 0 & M_z \end{bmatrix} \tag{4}$$

$$\boldsymbol{D} = \begin{bmatrix} D_x & 0 & 0 \\ 0 & D_y & 0 \\ 0 & 0 & D_\theta \end{bmatrix} \tag{5}$$

$$\boldsymbol{F}_{\text{applied}} = \begin{bmatrix} F_x \\ F_y \\ N_z \end{bmatrix}. \tag{6}$$

Fig. 2 shows the fundamental control block diagram of the robotic walking support system "Walking Helper." The applied force/torque is passed to the apparent dynamics to determine the desired states of the system, which are the velocity and the position. Based on the inverse kinematic equation of the system, each joint velocity is determined, and this is passed on to the motion controller for regulation.

IV. Center-of-Rotation Relocation

The center of rotation of the robotic walking support system is an arbitrary point in the system, and it is the basis in deriving the motion characteristics of the support system. The center of rotation can be relocated by software implementation, and

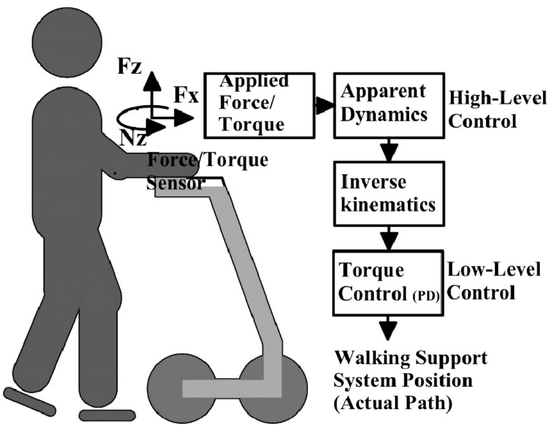


Fig. 2. General control block diagram of the robotic walking support system.

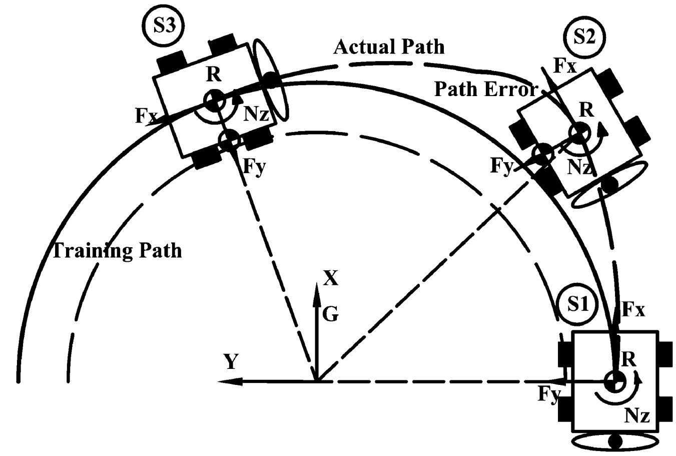


Fig. 3. Training path in evaluating and adapting a user's controlling characteristics.

this changes the motion characteristic or the maneuverability of the robotic walking support system. Based on (1), the equation of motion of the walking support system uses the applied force/torque to determine the desired velocities, and relocating the center of rotation leads to a new force/torque of the system. This new applied force/torque is

$$\boldsymbol{F}_{\text{cor}} = \boldsymbol{T}(X_{\text{cor}}, Y_{\text{cor}})\boldsymbol{F}_{\text{applied}} \tag{7}$$

where $\boldsymbol{T}(X_{\text{cor}}, Y_{\text{cor}})$ is the transformation matrix, which transforms the applied force/torque $\boldsymbol{F}_{\text{applied}}$ to the new center of rotation. This transformation matrix is a function of the center of rotation components along the X axis (X_{cor}) and Y axis (Y_{cor}) and is given by

$$\boldsymbol{T}(X_{\text{cor}}, Y_{\text{cor}}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ Y_{\text{cor}} & -X_{\text{cor}} & 1 \end{bmatrix}. \tag{8}$$

The system torque can be increased/decreased based on the location of the new center of rotation. This is based on the aforementioned force/torque transformation. As discussed in [9], the heading angle of the walker is highly correlated with the applied torque. It is possible to aid the users who have difficulties in steering their walking support system by relocating the center of rotation.

V. Approach in Adapting the User's Characteristics Based on a New Center of Rotation

This section discusses the proposed control approach of a robotic walking support system. The process in determining a new center of rotation to adapt a user's controlling characteristics will also be presented. This process is implemented by allowing a user to follow some training path. However, if large path errors occur between the training and actual path, the center of rotation is relocated. This process of relocating the center of rotation continues until the user can successfully follow the training path. Several training paths are considered in order to derive the relationship between the user's intention in the form of applied torque and the new center of rotation. The derived relationship is used to implement a variable center of rotation.

A. New Center-of-Rotation Determination

Let us consider Fig. 3 to illustrate the concept of determining a new center of rotation. At state S1, the user moves with the intention to follow the given training path. It is possible that due to some controlling disability the user cannot follow the training path. As illustrated in Fig. 3, at state S2, the user lacks counterclockwise torque or positive torque with respect to the robotic walking support system coordinate. The system torque can be increased or decreased based on (8). This can be implemented by relocating the center of rotation. The new center of rotation can be searched by a learning algorithm. As illustrated in Fig. 3 from state S2 to state S3, the user and the robotic walking support system return to the training path as the center of rotation is shifted to the left with respect to the walking support system coordinate. This is due to the contributed torque of the applied force along the X axis, which is multiplied with Y_{cor}. The aforementioned discussion describes the process in determining the Y component of the new center of rotation.

In determining X_{cor}, let us consider Fig. 4 and assume that Y_{cor} is equal to zero. X_{cor} is assumed to have an arbitrary value, and it is above the origin of the walking support system coordinate. Based on the above assumptions, an application of counterclockwise torque by a user will move the robotic walking support system away from the training path, and this leads to a negative path error. Therefore, we can state that X_{cor} is above the origin if a negative error exists. This path error can be reduced by shifting the X_{cor} downward.

We will define some reference points in the training environment to derive the path error's $(\text{error}(k))$ equation. This equation will be used as a basis in defining the rules to determine the new center-of-rotation components.

1) The center of the training path with radius R_i is defined as $(X_c, Y_c)_G$ with respect to the global coordinate.
2) The starting position of the robotic walking support system is $(X_c, Y_c - R_i)_G$ for counterclockwise training and $(X_c, Y_c + R_i)_G$ for clockwise training.

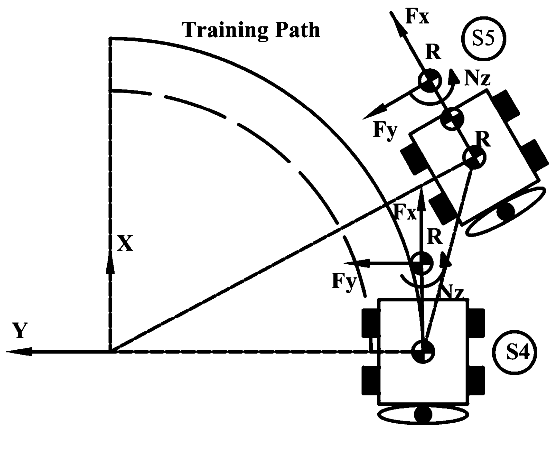


Fig. 4. X_{cor} determination concept based on relocated center of rotation.

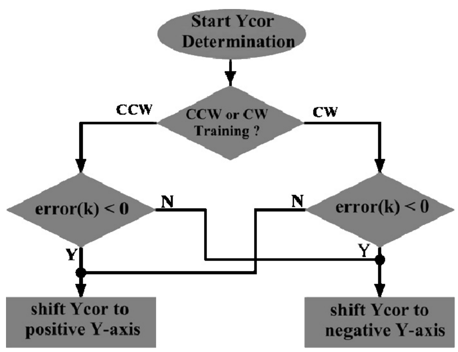


Fig. 5. Algorithm in determining Y_{cor} based on path error.

Based on the above reference point definition, error(k) is given by

$$\text{error}\,(k) = R_i - \sqrt{(X_{\text{pos}}(k) - X_c)^2 + (Y_{\text{pos}}(k) - Y_c)^2} \quad (9)$$

where $X_{\text{pos}}(k)$ and $Y_{\text{pos}}(k)$ are the components of the robotic walking support system position.

The determination of Y_{cor} based on the path error is implemented using some rules described in Fig. 5, and the learning algorithm is given in (10). This learning algorithm is similar to the one described in [15], [16]

$$Y_{\text{cor}}(k) = Y_{\text{cor}}(k-1) \pm \alpha_y \times \text{error}(k). \quad (10)$$

The determination of X_{cor} uses the rules described in Fig. 6. It can be observed from Fig. 6 that the training direction is not evaluated. This means that the rules in both training directions (counterclockwise and clockwise) are the same. X_{cor} determination also uses a learning algorithm given by

$$X_{\text{cor}}(k) = X_{\text{cor}}(k-1) + \alpha_x \times \text{error}(k) \quad (11)$$

where α_y and α_x are the learning rates in determining Y_{cor} and X_{cor}, respectively. The values of the learning rates α_y and α_x are between 0 and 1 $(\alpha_y, \alpha_x \epsilon [0\ 1])$.

X_{cor} is set to zero in determining Y_{cor}, and the equation of motion of the robotic walking support system in this stage is given in (12). This is based on the apparent dynamics, applied

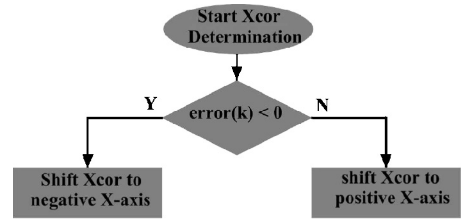


Fig. 6. Algorithm in determining X_{cor} based on path error in both clockwise and counterclockwise directions.

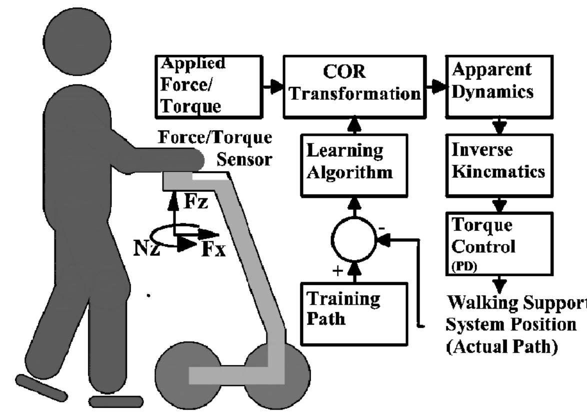


Fig. 7. Training block diagram in adapting a user's controlling characteristics based on a new center-of-rotation relocation.

force/torque, and center-of-rotation relocation

$$\boldsymbol{M}\ddot{x} + \boldsymbol{D}\dot{x} = \boldsymbol{T}(0, Y_{\text{cor}}(k))\boldsymbol{F}_{\text{applied}}. \quad (12)$$

First Y_{cor} is determined, then X_{cor}. The user is asked to follow the same training path. The equation of motion of the robotic walking support system in the determination of X_{cor} is given in (13). Y'_{cor} is the Y_{cor} taken from the previous training, and it is constant during X_{cor} determination

$$\boldsymbol{M}\ddot{x} + \boldsymbol{D}\dot{x} = T(X_{\text{cor}}(k), Y'_{\text{cor}})\boldsymbol{F}_{\text{applied}}. \quad (13)$$

The corresponding applied torque for the new center of rotation is considered after both components are determined. This is implemented by substituting the new center of rotation into the equation of motion.

The user is then be asked to follow the same training path, and the average applied torque is determined.

Several training paths are considered and are represented by a semicircular path with a certain radius R_i (Fig. 3). The training paths are represented by $\mathbf{TP} = \{TP_1, TP_2, \ldots, TP_n\}$, and their corresponding radii are represented by $\boldsymbol{R} = \{R_1, R_2, \ldots, R_n\}$. After training, the new center of rotation that allows the user to successfully follow each training path is represented by $\mathbf{COR} = \{\text{COR}_1, \text{COR}_2, \ldots, \text{COR}_n\}$. This new center of rotation has components along the X axis and Y axis, which are represented as $\boldsymbol{X}\text{cor} = \{X_{\text{cor}_1}, X_{\text{cor}_2}, \ldots, X_{\text{cor}_n}\}$ and $\boldsymbol{Y}\text{cor} = \{Y_{\text{cor}_1}, Y_{\text{cor}_2}, \ldots, Y_{\text{cor}_n}\}$, respectively. The average applied torque for each training path is determined and is represented by $\boldsymbol{N}z = \{N_{z_1}, N_{z_2}, \ldots, N_{z_n}\}$.

The determination of Y_{cor} and X_{cor} is not simultaneous. Y_{cor} is determined first, followed by X_{cor}. The determination of X_{cor}

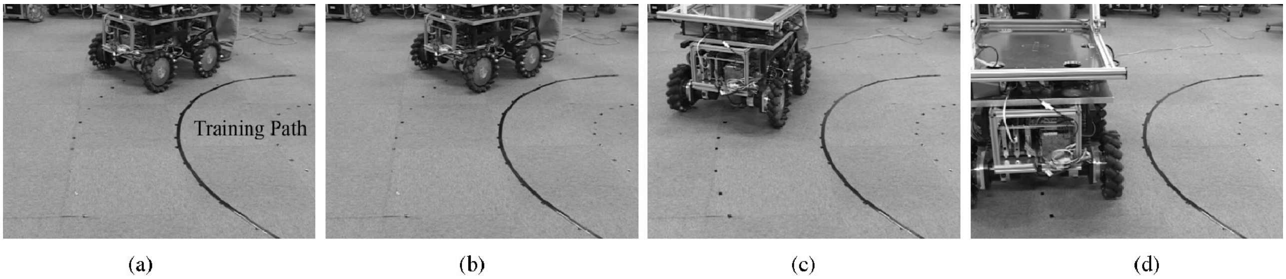


Fig. 8. Evaluation of the user's controlling characteristics prior to the determination of the new center of rotation.

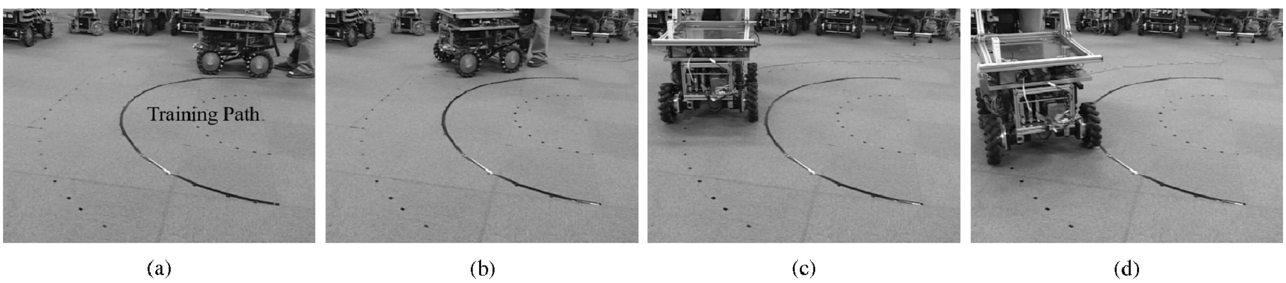


Fig. 9. Adaptation of the user's controlling characteristics by determining a new center of rotation ($Y_{\rm cor}$).

further reduces the path error. This nonsimultaneous determination is due to the complexity in searching for the new center of rotation that allows the user to successfully follow the training path. The new center-of-rotation components are selected when the path error is approximately equal to zero. Fig. 7 shows the block diagram in determining the new center of rotation for a certain training path.

B. Variable Center of Rotation

The actual application of the determined new center of rotation can be implemented by considering the relationship between the user's intention in the form of applied torque and the new center of rotation. This relationship is used to realize a variable center of rotation and is described by

$$\begin{bmatrix} X_{\rm cor} \\ Y_{\rm cor} \end{bmatrix} = \begin{bmatrix} f_{x\,{\rm cor}}(N_z) \\ f_{y\,{\rm cor}}(N_z) \end{bmatrix} \tag{14}$$

where $f_{x\,{\rm cor}}$ is a function describing the relationship between $X_{\rm cor}$ and N_z. $f_{y\,{\rm cor}}$ describes the relationship between $Y_{\rm cor}$ and N_z. These functions are determined on the basis of the results in training. The motion control algorithm of the robotic walking support system based on a variable center of rotation is given by

$$\boldsymbol{M}\ddot{x} + \boldsymbol{D}\dot{x} = \boldsymbol{T}(f_{x\,{\rm cor}}(N_z), f_{y\,{\rm cor}}(N_z))\boldsymbol{F}_{\rm applied}. \tag{15}$$

VI. Experimentation

This section comprising the training stage, new center-of-rotation evaluation, and variable center-of-rotation implementation discusses the training, implementation, and evaluation of the proposed control algorithm. The evaluation part of the study uses the concept of path following where the average deviation from the path is represented by the mean of the absolute error (MAE).

In implementing the proposed control algorithm, an elderly simulator (TMI-Elderly Simulator) [17] is used to simulate disability. This simulator can simulate walking and control the disability by adding weights to the feet and restricting hand motion, respectively. The elderly simulator is very important in testing a control algorithm since it does not endanger the safety of the elderly during the development phase of the control algorithm.

A. Training Stage

Training is used to evaluate and adapt the user's controlling characteristics with respect to the walking support system. It is likely that a user cannot follow a given training path due to some walking or controlling disability. This user's condition is illustrated in Fig. 8(a)–(d). Based on the aforementioned condition, the kinematic structure of the system is changed and is implemented by relocating the center of rotation of the robotic walking support system. The relocation of the center of rotation continues until the user can successfully follow the training path.

In the implementation of training, a user is asked to follow some training path, which is a semicircular curve with a radius R_i. Several training paths with different radii $\boldsymbol{R} = \{0.8, 1.3, 1.8\}$ [m] in both counterclockwise and clockwise directions are considered, in order to derive a relationship between the user's intention and the appropriate new center of rotation of the system that allows the user to properly control their support system.

An implementation of the adaptation process or determination of a new center of rotation for a specific training path is shown in Fig. 9. It can be seen from Fig. 9(a) and (b) that there is a path error between the training path and actual path. This leads to the relocation of the center of rotation (Y component) by the learning algorithm based on the path error. As the center of rotation is relocated, the robotic walking support system returns

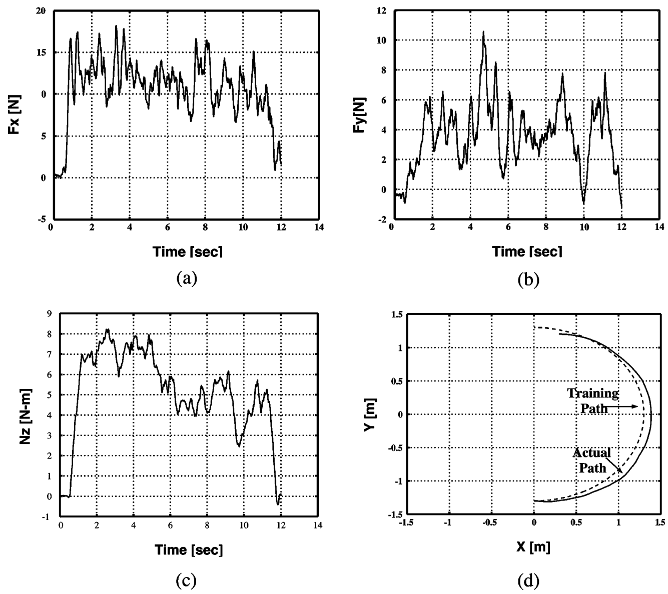


Fig. 10. Sample applied force/torque in training stage for a training path of radius $\mathrm{R} = 1.3$ [m]. The figure also shows the actual trajectory of the system with respect to the training path.

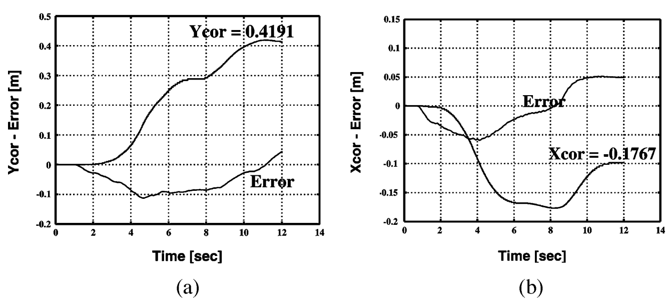


Fig. 11. Sample data on X_{cor} and Y_{cor} versus path error in training.

TABLE I
$X_{\mathrm{cor}}, Y_{\mathrm{cor}}$, AND APPLIED TORQUE DATA

	Xcor(m)	Ycor(m)	Torque(Nm)
Straight Path	0	0.28	0 ±0.5
CW			
R=0.8(m)	0	0	Nz<0
R=1.3(m)	0	0	Nz<0
R=1.8(m)	0	0	Nz<0
CCW			
R=0.8(m)	-0.1577	0.5316	5.45 ± 0.74
R=1.3(m)	-0.1767	0.4191	3.54 ± 0.69
R=1.8(m)	-0.1035	0.1216	1.71 ± 0.96

to the training path Fig. 9(c) and (d). In the aforementioned training, the user's intention in the form of applied force/torque is shown in Fig. 10(a)–(c), and the actual trajectory of the support system is shown in Fig. 10(d).

The next stage in training is to determine the X component of the new center of rotation. This is done to further reduce the path error. In this stage, Y_{cor} obtained in the previous steps is substituted in to the equation of motion given in (13). Based on the previous training, Fig. 11 shows the values of the center of rotation components as relocated by the learning algorithm. The

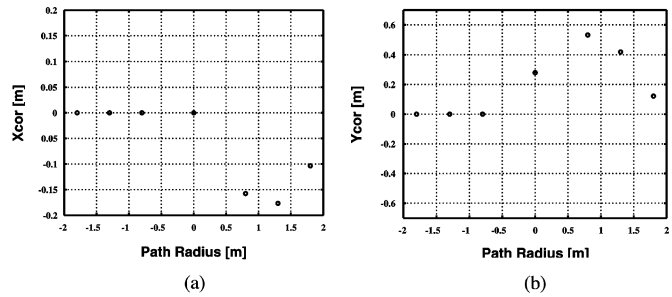


Fig. 12. X_{cor} and Y_{cor} data versus the training path radius.

TABLE II
AVERAGE MAE USING THE ORIGINAL AND RELOCATED CENTER OF ROTATION IN TRAINING PATH EVALUATION

Radius[m] and Direction CCW	MAE [m] Original COR	MAE [m] Using New COR
0.8	0.1021	0.0334
1.3	0.0851	0.0287
1.8	0.0819	0.0213

Y_{cor} value for curve R_i is selected when the path error returns to zero. X_{cor} is also selected by the same criterion.

The adaptation process pertains to the determination of a new center of rotation for a specific training path TP_i. This process is repeated for different training paths $TP_i, TP_{i+1}, \ldots, TP_n$ in order to model the user's characteristic. Table I shows the new center of rotation for each training path and the corresponding applied torque (average torque and the standard deviation). Fig. 12 shows the plot of X_{cor} and Y_{cor} versus the training path radius. It should be considered that the set of data in Table I is based on a certain user and different sets of data are taken for different users.

The steps in training can be summarized as follows.

Step 1) Y_{cor_i} determination: The user is asked to follow a training path TP_i (a semicircular path) with radius R_i. This is to determine the Y component of the new center of rotation, and the learning algorithm described in (10) is used. In this step X_{cor_i} is set to zero.

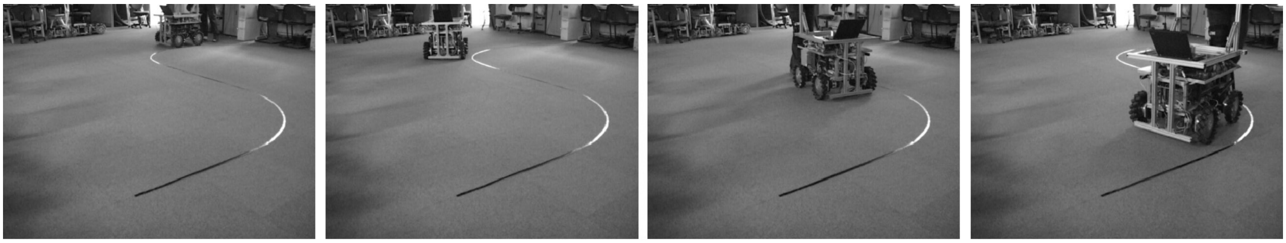
Step 2) X_{cor_i} determination: Y_{cor_i} from step 1) is substituted in to (13). X_{cor_i} is determined by allowing the user to follow the same training path TP_i and using the learning algorithm described in (11).

Step 3) N_{z_i} applied torque determination: The torque applied is determined on the basis of the new center of rotation $(X_{\mathrm{cor}_i}, Y_{\mathrm{cor}_i})$.

Step 4) The above process is repeated for a different training path TP_{i+1}.

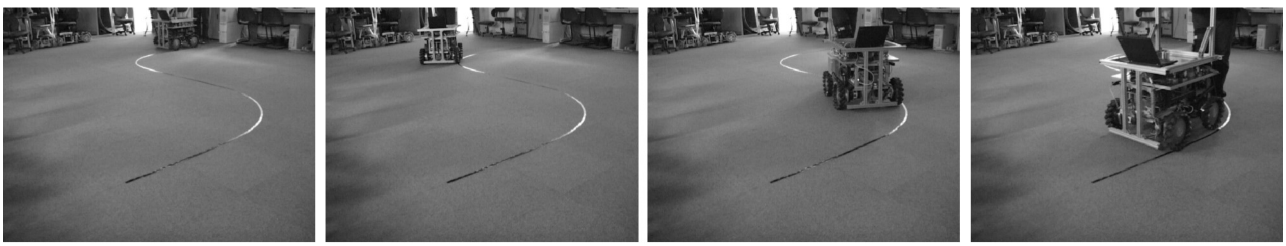
B. Training Evaluation

The MAE given in (16) is used as a criterion to evaluate the new center-of-rotation for a certain training path TP_i. It represents the average deviation of the walking support system in following the training path based on a user's controlling characteristics. The MAEs are obtained by allowing the user to follow the training path TP_i using the original center of rotation, which is located at the origin of the walking support system



(a) (b) (c) (d)

Fig. 13. Evaluation using S-path following prior to the implementation of variable center-of-rotation.



(a) (b) (c) (d)

Fig. 14. Evaluation using S-path following with variable center-of-rotation implementation.

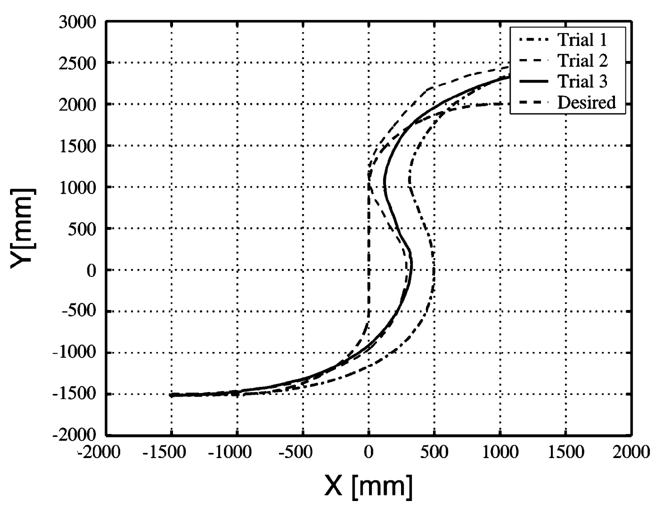


Fig. 15. Actual trajectories of the robotic walking support system in S-path following without using the variable center-of-rotation control.

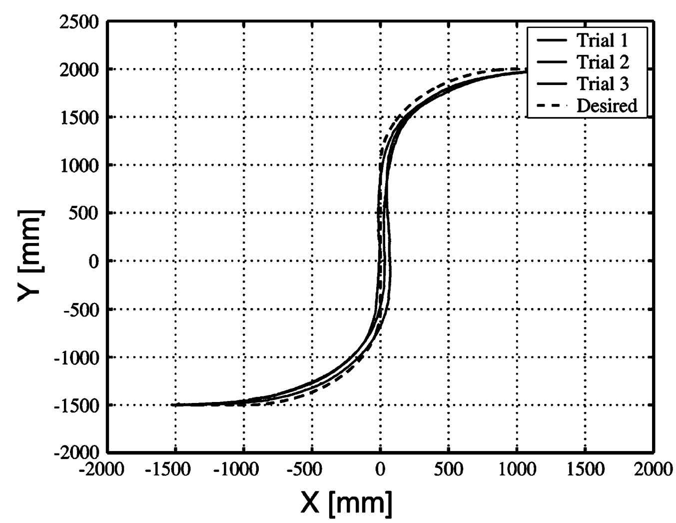


Fig. 16. Actual trajectories of the robotic walking support system in S-path following using the variable center-of-rotation control.

coordinates and the new center of rotation COR_i. The MAE is determined for all training paths $\boldsymbol{TP} = \{TP_1, TP_2, \ldots, TP_n\}$ with radius $\boldsymbol{R} = \{R_1, R_2, \ldots, R_n\}$. Table II shows that using the new center of rotation reduces the average deviation from the training path

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |e_i|. \tag{16}$$

C. Variable Center-of-Rotation Implementation and Evaluation

A new center-of-rotation controller was designed, its transfer function based on the data taken in training. This controller decides the new center of rotation of the system based on the user's intention. This approach leads to a variable center-of-rotation control of the robotic walking support system. The first center-of-rotation controller was implemented based on scheduling. This controller yields a single COR_i value for a certain range of torque as presented in Table I. In the implementation of the controller based on scheduling, the user sometimes experiences jerky movements and oscillations. These unwanted movements are due to the large and discrete variation of the center of rotation when the input torque moves between two torque conditions, endangering the safety of the user. A new center of rotation controller was considered to solve the oscillation problem.

The new center of rotation controller was a fuzzy-based controller. This controller accepts torque as its input and yields new

(a) (b) (c) (d)

Fig. 17. Environment-based training in adapting the user's characteristics.

COR as its output. This controller does not have a single output for a certain range of torques and is more continuous compared to scheduling. It works with rules, for example, if torque is positive large then X_{cor} is negative medium, Y_{cor} is positive large. Based on this rule, the controller's input is converted into fuzzy language such as positive large, positive small, etc. The conclusion part of the rules is in the fuzzy language, and there is also a need to convert the output into real values. The details in fuzzy controller design and definition of terms such as fuzzification, defuzzification, and inference mechanism are discussed in [18], and [19]. The implementation of a fuzzy-based controller removes the oscillation problem of the system. This is possibly due to a more continuous input–output relationship compared to scheduling.

The S-path following was used to evaluate the variable center-of-rotation implementation as it contains a straight path and curves, representing the actual trajectories in using the support system. Fig. 13(a)–(d) shows an evaluation using the robotic walking support system without implementing the variable center of rotation. It can be seen from Fig. 13 that a large path error exists. Fig. 14(a)–(d) shows another S-path evaluation in the implementation of variable center of rotation. It can be observed that the robotic walking support system is always near to the S-path. Based on the evaluation, the path error between the actual path and the S-path is reduced using a variable center of rotation. The actual trajectories of the robotic walking support system are shown in Figs. 15 and 16.

D. Environment-Based Training in Determining a New Center of Rotation

Environment-based training is an alternative method in determining a new center of rotation. This training approach uses environment information such as position and orientation of the support system with respect to walls, edges, and other landmarks. Environment-based training eliminates the process in preparing the training path, but this is limited to the structure of the environment. This approach is useful in determining the new center of rotation for a straight path and specific curves. In our current implementation, there is still a training stage, and not all environments can be used as a training environment. It is our future objective to remove the training stage and implement an online adaptation.

A preliminary result in environment-based training will be presented in this section. In this training approach, the user is asked to move from a starting point to a goal point without floor marks. This process possibly removes the mental load of the user in looking and following the training path. The same learning algorithm is used as described in Section V, and the error is computed based on the landmarks in the environment such as wall orientation and position.

Fig. 17 shows an implementation of environment-based training. In this training, the user's intention is to move parallel to the wall, and this represents a user moving along a corridor. Fig. 17(b) shows the user is moving toward the wall due to some controlling disability. Based on the user's condition, the center of rotation is moved by the learning algorithm, and the user is able to properly control the support system [Fig. 17(c)–(d)].

VII. Conclusion

This study proposed a new control approach for a robotic walking support system to adapt the user's controlling characteristics. This control approach is based on a variable kinematic structure, and it was implemented by changing the center of rotation of the robotic walking support system. With this new control approach, it is possible to aid users who are not able to properly control their walking support system.

Training was carried out to model and adapt the user's controlling characteristics by allowing the user to follow some training paths. The error between the training path and the actual path was used by a learning algorithm to relocate the center of rotation. This process continues until the user and the support system returns to the training path. Several training paths were considered to derive the relationship between the user's intention in the form of applied torque and a new center of rotation. The derived relationship was used to implement a variable center of rotation for the robotic walking support system. The evaluation results show that the path deviation represented by MAE was reduced using the variable center of rotation. The experimental and calculated results show the validity of the proposed control approach.

Future studies will consider the implementation and evaluation of the robotic walking support system in healthcare facilities for use by the elderly. The implementation will not only consider a variable center of rotation but also other high-level functions such as obstacle avoidance, guidance, aiding the user in standing, etc. Another walking support system is being developed and considers human–robotic walker interaction in developing the support system motion control algorithm. Research directions in estimating and predicting the user's state (e.g., posture) based on the relative position between the user and the support system, and the user's intention in the form of applied force/torque, are currently being studied. The estimation and prediction of the user's state will improve the human–robotic walker interaction.

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Oscar Chuy, Jr. (S'04) received the B.S.E.C.E. and B.S.E.E. degrees from Mindanao State University-Iligan Institute of Technology (MSU-IIT), Illigan City, Philippines, the M.S.E.E. degree from the University of the Philippines, Quezon City, and in 2006, the Ph.D. degree from Tohoku University, Sendai, Japan.

He is currently a Researech Associate in the Department of Bioengineering and Robotics, Tohoku University. From 1995 to 1997 and 2000 to 2002, he was as Instructor at MSU-ITT. His research interests include control theory, mobile robot control application to healthcare robotics, and service robots.

Yasuhisa Hirata (M'04) received the B.E., M.E., and Ph.D. degrees from Tohoku University, Sendai, Japan, in 1998, 2000, and 2004, respectively, all in mechanical engineering.

He is currently an Associate Professor in the Department of Bioengineering and Robotics, Tohoku University. From 2000 to 2006, he was Research Associate in the Department of Bioengineering and Robotics, Tohoku University. From 2002 to 2004, he was also a Researcher of PRESTO (Precursory Research for Embryonic Science and Technology), Japan Science and Technology. His research interests include intelligent control of multiple mobile robots in coordination, power assist, walking support system, and human–robot cooperation.

Kazuhiro Kosuge (SM'00–F'06) received the B.S., M.S., and Ph.D. degrees from the Tokyo Institute University, Tokyo, Japan, in 1978, 1980, and 1988, respectively, all in control engineering.

He is currently a Professor in the Department of Bioengineering and Robotics, Tohoku University, Sendai, Japan. From 1982 through 1990, he was a Research Associate in the Department of Control Engineering, Tokyo Institute of Technology. From 1989 to 1990, he was a Visting Scientist in the Department of Mechanical Engineering, Massachusetts Institute of Technology. From 1990 to 1995, he was an Associate Professor at Nagoya University. He has over 200 technical publications in the area of robotics and is the Editor-in-Chief of *Advance Robotics*.

Dr. Kosuge is an AdCom member of the IEEE Robotics and Automation Society.