

Development of Moment Assist and System Weight Compensation Control for Wearable Walking Assist System

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ABSTRACT

With the aim of realizing a “user-friendly walking assist system” to support the lifestyles of elderly persons, a new assist control method was developed that combines assist functionality for the user with system weight compensation.

Different computational processing models were developed for the user and the unit. A processing method was proposed in which inverse dynamics analysis is used to calculate the assist moment from user processing and the system weight compensation from unit processing. A floor reaction force for the system weight compensation processing method was established to allow system weight compensation control. A high degree of stability in the vector orientation of the floor reaction force for system weight compensation was shown in tests. In addition, this method enables estimation of the user’s floor reaction force vector by applying the user’s dynamics model. Thus, it was shown that there are good prospects for the realization of a user-friendly walking assist system that does not employ floor reaction force sensors in the system.

1. Introduction

It is predicted that the aging of Japanese society will continue to increase in pace in the future. The elderly tend to withdraw from participation in society when they begin to lose confidence in their health or physical strength⁽¹⁾. Taking this social background into consideration, Honda is seeking to contribute to supporting the lives of the elderly by conducting research on a wearable walking assist system that reduces the load on the body during movement. Prioritizing the comfort of the user, the goal of the research is to realize a “user-friendly walking assist system.” Research to date has focused on enabling the motion of the system to follow the user’s intentions, and has sketched an outline of a system using a proposed joint moment assist method that estimates joint moment as the user is moving and provides assist power depending on the estimated joint moment⁽²⁾.

In an attempt to increase the user-friendliness of the system, the goal of the research discussed in this paper was to help prevent the user from having to support the

weight of the system, through the development of a new control method that enables the weight of the system to be compensated at the same time as assist is provided to the user.

2. Conventional Methods and Associated Issues

The use of inverse dynamics analysis^{(2), (3)} and the use of measurements of the electromyography (EMG) of the joints⁽⁴⁾ are the two standard control methods used in joint moment assist. The method using inverse dynamics analysis⁽⁵⁾ roughly models the user using a rigid body link model. Based on this model, the method uses translation motion Eq. (1) to calculate the force on the distal end of the user’s legs (i.e. the floor reaction force) and the reaction forces on the user’s ankle, knee, and hip joints, in that order. Using these joint reaction forces, the method employs a rotational motion equation to calculate the moment of the user’s ankle, knee, and hip joints. Assist is provided to the joints based on these joint moments.

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$$\begin{aligned} \mathbf{F}_{foot_distal} &= \mathbf{Frf} \\ \mathbf{F}_{n_proximal} &= m_n(\ddot{\mathbf{u}}_{n_G} + \mathbf{G}) - \mathbf{F}_{n_distal} \\ \mathbf{F}_{n+1_distal} &= -\mathbf{F}_{n_proximal} \end{aligned} \quad (1)$$

$\mathbf{F}$: Force vector on ends of links

$\mathbf{Frf}$: Floor reaction force vector

$\mathbf{u}_G$: Vector at position of center of gravity

$\mathbf{G}$: Vector of acceleration due to gravity

m : Mass

n : Link number

distal: Distal end (Link end furthest from hips)

proximal: Proximal end (Link end closest to hips)

This method requires multiple sensors to determine the floor reaction force vector and the direction of the center of gravity to be used in Eq. (1). These sensors should be positioned in the user's shoes and on the system body. A number of issues should therefore be addressed before this method can be used in practice, including optimization of the shape of the sensors, and their miniaturization, to attempt to help prevent them from causing discomfort to the user.

The other method, which measures the electromyography of the user's muscles, estimates muscular tension from electromyography and provides joint assist on that basis. This method requires EMG sensors to be directly applied to the user's skin, and the issues here are to develop EMG sensors that place a minimal burden on the user, and to determine an appropriate method of placing the sensors.

Whichever method is used, to further reduce the burden on the user, it is important to attempt to help

prevent the user from having to support the weight of the unit. A control method that has been developed to reduce the burden on the user when shifting loads from place to place⁽⁶⁾ represents one example of the use of control for system weight compensation. This system switches between a dynamic mode, when supporting one leg (single support), and a static mode, when supporting both legs (double support). The issues in this system are to achieve continuity when switching between modes, and to enable compensation for dynamic motion, even when the system is providing double support.

3. A User-friendly Assist Method

Figure 1 shows the relationship between joint moment assist and the user. When the user moves, the nerves in his or her brain and spinal cord send signals causing the

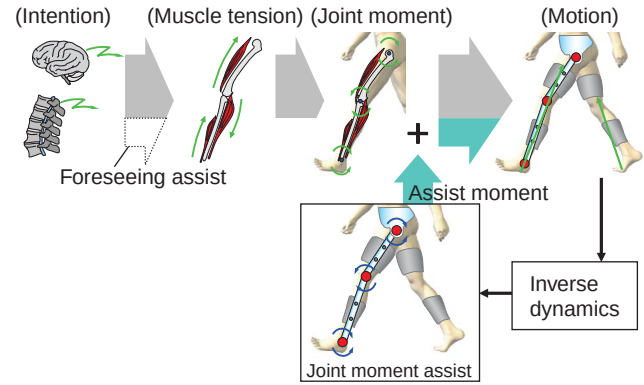


Fig. 1 Human intention and moment assist

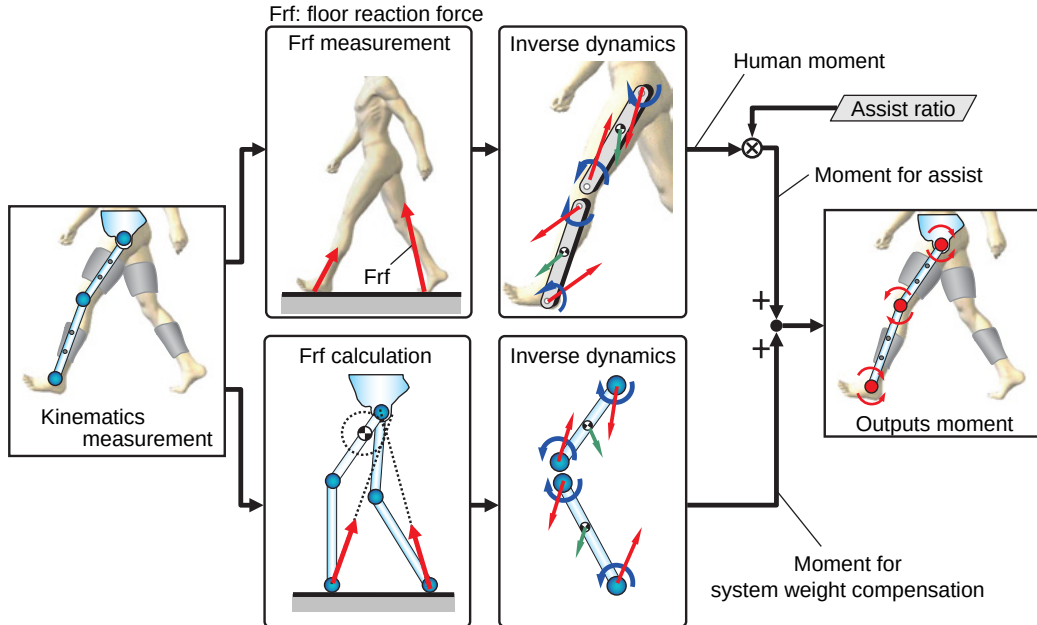


Fig. 2 Assist and system weight compensation

muscles to contract. This force of contraction generates a rotational moment around the axis of the joint, and the joint moves. The joint moment is considered to reflect the intention of the user. If this joint moment could be determined by inverse dynamics analysis, and assist moment provided on this basis, it would enable the system to move as the user intended. Furthermore, balancing this joint moment assist with system weight compensation would produce a user-friendly assist system.

One potential method of achieving this would be to regard the user and the system as an integrated whole, and to apply inverse dynamics analysis using a dynamics model incorporating physical properties, including the mass and moment of inertia of the thigh and shin, in order to calculate actuator output values that include compensation for the weight of the unit. However, when the physical characteristics of the system and the user (position of center of gravity of joints, etc.) differ in this integrated dynamics model, assist and system weight compensation cannot be accurately controlled. Given this, in order to realize a form of system weight compensation control suited to a walking assist system, this research proposes a method in which the user and the system are considered separately, separate dynamics models are defined, and inverse dynamics analyses conducted for each.

The flow of this control method is shown in Fig. 2. There are two flows: The “user-side” calculation that determines the assist moment to be provided to the user, and the “system-side” calculation that determines the moment for system weight compensation. In order to estimate the user’s joint moment, in the user-side, flow sensors are first used to determine the floor reaction force received by the user’s leg from the ground, and inverse dynamics analysis is conducted using this floor reaction force and motion data (the angle of the user’s joints, etc.). The joint moment obtained from this calculation is multiplied by a proportion between 0 and 1 to determine the assist moment.

To calculate the moment required for system weight compensation, the system-side flow first determines the floor reaction force for system weight compensation

received by the leg section of the system from the floor, and conducts inverse dynamics analysis using this floor reaction force and motion data (the angle of the joints in the unit, etc.).

The addition of the assist moment and the system weight compensation moment determined in this way gives the target value for the actuator output moment.

4. Calculations for System Weight Compensation

4.1. Dynamics Model and Coordinate System

For dynamics calculations, the system is considered to be made up of rigid body links. As Fig. 3 shows, calculations use a seven-link model considered separately from the user, consisting of hip, right thigh, left thigh, right shin, left shin, right foot, and left foot links.

A body-fixed coordinate system (BCS) centered on the system is employed in the calculations. The point of origin of this coordinate system is the center point of the hip joints of the system. The z axis is extended in the proximal direction of the hip link, the y axis is extended to the right, and the x axis is extended in the direction of the cross product of the z and y axes. The BCS is a non-inertial coordinate system⁽⁷⁾ capable of rotational and translational motion, and uses the equation of motion shown as Eq. (2) for rotational motion. Equation (3) is used for translational motion. The coriolis and centrifugal forces generated by the rotation of the coordinate system are low, compared to the translational inertia in this translational motion equation, and these forces are therefore not considered.

$$I \times \dot{\omega} = M - I \times \dot{\omega}_0 \quad (2)$$

$$m \times \ddot{u}_G = F - m \times acc_0 \quad (3)$$

I : Moment of inertia

m : Mass

M : Moment

F : Translational force

ω : Angular velocity

ω_0 : Angular velocity of coordinate system

acc_0 : Acceleration of point of origin of coordinate system

Absolute coordinate systems were not used for any of the equations in this research; all equations were defined in terms of non-inertial coordinate systems.

This makes data on angles from the vertical unnecessary, and enables a system to be constructed without the use of sensors to measure the direction of the force of gravity.

4.2. Calculation of System Floor Reaction Force required for System Weight Compensation

4.2.1. Concept of system weight compensation floor reaction force

System weight compensation should not require any

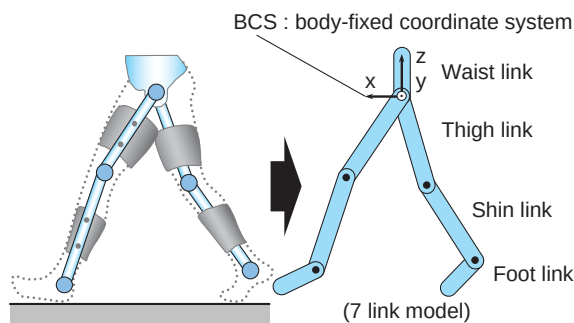


Fig. 3 Link modeling of system

force from the user, and should function under static and dynamic operating conditions. The floor reaction force required for this type of operation is termed the system weight compensation floor reaction force.

When only one leg is being supported, a unique floor reaction force can be determined dynamically, if data on the movement of the system as a whole is available. However, as three examples in Fig. 4 show, when two legs are being supported, while the resultant force remains the same, there are an infinite number of combinations of the floor reaction force between the left and right legs. Given this, it was decided that new constraint conditions for the floor reaction force should be set.

4.2.2. Issues in previous method of calculation of floor reaction force

As Fig. 5 shows, in the initial method of calculation of floor reaction force⁽²⁾, the floor reaction force vector during single support was calculated from acceleration data for the entire system. A constraint condition was applied during double support, in which the floor reaction force vector was considered to be moving in the direction of the center of gravity of the entire unit. However, when the entire unit is displaying angular acceleration motion around the center of gravity, the floor reaction force vector

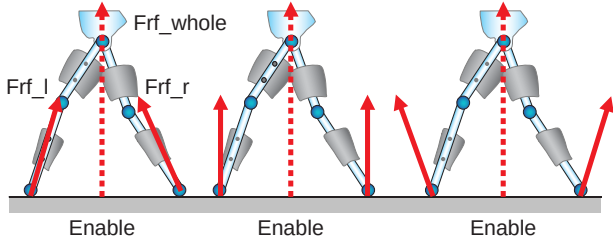


Fig. 4 Three examples of numberless floor reaction force patterns

should have a moment arm in relation to the center of gravity, and therefore the direction of the floor reaction force vector during double support was inaccurate.

In addition, because of this inaccuracy, the direction of the floor reaction force vector was discontinuous when the system switched between single and double support. It was possible, as a result, that the system would not be able to compensate for its weight, and that the user would experience a feeling of discontinuity.

The direction of the floor reaction force vector also fluctuated during single support. This is conjectured to have been because variations in the results of the second-order differential equations, used to determine the acceleration of each link position, affected the acceleration data for the system as a whole, resulting in instability in the direction of the floor reaction force vector.

4.2.3. Constraint condition for floor reaction force vector that considers angular acceleration motion

In order to address the issues relating to the constraint condition in the previous calculation method, a constraint condition was proposed in which the system weight compensation floor reaction force vector had a moment

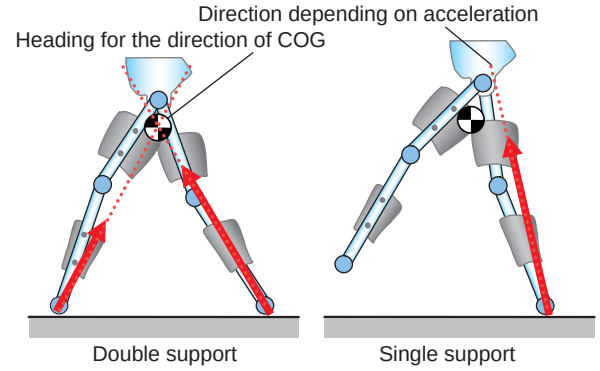


Fig. 5 Previous calculation method

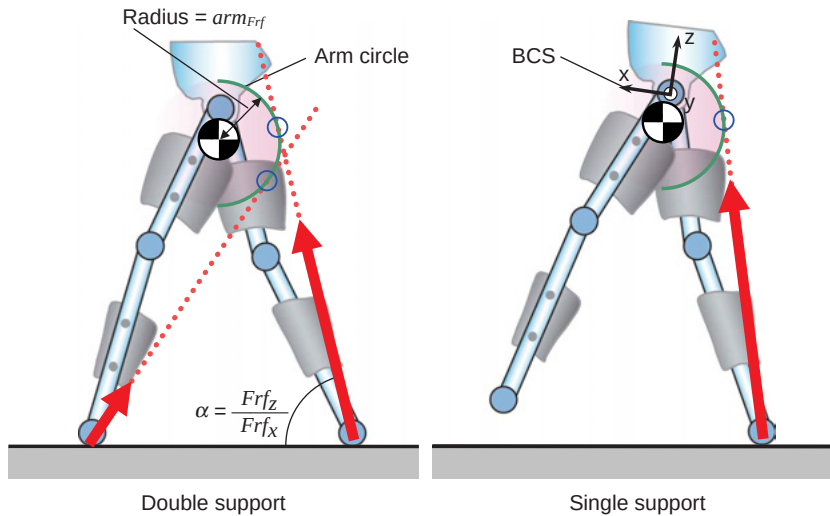


Fig. 6 Constraint of floor reaction force vector

arm in relation to the center of gravity. As Fig. 6 shows, the constraint condition operates within a two-dimensional plane extending from the x and y axes of the BCS. The constraint condition applied is contact between the system weight compensation floor reaction force vector and an arm circle within this plane, with the center of gravity of the system as its center and the moment arm as its radius. When angular acceleration motion is moving forward, the vector contacts the rear of the arm circle; when angular acceleration motion is moving backwards, the vector contacts the front of the arm circle. The moment arm is calculated from Eq. (4), which is based on the principle that a change in the degree of angular momentum is equivalent to the impulse moment during the change, and Eq. (5), based on the law of inertia.

$$\frac{d^{BCS}L_{whole}}{dt} = arm_{Frf} \cdot |^{BCS}\mathbf{Frf}_{whole}| \quad (4)$$

$$^{BCS}\mathbf{Frf}_{whole} = m_{whole} \cdot (^{BCS}\ddot{\mathbf{u}}_{whole_G} + ^{BCS}\mathbf{acc}_{BCS_o}) \quad (5)$$

L_{whole} : degree of angular motion of system around system center of gravity

arm_{Frf} : Moment arm of floor reaction force vector in relation to system center of gravity

$^{BCS}\mathbf{Frf}_{whole}$: Comprehensive reaction force vector from perspective of BCS

Application of this constraint condition to both single and double support would make the floor reaction force vector continuous when switching between the modes. In addition, it also possesses the benefit of making the floor reaction force vector during single support stable.

4.2.4. Calculation of moment arm for floor reaction force vector

As Eq. (6) indicates, the change over time in the degree of angular motion around the center of gravity of the system is expressed as the sum of the rotational inertia force generated by the rotation of the links, and the rotational inertia force generated by the revolution of the links around the system center of gravity.

$$\frac{d^{BCS}L_{whole}}{dt} = \sum_n \left\{ I_n \cdot (^{BCS}\dot{\omega}_n + ^{BCS}\dot{\omega}_{BCS})_y \right\} + \sum_n \left\{ m_n \cdot arm_{n_acc} \cdot |^{BCS}\ddot{\mathbf{u}}_{n_G} - ^{BCS}\ddot{\mathbf{u}}_{whole_G}| \right\} \quad (6)$$

$^{BCS}\dot{\omega}_n$: Angular acceleration vector of nth link from perspective of BCS

$^{BCS}\dot{\omega}_{BCS}$: BCS angular acceleration vector

arm_{n_acc} : Moment arm of acceleration vector of nth link in relation to system center of gravity

$^{BCS}\ddot{\mathbf{u}}_{n_G}$: Acceleration vector of nth link from perspective of BCS

$^{BCS}\ddot{\mathbf{u}}_{whole_G}$: Acceleration vector of system center of gravity from perspective of BCS

As Fig. 7 shows, arm_{n_acc} in Eq. (6) is the moment arm of the acceleration vector of the center of gravity of link n around the center of gravity of the system. The parallelogram shown in Fig. 7 is formed from the vector of the position of the center of gravity of the link, from the perspective of the center of gravity of the system and the acceleration vector of the position of the center of gravity of the link from the perspective of the center of gravity of the system. Because the acceleration vector moment arm corresponds to the height of the parallelogram when the acceleration vector is taken as its base, arm_{n_acc} can be calculated from Eq. (7).

$$arm_{n_acc} = \frac{|(^{BCS}\mathbf{u}_{n_G} - ^{BCS}\mathbf{u}_{whole_G}) \times (^{BCS}\ddot{\mathbf{u}}_{n_G} - ^{BCS}\ddot{\mathbf{u}}_{whole_G})|}{|^{BCS}\ddot{\mathbf{u}}_{n_G} - ^{BCS}\ddot{\mathbf{u}}_{whole_G}|} \quad (7)$$

Inputting arm_{n_acc} determined in this way for all the links in Eq. (6) and inputting the result and the comprehensive floor reaction force vector calculated in Eq. (5) in Eq. (4) gives the floor reaction force vector moment arm, arm_{Frf} .

4.2.5. Formularization of floor reaction force vector

During single support, the floor reaction force vector contacts the arm circle discussed above, and the magnitude of the vector is assumed to be the magnitude of the comprehensive floor reaction force vector, $^{BCS}\mathbf{Frf}_{whole}$. Equation (8), which enables calculation of floor reaction force during right leg support, can be obtained based on these conditions. A similar equation is used for left leg support.

$$\begin{aligned} ^{BCS}Frf_{R_x} &= |^{BCS}\mathbf{Frf}_{whole}| \cdot \cos(\tan^{-1}\alpha_R) \\ ^{BCS}Frf_{R_z} &= |^{BCS}\mathbf{Frf}_{whole}| \cdot \sin(\tan^{-1}\alpha_R) \\ ^{BCS}Frf_{L_x} &= 0 \\ ^{BCS}Frf_{L_z} &= 0 \end{aligned} \quad (8)$$

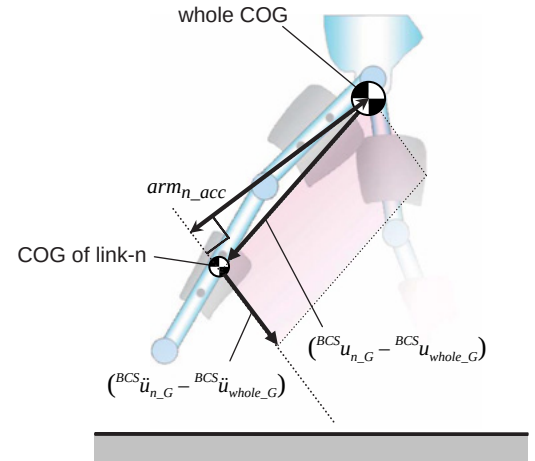


Fig. 7 Moment arm of link acceleration

${}^{BCS}Fr_{R,x}$: x component of floor reaction force vector for right leg

α_R : Inclination of floor reaction force vector ($Fr_{f,z}/Fr_{f,x}$) (See Fig. 6)

In the same way, during double support, both the right and left floor reaction force vectors contact the arm circle, and the sum of the x components of the right and left floor reaction force vectors and the sum of the z components of the right and left reaction force vectors are equivalent to each component of the respective comprehensive floor reaction forces (${}^{BCS}Fr_{f,whole}$). Equation (9), which enables calculation of each component of the floor reaction force vector, can be obtained from this condition.

$$\begin{aligned} {}^{BCS}Fr_{R,x} &= \frac{{}^{BCS}Fr_{f,whole,z} - \alpha_L \cdot {}^{BCS}Fr_{f,whole,x}}{\alpha_R - \alpha_L} \\ {}^{BCS}Fr_{R,z} &= \frac{\alpha_R \cdot {}^{BCS}Fr_{f,whole,z} - \alpha_L \cdot {}^{BCS}Fr_{f,whole,x}}{\alpha_R - \alpha_L} \\ {}^{BCS}Fr_{L,x} &= \frac{{}^{BCS}Fr_{f,whole,z} - \alpha_R \cdot {}^{BCS}Fr_{f,whole,x}}{-\alpha_R + \alpha_L} \\ {}^{BCS}Fr_{L,z} &= \frac{\alpha_L \cdot {}^{BCS}Fr_{f,whole,z} - \alpha_R \cdot {}^{BCS}Fr_{f,whole,x}}{-\alpha_R + \alpha_L} \end{aligned} \quad (9)$$

The y component of the floor reaction force vector is calculated in the same way, using a two-dimensional plane extending from the y and z axes of the BCS.

4.2.6. Results of calculation of system weight compensation floor reaction force

Figure 8 shows the results of calculations of the system weight compensation floor reaction force for an experimental system fitted with acceleration and angular velocity sensors at the hips. The horizontal axis shows time, and the vertical axis shows the angle of inclination of the floor reaction force vector. Using the previous system (results shown as the fine line in the graph), in which the direction of the system weight compensation floor reaction force vector was determined from

acceleration data, fluctuations can be observed during single support, and there is discontinuity when the system switches between single and double support. By contrast, the results obtained using the method developed in this research (bold line in the graph), which considers the moment arm of the system weight compensation floor reaction force vector, are stable and do not display fluctuations. In addition, the direction of the vector is continuous when switching between single and double support. This demonstrates that the method possesses sufficient performance as a method of calculating the floor reaction force for system weight compensation.

In addition, the application of the method to a dynamics model of the user enables calculation of the floor reaction force vector for the user. This makes a floor reaction force sensor, as employed in the previous assist method, unnecessary and thus brings the realization of a user-friendly walking assist system closer.

5. Conclusion

A control logic that balances the provision of assist for walking and system weight compensation has been developed in order to realize a user-friendly walking assist system that will contribute to the lives of the elderly. The main details of this development can be summarized as follows:

- (1) A calculation method has been proposed in which the user and the system are considered separately and separate inverse dynamics analyses are used to calculate the assist moment for the user and the system weight compensation moment for the system.
- (2) A method of calculating the floor reaction force required for system weight compensation has been developed. This method enables system weight compensation for both rotational and translational motion. Tests showed that the direction of the system weight compensation floor reaction force that is generated by the calculation method is highly stable. The application of the method enables the floor reaction force vector, received by the user's

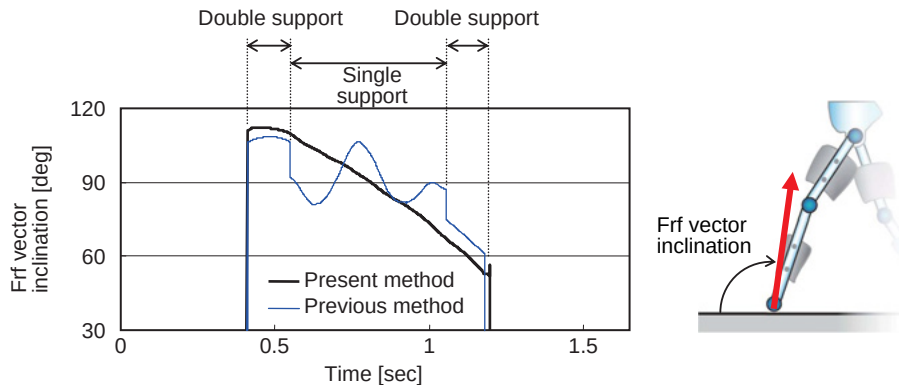


Fig. 8 Result of floor reaction force calculation

leg, to be estimated, thus eliminating the requirement for a floor reaction force sensor, bringing the realization of a user-friendly walking assist system closer to reality.

6. Afterword

Prioritizing user comfort, Honda is attempting to develop a user-friendly walking assist system. The research discussed in this paper has proposed a method that enables the system both to provide assistance and compensate for its own weight. By refining the calculation methods employed, this research has attempted to further reduce the burden on the user.

The author is committed to continuing research on a walking assist system that prioritizes user comfort, in an attempt to make it easier for the elderly and others in need of assistance to participate in society.

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