Development of Adaptive Gait Assist Algorithm Using Ground Reaction Force

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Abstract: Nowadays, physical assistant robots are considered as a solution against aging of society. Especially, it is essential to support the elderly to walk because walking is an important activity of the daily life. However, the physical assistant robot is required to adapt to the change of motion of the wearer for being used in the daily living environment. Our research aims to develop an adaptive walking assist algorithm which can follow the change of motion of the wearer smoothly. Instead of measuring the joint torque of the wearer directly, pattern of ground reaction force was used to estimate the joint torque based on the hypothesis that the wearable robot can adjust assist timing and assist torque using a ground reaction force as the input signal. The result of the walking experiment, which utilized the adaptive gait assist algorithm, suggested that the change of gait motion strongly differed among individuals. Also the assist improved gait parameters of some subjects, it was not effective for the subject who was not accustomed to the assist robot.

Keywords: Physical assistant robot, Assist algorithm, Gait motion

1. INTRODUCTION

Aging of society is a common social problem among many countries. The gait ability, such as muscle strength, reaction time, and sense of balance decreases with aging. Thus, the elderly sometimes gradually becomes inactive.

Physical assistant robots potentially improve the quality of life of such elderly people through assisting their gait motion and enhancing their daily living activities. Thus, recently, the usage of the physical assistant robot is spreading from the rehabilitation in the hospital to the daily living environment. However, the variety of motion required in the daily living environment is much larger than that in the hospital. For example, up and down stairs, curving, and stopping are frequently required in the daily life. Furthermore, probably, the gait timing is not stable owing to the various perturbations even during normal walking. Thus, the gait assist algorithm is required to adapt to the change of gait timing during gait.

There are some methods to sense or anticipate the intention of the wearer. To embed the encoder to the robotic joint is a basic method. However, this method can be used only when the wearer can move the joint by themselves. Thus, the assist algorithm, which also affects the joint motion, should not be so complex and strong for the safety. To attach the force or torque sensor to the joint is another method. It can observe the intention of the wearer more directly through measuring interaction force or torque between the wearer and assist robot. GRF (ground reaction force) is another measure to monitor the motion of the wearer. It can be used not only to estimate the intention of the wearer but also the balance of the body through monitoring the position and motion of the center of pressure.

In this study, the adaptive gait assist algorithm, which can follow the change of gait timing of the wearer, is developed for the gait assist in the daily living environment. Although the joint torque of the wearer is an accurate signal of gait motion, it is not general for the assist robot to measure the joint torque directly. Instead, GRF, which the assist robot sometimes monitors using pressure sensing sole for gait evaluation, was used to detect the gait timing and estimate the joint torque.

2. DESIGN OF ASSIST ALGORITHM

The assist algorithm, which aimed to assist hip and knee joints during stance phase in the sagittal plane, was developed. The overview of the timing and magnitude of the assist torque applied to each joint is displayed in Fig. 1. Pattern of assist torque was determined based on the gait cycle, which was the time period between successive heel contacts (HC) of the leg. Furthermore, stance phase, which generally started from 0% and ended

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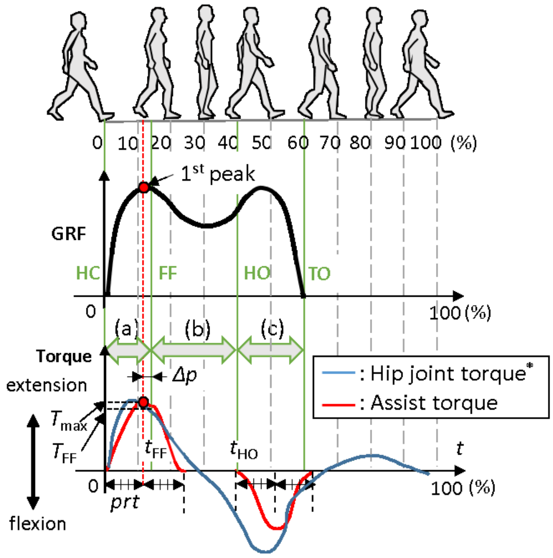

Fig. 1. Pattern of GRF and assist torque applied to hip joint (* Hip joint torque is cited from Winter DA et.al(1996))

Fig. 2. MALO : Motor Actuated Lower-limb Orthothis

at approximately 60%, was separated to three phases as follows using gait events. The period from HC to foot flat (FF) was determined as phase (a). Then, phase (b) continued to heel off (HO). The residual phase, which ended at toe off (TO) was determined as phase (c). Gait events, which separate these phases, were detected based on GRF in normal direction.

The target of the gait assist during phase (a) was to absorb the impact of HC and support body weight. Thus, the assist torque helped the extension of both hip and knee joints. In contrast, during phase (c), the assist torque was applied to help hip and knee flexion, which were the pre-swing before swing phase. phase (b) was the phase which connected neighboring phases smoothly.

Formulae, which calculated the assist torque in direction to the joint extension, T, of each phase, were determined as equations (1)-(3). t, which is the gait phase in %, is the parameter of these formulae. t_{FF} and t_{HO} are the gait phase which separate assist phases. $GRF(t)$ is the GRF of stance leg at t. Tt is the maximum value of assist torque expressed in Nm. They were set at 20.0 Nm for hip joint and 11.7 Nm for knee joint, which are the capacity of motors. BW is the summation of the weight of the wearer and MALO. prt is the time duration from HC to the peak of GRF. Δp is the time distance from prt to t_{FF}. Then, T_{FF} is the torque in Nm exerted at the beginning of phase (b), which is same as the torque applied at the end of phase (a). Furthermore, T_{max} is the maximum assist torque exerted during phase (a). These parameters were indicated in Fig. 1.

$$T(t) = Tt \times \frac{GRF(t)}{BW} \tag{1}$$

$$T(t) = T_{FF} \times \cos^2\left(\frac{t - t_{FF}}{prt - \Delta p}\frac{\pi}{2}\right) \tag{2}$$

$$T(t) = -0.9T_{max} \times \sin^2\left(\frac{t - t_{HO}}{prt}\frac{\pi}{2}\right) \tag{3}$$

As suggested in equation (1), this algorithm is based on the hypothesis that the required assist torque is correlated to GRF. In this hypothesis, GRF is related to the joint torque which supports the body weight in the stance phase. Perhaps, it is better to tune Tt of each joint for each wearer although it was set according to the limitation of actuator in this study.

Although the assist algorithm anticipates the typical shape of GRF pattern drawn in Fig. 1, it varies among individuals. Thus, the developed algorithm determines the target value and timing of successive assist phases using the shape of GRF of phase (a), whose GRF shape becomes similar among individuals.

3. EXPERIMENT OF ASSISTED WALKING

The experiment was performed with the permission of the institutional review board of Nagoya University.

Three healthy young males were participated in the experiment of assisted walking. The developed algorithm was installed to a lower limb assist robot named MALO (Motor Actuated Lower-Limb Orthosis), which was developed in our lab. The overview of MALO is shown in Fig. 2. MALO is attached to the wearer using cuffs of thigh and shank, shoes, and corset. Hip, knee, and ankle joints are only capable of rotating in the sagittal plane. Actuators (RE 40, Maxon Motor AG, Sachseln, Switzerland) are attached to both hip and knee joints to apply assist torque. To measure GRF of toe and heel part of each foot, mobile force plates (M3D, Tec Gihan Co., Ltd., Kyoto, Japan) are fixed under the sole of MALO.

To stabilize the gait timing of subject among trials, a metronome, which was adjusted to the comfortable frequency of each subject, was used. Furthermore, to test the adaptability of the assist algorithm to the various gait timing, slow condition, whose frequency decreased by 6% from the comfortable frequency, was also used. This condition covered the range of walking speed in the daily living environment.

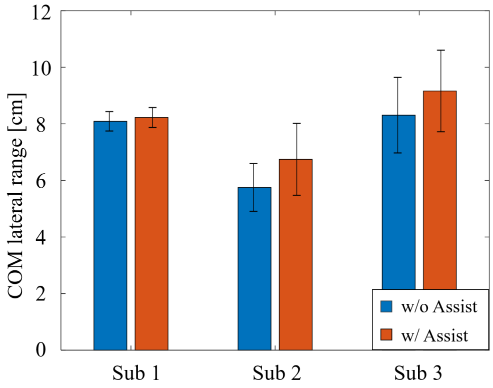

Fig. 3. CoM lateral range (Normal)

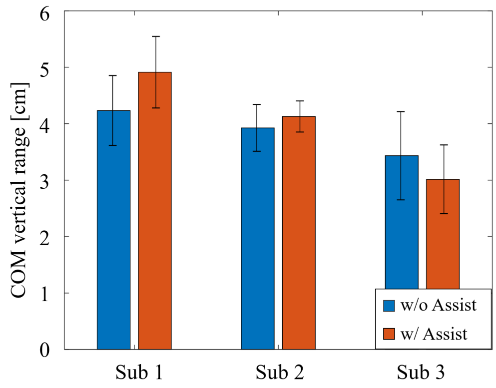

Fig. 4. CoM vertical range (Normal)

The gait motion of these two gait speeds were recorded under the conditions with and without gait assist. For all subjects, normal speed trials were recorded at first. Then, slow speed trials were recorded. The order of assisted and not assisted trials were randomized for each subject. Trials of each condition were recorded eight times. Thus, in total, 32 trials were recorded for each subject.

The gait motion in the walking lane, whose length was 3 m except for the acceleration and deceleration area, was recorded using motion capture system (MAC 3D System, Motion Analysis Corp., Rohnert Park, CA, US). The angle of hip and knee joints and the position of the CoM (center of mass) were calculated from the human mode fitted to markers attached to the subject.

4. RESULT

Representative gait parameters of each subject under each condition are shown in table 1. Although the gait timing was controlled by the metronome, it varied approximately 1 to 2 strides/min. The result suggested that there were strong individual difference among subjects against the assist. Although the assist torque was applied, the walking speed decreased in the normal case of subject 3. In this condition, stride length also decreased. However, in the slow speed condition, this trend was disappeared from the subject 3.

Then, CoM sway, which is determined as the range of motion of CoM in the lateral direction of each gait cycle, is shown in Fig. 3. The result suggested that the CoM motion increased in assisted condition except for subject 1 in normal speed. In contrast, the CoM sway of subject 3 decreased in the assisted condition in slow speed. However, the trend of CoM range in vertical direction did not match to the CoM sway as shown in Fig. 4.

The maximum and minimum angle of hip joint of each gait cycle is shown in Fig. 5. This trend of peak angle suggested that the maximum angle increased in the assisted condition through all subjects. Furthermore, the maximum knee angle also increased in the assisted condition as shown in Fig. 6.

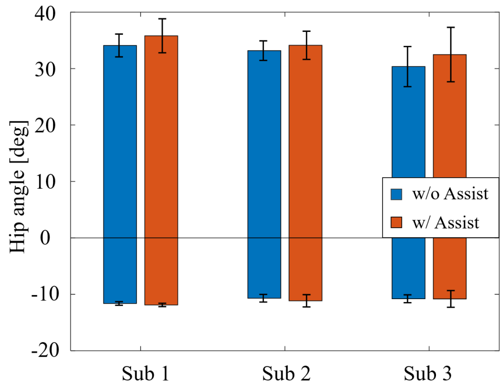

Fig. 5. Maximam and minimam hip angle (Normal)

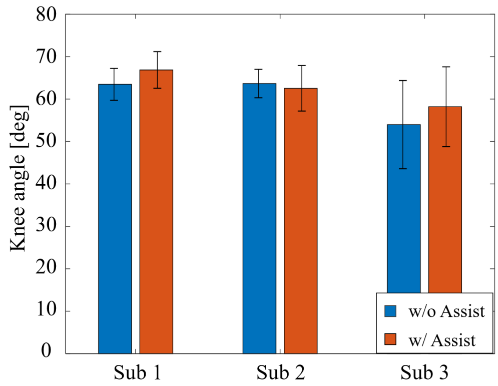

Fig. 6. Maximam knee angle (Normal)

5. DISCUSSION

According to table 1 and Fig. 5, it seems that gait assist improved gait parameters of subjects 1 and 2. The CoM range in vertical direction shown in Fig.4 is consistent to the maximum hip angle, because the CoM height becomes minimum when the leg maximally opens. However, the assist torque slightly affected on some parameters. Perhaps, it is necessary to tune parameters of assist algorithm such as Tt and prt shown in equations (1)-(3) to increase the

Table 1. Walking parameter

		Normal		Slow	
		w/o Assist	w/ Assist	w/o Assist	w/ Assist
Walking speed [m/s]	Sub1	1.08 ±0.05	1.12 ±0.07	0.91 ±0.03	0.95 ±0.04
	Sub2	0.92 ±0.04	1.00 ±0.08	0.89 ±0.04	0.94 ±0.06
	Sub3	0.77 ±0.04	0.72 ±0.07	0.89 ±0.04	0.94 ±0.06
Walking speed [strides/min]	Sub1	49.9 ±1.1	48.0 ±1.2	47.7 ±1.1	47.8 ±1.1
	Sub2	46.2 ±1.8	47.2 ±1.4	45.5 ±1.9	47 ±2
	Sub3	43.7 ±1.2	42.9 ±0.7	41.9 ±0.9	41.0 ±1.1
Stride length [cm]	Sub1	130 ±7	141 ±9	114 ±6	120 ±6
	Sub2	123 ±4	125 ±9	121 ±4	120 ±4
	Sub3	124 ±9	119 ±9	130 ±10	132 ±5

assist torque. Furthermore, it is an option to expand the assist phase to the swing phase.

The increase of CoM sway of assisted condition shown in Fig. 3 suggested that this gait assist did not contribute to improve gait balance in lateral direction. However, according to table 1 and Fig. 3, the gait parameters and CoM sway was changed in an opposite way among subjects. For example, CoM sway of subject 1 slightly increased in the assisted trials whereas the walking speed and stride length increased. In contrast, the improvement of gait parameters of subject 2 and 3 was not large whereas the CoM sway increased. This difference of the change of gait motion among subjects suggested the large individual difference against the assist robot. Perhaps, the adaptation of each subject to the robot affected the gait motion because the subject 1, whose gait motion improved in the assist trials than the other subjects, was accustomed to MALO.

6. CONCLUSION

The adaptive gait assist algorithm, which can fit to the daily living environment, was developed in this study. Such an adaptation to the change of gait motion is essential to spread the physical assistant robot to the society. The developed assist algorithm was designed to apply assist torque to the hip and knee joints based on the pattern of GRF. GRF of each foot was used as not only to switch assist phases but also determine the magnitude of assistive torque instead of measuring joint torque directly. The change of gait motion caused by assist torque under different speeds was observed.

The peak flexion angle of hip joint increased in the assisted cases common to subjects. Furthermore, gait parameters such as walking speed and stride length improved in some subjects. In contrast, the CoM sway in the lateral direction, which probably affected the stability, increased in the assisted cases of some subjects. Considering the trend that the improvement of gait parameters and increase of CoM sway did not occur at the same time, the gait assist improved the gait of some wearer whereas it negatively affected to the other subject. The adaptation to the assist robot perhaps improves the effect of gait assist.

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