The Eighteenth International Symposium on Artificial Life and Robotics 2013 (AROB 18th '13),
Daejeon Convention Center, Daejeon, Korea, January 30-February 1, 2013

The Ground Reaction Force generation algorithm for tracking the wearer's motion

Sukwoo Lee[1], Jongwon Lee[1], Hyogon Kim[2], Jaeho Jang [2] and Sangdeok Park[2]

[1]University of Science and Technology, Republic of Korea
[2]Korea Institute of Industrial Technology, Republic of Korea
(Tel: 81-31-8040-6348, Fax: 81-31-8040-6310)

[1]sukwoo22@kitech.re.kr

Abstract: This paper explains the desired ground reaction force (GRF) generation algorithm for exoskeleton. Its key point is to generate the desired torque of exoskeleton for tracking the wearer's motion. We can obtain the torque by using the GRF when exoskeleton foot is in contact with the ground. It is not necessary to measure exerted force at contact point. It requires only simple calculation in contrast with inverse dynamics of full body. It can adapt to environment such as flat ground, stairs and uneven surfaces. We present simulation result using our two-leg model, which demonstrates the algorithm is applicable to exoskeleton.

Keywords: Exoskeleton, walking, center of pressure (CoP), zero moment point (ZMP), ground reaction force(GRF).

1 INTRODUCTION

The external forces by the surrounding environment is exerted to the locomotive system During waking. The ground reaction force (GRF) that is one of them has been used for research on control of locomotive system. Satoshi Ito and Haruhisa Kawasaki has been doing research on balance control of the legged system by the method which keeps GRF measured by the force sensor at the foot positive [1]. Since elderly people and persons with hemiplegia may be difficult to maintain balance of their bodies, a wearable lower extremity exoskeleton (LEE) which has been developing at Nanyang Technological University, Republic of Singapore maintain balance instead of wearers by using the zero moment point (ZMP) [2]. The ZMP can be obtained by the GRF measurement of exoskeleton and wearer. The above mentioned control algorithm require force sensor at the ground contact point. Without them, the system cannot adapt to the GRF. But although we install force sensors at all the ground contact point, it is causing complicated calculations because of the number of contact Jacobians. To resolve this issue, Sang-Ho Hyon proposed how to compute the commanded joint torque for a desired contact force without force sensor [3]. As this method is applicable to the exoskeleton, we explain that the method calculate desired ground reaction force for tracking wearer's motion.

2 GAIT OF EXOSKELETON

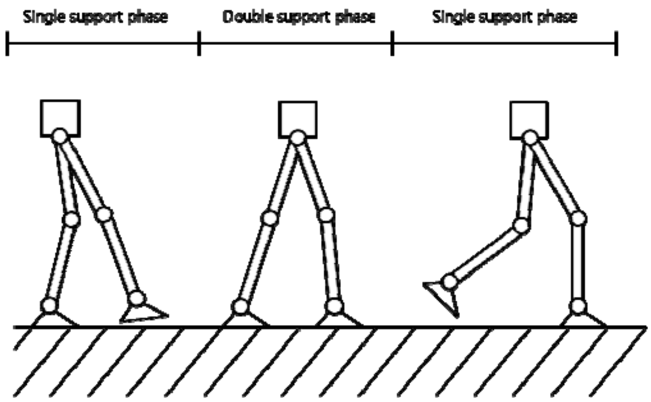

Fig. 1. Gait phases of the exoskeleton. Adapted from [5].

A walking gait of the exoskeleton like figure 1 can be divided into the single support phase and the double support phase [4]. In the single support phase, the only one leg is in contact with the ground. But in the double support phase, both legs are in contact with the ground. The two support phases take place alternately during walking.

Figure 2 shows the connection between ZMP, CoP and GRF in the single support phase. The ZMP introduced in 1968 for the first time is a concept related with dynamics and control of locomotive system [6]. It is the point where the sum of all moments of active forces is equal to zero. If the ZMP trajectory remains within the support area when the locomotive system is walking, gait of the system is stable. The support area is distinguished by the single support phase and the double support phase. In the single

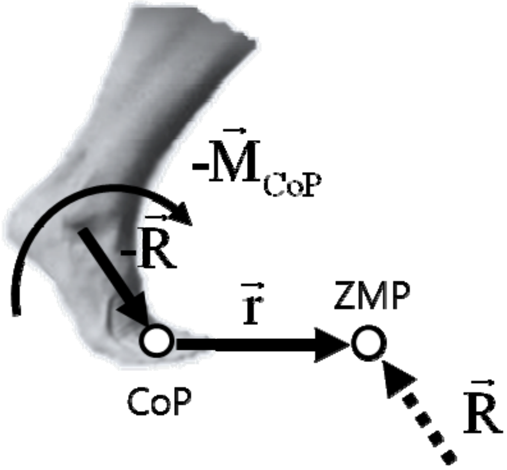

Fig. 2. ZMP, CoP and GRF. Adapted from [6].

support phase, support area is foot surface in contact with ground. In the double support phase, support area is foot surface and the distance between the two feet. And The center of pressure(CoP) is the point on the supporting surface where moment of ground reaction force is zero [7]. If the ZMP is within the support area, the ZMP coincides with CoP. In this paper, we use a concept of ZMP and CoP for calculation of GRF.

3 GRF GENERATION ALGORITHM

The object of our algorithm is to find desired ground reaction force of exoskeleton. Ahead of description of the algorithm, we have to make several assumptions. First, at least one of the feet of the exoskeleton is always in contact with the ground. Second, the acceleration of the exoskeleton seems as that of wearer because the exoskeleton tracks the motion of wearer. Third, ZMP of the exoskeleton always coincides with CoP. Forth, we do not consider swing phase.

3.1 Calculation of GRF

Figure 3 shows Forces exerted to the exoskeleton such as inertia force, gravity force and GRF. Therefore, the sum of the force is as follows:

$$\begin{aligned} \sum \vec{F} &= m\vec{a} \\ mg - \vec{R} &= m\vec{a} \end{aligned} \tag{1}$$

where m is mass of the exoskeleton, $\vec{R}$ is ground reaction force, g is the acceleration of gravity and $\vec{a}$ is the acceleration of the exoskeleton. We can determine the acceleration of exoskeleton provided that we use an accelerometer. In other words, it is possible to calculate desired GRF with accelerometer by using equation (2).

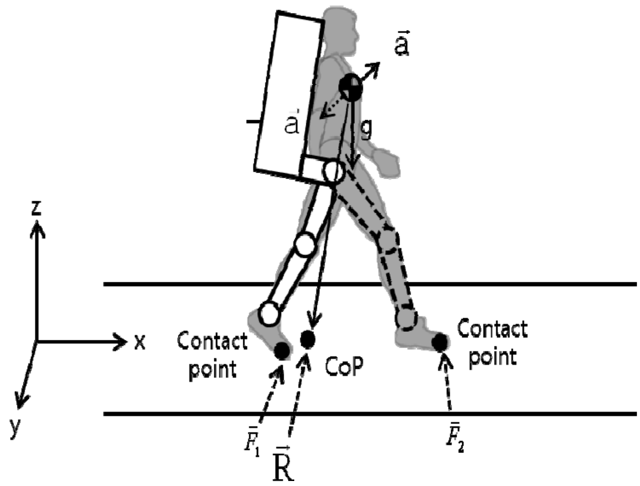

Fig. 3. Forces exerted to the exoskeleton.

$$\vec{R} = m(g - \vec{a}) \tag{2}$$

3.2. Load Distribution in Double Support Phase

In the single support phase and the double support phase, GRF is the same at the CoP of the exoskeleton. But in the double support phase, we have to do load distribution of GRF because both feet are in contact with the ground. Total GRF is sum of GRF at the contact point of feet. If we know GRF and CoP, we can derive (3)

$$\begin{bmatrix} x \\ 1 \end{bmatrix} R_z = \begin{bmatrix} x_1 & x_2 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \vec{F}_1 \\ \vec{F}_2 \end{bmatrix} \tag{3}$$

where x is distance between CoP and center of mass (CoM), $\vec{R}_z$ is the vertical GRF, x_1 and x_2 are distance between point of application of GRF at the contact point of each foot and CoM. And $\vec{F}_1$ and $\vec{F}_2$ are the vertical GRF at the contact point of feet. CoP can be calculated as

$$x = \frac{\sum_i^n x_i F_i}{\sum_i^n F_i} \tag{4}$$

But as we do not know the distributed force F_i, we could not calculate CoP. Instead, CoP can be replaced by ZMP because ZMP remain within the support area. ZMP can be calculated as

$$x_{ZMP} = \frac{m(g + \ddot{z})x - m\ddot{x}z}{m(g + \ddot{z})} \tag{5}$$

We do not consider the angular momentum around CoM. Finally, we can calculate the desired contact forces by using a GRF and ZMP as (6). Figure 4 shows Distance Between point of application of GRF and CoM.

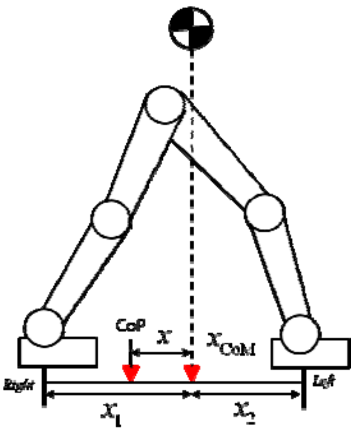

Fig. 4. Distance between point of application of GRF and CoM.

$$\begin{bmatrix} \vec{F}_1 \\ \vec{F}_2 \end{bmatrix} = \begin{bmatrix} x_1 & x_2 \\ 1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} x \\ 1 \end{bmatrix} \vec{R}_z \tag{6}$$

4 SIMULATION

In this section, the exoskeleton walking simulation on flat ground is described. We simulated two cases: the single support phase and the double support phase. Figure 5 shows how to prove the effectiveness of our algorithm. We compare GRF by the algorithm with Actual GRF. In the simulation, we used a 6-DOF model and we gave a specific desired trajectory to controller instead of human.

In the single support phase, we gave the exoskeleton model sine trajectory. Amplitude of sine trajectory was 0.1 m. Figure 6 shows result of calculation of the desired GRF. Errors of GRF by the algorithm and actual GRF was measured within about ± 0.2 N. This value represents our algorithm generates desired GRF for tracking wearer's motion.

In the double support phase, we compared GRF by the load distribution with actual GRF at the contact point. Motion trajectory in the double support phase was the same as that in the single support phase. In figure 7, we can

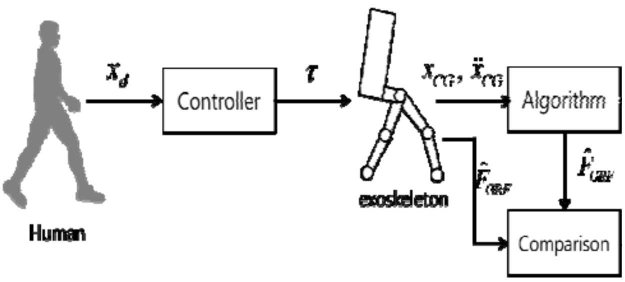

Fig. 5. Block diagram for proof of the algorithm

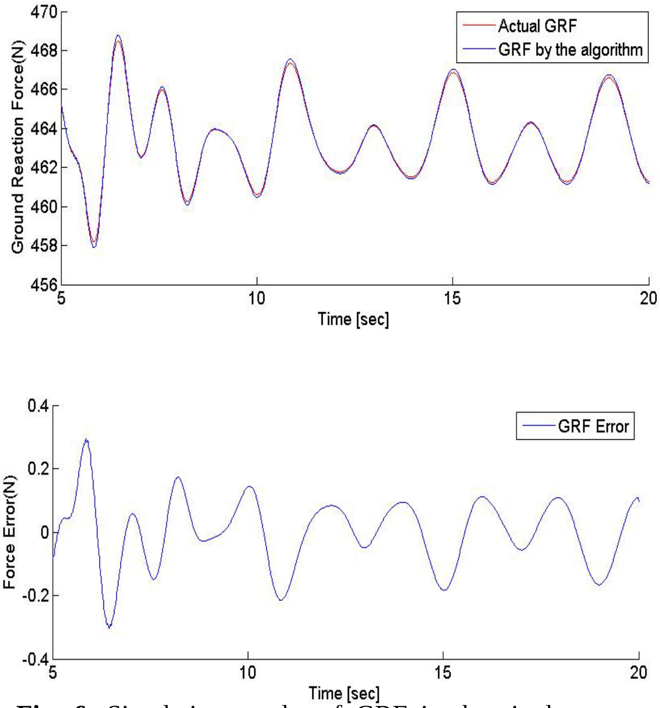

Fig. 6. Simulation results of GRF in the single support phase.

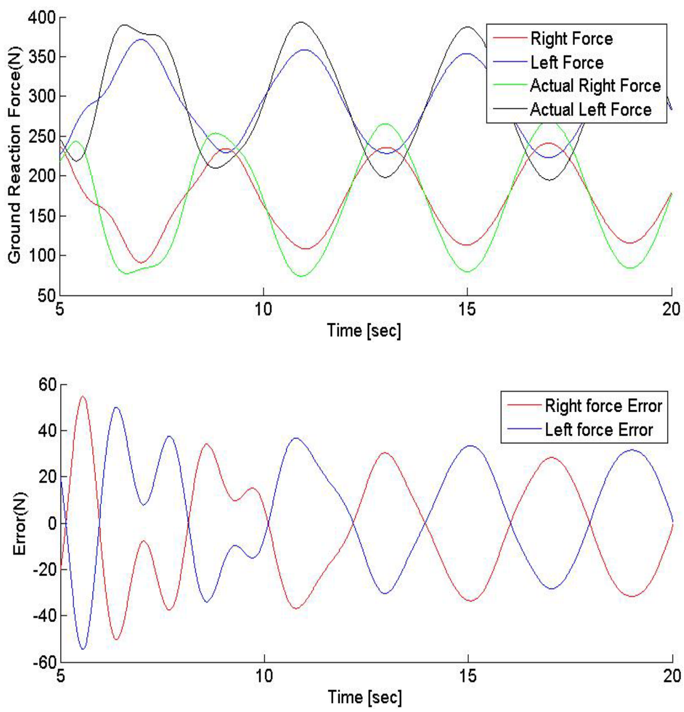

Fig. 7. Simulation results of GRF at the contact point of each foot in the double support phase.

confirm range of errors are ± 30 N. As a margin of errors is less than 10 percent, the algorithm for load distribution is applicable to the exoskeleton. Errors tend to be increased when the acceleration of exoskeleton is increased because

ZMP is affected by the acceleration. To raise the accuracy of the load distribution, more accurate ZMP model is needed.

5 CONCLUSION

This paper described the desired GRF generation algorithm for tracking wearer's motion. We demonstrated effectiveness of the algorithm with simulation experiments. The algorithm has the following benefits. First, force sensor is not required at the contact point of the exoskeleton. Second, we can calculate ground contact force regardless of number of contact point. Third, it is not necessary to solve a complicated inverse dynamics of the exoskeleton by using ZMP.

As future research, it is necessary to use accurate ZMP model for more accurate load distribution. Next, we will transform desired contact ground forces into joint torques directly. We will apply the algorithm to the actual exoskeleton.

REFERENCES

[1] Satoshi Ito and Haruhisa Kawasaki (2000), A standing posture control based on ground reaction force, Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, Takamatsu, Japan, Oct. 30 – Nov. 5, 2000, pp.1340 -1345 vol.2.

[2] K.H.Low, Xiaopeng Liu, C.H.Goh and Haoyong Yu (2006), Locomotive control of a wearable lower exoskeleton for walking enhancement, Journal of Vibration and Control, Dec 11, 2006, pp.1311-1336 vol.12

[3] Sang-Ho Hyon, Joshua G. Hale, and Gordon Cheng(2007), Full-Body Compliant Human-Humanoid Interaction: Balancing in the Presence of Unknown External Forces, IEEE TRANSACTIONS ON ROBOTICS, Saitama, Japan, Oct, 2007, pp884-898 vol.23

[4] Whittle, M. W. (2007), Gait Analysis: An Introduction, Butterworth-Heinemann, Oxford, UK. pp.54

[5] J. Rose and J.G. Gamble(1994), Human Walking 2nd ed, Boltimore, MD: Williams and Wikins

[6] Vukobratovic, M., Borovac, B. and Surdilovic, D. (2001), Zero-moment point: Proper interpretation and new applications, Proceeding of IEEE-RAS International Conference on Humanoid Robots, Tokyo, Japan, Nov 22-24, 2001, pp.135-144

[7] Phillippe Sardain and Guy Bessonnet (2004), Forces acting on a biped robot. Center of pressure-Zero moment point, IEEE TRANSACTIONS ON SYSTE MS AND HUMANS, Sec, 2004, pp. 630-637 vol.34