International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:10, No:7, 2016

Analysis of the Gait Characteristics of Soldier between the Normal and Loaded Gait

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Abstract**—**The purpose of this research is to analyze the gait strategy between the normal and loaded gait. To this end, five male participants satisfied two conditions: the normal and loaded gait (backpack load 25.2 kg). As expected, results showed that additional loads elicited not a proportional increase in vertical and shear ground reaction force (GRF) parameters but also increase of the impulse, momentum and mechanical work. However, in case of the loaded gait, the time duration of the double support phase was increased unexpectedly. It is because the double support phase which is more stable than the single support phase can reduce instability of the loaded gait. Also, the directions of the pre-collision and after-collision were moved upward and downward compared to the normal gait. As a result, regardless of the additional backpack load, the impulse-momentum diagram during the step-to-step transition was maintained such as the normal gait. It means that human walk efficiently to keep stability and minimize total net works in case of the loaded gait.

Keywords**—**Normal gait, loaded gait, impulse, collision, gait analysis, mechanical work, backpack load.

I. Introduction

THE loaded gait is an inevitable part of human walking in daily life. In particular, for soldiers, the load carriage is an indispensable part of life compared to the ordinary person. Throughout history, foot soldiers have been required to carry heavy loads compared to the past. Until about the 18th century, troops carried loads that seldom exceeded about 15 kg while they marched.

After the 18th century, auxiliary transport was de-emphasized and more disciplined armies required troops to carry their own loads. Therefore, modern soldiers often carried more equipment on the march. This is because the demand of increasing firepower and protection ability of soldiers and technological advances made individual combat equipment much heavier than in the past [1]. Nevertheless, the loaded gait of soldier was not widely studied for decades due to the complexity of the loaded gait.

Castro [2] analyzed the plantar pressure peaks and GRF among normal-weight, backpackers and obese participants. He found that the obese participants may have developed gait pattern adaptation for preventing the injury: while the backpackers seem to be more likely to have a blister as contrasted with normal-weight group.

Safikhani [3] found the effect of different backpack loading systems on trunk forward lean angle during walking. They suggested that carrying the load with counterbalance backpack allows a more upward position, by shifting the center of gravity of the load forward and this posture modification resulted in a better comfort.

Harman [4] proved how backpack load and gait speed are interconnected. It is apparent that percentage of stride in the double-support and time of toe-off increased, and maximum hip angle decreased as load increased. However, increases in the walking speed tended to cancel these adaptations. However, these previous studies have not studied about the difference of characteristics between the normal and loaded gait by the finite collision model [7], [8]. To this end, the push-off and heel strike impulses, pre-collision and after-collision momentums, center of gravity (CG), and the mechanical works of the normal and loaded gait are analyzed by the experimental data.

In Section II, the analysis methods adopted in the paper are introduced, and the result of actual experimental data is analyzed in Section III. Lastly, the concluding remarks follow in Section IV.

II. Analysis Methods

A. Subjects

Five healthy subjects trained in military more than two years participated in the experiment. Each subject walked on 12 m walk way repeatedly until getting dependable experimental data. Their mean height, weight and age were 175.59 ± 3.63 cm, 75.4±7.96 kg, and 29.6±2.5, respectively. They are informed about the experimental procedure in detail and have signed on the content form approved IRD of by KAIST.

B. Experiment and Procedure

The motion capture system (Hawk, Motion Analysis, CA, US) was used to collect the kinematic data with a frequency of 200 Hz (sampling time 0.005 s). Total three force plates (AccuGait, AMTI, MA, US) were used to obtain GRFs. The size of the military backpack is width 36 cm × length 18 cm × height 52 cm and the load was 25.2 kg. The weight is the sum of all the weight of buckets, raincoat, military boots, shovels, long underwear, combat uniforms, blankets, rifle, canteen, combat helmet, cartridge belt, MREs, Personal ammunition, socks and etc. It is assumed that the center of gravity (CG) is located on exact center of the backpack.

Total eleven reflective markers were attached on the body of subject - two on each shoulder, one on a sacral, two on each pelvic, two on each knee joint (lateral side), two on each ankle

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lateral side, two on each metatarsal (little toe). The ankle and metatarsal markers are located approximately 5 cm and 3 cm above the ground, respectively. Also, the marker of sacral is located in the upper part of the tailbone (L5 of vertebrae).

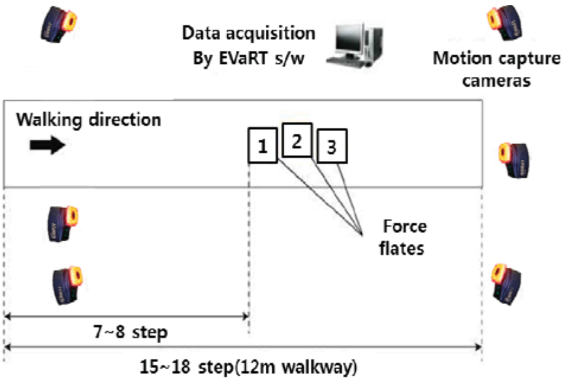


Fig. 1 Experiment setup

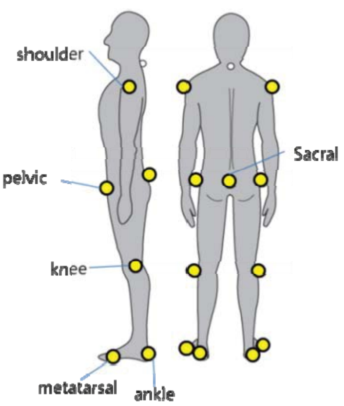


Fig. 2 Marker placement details

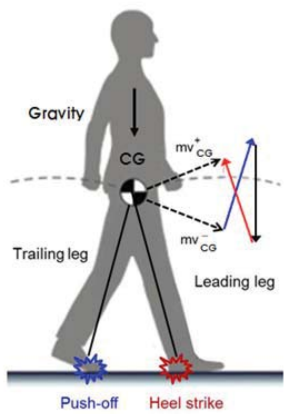


Fig. 3 Impulse-momentum diagram of the step-to-step transition process. The momentum of the CG move upward by the push-off, heel strike, and gravitational impulses during the double support phase

C. Data Analysis

The magnitudes of push-off (P*) and heel strike impulse (H*) were computed by integral of the GRFs data over the double support phase, and the gravitational impulse (G*) was calculated by mgΔt. Here, t_0 and t_f denote the time of the pre-collision and after-collision.

$$P^* = \int_{t0}^{tf} \overrightarrow{GRF}_{push} dt \quad (1)$$

$$H^* = \int_{t0}^{tf} \overrightarrow{GRF}_{heel} dt \quad (2)$$

$$G^* = \int_{t0}^{tf} mgdt \quad (3)$$

The directions of impulses were computed from the direction of average vertical and shear GRFs during the double support phase, as in (4). Here, the average GRFs were obtained by dividing each impulse by the double support time. The method to calculate the average impulse force is as shown in (5).

$$\text{Direction of P*} = \arctan\left(\frac{F_{push(y)}}{F_{push(x)}}\right)$$
$$\text{Direction of H*} = \arctan\left(\frac{F_{heel(y)}}{F_{heel(x)}}\right) \quad (4)$$

$$F_{push(x)} = \frac{\int_{t0}^{tf} GRF_x dt}{\Delta t},\ F_{push(y)} = \frac{\int_{t0}^{tf} GRF_y dt}{\Delta t}$$
$$F_{heel(x)} = \frac{\int_{t0}^{tf} GRF_x dt}{\Delta t},\ F_{heel(y)} = \frac{\int_{t0}^{tf} GRF_y dt}{\Delta t} \quad (5)$$

The mechanical works on the CG are calculated by the integration of GRFs and velocity of the CG as follows in (6). The mechanical work done by P* was computed by integration of GRFs of trailing leg, and velocity of the CG and mechanical work done by H* was computed by integration of GRFs of leading leg and velocity of the CG. Also, the mechanical work done by gravity G* was derived from integration of the scalar product of the body weight and the CG velocity. Equations of mechanical work done by each impulse are as follows.

$$\begin{cases} w_{push} = \int_{ti}^{tf} \vec{F}_{trail} \cdot \vec{v}_{CG} dt = \int_{ti}^{tf} F_y \cdot v_{y(CG)} + F_z \cdot v_{z(CG)} dt \\ w_{heel} = \int_{ti}^{tf} \vec{F}_{lead} \cdot \vec{v}_{CG} dt = \int_{ti}^{tf} F_y \cdot v_{y(CG)} + F_z \cdot v_{z(CG)} dt \\ w_{gravity} = \int_{ti}^{tf} mg \cdot \vec{v}_{CG} dt \end{cases} \quad (6)$$

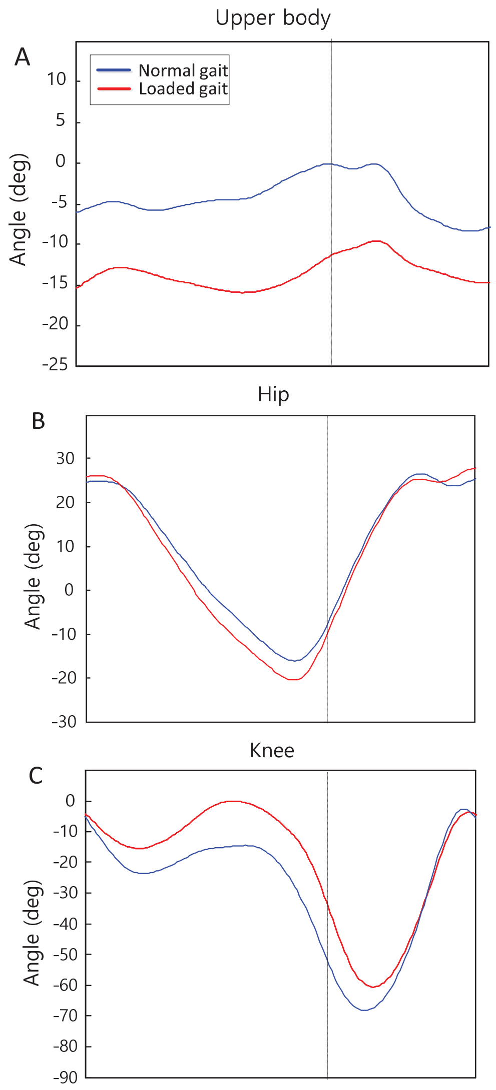
III. Result

A. Joint Angle

Joint angles of the ankle, knee, hip and waist (upper body) joint are displayed in Fig. 4. It shows some observable differences in the upper body, hip and knee angle. In case of loaded gait, subjects were apt to bend at the waist to balance the center of gravity. In the meanwhile, the peak of knee flexion angle was reduced, and swing angle of hip joint was increased conspicuously. However, there is no difference in the ankle joint angle between the normal and loaded gait.

B. Impulse Magnitude

As unexpected, the result shows that the impulse magnitudes of the loaded gait were slightly larger than normal gait in spite of normalization by masses of the body and an additional backpack. It is because the double support phase time of the loaded gait was longer than normal gait in Fig. 6.



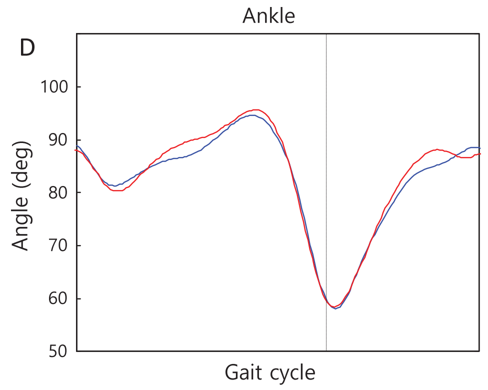


Fig. 4 Joint angles during one gait cycle. Clockwise is negative direction

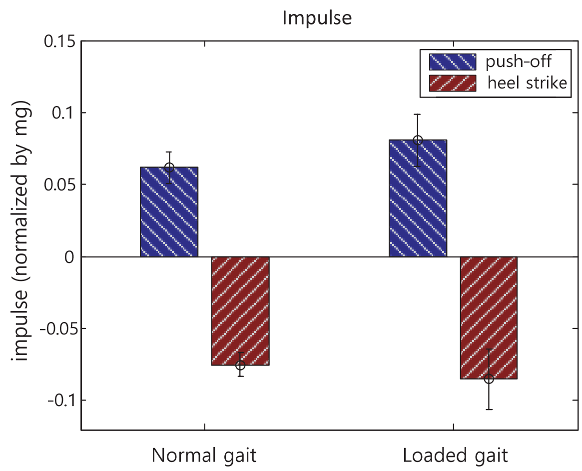


Fig. 5 Comparison of the impulse between normal and loaded gait. All impulses were normalized by the subject's body mass and the military backpack mass (+25.2 kg)

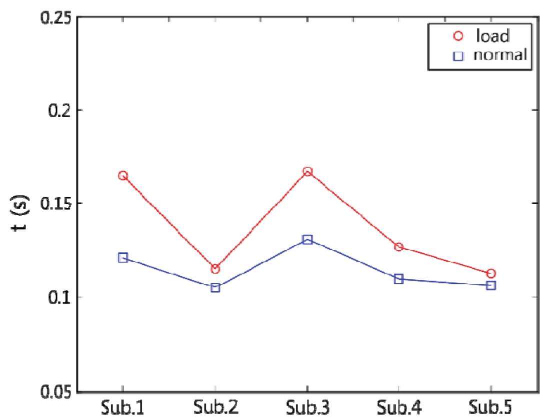


Fig. 6 Comparison of the double support phase time between the normal and loaded gait. It can be seen that the double support phase time of the loaded gait was increased to bear additional weight by backpack

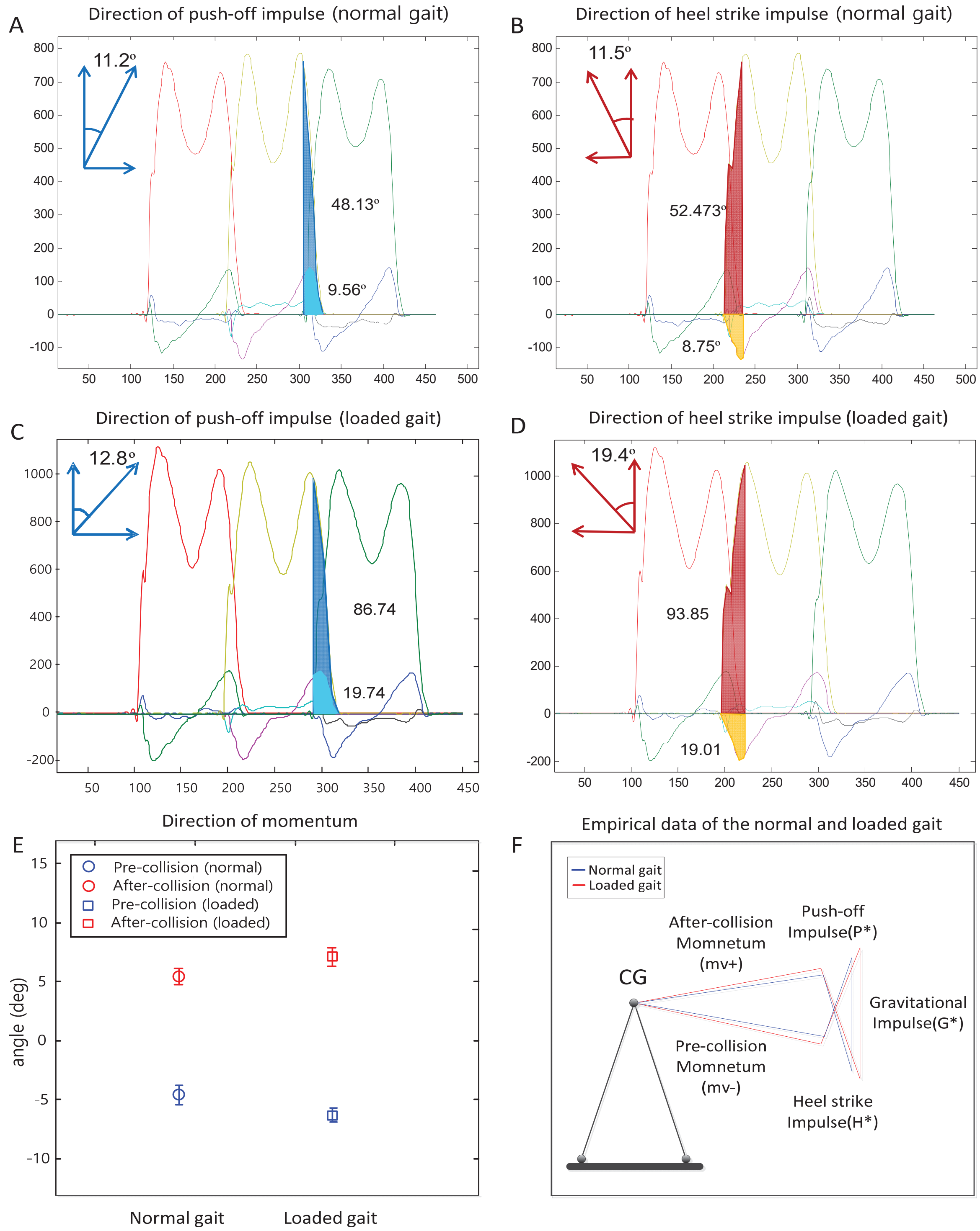


Fig. 7 Comparison of the impulse and momentum between the normal and loaded gait. In case of the loaded gait, the angle of the push-off impulse became smaller (A, C). It means the growth of the shear GRF was bigger than the growth of the vertical GRF. The angle of the heel strike impulse became larger than the normal gait (B, D). It is since the growth of the shear GRF is higher than that of the normal gait. Also, the pre-collision momentum (mv-) of the loaded gait moves downward and the after-collision momentum (mv+) of the loaded gait moves upward slightly compared to the normal (E). In the other words, the CG of the body during the collision moved up and down increasingly. Ultimately, the empirical data of the normal and loaded gait explain the momentum changing process during the step-to-step transition synthetically (F). Here, the difference of the gravitational impulse between the normal and loaded gait was due to the double support phase time variation in Fig. 6

C. Directions of the Impulse and Momentum

Comparison of the impulse and momentum directions between the normal, and loaded gait is shown in Fig. 7 (E). It is noted that the additional backpack load affect the direction of the impulse and momentum.

D. Mechanical Works on CG

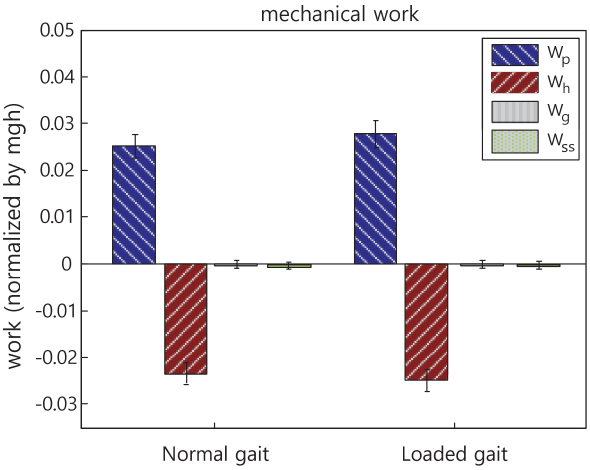


Fig. 8 Mechanical works between the normal and loaded gait. W_p, W_h, W_g and,W_{ss} are mechanical works done by push-off, heel strike, gravity, and single support phase, respectively

From the look of each mechanical work in Fig. 8, it is obvious that the gait pattern between the normal and loaded gait is practically the same. As stated before, the mechanical work done by the heel strike impulse should be compensated by the total energy inputs by the push-off impulse and hip torque to maintain the steady-state gait [5]. It is because using only the mechanical work done by the push off impulse is the most efficient way of walking. The same results were also shown even if the angle of the waist was varied from 0° to 40° during loaded gait [9], [10].

The loaded gait also used only the mechanical work done by push-off so as to minimize additional mechanical work done by the hip torque in common with the normal gait. However, it can be observed that the total mechanical work of the load gait by the push-off, heel strike impulse and hip torque increased compared to the normal gait. It is because the GRFs and the double support phase time are increased by the additional backpack mass (+25.2 kg).

IV. Concluding Remarks

In the present research, we obtained several different features of the normal and loaded gait based on the finite collision model and experimental data. First of all, impulses and momenta were computed to compare the normal gait with loaded gait. It can be known that the normalized impulses of the loaded gait were a little smaller than normal gait. It is because the double support phase time of the loaded gait had risen slightly to endure the additional backpack mass (25.2 kg). For such a reason, the mechanical works of the loaded gait also showed higher numerical values than the mechanical works of the normal gait despite normalization by body and backpack mass. However, it is almost certain that the energy lost by the heel strike of the loaded gait was compensated by the mechanical work done by push-off impulse in common with the normal gait and the single support work was close to zero. It means that Kuo's thesis [6] in which the least costly gait is achieved by providing all the energy with only push-off applied the loaded gait in the same manner. In the other words, it means that humans have a tendency to walk efficiently to minimize the total net work under any circumstances like load carriage. Besides, it can be known that the double support phase is the almost important step because the total works are determined by the step-to-step transition process.

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